DISSERTATIONES GEOLOGICAE UNIVERSITATIS TARTUENSIS

14

DISSERTATIONES GEOLOGICAE UNIVERSITATIS TARTUENSIS
14

SUBGLACIAL ENVIRONMENTS IN THE FORMATION OF DRUMLINS –
The case of the Saadjärve Drumlin Field, Estonia

MARIS RATTAS

TARTU UNIVERSITY
PRESS

Institute of Geology, Faculty of Biology and Geography, University of Tartu, Estonia.

This dissertation is accepted for the commencement of the degree of Doctor of Philosophy (in Geology) on February, 18, 2004 by the Council of the Faculty of Biology and Geography, University of Tartu.

Opponent: Professor Dr. Vitalijs Zelčs, University of Latvia, Latvia.

The thesis will be defended at the University of Tartu, Estonia, on May, 12, 2004 at 13.15 in Vanemuise 46, room 246.

The publication of this dissertation is granted by the University of Tartu.

Tartu Ülikooli Kirjastus
www.tyk.ut.ee
Tellimus nr. 93

CONTENTS

LIST OF ORIGINAL PUBLICATIONS

The present thesis is based on the following original papers which are referred to by their Roman numerals:

I **Rattas, M.** and Kalm, V. 2004. Glaciotectonic deformation patterns in Estonia. *Geological Quarterly,* **48** (1), 15–22.

II **Rattas, M.** and Kalm, V. 2001. Lithostratigraphy and distribution of tills in the Saadjärve Drumlin Field, east-central Estonia. *Proceedings of the Estonian Academy Sciences, Geology*, **50** (1), 24–42.

III **Rattas, M.** and Kalm, V. 2001. Glaciotectonic deformation pattern in the hummocky moraine in the distal part of the Saadjärve Drumlin Field, east-central Estonia. *Slovak Geological Magazine*, **7** (3), 243–246.

IV **Rattas, M.** and Piotrowski, J.A. 2003. Influence of bedrock permeability and till grain size on the formation of the Saadjärve drumlin field, Estonia, under an east-Baltic Weichselian ice stream. *Boreas*, **32** (1), 167–177.

V Raukas, A., Kalm, V., Karukäpp, R. and **Rattas, M.** 2003. Pleistocene Glaciations in Estonia. In: Ehlers, J. & Gibbard, P. (eds.). *Quaternary Glaciations – Extent and Chronology, Part 1: Europe*, 83–91. Elsevier, Amsterdam (CD included).

The author of this thesis is fully responsible for data collection, for the morphological, lithological, and sediment deformation analysis and for writing the manuscripts of papers I–IV. In the paper V, the author was responsible for writing in part and for digital data collection presented on CD. In the paper IV, hydraulic calculations and 50% of the writing was done by the prof. Dr.rer.nat.habil. Jan A. Piotrowski, Aarhus University, Denmark.

Rattas, M. 2004. Subglacial environments in the formation of drumlins – The case of the Saadjärve Drumlin Field, Estonia. Dissertationes Geologicae Universitatis Tartuensis, 14, Tartu University Press, 117 pp.

ABSTRACT

This research focuses on the morphological and structural complexity of drumlins in the Saadjärve Drumlin Field, Estonia and integrates the data of local subglacial environment conditions into the theory of drumlin formation. The Saadjärve Drumlin Field marks an onset area of a local ice stream, *i.e.* the Saadjärve ice stream of the Peribaltic (east-Baltic) Ice Sheet during the Late Weichselian glaciation around 12.5 ka BP. The drumlin field contains about 120 drumlins arranged in a distinct down-ice tapering funnel indicating converging ice flow. The diversity of morphological types of drumlins reflects the variable response of ice substratum to changing subglacial conditions at ice/bed interface in restricted areas.

An apparent correlation between drumlin size and shape, and between bedrock permeability and till granulometry suggests that drumlin formation was controlled by pore-water drainage from, and the texture of, the subglacially deforming till. The region with large, conspicuous drumlins coincides with areas of high-permeability bedrock, whereas the region with smaller, more elongated and densely spaced drumlins is underlain by low-permeability bedrock. Moreover, larger drumlins tend to be composed of coarser-grained till than smaller drumlins, whereas the finest-grained till is found in the inter-drumlin areas. These relationships indicate that drumlin growth was facilitated in areas of relatively well drained, coarse-grained till within a subglacially deforming bed.

The Late Weichselian Saadjärve ice stream flow resulted from a combination of subglacial bed deformation and basal sliding on a thin film of water. The inferred bed decoupling, localised sediment deformations and evidence of basal sliding indicate relatively large quantities of meltwater at the ice/bed interface. Faster ice flow was initiated in the south-eastern part of the area, where the build-up of subglacial pore-water pressure was the greatest. Once initiated, the ice stream area would have expanded up-ice affecting successively larger parts of the glacier, from which ice would eventually be funnelled into a narrow track at the most distal part of the drumlin field.

INTRODUCTION

Drumlins, the most attractive landforms created by glacier ice, have fascinated researchers for over the past one and a half centuries. However controversy remains with respect to the processes controlling their formation.

The term *drumlin* is derived from the Gaelic word *druim* meaning a rounded hill (Close 1867). A general definition of drumlin morphology is given by Menzies (1979a): *typically smooth, oval-shaped hills or hillocks of glacial drift resembling in morphology an inverted spoon or an egg half-buried along its long axis. Generally the steep, blunter end points in the up-ice direction and the gentler sloping, pointed end faces in the down-ice direction, these two ends being respectively known as the stoss and lee sides*. Drumlins tend to be concentrated in fields, often numbering several thousand individuals (Glückert 1973; Goldstein 1989; Zelčs & Dreimanis 1997). They vary in length, width, and height both between fields and within a single field. Drumlins are composed of a vast range of sediment types and sediment provenance. Sediment types and structures found in drumlins range from bedrock (so-called *rock-cored* drumlins) to sediments of almost of any glacial depositional environment, *i.e.* tills or stratified sediments (Menzies & Shilts, 1996). Sediment structures, such as folds, faults, fissures and joints, lenses and laminae, clast pavements, injections or intrusions, are detected in drumlins.

Drumlins are common glacial landforms in areas of former Pleistocene glaciations formed beneath the continental ice sheets and mountain glaciers. A few drumlins outcrop from current ice masses in Antarctica (Rabassa 1987), Iceland (Krüger 1987; Krüger & Thomsen 1984), Spitsbergen (Boulton 1987; Larsen *et al.* 2003) and Swiss Alps (Van der Meer 1983). Drumlins contain crucial sedimentary evidence of changes in the nature and pattern of subglacial deposition during a glacial cycle. Therefore, drumlin research has become fundamental to reconstruct glacier movement, to understand sediment re-distribution processes on a continental-scale, and ultimately to discern the course of past glaciations.

The diversity of drumlins in almost all aspects – size, shape, composition, topographic size, landform association and interrelationship with one another – has led to the development of many hypotheses to account for their formation (Menzies 1987). Drumlin formation can be grouped into three hypotheses:

(1) Formation due to anisotropic differences in subglacial debris due to dilatancy, pore-water dissipation, local freezing, localised helicoidal basal ice flow patterns or localised subglacial debris deformation (Smalley & Unwin 1968; Boulton 1987; Smalley & Piotrowski 1987; Menzies 1979b, 1989; Hart 1997; Hindmarsh 1998, 1999);

(2) formation by erosional moulding of previously deposited material within a subglacial environment with a limited amount of subglacial meltwater

activity (Whittecar & Mickelson 1979; Krüger & Thomsen 1984; Krüger 1987; Iverson 2000);

(3) formation due to the influence of active basal meltwater carving cavities beneath an ice mass and later infilling with stratified sediment or erosion of previously deposited sediments by subglacial meltwater at the upper ice/bed interface (Shaw 1983, 2002; Shaw & Sharp 1987; Shaw *et al*. 1989).

However, regardless of hypotheses, drumlins are subglacial bedforms whose formation is controlled by the interaction of subglacial ice/bed interfaces. In turn, the nature and mechanics of ice/bed interfaces are controlled by basal ice dynamics, subglacial sediments and bedrock, subglacial hydraulics and the thermal state of glacier bed (Drewry 1986; Boulton & Hindmarsh 1987; Menzies 1987, 1989; Menzies & Shilts 1996), all of which could have changed frequently in time and space. The formation of drumlins and associated subglacial bedforms (flutings, Rogen moraine *etc.*) result from a glaciodynamic response to changing ice/bed interface conditions, which depend on the interplay of rheological and glaciological properties of sediment and ice (Menzies 1987, 1989). Changes in ice and bed conditions may be widespread or local, and the diversity of drumlins and drumlin fields emphasise the significance of local conditions for their formation.

There are about one thousand drumlins and drumlin-like streamlined forms in Estonia (Rõuk & Raukas 1989; Raukas & Tavast 1994; Fig. 1). These are distributed unevenly and occur almost equally on uplands (Sakala and Pandivere) and their slopes or in lowland areas (Võrtsjärve depression). Some drumlin-like ridges have been noted on the bottom of the Gulf of Finland and the West Estonian Inland Sea (Väinameri) (Karukäpp & Vassiljev 1992). The main period of drumlin formation in Estonia was likely the general decay of the last, Late Weichselian glacier (13,500–11,000 ^{14}C years BP; Pirrus & Raukas 1996; Paper V), which was interrupted by temporary short-term glacial advances.

Six principal drumlin fields — the Saadjärve, Türi, Kolga-Jaani, Põltsamaa, Suure-Jaani and Raasiku — have been distinguished in Estonia (Fig. 1; *cf.* Rõuk & Raukas 1989), although many smaller and poorly developed drumlin groups and individual drumlins are common throughout Estonia. Most drumlins (including rock-cored drumlins of Türi and Raasiku) consist of a uniform till and were probably formed during a sinlge glacial advance (Barkla 1935; Rõuk 1972, 1990; Rõuk & Raukas 1989). More complicated drumlin structures have been observed in the Saadjärve Drumlin Field, where several till units are interbedded with thick layers of outwash sand and gravel. So-called stratified drumlins (Hausen 1913) might have formed during multiple ice advances or even during different glaciations and may also indicate an accretionary origin of drumlins (Paper II; Goldstein 1989).

Drumlins in Estonia are considered to be erosive-accumulative forms created by the gradual accumulation and continuous remolding beneath the actively moving ice (Orviku 1961; Kajak 1965b; Rõuk 1974a, 1974b, 1984; Rõuk & Raukas 1989). Progress in understanding subglacial environment enables glaciologists to focus on the morphological and structural complexity of drumlins and to analyse their formation in the context of other associated subglacial processes, landforms and sediments. The purpose of this study is to integrate knowledge on subglacial conditions, in which the drumlins have formed, and to interpret the local ice flow patterns under the Peribaltic (east-Baltic) Weichselian ice stream. The main observations of the study were carried out in the Saadjärve Drumlin Field, where individual drumlins have a distinct morphological expression, but vary greatly in size and spatial arrangement and have complicated internal structures (Fig. 1). The aims and objectives of this research are:

(1) to study in detail morphological and structural aspects of drumlins with special focus on features of subglacial environments (Papers II, III, IV);
(2) to analyse and interpret geological-sedimentological data in the context of subglacial processes related to the formation of drumlins and associated landforms (Papers II, III, IV);
(3) to estimate the influence of substratum and till rheology on the dynamics of drumlin forming processes (Paper IV);
(4) to interpret drumlin formation in relation to subglacial deforming bed processes (Papers III, IV);
(5) to propose a possible model of formation for the Saadjärve Drumlin Field (Papers II, III, IV);
(6) and to evaluate this model in the context of the past ice streaming, dynamics and evolution of the area (Papers I, II, III, IV, V).

This thesis is a compilation of five papers, which are summarised in the next section.

PAPER I

Rattas, M. and Kalm, V. 2004. Glaciotectonic deformation patterns in Estonia. *Geological Quarterly*, **48** (1), 15–22.

The Glaciotectonic Map of Estonia has been compiled, which represents a synthesis of current knowledge concerning the types and locations of glacio-tectonic landforms and structures in Estonia. Two principal types of glaciotectonic deformations are discussed: (a) bedrock dislocations associated with a rigid environment, and (b) soft bed deformations associated with unconsolidated drift masses. Most bedrock disturbances occurred in the narrow zone to the south of the Baltic Klint, in a tectonically crushed zone, where the fractured bedrock (limestone and dolomite) was readily broken, displaced and deformed by the moving glacier. Deformations of soft drift sediments were formed either proglacially by compressive deformation or subglacially by shearing movements. Ice marginal formations from the Late Weichselian deglaciation have been subjected to no large-scale compressive deformation. Therefore, most marginal formations were formed as the result of standstills of the ice margin, which being in equilibrium for only brief periods caused sediment deformation either at the ice margin or beneath the ice sole. Subglacial deformations of soft sediments show simple shear and ductile deformations, which are restricted to a thin deformed layer (Papers III, IV). The spatial organisation and efficiency of drainage beneath the local ice streams determined the deformational behaviour of sediments at the ice/bed interface in the formation of drumlins (Paper IV).

PAPER II

Rattas, M. and Kalm, V. 2001. Lithostratigraphy and distribution of tills in the Saadjärve Drumlin Field, east-central Estonia. *Proceedings of the Estonian Academy Sciences, Geology*, **50** (1), 24–42.

The Middle and Upper Pleistocene till beds with stratified meltwater deposits constitute the structure of the drumlins. Because the only interglacial deposits in the area (Karuküla Formation/Holsteinian) are found in the distal end of the drumlin field, the superposition and compositional data (grain-size distribution, mineralogical and chemical composition) of the tills have been used to correlate till beds lithostratigraphically. Four different till units were distinguished in the Saadjärve Drumlin Field. The lithostratigraphy and distribution of tills prove an accretionary origin of drumlins, which might have started to form during Saale glaciation. The uppermost, Late Weichselian till occurs as a continuous, distinct layer throughout the drumlin field and exemplifies the contemporary morphology of the drumlin field. Detail structural properties of this till are presented in Paper IV.

PAPER III

Rattas, M. and Kalm, V. 2001. Glaciotectonic deformation pattern in the hummocky moraine in the distal part of the Saadjärv Drumlin Field, east-central Estonia. *Slovak Geological Magazine*, **7** (3), 243–246.

This paper describes glaciotectonic deformation structures in the distal part of the Saadjärve Drumlin Field. Deformation structures are present in two different till layers, which are separated by undeformed meltwater sand and gravel deposits. These structures together with lithostratigraphic and superposition records suggest that deforming processes took place during at least two glacial episodes. The dislocations in the lower till (the Valgjärve till/Early-Middle? Weichselian), is a result of either ice push or caused by gravitational loading of a semi-liquid plastic material into the basal crevasses. The upper till (the Võrtsjärve till/Late Weichselian) was definitely deposited and deformed during the drumlinization event by deforming pressure from west to east.

PAPER IV

Rattas, M. and Piotrowski, J. A. 2003. Influence of bedrock permeability and till grain size on the formation of the Saadjärve drumlin field, Estonia, under an east-Baltic Weichselian ice stream. *Boreas*, **32** (1), 167–177.

The paper concerns the relationship between drumlin size and shape on one hand, and bedrock permeability and till granulometry on the other, suggesting that drumlin formation was controlled by pore-water drainage from and the texture of the subglacially deforming till. The region with large, conspicuous drumlins coincides with high-permeability bedrock, whereas the region with smaller, more elongated and densely spaced drumlins is underlain by low-permeability bedrock. Moreover, larger drumlins tend to be composed of coarser-grained till than smaller drumlins, while the finest-grained till occurs in the inter-drumlin areas. These relationships indicate that drumlin growth was facilitated in areas of relatively well-drained, coarse-grained till within a subglacially deforming bed. The Saadjärve Drumlin Field was formed by a second-rank ice stream — the Saadjärve ice stream — between two major ice lobes occupying the surrounding lowlands.

PAPER V

Raukas, A., Kalm, V., Karukäpp, R. & Rattas, M. 2003. Pleistocene Glaciations in Estonia. In: Ehlers, J. & Gibbard, P. (eds.). *Quaternary Glaciations – Extent and Chronology, Part 1: Europe,* 83–91. Elsevier, Amsterdam.

The paper summarises the glacial history of the Estonian territory during the Pleistocene. Two interglacials (Holsteinian and Eemian) and three glacials (Elsterian, Saalian and Weichselian) have been recognised by means of lithostratigraphical, biostratigraphical and geochronological data. No deposits of the Lower Pleistocene age are known and even the Middle Pleistocene sequence is incomplete. The ice-movement directions varied for each glaciation, which enabled correlation of till units based on lithological composition inherited from the bedrock (see Paper II). The glacial relief of Estonia originates principally from the Late Weichselian glaciation. Ice-marginal positions are marked in the present topography by interrupted chains of endmoraines and glaciofluvial formations, which formed either as the result of standstills of the ice margin or in some cases as a result of readvances. Four ice-marginal zones have been indirectly dated (^{14}C years): Haanja (ca 13,500 BP), Otepää (12,800–12,600 BP), Pandivere (12,480–12,230 BP) and Palivere (11,800–11,630 BP). The Sakala phase, represented by endmoraines on the Sakala Upland, and with eskers and kame fields in the Saadjärve Drumlin Field area (see Fig. 1), is estimated to date between the Otepää and Pandivere phases.

The digital data on glacial limits, morphologically expressed endmoraines, distribution of ice-dammed lakes and location of key sections through which the glacial limits are defined and dated are presented on CD.

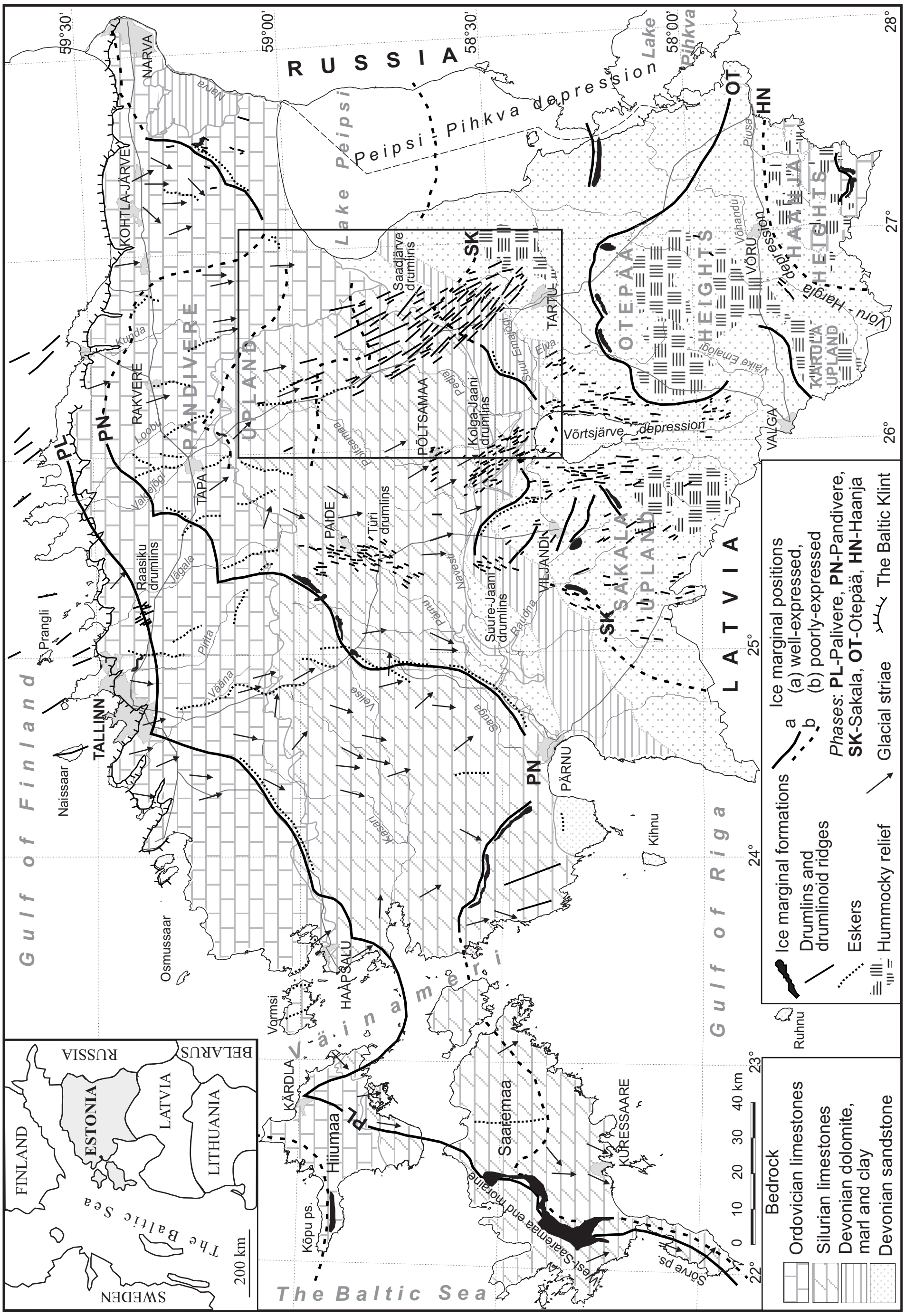

Figure 1. Bedrock geology and glacial depositional landforms of Estonia. Retangle – the study area.

1. GEOLOGICAL BACKGROUND AND INVESTIGATION HISTORY

The Saadjärve Drumlin Field is located in east-central Estonia on a lee-side of the bedrock elevation (Pandivere Upland) and represents, as a whole, a watershed upland between the Central-Estonian Plain and the Lake Peipsi depression (Fig. 2). The drumlin field contains about 120 drumlins and drumlinoid ridges within an area of 1200 km^2 (Rõuk 1974b, 1976, 1987; Rõuk & Raukas 1989; PLATE I: A, B). In accordance with the principal direction of ice movement during the Late Weichselian (Kajak 1963; Raukas 1978; Karukäpp & Tavast 1985), the drumlins are oriented from NW to SE. The drumlin field is about 55 km long, the maximum width is 27 km on the proximal (NW) end, and less than 5 km on the distal (SE) end, giving the entire field a distinct shape of a down-ice tapering wedge. The overall shape (down-ice convergence) of the drumlin field is unusual compared to most drumlin fields, whose width often increases down-ice (*e.g.* Trenhaile 1971; Glückert 1987; Mooers 1989).

1.1. Bedrock

The Pandivere Upland is a prominent bedrock unit reaching 130 m a.s.l. in the NW part of the study area (Fig. 2) and descending to about 40–70 m a.s.l. on the Central-Estonian Plain (Tavast & Raukas 1982) and to *c.* 60 m b.s.l. in the centre of the Lake Peipsi depression (Hang *et al.* 2001). In the central part of the Saadjärve Drumlin Field the bedrock falls to c. 20 m a.s.l., from where it gradually rises towards the south on the Devonian Plateau. Consequently, after overrunning the Pandivere Upland, ice sheets moved down-slope over the drumlin field with an altitude difference of 110 m over a horizontal distance of 60 km (general dip angle about 0.1°). Accelerating ice flow in the lee of the Pandivere upland has been suggested as a possible factor facilitating drumlin formation (Raukas & Tavast 1994).

Two ancient valleys, deeply incised into the Devonian terrigenous bedrock, cross the drumlin field in the NE–SW direction. The floor of the valleys lies about 27 m b.s.l. near Lake Peipsi dipping south-westerly to about 100 m b.s.l. (Eltermann & Raukas 1963; Kajak 1965a, 1965b; Tavast & Raukas 1982). The valleys, formed in the pre-Quaternary period, contain mainly several till beds and accompanying aquaglacial deposits (Kajak 1963, 1965a).

Bedrock lithology of the study area consists of Paleozoic sedimentary formations: the northern part consists of Upper Ordovician and the Lower Silurian carbonate rocks (limestone and dolomite) and the southern part of Middle Devonian terrigenous rocks (Figs 1, 2). The Paleozoic sedimentary rocks dip monoclinally southward at an angle of 6–18' (Puura & Mardla 1972; Rõuk & Raukas 1989). This suggests that Devonian rocks may have extended more northerly before the glaciations, and the repeated glacial erosion has "shifted" southwards the area of easily erodable Devonian terrigenous rocks, as indicated by the presence outcropping "islands" of Devonian rocks some kilometres north of the continuous outcrop area.

The Lower Silurian dolomitized limestone and dolomite (Raikküla and Juuru regional stages), which occur in the north-western part of the drumlin field, are extremely cavernous with abundant cracks, fissures, channels, and karst cavities (Heinsalu 1977). Karst cavities can form half-metre-high canals, which can extend into interconnected metre-large voids close to the ground surface (Perens & Vallner 1997). According to pump tests and flowmeter logging the bulk lateral hydraulic conductivity of these rocks varies from 1.2–5.8 • 10^{-4} m/s (Perens & Vallner 1997), and the area is characterised by bedrock substratum with high water permeability. In contrast, the central part of the drumlin field is underlain by siltstones, dolomites, marls and clays of the Middle Devonian Narva Stage. These layers form the uppermost regional bedrock aquitard with a low lateral hydraulic conductivity of between 10^{-9} to 10^{-11} m/s (Perens & Vallner 1997). Therefore, the central zone of the drumlin field is characterised by bedrock substratum with very low water permeability. The distal end of the drumlin field is underlain by the rocks of Aruküla Stage (Middle Devonian) consisting of sand- and siltstones interbedded with clay. The mean hydraulic conductivity is between 1.2–3.5 • 10^{-5} m/s (Perens & Vallner 1997), which is similar to that of the Silurian rocks in the north.

Consequently, the study area can be separated into three zones with respect to hydraulic conductivity of the bedrock — northern and southernmost zones of high water permeability and a central zone with low water permeability. The spatial organisation and drainage efficiency of subglacial meltwater beneath the ice streams determine the rheological behaviour of sediments in ice/bed interface and ice flow dynamics (Boulton & Hindmarsh 1987; Boulton *et al.* 1993; Piotrowski 1997; Piotrowski & Tulaczyk 1999; Boulton *et al.* 2001), which under certain circumstances may result the drumlin formation (Menzies 1987). Hereby the form of drumlins can be related to variations in substratum and/or bedrock hydraulic properties, *i.e.* ability to drain meltwater from the ice/bed interface (Paper IV).

1.2. Quaternary

The overall thickness of the Quaternary deposits varies between 0 m at locales on the Pandivere Upland to over 100 m in the incisions valleys. The thickness of the Quaternary deposits in the drumlins reaches 60–70 m. The Pleistocene sequence comprises the Middle and Upper Pleistocene tills and aqueoglacial deposits (Kajak 1965b; Paper II), whereas the only interglacial deposits (the Holsteinian/Karuküla Formation) occur in the very distal end of the drumlin field (Liivrand & Saarse 1983; Levkov & Liivrand 1988; Liivrand 1991). The Holocene sediments, up to 15 m thick, predominantly gyttja, lake lime, and peat, occur in bogs, lakes and interstitial troughs between the drumlins.

In addition to drumlins, other subglacial landforms (eskers, kames and hummocky moraine) in the study area (Figs. 2, 3) were formed during the decay of stagnant ice. Hummocky moraine is found between the distal end of the drumlin field and the Emajõgi River Valley (Rõuk 1977). Hummocks are 2–12 m high and transverse the ice flow. Hummocks is composed of sandy clayey till interlayered with chaotic layers, lenses and pods of sand (Rõuk 1977). The hummock belt marks the position of the outer stagnant margins of ice lobes, which were probably in equilibrium for short periods, causing subglacial sediment deformations, behind which the drumlins were formed (Paper III). Corrugated hummocks are also superimposed on a few drumlins in the distal part of the drumlin field, but they show slightly ductile internal sediment deformations caused by shearing of active ice (Papers I, III, IV).

The marginal esker at Laeva, the esker system that extends from the Pandivere upland and ends with glaciofluvial delta near Siimusti, and kames between the drumlin field and the Lake Peipsi basin were formed during the Sakala phase of the Late Weichselian deglaciation (Raukas *et al.* 1971; Pirrus & Raukas 1996; Paper V). A pause in ice flow is also evident north of the drumlin field, along Koeru-Emumäe-Torma line, which features few ice-marginal formations. Individual morainic hillocks, eskers and kames are also superimposed upon drumlins. Transverse meltwater channels cross the drumlins in the central part of the drumlin field, forming a meltwater drainage system between Lake Peipsi and the Võrtsjärve depressions.

1.3. Investigation history

Geological investigation of the Saadjärve Drumlin Field has been conducted since the end of the 19th century (see Paper II). The first comprehensive, mostly morphological descriptions of the drumlins were published by B. Doss (1896, 1906), L. zur Mühlen (1910, 1912) and H. Hausen (1913). Detailed lithological and stratigraphical studies were based on geological mapping on 1:200 000 scale (Eltermann & Raukas 1963; Kajak 1965b; Raukas 1978). Five different-age till beds, based chiefly on petrography, were distinguished in the drumlin field (Kajak 1965b), whereas the interglacial and/or interstadial deposits between different till beds are absent. In the 1980s, much new information, primarily lithological and stratigraphical data, was obtained through geological mapping on 1:50 000 scale. The first interpretation of these data was done by the author (Rattas 1997) and is presented in this thesis (Paper II). Morphological description and classification of the drumlins and preliminary till texture observations were done by A.-M. Rõuk (1974a, 1974b). A number of theories to account for the formation of these drumlins (Orviku 1958, 1961; Kajak 1965b; Rõuk 1974b, 1976, 1984; Rõuk & Raukas 1989) arose from the different ideas on drumlin formation proposed during earlier research (Menzies 1979a, 1984). Therefore, the first theories viewed the Saadjärve drumlins strictly as either erosional landforms (Doss 1896; zur Mühlen 1910) or only as depositional features (Hausen 1913). Later, both these processes have been given equal merit with respect to drumlin formation and genetic aspect of drumlins has been discussed from the standpoints of specific glaciodynamic conditions of ice and morphological evolution (Orviku 1961; Kajak 1965b; Rõuk 1984; Rõuk & Raukas 1989). Topography of the bedrock surface has been regarded as one of the factors controlling the formation of drumlins in Estonia, as it caused the form of ice flows and streams with different size and velocity (Raukas & Tavast 1994).

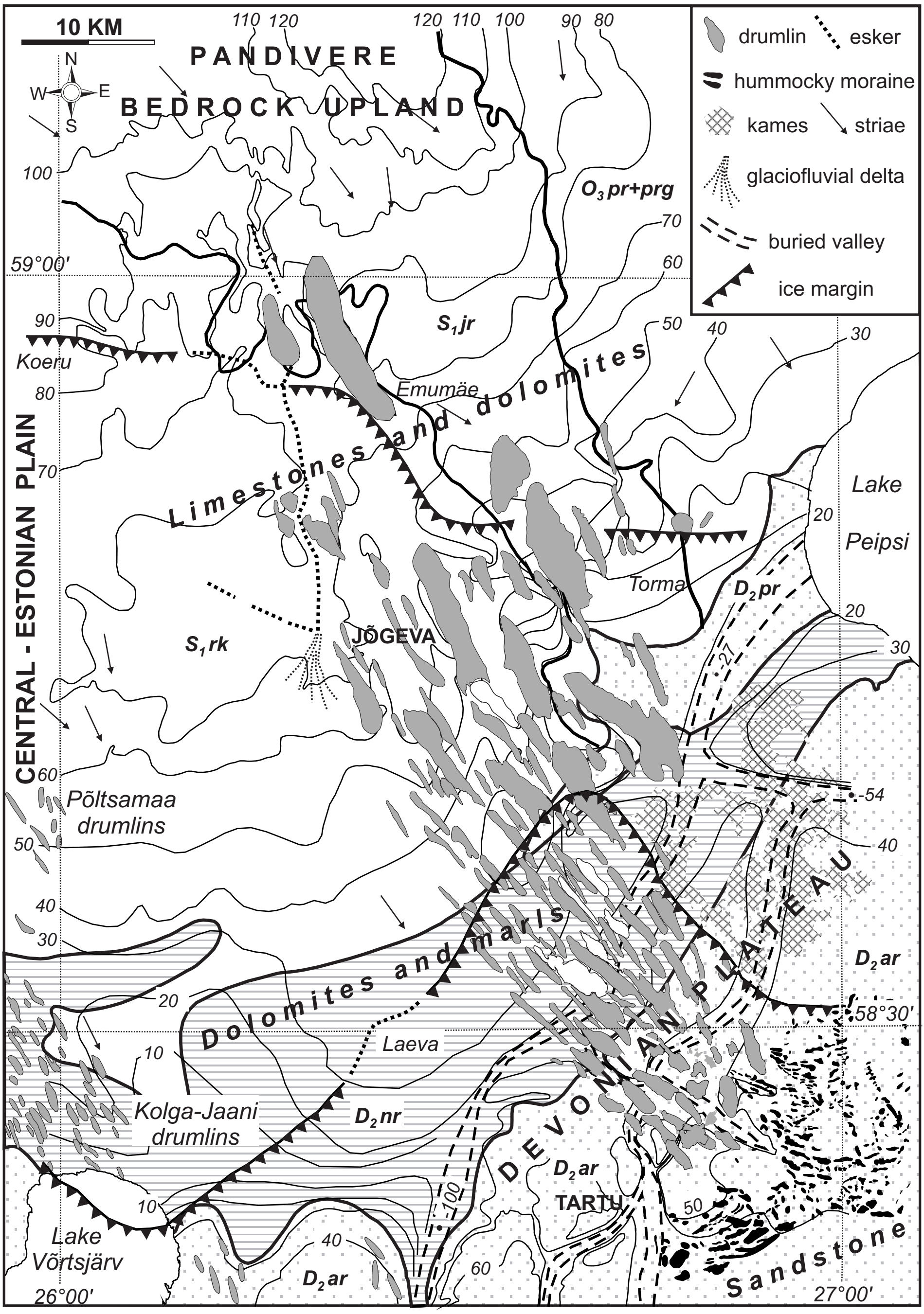

Figure 2. Bedrock surface topography (m a.s.l.) and major glacial landforms in east-central Estonia. Bedrock formations: O_3pr+prg – the Upper Ordovician, Pirgu and Porkuni regional stages; S_1rk and S_1jr – the Lower Silurian, Raikküla and Juuru stages; D_2pr, D_2nr and D_2ar – the Middle Devonian, Pärnu, Narva and Aruküla stages.

2. METHODS AND DATA

The geological-sedimentological data on drumlins were obtained during geological mapping on 1:200 000 and 1:50 000 scale by the Geological Survey of Estonia. The author of this thesis participated in the geological mapping (1:50 000) as a geologist in 1989–1993. In total, 190 boreholes have been drilled in the area, of which 65 penetrate the entire Quaternary cover (see Paper II: *Fig. 1*). Sampling and macroscopic descriptions of sediments were mostly done in the field during drilling. All existing exposures were investigated with special attention paid to sedimentary structures and glaciotectonic deformations (*Fig. 3*).

Previous detailed stratigraphic and sedimentological work (Eltermann & Raukas 1963; Kajak 1965b; Rõuk 1974a, 1974b; Raukas 1978) was incorporated and combined with new observations in order to integrate all available information from the Saadjärve Drumlin Field pertinent to subglacial sedimentation and drumlin formation. Conventional air photos, geological maps and well log data were evaluated for regional background information.

2.1. Morphological methods

The delineation and three-dimensional analysis of drumlin morphology was made from digital topographical maps on 1:25 000 scale with contour intervals of 2.5 m with *MapInfo Professional*® software. A total of 118 drumlins were identified within the Saadjärve Drumlin Field. Three primary morphometric parameters, length (l), width (w) and height (h) were measured for each drumlin. In order to express the shape of drumlins, l/w ratio and Chorley's (1959) parameter (k) were calculated. The k value is a dimensionless number expressing the elongation of a drumlin calculated from the equation

$$k = l^2\pi/4A$$

where l is the length of drumlin's long axis and A is the area of a lemniscate loop into which the drumlin is fitted. The value k increases from 1 (a circular drumlin) with drumlin elongation. The area of a lemniscate loop (A) was calculated by assuming that the shape of the drumlin base is approximately elliptical (*i.e.* $A=lw/4$). Since the early work of Smalley & Unwin (1968), this parameter has been used to describe drumlin morphometry (*e.g.* Trenhaile 1975; Harry & Trenhaile 1987; Piotrowski 1987; Wysota 1994), because it elegantly combines shape description with the mode of formation. Even some researchers have affirmed its merits to describe drumlin shape and mechanics of drumlin formation (Evans 1987; Smalley & Warburton 1994). This research marks the first time ratios of drumlin dimensions (l, w and h) and the area (A) were incorporated in the morphological description of drumlins in the Saadjärve

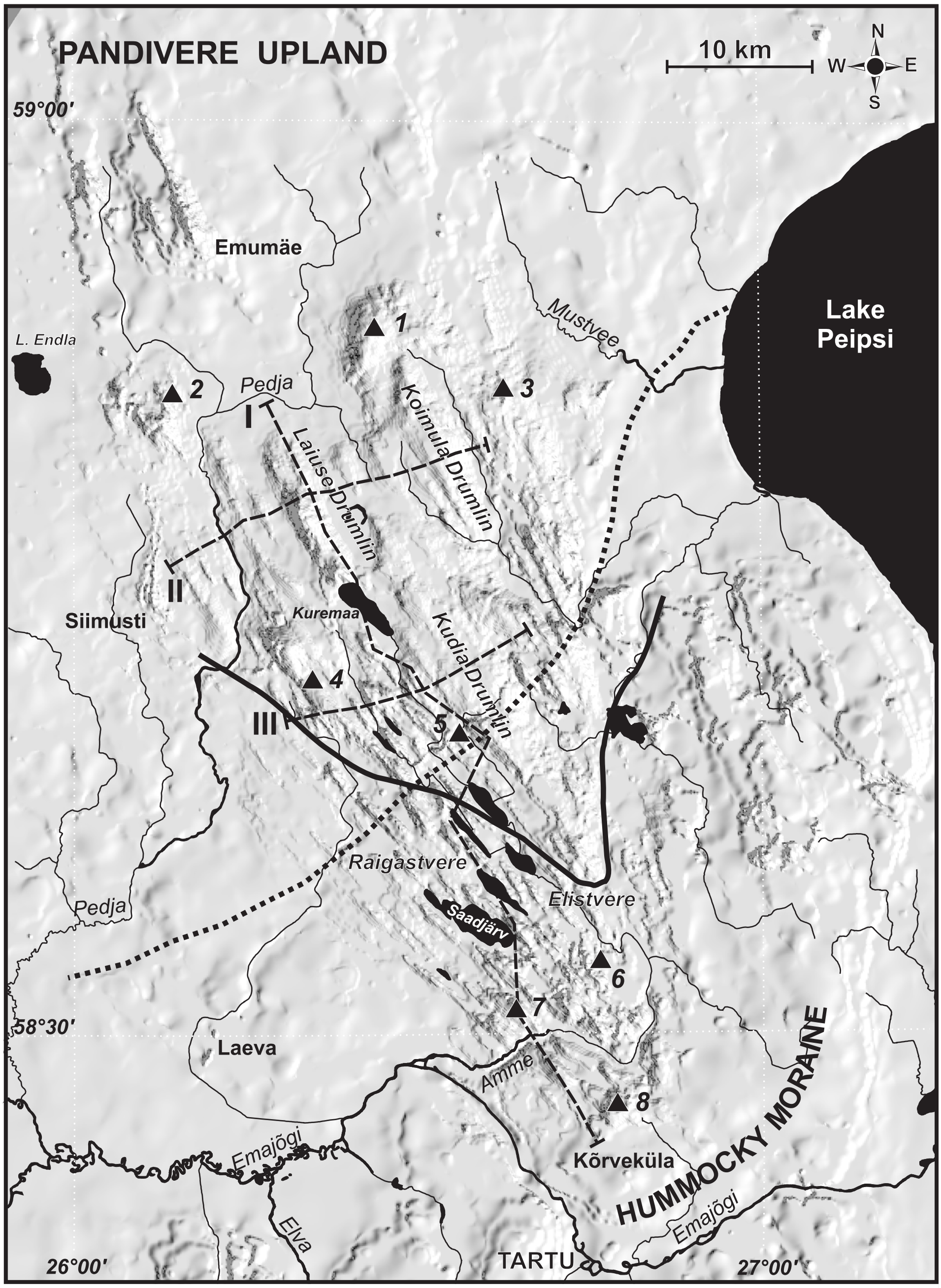

Figure 3. Digital terrain model of the Saadjärve Drumlin Field (based on 2.5 m interval contour lines, exaggeration 20x). Solid line – boundary between big and small drumlins; dotted line – boundary between Silurian and Devonian bedrock formations; dashed line – cross-section line. Studied outcrops 1–8.

Drumlin Field. The decipherment of basal outlines of drumlins is always subject to a degree of subjectivity, therefore there are small differences in drumlin morphometry compared with previous data (Rõuk 1974b).

2.2. Sedimentological studies

Drumlin sedimentology was investigated with special focus on sedimentary structure, texture, lithology and glaciotectonic deformation at eight sand and gravel pits and at natural exposures. Due to a scarcity of suitable sections most data on the internal composition of the drumlins emanated from boreholes and therefore, the textural description of the lower sediment units was impossible.

Till fabrics were measured on at least 30 elongated (*a–b* axis ratio >1.5) clasts at each site. Strike and dip of glaciotectonic structural elements were measured for deformed strata. Data are presented on the equal-area, lower-hemisphere Schmidt net and statistical data were calculated using *StereoNet 3.03* software.

2.3. Lithology

A total of 360 till samples, taken from sediment cores, were analysed for grain-size, mineralogical and chemical compositions in the laboratory of the Geological Survey of Estonia (Paper II). Grain-size distribution was determined for the fraction finer than 2 mm. Clay (<0.002 mm) and silt (0.002–0.01; 0.01–0.05 mm) fractions were determined using pipette method; sand fractions (2–1, 1–0.5, 0.5–0.25, 0.25–0.1, 0.1–0.05 mm) by wet-sieving. For the grain-size analysis four grain-size characteristic coefficients (Wentworth 1936) were determined: arithmetic mean – M_d (mean grain-size), standard deviation – σ (sorting), coefficient of asymmetry – S_k, and excess – E. The mineralogical composition of tills was analysed from the 0.1–0.25 mm fraction by examination under light microscope. Heavy minerals were separation with bromophorm diluted to a density of 2.89 g/cm^3. Approximately 300 light and 500 heavy mineral grains were counted in each sample and are presented as volume percentages (vol%) and weight percentages (wt%). Chemical composition was determined for the <1 mm fraction by wet-silicate analysis.

3. RESULTS

3.1. Drumlin morphology

Any theory of drumlin origin accounts for the systematic variation in drumlin morphology within drumlin fields. This variation is related to theoretical energy gradients within the subglacial environment, which affect drumlin genesis (Smalley & Unwin 1968; Trenhaile 1975; Smalley & Piotrowski 1987; Smalley & Warburton 1994). Although the smooth, clearly discernible elongated shapes define drumlins, they may show considerable variation in form, as well as in size and spatial arrangement within the entire drumlin field.

Drumlins vary greatly in shape, size and spatial arrangement within the Saadjärve Drumlin Field (Fig. 3). The major shape categories include (Fig. 4; *cf.* Rõuk 1974b; Rõuk & Raukas 1989):

(1) typical drumlins with well-defined streamlined outlines characterised by steep, high stoss sides and tapering low lee sides (subtypes 1a-d in Fig. 4),
(2) strongly elongated drumlins with isometric shapes (PLATE I: B) often arranged in an echelon (subtype 2),
(3) reversed drumlins which possess all the characteristics of classical drumlins, but whose stoss ends face down-ice (subtypes 3a, b), and
(4) complex drumlins with irregular shapes possibly consisting of multiple superimposed drumlins of different sizes. Twin (subtype 4a) and triplet (4b) drumlins are common. Several ridges have grown together at their proximal or in the middle to form a huge drumlin shield (4c).

Many drumlins have either a two-branched stoss end or a long narrow "tail". The former are termed barchanoid drumlins (subtypes 1a, 1d, 4c) and could form by the accumulation of sediment around a resistant, unyielding mass of sediment so that sediment moves over the summit and around the flanks of the core, thus leaving lee-side "horns" (Boulton 1987). The second type, spindle-shaped drumlins (subtype 1b) are those in which enough sediment has moved into the lee-side position to form a single continuous "tail". These could reflect either an early stage of drumlin formation, or sediment starvation (Boulton 1987).

Typically the transverse cross section of drumlins is asymmetrical. One side has a distinctly convex-concave profile, with the steepest slope angle less than 5°, whereas the other side is rectilinear and may have a slope of up to 15°. Throughout the drumlin field the steeper slopes are consistently on the north-east-facing sides of the drumlins, only few drumlins have the steeper south-west-facing slope.

Individual drumlins in the Saadjärve Drumlins Field may be regular, compound or asymmetrical in long-profile as well as in transverse-profile. Rõuk (1974b) divides the drumlin field into two subregions: the northern less drumlinised and the southern more drumlinised, and into several districts containing drumlins with similar or typical morphology. The diversity of drumlin morphology in the Saadjärve Drumlins Field reflects the variable response to changing ice/bed interface conditions in very restricted areas.

Two main parameters were used to describe drumlin morphometry: the length to wide ratio (*l/w*) and Chorley's *k*-value. A summary of drumlin morphometry is presented in Table 1. The frequency distribution of drumlin sizes is bimodal with a boundary at around 5 km^2 of the lemniscate loop area (*A*), which was used to divide the population into "big" and "small" drumlins. Spatial distribution of these two populations also differentiates the field into a north-western region dominated by big drumlins (A>5 km^2) and south-eastern region with chiefly small drumlins (A<5 km^2). The big drumlins, relatively flat and less elongated (*l/w*=3.1 and *k*=3.15), are typically 7–13 km long, 1–3.5 km wide, and up to 60 m high (PLATE I: A). Smaller drumlins, dominated in south-eastern region, are more elongated (*l/w*=6.8 and *k*=4.96) with lengths varying between 1.4–6 km, widths between 0.1–1 km, and heights up to 23 m (PLATE I: B). Furthermore, drumlins in the south-eastern region are more densely spaced, which makes this region appear more compact than the north-western region.

The model of Smalley & Unwin (1968), further elaborated by Trenhaile (1975), predicts that drumlins, in response to a progressive decrease in ice thickness and velocity, will be smaller and less elongated towards the down-ice margin of the drumlin field. Drumlin morphology in the Saadjärve Drumlin Field show that drumlins are indeed smaller, yet more elongated towards the down-ice margin, which indicates an increase in ice velocity in this direction. Furthermore, the boundary between the "big" and "small" drumlin regions coincides with the bedrock contact zone between the Silurian and Devonian formations (Fig. 3) noted for their different hydraulic conductivity (see chapter 1.1). Because ice-movement dynamics are influenced by the meltwater drainage through the substratum, bedrock hydraulic properties can affect the formation of drumlins resulting in a varied spatial arrangement in the drumlin field (Paper IV).

Table 1. Summary of drumlin morphometry. *l* – length; *w* – width; *h* – height; *A* – area of the lemniscate loop into which a drumlin is fitted; *k* – drumlin elongation parameter (Chorley 1959); SD – Standard Deviation; x – number of drumlins.

	Big drumlins A>5 km^2 (x=18)	Small drumlins A<5 km^2 (x=100)
l (km)		
Min	5.30	1.35
Max	12.45	5.83
w (km)		
Min	1.12	0.11
Max	3.50	1.00
h (m)		
Min	15.0	5.0
Max	60.0	23.0
l/w ratio		
Min	2.70	3.28
Max	5.98	15.95
Mean	3.1	6.8
SD	0.80	2.37
w/l ratio		
Min	0.17	0.06
Max	0.37	0.30
Mean	0.26	0.17
SD	0.04	0.06
A [km^2]		
Min	5.65	0.30
Max	24.03	4.69
Mean	12.00	1.75
SD	5.50	1.10
Chorley's *k*		
Min	2.28	1.97
Max	5.74	9.79
Mean	3.15	4.96
SD	0.92	1.58

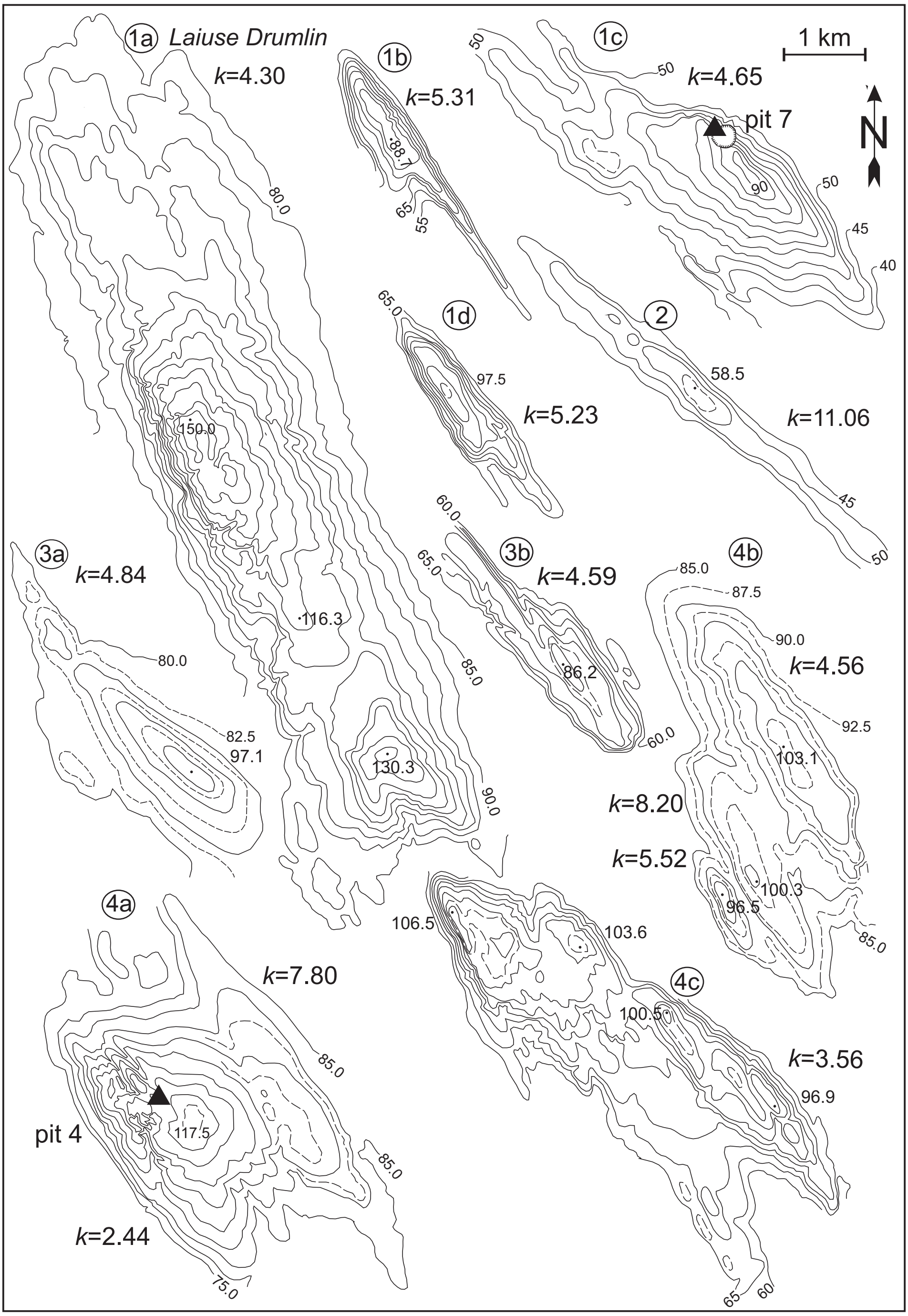

Figure 4. Various morphological types of drumlins in the Saadjärve Drumlin Field. Subtypes: 1a-1d – typical drumlins; 2 – elongated symmetric drumlin; 3a, 3b – reversed drumlins; 4 – complex drumlins: 4a – twin-drumlin, 4b – triplet-drumlin, 4c – drumlin shield; *k* – Chorley's parameter.

3.2. Internal composition of drumlins

Four lithostratigraphical till horizons have been identified in the area based on distinct textural and mineralogical characteristics (see Paper II: *Table 2*). The oldest, Elsterian till is restricted to the bottom of deep buried valleys and plays no role in drumlin formation (Fig. 5). The Saalian sequence is represented by a uniform till with thin lenses of outwash sand deposits and forms the oldest core of several drumlins. The Saalian till is overlain by a widespread Early Weichselian till. In the north-western part of the field the Early Weichselian till is covered by a thick (up to 60 m) outwash sand and gravel deposited in a depression in the lee of the Pandivere Upland as an extensive outwash plain. The outwash wedges out approximately at the Silurian/Devonian bedrock boundary. The topmost till (the youngest) from the Late Weichselian glaciation occurs throughout the drumlin field as a continuous, distinct layer ranging in thickness from a few meters to about 40 m. Lithostratigraphical correlation of till horizons through the drumlin field is presented in Paper II.

According to sediment distribution three major categories of drumlins can be distinguished:

(1) drumlins consisting of the youngest till only. These drumlins occur mostly in the western part of the field and rest directly on the bedrock;
(2) drumlins composed of an older till at the base and overlain by the youngest till, most commonly occurring in the central part of the drumlin field;
(3) drumlins with outwash cores resting on older tills and covered by a veneer of the youngest till. These drumlins are sporadically found in both the proximal and the distal part of the drumlin field (PLATE I: C–F).

The contemporary morphology of the drumlin field is given by the uppermost, the Late Weichselian till, even though the geology of some drumlins suggests older drumlinizing events. Beneath the uppermost till cover, the drumlins feature mostly an undisturbed core of older tills or outwash sediments.

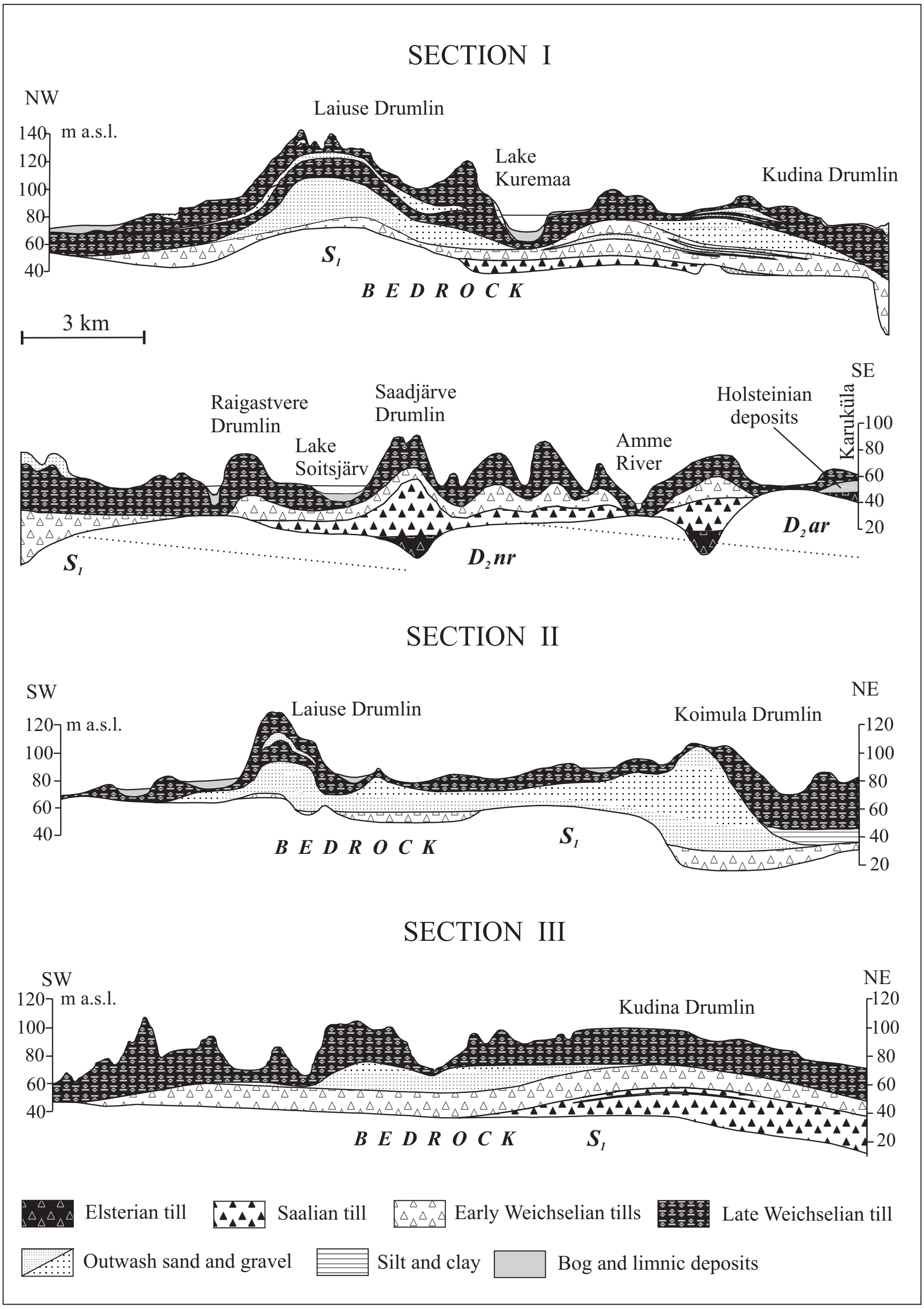

Figure 5. Geological cross-sections through the Saadjärve Drumlin Field. Location of sections in Fig. 3.

3.3. Structure of the drumlin-forming till

The uppermost, the Late Weichselian, hereafter the drumlin-forming till, varies considerably both in texture and structure, reflecting in part differences in bedrock lithology. Till overlying the Ordovician-Silurian carbonate rocks is typically grey, mostly massive sandy clayey till, whereas the till on the Devonian bedrock is reddish-brown, matrix-supported sandy till (PLATE II). The mean grain size of the drumlin-forming till varies greatly, from 0.004 to 0.269 mm (Table 2). In order to test a possible till texture/landform relationship in the drumlin field, mean grain sizes from big drumlins, small drumlins and the inter-drumlin areas were compared, respectively (Paper IV). This comparison revealed that large drumlins are composed of coarser till (Md = 0.069 mm), with the average texture of 61% sand, 26% silt and 13% clay. Small drumlins consist of slightly finer-grained till (Md = 0.051 mm), but the average texture is very close to the till of large drumlins (59% sand, 28% silt and 13% clay). The till in the inter-drumlin areas has the finest grain-size (Md = 0.040 mm), the result of higher clay-silt fractions (55% sand, 30% silt and 15% clay), compared to the till in drumlins.

Fabric analyses in the drumlin-forming till have variable strength (S1 eigenvalues between 0.530 and 0.770), showing a prevailing direction of ice movement from north-west to south-east, on average 290° (Fig. 6). The fabric striation of a few drumlins in the eastern part of the drumlin field is oriented north-south. The striation of fabrics and a dominant down-ice dip of the clasts are consistent with the orientation of drumlins. Up-slope dip of the clasts towards the lee-side of the drumlins has been observed on the slopes of several drumlins. This may have been caused by the dynamic extrusion on the fabrics from a zone of higher pressure on slopes towards a lower pressure zone on the top of the drumlins (Rõuk 1974a). The striation can vary up to 40° through the till section, but reveal no obvious trends in vertical profiles. A boulder pavement is found at the base of drumlin-forming till of a few drumlins, where the stones either rest horizontally or dip slightly down-ice (to the SE).

The drumlin-forming till often contains subglacial soft-sediment deformation structures (Papers I, III, IV). Intensely contorted lenses and pockets of outwash sand are visible throughout the till profile. Contacts between the outwash pods and the matrix of the surrounding till are smudged and gradational, indicating mixing and granular sediment diffusion (Paper IV: *Fig. 4*). Similar structures and the nature of sand/till contact in particular are predicted by the deformation model of Weertman (1968) and more recently elaborated by Piotrowski & Tulaczyk (1999) and Hooyer & Iverson (2000), but contested by Boulton *et al.* (2001) with respect to subglacial soft-sediment deformation. At sites where the till rests directly on outwash sediments, the till basal contact is typically gradational with a several-cm-thick transition zone enriched in material derived from the substratum (Paper IV: *Fig. 5*; PLATE I: C, D). Such structures indicate that soft drumlin-forming till was subjected to ductile deformation. In a few drumlins the boundary between till and outwash deposits is sharp with none of the visible vertical change in till texture and no diffusive mixing expected in a deforming bed (PLATE I: E). At these sites the bed was either not deformed or restricted to a thin (mm-scale) zone (Piotrowski *et al.* 2001). The largest deformation structures due to ice-induced shear were noted in the distal part of the drumlin field (Papers I, III; PLATE II). Large-scale ice-induced shear structures were observed on the flank of the drumlin. The drumlin-forming till is folded in its lower part and a large sand lens has been thrust into the till. The till contains also thin subhorizontal layers and lenses of waterlain deposits. These could be interpreted as drag or washout features formed during basal decoupling. The measurements of structural elements show a dominant stress direction from the west or north-west (Fig. 6).

Table 2. Summary of grain size data from the drumlin-forming till. *Md* – median; SD – Standard Deviation; x – number of drumlins; n – number of samples analysed.

	Big drumlins (x=18, n=75)	Small drumlins (x=100, n=186)	Inter-drumlin areas (n=30)
Sand (0.05–2 mm)			
Min	57.28	27.18	35.74
Max	79.02	80.28	69.76
Mean	61.34	58.91	54.70
SD	7.87	8.04	6.69
Silt (0.002–0.05 mm)			
Min	6.52	12.16	13.91
Max	46.82	64.71	47.77
Mean	25.67	28.35	30.67
SD	6.80	6.82	6.69
Clay (<0.002 mm)			
Min	3.99	3.56	10.64
Max	26.66	27.01	26.08
Mean	12.99	12.74	14.63
SD	3.42	3.61	2.91
Md [mm]			
Min	0.022	0.004	0.021
Max	0.292	0.169	0.163
Mean	0.069	0.051	0.040
SD	0.050	0.019	0.009

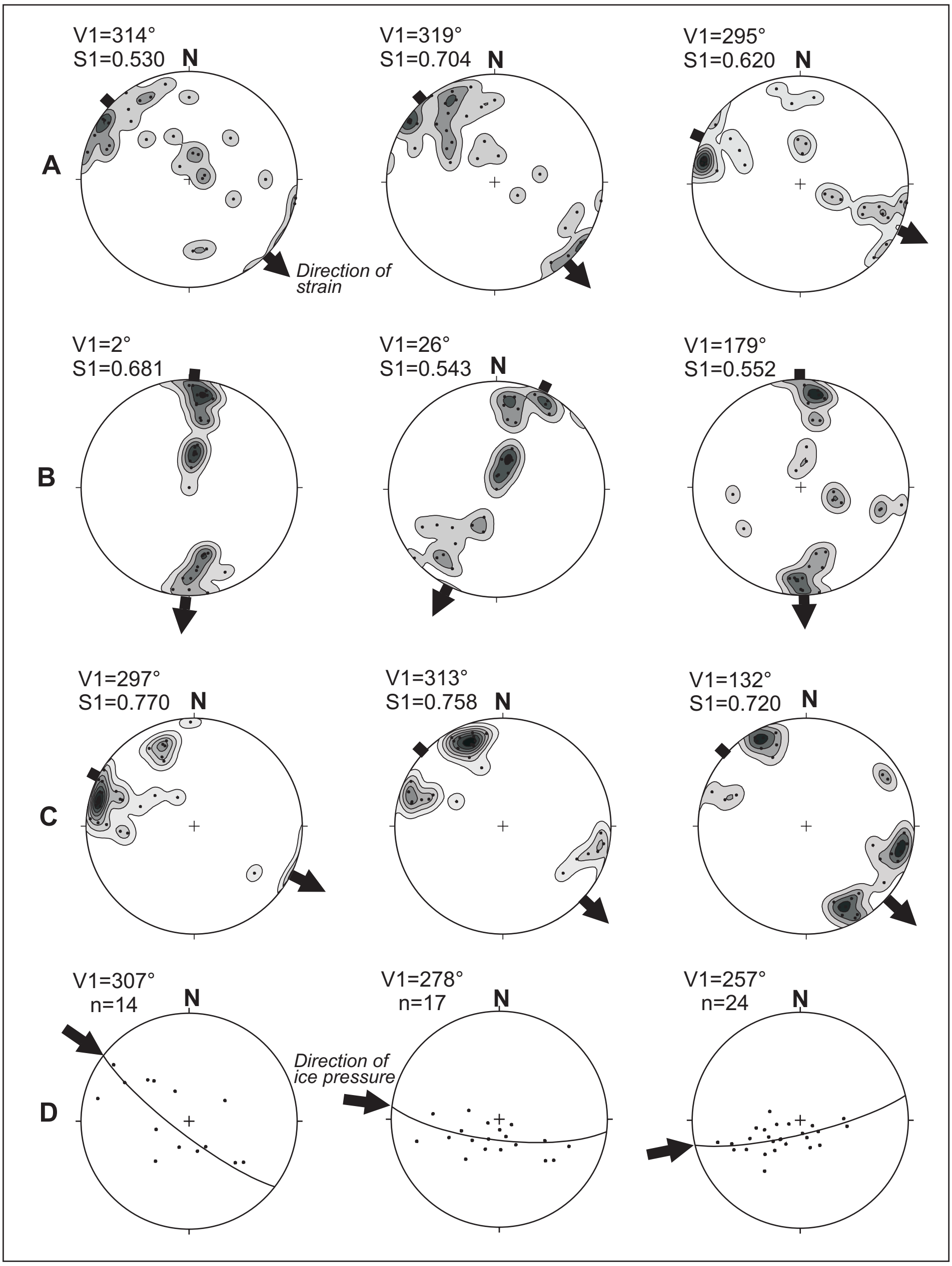

Figure 6. Fabrics in the drumlin-forming till (A–C) and orientation of structural elements of the deformed strata (D). A – from the proximal part (pit 1); B – pit 6; C and D – from the distal part of the drumlin field (pit 8). Lower-hemisphere Schmidt projection, 2σ contour interval, n=30 in each fabric case.

4. DISCUSSION

4.1. Till texture and drumlin size

There is a statistically significant difference between the morphological characteristics of drumlins and the till texture in drumlins. Big drumlins (A>5 km^2) are composed of slightly coarser till than small drumlins (A<5 km^2), whereas the till in the inter-drumlin areas has the finest grain-size (Table 2). This relationship attests to the drumlin forming process in which the intensity of till deformation is determined by the shear strength of the till and reflects different rheological behaviour of tills of different grain size (Smalley & Unwin 1968). Coarse-grained till offers greater resistance to stresses imposed by the moving glacier, which favours drumlin accretion to substantial sizes. Fine-grained till of a relatively low shear strength is more readily deformed and stretched down-ice, so that smaller and more elongated drumlins form. Areas of till with finer granulometric composition would be subjected to most intense deformation and would thus form inter-drumlin depressions of net erosion where till is smeared down-glacier. This scenario is further supported by Chorley's (1959) drumlin elongation ratio *k* and *l/w ratio*, which are much greater for small than for big drumlins. The correlation between drumlin shape and size, and till granulometry is similar for the Woodstock drumlin field in southern Ontario, Canada, where drumlins composed of coarser till were about 3 times bigger and less elongated then drumlins consisting of finer till (Piotrowski 1987; Piotrowski & Smalley 1987).

4.2. Meltwater flow through the substratum

Ice movement dynamics are influenced by hydraulic properties of the substratum, especially by its ability to drain meltwater from the ice/bed interface and from the soft, deformable sediment immediately beneath the ice sheet (Brown *et al*. 1987; Boulton *et al*. 1993; Piotrowski 1997; Piotrowski & Tulaczyk 1999).

In order to test the influence of hydrogeological properties of the bed on the formation of Saadjärve drumlins, an estimate of meltwater drainage through the bedrock was calculated. The bedrock was subdivided into regions A (primarily Silurian carbonate rocks) and B (Devonian terrigenous rocks), which correspond to areas dominated by big and small drumlins, respectively (Fig. 7). Region B is further split into B1 (dolomite, marl and clays of the Narva Regional Stage) and B2 (sand- and siltstones of the Aruküla Regional Stage), with respect to differences in hydraulic conductivity (see chapter 1.1).

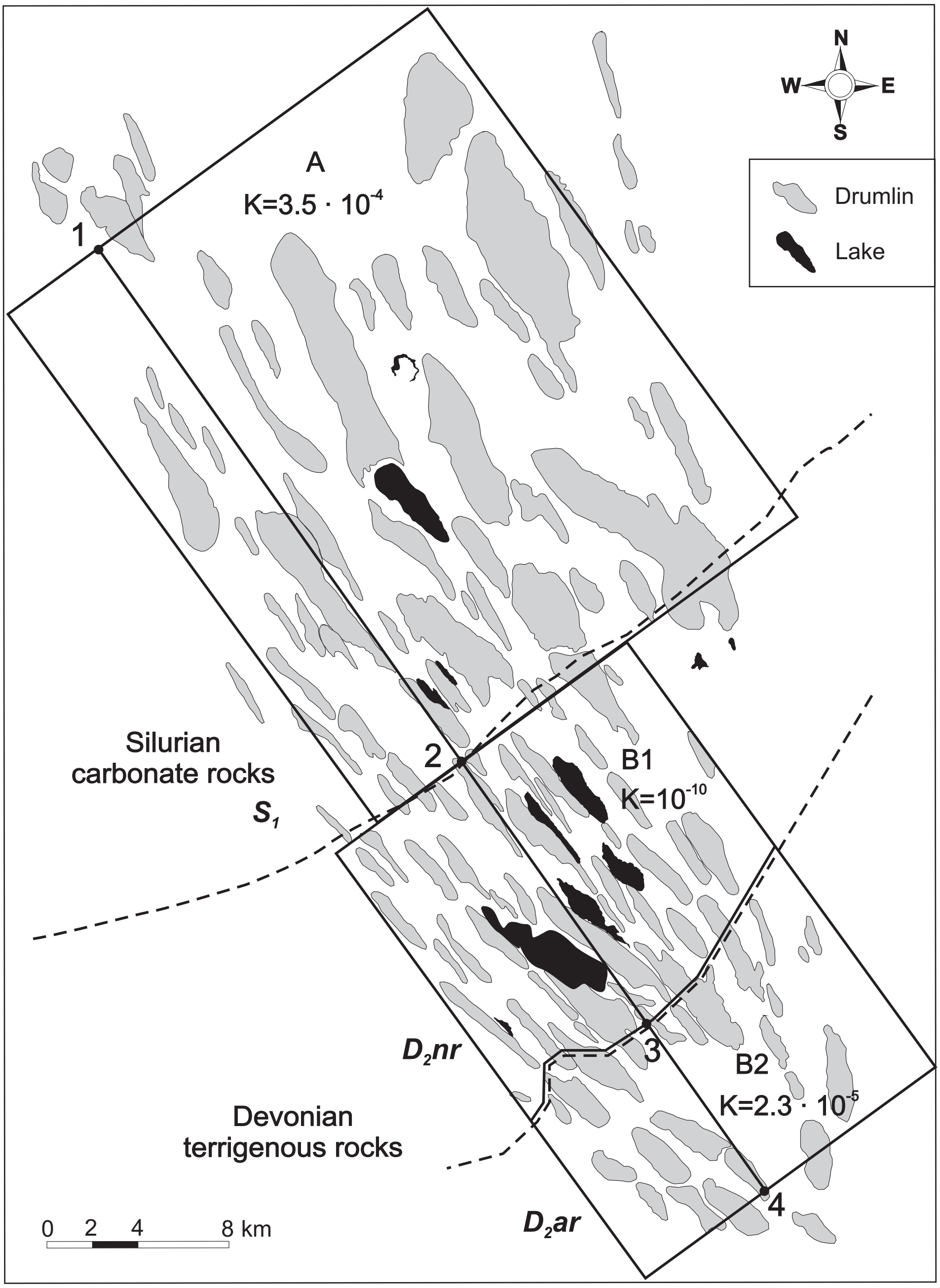

Figure 7. Bedrock regions (A, B1 and B2) with hydraulic conductivities K (in m/s).

The calculation was based on following assumptions:

1. The ice sheet was warm-based (at or above the pressure melting point) throughout the study area during the formation of the drumlins, inasmuch as drumlin formation itself presumes warm wet-bed conditions (see hypothesis in Introduction; Menzies 1987, 1989).
2. Ice thickness H can be estimated as for a perfectly plastic body using Orowan's (1949) formula $H=A \cdot L^{½}$ in which parameter $A = 1$ corresponds to an average basal shear stress of about 17 kPa (see in Piotrowski & Tulaczyk 1999) and L is the distance to the ice margin.
3. Subglacial sediment is fully water-saturated and the potentiometric surface representing pore-water pressure is at the flotation point (*i.e.* at 90% of ice thickness).
4. Pore-water at the ice margin is at atmospheric pressure.
5. Drumlin-forming till and bedrock are hydraulically connected. This is suggested by frequent coarse-grained inclusions in all till units, by thick sand layers between the tills and by the generally sandy till texture.
6. Groundwater flow through the bedrock can be considered as Darcian flow.
7. The model is a snapshot of when ice margin was at the south-eastern margin of the drumlin field.

The calculation ignores the Quaternary strata overlying the bedrock because, as a heterogeneous sequence of variable thickness, there is no means by which to approximate its hydraulic conductivity with a single value.

Groundwater discharge through the bedrock was calculated for each region using Darcian flow equation

$$Q_d = K \cdot i \cdot F$$

where K is hydraulic conductivity, i is hydraulic gradient determined from the slope of the potentiometric surface at flotation level, and F is cross sectional area of flow perpendicular to flow direction.

Groundwater recharge from the ice sheet sole was estimated from the basal melting rates due to geothermal and frictional heat, which melt 6 mm/yr and another 6 mm/yr of basal ice, respectively, for a sliding velocity of 20 m/yr (Paterson 1994: p. 112). Assuming an average velocity of 100 m/yr (estimated by Ehlers (1981) and Liedtke (1981) for other parts of the Peribaltic area) gives a total basal melting rate of 36 mm/yr ($1.14 \cdot 10^{-9}$ m/s) in the study area. Groundwater recharge was then calculated for each region as

$$Q_r = M \cdot S$$

where M is basal melting and S is recharge area.
Flow parameters used for the calculation are given in Table 3 and the geological situation is schematically shown in Figs. 7 and 8.

Table 3. Summary of parameters used for subglacial water balance estimation for different bedrock regions.

	Big drumlins	Small drumlins	
	Region A	Region B1	Region B2
Surface area [m^2]	656 490 000	200 960 000	157 000 000
Bedrock thickness [m]	60	15	20
Hydraulic conductivity K [m/s]	$3.5 \cdot 10^{-4}$	10^{-10}	$2.3 \cdot 10^{-5}$
Hydraulic gradient $i=h/l$ [–]	0.0024	0.0036	0.0098
Flow cross sectional area F [m^2]	1 422 000	235 500	314 000
Groundwater recharge Q_r [m^3/s]	0.75	0.23	0.18
Groundwater discharge Q_d [m^3/s]	1.19	$8.48 \cdot 10^{-7}$	0.07

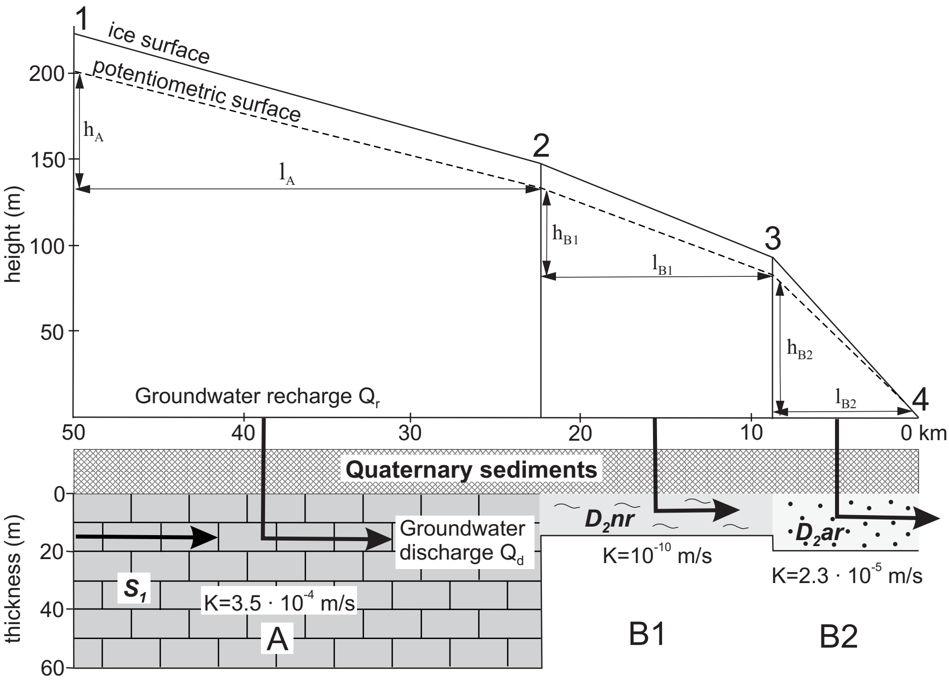

Figure 8. Cartoon showing glacier and bedrock parameters used for subglacial groundwater flow calculations. Location of the section (1–4) is given in Fig. 7.

Comparison of meltwater recharge and discharge through the bedrock (Table 3) shows that the drainage capacity (*i.e.* discharge) was greater than the recharge in region A, contrary to the situation in region B. This is particularly apparent in region B1, where meltwater volume produced at the ice base was several orders of magnitude greater than the drainage capacity of the substratum. The role of tills overlying the bedrock casts considerable uncertainty in the above inferences. These tills would unquestionably constitute a hydraulic buffer between the ice sole and the bedrock, thereby limiting the amount of meltwater able to enter the bedrock aquifers. Till thickness varies greatly, which hinders reliable estimation of hydraulic transmissivity. In addition, available hydrogeological data of these tills are limited, general K-values for loamy-sandy till range from 10^{-5} to 10^{-7} m/s (Perens & Vallner 1997). Therefore, the qualitative assumption — that basal meltwater was hydraulically coupled with bedrock through the Quaternary strata — seems justified by typically coarse-grained sandy till texture including sand pods as observed in the field and by thick outwash sediments occurring between till layers.

4.3. Subglacial water pressure and bed deformation

Under certain circumstances subglacial sediment undergoes deformation in response to stress applied to it by the glacier, which may result in generation of landforms such as drumlins. Till will deform readily when pore-water pressure is at least 90–95% of the overburden pressure, *i.e.* close to the glacier flotation point (Paterson 1994: p. 169). This situation occurs when there is a high water recharge into the till and when drainage from the till is hampered, for example, by a low-permeability of substratum. The rate of deformation and erosion is expected to be proportional to water pressure.

The highest pore-water pressure in the basal till occurred in region B ($Q_r > Q_d$; see Table 3), leading to the greatest reduction in till strength and thus enhanced erosion. The material would be smeared out more readily, leading to formation of much smaller and more elongated drumlins. In region A, where till strength was greater due to larger grain-size and lower pore-water pressures caused by more efficient drainage through the bedrock ($Q_r < Q_d$), the material was stabilised into proto-drumlin nuclei around which more till would accrete to form big, conspicuous drumlins. Superimposed on this first-order trend is that small, elongate drumlins tend to consist of finer-grained till than bigger drumlins (see chapter 4.1).

In areas where the till rests directly on high-permeability outwash deposits (broadly in region A and few drumlins in region B2), the basal contact is either transitional or sharp with restricted deforming bed or without obvious evidence of deformation (PLATE I: C–F). Coarse grained, permeable outwash sediments would tend to be resistant to deformation, and form resistant cores of drumlins around which the till accreted. This shows that there was no strong interlocking at the ice-bed interface, despite the effective meltwater drainage through the substratum. No widespread existence of a deforming bed and pervasive till deformation occur. The till is either deformation till or lodgement till. Fluctuation of subglacial water pressure led to changes in ice-movement mechanism between bed deformation and sliding with erosion and ploughing, resulted the moulded drumlinization of an extensive outwash plain.

The deformation structures in the drumlin-forming till, and highly probable basal decoupling due to surplus meltwater at the ice/bed suggest that glacier movement resulted in a combination of sediment deformation and basal sliding on a thin water film. Unfortunately, the lack of outcrops in the field made detailed investigation of the till/till and till/bedrock interfaces impossible.

At the distal end of the drumlin field, where the ice thickness was relatively thin, the ice dynamic was although controlled by rising bedrock topography (Fig. 2). Deformation styles pertain either to an ice-induced shear, as well as to an ice pressure almost from the west (Fig. 6; PLATE II). The restricted layer of stratified till, consisting of mm- to dm-thick sand layers in the till matrix, might be attributed to meltwater washing at the ice/bed interface and which was deformed at a very late stage of the ice advance (Paper III).

The Saadjärve Drumlin Field clearly represents a zone of converging ice flow. The inferred bed decoupling, localised sediment deformation and evidence of basal sliding indicate relatively large quantities of meltwater at the ice-bed interface.

The described model corresponds to a common, *i.e.* deformational, hypothesis of drumlin formation (Menzies 1979b; Boulton 1987; Smalley & Piotrowski 1987), and a similar combination of ice movement mechanisms was proposed for the Baltic Ice Stream (Piotrowski & Kraus 1997; Jørgensen & Piotrowski 2003).

4.4. The Saadjärve ice stream and its dynamics

The overall shape of the Saadjärve Drumlin Field is unusual compared to other drumlin fields. The down-ice convergence of drumlin axes in the study area does not conform to most drumlin fields, which feature either parallel (e.g. Shaw *et al*. 1989; Meehan *et al*. 1997; Pair 1997; Rõuk 1972) or diverging down-ice (e.g. Zakrzewska Borowiecka & Erickson 1985; Goldstein 1989; Colgan & Mickelson 1997; Zelčs & Dreimanis 1997), indicating lobate ice flow close to the edge of the ice sheet. Zones of converging ice flow are expected to have increasing ice flow velocity in the down-ice direction (Mitchell 1994) reaching a maximum where the ice stream is narrowest. Similar converging flow patterns have been identified in the Dubawnt Lake ice stream in Canada (Stokes & Clark 2002) and at several ice streams within the Late Devensian ice sheet in the western Pennines in northern England (Mitchell 1994). An elongation ratio of streamlined landforms (drumlins, flutes and megalineations) indicative of fast flow is ≥10:1 (Stokes & Clark 1999, 2001, 2002). The Saadjärve drumlins are less attenuated, but the length/width ratio of several drumlins is around 10:1. Therefore, the Saadjärve drumlin field indicates an onset area of a local ice stream, the *Saadjärve ice stream*. The fast ice flow was initiated in the central part of the area, where the increase in subglacial pore-water pressure was the greatest. Once initiated, the ice stream area would have expanded up-ice, affecting successively larger parts of the glacier, from which ice would eventually be funnelled into a narrow track at the most distal part of the drumlin field. The orientation of drumlins and the striation of fabrics in the eastern border of the drumlin field (Figs. 3 and 6) suggest that a southerly flow along the Peipsi depression bounded the Saadjärve ice stream from the east, which also induced the Saadjärve stream to flow southerly. The area west of the drumlin field was probably occupied by a south-easterly moving glacier, under which the Kolga-Jaani and Põltsamaa drumlins probably formed (Fig. 1). The velocity of the Saadjärve ice stream in the most distal part of the drumlin field was reduced by the higher bedrock topography (see Paper IV: *Fig. 3*). The distal margin of the Saadjärve ice stream is marked by the hummocky moraine between the drumlin field and the Emajõe River valley (Figs. 2 and 3; Paper III). This association of glacial landforms, where hummocky moraine were deposited below the outer stagnant ice margin on topographic highs and drumlinised topography in lows, concurs with the conceptual model of subglacially deposited soft bed terraine at the margin of the Laurentide Ice Sheet in southern Alberta (Eyles *et al.* 1999; Boone & Eyles 2001). The transitional zone between drumlins and the hummocky moraine is so called till-cored corrugated (washboad) moraine, which are weakly-oriented parallel to ice flow and are interpreted as drumlins deformed by gravitational load and pressure beneath dead ice. Such hummocks occur on the tops of several drumlins in the distal part of the Saadjärve Drumlin Field (Paper III).

CONCLUSIONS

(1) The Saadjärve drumlin field represents an onset area of a local ice stream, *i.e.* the *Saadjärve ice stream* of the Peribaltic (east-Baltic) Ice Sheet during the Weichselian glaciation about 12.5 ka BP. The ice stream flowed from NW to SE, as demonstrated by the orientation of the entire drumlin field, single drumlins, and fabrics, all of which show convergent flow towards the distal part of the drumlin field, atypical for most of other drumlin fields.

(2) The drumlin field has been divided into several districts of drumlins with similar or typical morphology (Rõuk 1974b). The variety of morphological types of drumlins, *e.g.* typical asymmetrical, reversed, twin and triplet drumlins, although barchanoid and spindle drumlins, and complex drumlins with irregular shapes, reflect the variable response to changing subglacial conditions at the ice/bed interface in limited areas. The bimodal distribution of drumlin size and the drumlin elongation parameters classifies the drumlin field into a north-western region dominated by big (A>5 km^2) and less elongated (l/w=3.1 and k=3.15) drumlins, and a south-eastern region featuring small (A<5 km^2) more elongated drumlins (l/w=6.8 and k=4.96). This morphological distribution agrees with the models of Smalley & Unwin (1968) and Trenhaile (1975), which predict that drumlins are smaller and less elongated towards the down-ice margin of the drumlin field in response to a progressive decrease in ice thickness and velocity.

(3) The internal composition of the drumlins shows that the accumulation of the Quaternary deposits behind the Pandivere bedrock upland occurred during several glacial advances. Four till horizons have been recognised by superposition and compositional data (grain-size distribution, mineralogical and chemical composition). The morphology of the drumlin field is governed by the youngest till, the Late Weichselian till, even though the geology of some drumlins could attests to earlier drumlinisation. This till, also called as drumlin-forming till, varies considerably both in texture and structure, partly reflecting differences in bedrock lithology. There is a statistically significant difference between till morphology and till texture: big drumlins are composed of slightly coarser till than small drumlins with even finer grained till in the inter-drumlin areas. This relationship reflects rheological behaviour of tills caused by different grain sizes (Smalley & Unwin 1968) and corresponds to the drumlin forming process in which the intensity of till deformation is determined by the shear strength of the till.

(4) Deformational structures of drumlin-forming till reveal that Saadjärve drumlins were created by non-uniform till deformation in which till flowed around and accreted on less mobile nuclei shaping them into drumlin forms.

The model corresponds to a common, *i.e.* deformational, hypothesis of drumlin formation.

(5) The local hydro(geo)logical and geotechnical properties of the subglacial bed are related to variations in the local bedrock hydraulics, indicating the influence of substratum and till rheology on the dynamics of the drumlin forming process. The highest pore-water pressure in the basal till, occurring in the south-eastern part of the drumlin field *(i.e.* region B), led to the greatest reduction in till strength and thus enhanced erosion. Then the material was smeared out easily, leading to the formation of relatively small and elongated drumlins. In the north-western part (*i.e.* region A), where coarser grain-size and lower pore-water pressure resulted in greater till strength and more efficient drainage through the bedrock, deposits were stabilised into proto-drumlin nuclei around which the till was accreted to form big drumlins.

(6) The Late Weichselian Saadjärve ice stream flow resulted from a combination of subglacial bed deformation and basal sliding on a thin water film. The inferred bed decoupling, localised sediment deformation and evidence of basal sliding indicate relatively large quantities of meltwater at the ice/bed interface. Fast ice flow was initiated in the south-eastern part of the area, where the increase in subglacial pore-water pressure was the greatest. Once initiated, the ice stream area expanded up-ice, affecting successively larger parts of the glacier, from which the ice was funnelled into a narrow track at the most distal part of the drumlin field.

ACKNOWLEDGEMENTS

I am most thankful to my supervisor professor, Volli Kalm, for support and for finding time to discuss, read and improve the manuscripts. I am particularly grateful to Professor Dr.rer.nat.habil. Jan A. Piotrowski from Aarhus University, Denmark, for his great interest in my research, invaluable discussions and suggestions, and for co-authorship. The Geological Survey of Estonia provided the geological mapping data. I thank my colleagues Dr. Kalle Kirsimäe for reading and commenting on the first draft of the manuscript, and Alar Rosentau for field assistance. Dr. Robert Szava-Kovats is thanked for linguistic help.

Special thanks go to my parents and friends for their support, advice and help during my studies.

This research was financially supported by the Basic Funding Grant no. 0182530s03 from the Estonian Ministry of Education and Research and by Estonian Science Foundation Grants no. 3886 and 5370.

REFERENCES

Barkla, H. 1935. The drumlins of Türi (Estonia). *Publications of the Geological Institution of the University of Tartu,* **48**, 3–11.

Boone, S. J. & Eyles N. 2001. Geotechnical model for great plains hummocky moraine formed by till deformation below stagnant ice. *Geomorphology,* **38**, 109–124.

Boulton, G. S. 1987. A theory of drumlin formation by subglacial sediment deformation. *In* Menzies, J. & Rose, J. (eds.): *Drumlin Symposium*, 25–80. A. A. Balkema, Rotterdam.

Boulton, G. S. & Hindmarsh, R. C. A. 1987. Sediment deformation beneath glaciers: Rheology and geological consequences. *Journal of Geophysical Research,* **92***,* 9059–9082.

Boulton, G. S., Dobbie, K. E., Zatsepin, S. 2001. Sediment deformation beneath glaciers and its coupling to the subglacial hydraulic system. *Quaternary International,* **86**, 3–28.

Boulton, G. S., Slot, T., Blessing, K., Glasbergen, P., Leijnse, T., van Gijssel, K. 1993. Deep circulation of groundwater in overpressured subglacial aquifers and its geological consequences. *Quaternary Science Reviews,* **12**, 739–745.

Brown, N. E., Hallet, B., Booth, D. B. 1987. Rapid soft bed sliding of the Puget Glacial Lobe. *Journal of Geophysical Research,* **92***,* 8985–8997.

Chorley, J. 1959. The shape of drumlins. *Journal of Glaciology,* **3**, 339–344.

Colgan, P. M. & Mickelson, D. M. 1997. Genesis of streamlined landforms and flow history of the Green Bay Lobe, Wisconsin, USA. *Sedimentary Geology,* **111**, 7–26.

Close, M. H. 1867. Notes on the general glaciation of Ireland. *Royal Geological Society of Ireland Journal,* **1**, 207–242.

Doss, B. 1896. Über das Vorkommen von Drumlins in Livland. *Zeitschrift der deutsch. geol. Gesellschaft,* **48**, 5–13.

Doss, B. 1906. *Gutachten über das Projekt einer Grundwasserversorgung der Stadt Dorpat*. Riga, 39 pp.

Drewry, D. 1986. *Glacial Geologic Processes.* Edward Arnold, London, 276 pp.

Ehlers, J. 1981. General discussion. Proceedings of the Symposium on Processes of Glacier Erosion and Sedimentation, Geilo, Norway. *Annals of Glaciology,* **2**, p. 191.

Eltermann, A. & Raukas, A. 1963. Some examples of comparison by lithological methods of macroscopically similar moraines of different age. *ENSV TA Geoloogia Instituudi Uurimused,* **12***,* 23–37 (In Russian).

Evans, I. S. 1987. A new approach to drumlin morphometry. *In* Menzies, J. & Rose, J. (eds.): *Drumlin Symposium*, 119–130. A. A. Balkema, Rotterdam.

Eyles, N., Boyce, J. I., Barendregt, R. W. 1999. Hummocky moraine: sedimentary record of stagnant Laurentide Ice Sheet lobes resting on soft beds. *Sedimentary Geology,* **123**, 163–174.

Glückert, G. 1973. Two large drumlin fields in central Finland. *Fennia,* **120**, 5–37.

Glückert, G. 1987. The drumlins of central Finland. *In* Menzies, J. & Rose, J. (eds.): *Drumlin Symposium*, 291–294. A. A. Balkema, Rotterdam.

Goldstein, B. 1989. Lithology, sedimentology, and genesis of the Wadena drumlin field, Minnesota, U.S.A. *Sedimentary Geology,* **62**, 241–277.

Hang, T., Miidel, A., Kalm, V., Kimmel, K. 2001. New data on the distribution and stratigraphy of the bottom deposits of Lake Peipsi, eastern Estonia. *Proceedings of the Estonian Academy Sciences, Geology,* **50** (4), 233–253.
Harry, D. G. & Trenhaile, A. S. 1987. The morphology of the Arran drumlin field, southern Ontario, Canada. *In* Menzies, J. & Rose, J. (eds.): *Drumlin Symposium*, 161–173. A. A. Balkema, Rotterdam.
Hart, J. K. 1997. The relationship between drumlins and other forms of subglacial glaciotectonic deformation. *Quaternary Science Reviews,* **16**, 93–107.
Hausen, H. 1913. Materialen zur Kenntnis der Pleistozänen Bildungen in den russischen Ostseeländern. *Fennia,* **34** (2), 181 pp.
Heinsalu, Ü. 1977. *Karst ja looduskeskkond Eesti NSV-s.* Valgus, Tallinn, 96 pp.
Hindmarsh, R. C. A. 1998. Drumlinization and drumlin-forming instabilities: viscous till mechanisms. *Journal of Glaciology,* **44**, 293–314.
Hindmarsh, R. C. A. 1999. Coupled ice-till dynamics and the seeding of drumlins and bedrock forms. *Annals of Glaciology,* **28**, 221–230.
Hooyer, T. S. & Iverson, N. R. 2000. Diffusive mixing between shearing granular layers: constraints on bed deformation from till contacts. *Journal of Glaciology,* **46**, 641–651.
Iverson, N. R. 2000. Sediment entrainment by a soft-bedded glacier: A model based on regelation into the bed. *Earth Surface Processes and Landforms,* **25**, 881–893.
Jørgensen, F. & Piotrowski, J. A. 2003. Signature of the Baltic Ice Stream on Funen Island, Denmark during the Weichselian glaciation. *Boreas,* **32***,* 242–255.
Kajak, K. 1963. On the ice-marginal formations in South-East Estonia. *Trudy Komissij po izucheniju chetvertichnogo perioda,* **21**, 66–75 (In Russian).
Kajak, K. 1965a. Geological features of the ice-marginal formations in Estonia. *In* Basalikas, A. B. (ed.): *Krajevye obrazovaniya materikovogo oledeneniya*, 59–64. Vilnius (In Russian).
Kajak, K. 1965b. On the geology of drumlins of Saadjärv. *In* Orviku, K. (ed.): *Litologiya i stratigrafiya chetvertichnykh otlozhenij Estonii*, 23–28. Institut Geologij AN Estonskoi SSR, Tallinn (In Russian).
Karukäpp, R. & Tavast, E. 1985. Tectonic structure and glacial morphogenesis of Pandivere Upland. *ENSV TA Toimetised, Geoloogia,* **34** (1)*,* 22–29 (In Russian).
Karukäpp, R. & Vassiljev, J. 1992. Geomorphology of the Gulf's floor. In Raukas, A. & Hyvärinen, H. (eds.): *Geology of the Gulf of Finland*, 72–86. Tallinn (In Russian).
Krüger, J. 1987. Relationship between drumlin shape and distribution to drumlin stratigraphy and glacial history, Myrdalsjökull, Iceland. *In* Menzies, J. & Rose, J. (eds.): *Drumlin Symposium*, 257–266. A. A. Balkema, Rotterdam.
Krüger, J. & Thomsen, H. H. 1984. Morphology, stratigraphy and genesis of small drumlins in front of the glacier Myrdalsjökull, south Iceland. *Journal of Glaciology,* **30**, 94–105.
Larsen, N. K., Piotrowski, J. A., Christoffersen, P., Wysota, W. 2003. Landforms from a glacier surge on a gravel bed: Elisebreen, NW Spitsbergen. *In*: Lancaster, N. (ed.) *INQUA XVI International Congress, Reno, Nevada, USA, July 23–30, 2003, Programs with Abstracts*, p. 137 (Abstract).
Levkov, E. & Liivrand, E. 1988. On glaciotectonical dislocations of interglacial deposits in Karuküla and Kõrveküla sections (Estonia). *ENSV TA Toimetised, Geoloogia,* **37** (4), 161–167 (In Russian).

Liedtke, H. 1981. Glaziale Rinnen und glaziale Tiefrinnen. *Bochumer Geographische Arbeiten,* **40**, 7–19.

Liivrand, E. 1991. *Biostratigraphy of the Pleistocene deposits in Estonia and correlations in the Baltic region*. Ph.D. dissertation, Stockholm University, 114 pp.

Liivrand, E. & Saarse, L. 1983. Interglacial deposits in Kõrveküla section (South-eastern Estonia) and their stratigraphic importance. *Palynologic researches in geologic studies of the Baltic Region and the Baltic Sea,* 41–50. Riga (In Russian).

Meehan, R. T., Warren, W. P., Gallagher, C. J. D. 1997. The sedimentology of a Late Pleistocene drumlin near Kingscourt, Ireland. *Sedimentary Geology,* **111**, 91–106.

Menzies, J. 1979a. A review of the literature on the formation and location of drumlins. *Earth Science Reviews,* **14**, 315–359.

Menzies, J. 1979b. The mechanics of drumlin formation with particular reference to the change in pore-water content of the till. *Journal of Glaciology,* **22**, 373–384.

Menzies, J. 1984. *Drumlins: A Bibliography*. Geo Books, Norwich.

Menzies, J. 1987. Towards a general hypothesis on the formation of drumlins. *In* Menzies, J. & Rose, J. (eds.): *Drumlin Symposium*, 9–24. A. A. Balkema, Rotterdam.

Menzies, J. 1989. Drumlins — products of controlled or uncontrolled glaciodynamic response? *Quaternary Science Reviews,* **8**, 151–158.

Menzies, J. & Shilts, W. W. 1996. Subglacial environments. *In* Menzies, J. (ed.) *Past Glacial Environments — Sediments, Forms and Techniques*, 15–136. Butterworth-Heinemann, Oxford.

Mitchell, W. A. 1994. Drumlins in ice sheet reconstructions, with reference to the western Pennines, northern England. *Sedimentary Geology 91*, 313–331.

Mooers, H. D. 1989. Drumlin formation: a time transgressive model. *Boreas,* **18**, 99–107.

Orowan, E. 1949. Remarks at joint meeting of the British Geological Society, the British Rheologists Club and the Institute of Metals. *Journal of Glaciology,* **1**, 231–236.

Orviku, K. 1958. Lithological investigation of the till of the last glaciation in Estonia by quantitative methods. *ENSV TA Geoloogia Instituudi Uurimused,* **3**, 213–252 (In Russian).

Orviku, K. 1961. Geological structure of drumlins in Estonia. *Materialy Vsesoyuznogo soveshchaniya po izucheniy chetvertichnogo perioda,* Vol. **2**, 64–72. Moscow (In Russian).

Pair, D. L. 1997. Thin film, channelized drainage, or sheetfloods beneath a portion of the Laurentide Ice Sheet: an examination of glacial erosion forms, northern New York State, USA. *Sedimentary Geology,* **111**, 199–216.

Paterson, W. S. B. 1994. *The Physics of Glaciers*. Pergamon, Oxford, 480 pp.

Perens, R. & Vallner, L. 1997. Water-bearing formation. *In* Raukas, A. & Teedumäe, A. (eds.): *Geology and Mineral Resources of Estonia*, 137–145. Estonian Academy Publisher, Tallinn.

Piotrowski, J. A. 1987. Genesis of the Woodstock drumlin field, southern Ontario, Canada. *Boreas,* **16***,* 249–265.

Piotrowski, J. A. 1997. Subglacial hydrology in northwestern Germany during the last glaciation: groundwater flow, tunnel valleys, and hydrological cycles. *Quaternary Science Reviews,* **16**, 169–185.

Piotrowski, J. A. & Kraus, A. M. 1997. Response of sediment to ice-sheet loading in northwestern Germany: effective stresses and glacier-bed stability. *Journal of Glaciology,* **43**, 495–502.

Piotrowski, J. A. & Smalley, I. J. 1987. The Woodstock drumlin field, southern Ontario, Canada. *In* Menzies, J. & Rose, J. (eds.): *Drumlin Symposium*, 309–321. A. A. Balkema, Rotterdam.

Piotrowski, J. A. & Tulaczyk S. 1999. Subglacial conditions under the last ice sheet in northwest Germany: Ice-bed separation and enhanced basal sliding? *Quaternary Science Reviews,* **18**, 737–751.

Piotrowski, J. A., Mickelson, D. M., Tulaczyk, S., Krzyszkowski, D., Junge, F. W. 2001. Were deforming subglacial beds beneath past ice sheets really widespread? *Quaternary International,* **86**, 139–150.

Pirrus, R. & Raukas, A. 1996. Late-Glacial stratigraphy in Estonia. *Proceedings of the Estonian Academy of Sciences, Geology,* **45**, 34–45.

Puura, V. & Mardla, A. 1972. The structural dissection of the sedimentary cover of Estonia. *ENSV TA Toimetised. Keemia, Geoloogia,* **21**, 71–77 (In Russian).

Rabassa, J. 1987. Drumlins and drumlinoid forms in northern James Ross island, Antarctic Peninsula. *In* Menzies, J. & Rose, J. (eds.): *Drumlin Symposium*, 267–290. A. A. Balkema, Rotterdam.

Rattas, M. 1997. *Moreenide litoloogia ja stratigraafia Saadjärve voorestikus* [Lithology and stratigraphy of tills in the Saadjärve Drumlin Field area]. MSc Thesis, University of Tartu, 73 pp. (unpublished).

Raukas, A. 1978. *Pleistocene Deposits of the Estonian SSR*. Valgus Publications, Tallinn, 310 pp. (In Russian)

Raukas, A. & Tavast, E. 1994. Drumlins location as response to bedrock topography on the southeastern slope of the Fennoscandian Shield. *Sedimentary Geology,* **91**, 373–382.

Raukas, A., Rähni, E., Miidel, A. 1971. *Marginal glacial formations in North Estonia.* Valgus, Tallinn, 219 pp. (In Russian)

Rõuk, A.-M. 1972. Türi voorestiku geomorfoloogiast [On the geomorphology of the Türi drumlin field]. *In* Merikalju, L. (ed.): *Eesti Geograafia Seltsi Aastaraamat 1970*, 19–37. Valgus, Tallinn.

Rõuk, A.-M. 1974a. On the till structures in the drumlins of central Estonia. *ENSV TA Toimetised. Keemia, Geoloogia,* **23***,* 147–160 (In Russian).

Rõuk, A.-M. 1974b. Voorte ja voorelaadsete pinnavormide morfoloogiline vaheldusrikkus Saadjärve voorestikus [Morphological variety of drumlins and drumlin-like ridges in the Saadjärve Drumlin Field]. *In* Merikalju, L. (ed.): *Eesti Geograafia Seltsi Aastaraamat 1973,* 5–35. Valgus, Tallinn.

Rõuk, A.-M. 1976. Drumlins and drumlin-like landforms in the North-East Baltic. *In* Raukas, A. & Tulp, L. (eds.): *Estonia. Regional Studie*s, 21–33. Academy of Sciences of the Estonian SSR, Estonian Geographical Society, Tallinn.

Rõuk, M.-A. 1977. Pinnamood Vooremaa ja Emajõe vahel. *Eesti Loodus,* **3**, 154–160.

Rõuk, A.-M. 1984. Eesti voorte ja voorelaadsete pinnavormide kujunemise probleeme [Some problems concerning the formation of drumlins and drumlinoids in Estonia]. *In* Merikalju, L. (ed.): *Eesti Geograafia Seltsi Aastaraamat 1980*, 49–55. Valgus, Tallinn.

Rõuk, A.-M. 1987. Physiography of the central part of Saadjärv Drumlin Field with special reference to Lake Raigastvere and its surroundings. *In* Raukas, A. & Saarse, L. (eds.): *Palaeohydrology of the temperate zone II. Lakes,* 81–100. Valgus, Tallinn.

Rõuk, A.-M. 1990. Kolga-Jaani voorestik [The Kolga-Jaani drumlin field]. *Eesti Loodus,* **11**, 730–734.

Rõuk, A.-M. & Raukas, A. 1989. Drumlins of Estonia. *Sedimentary Geology,* **62***,* 371–384.

Shaw, J. 1983. Drumlins formation related to inverted meltwater erosional marks. *Journal of Glaciology,* **29**, 461–479.

Shaw, J. 2002. The meltwater hypothesis for subglacial bedforms. *Quaternary International,* **90**, 5–22.

Shaw, J. & Sharp, D. R. 1987. Drumlin formation by subglacial meltwater erosion. *Canadian Journal of Earth Sciences,* **24**, 2316–2322.

Shaw, J., Kvill, D., Rains, B. 1989. Drumlins and catastrophic subglacial floods. *Sedimentary Geology,* **62**, 177–202.

Smalley, I. J. & Piotrowski, J. A. 1987. Critical strength/stress ratios at the ice-bed interface in the drumlin forming process: from "dilatancy" to "cross-over". *In* Menzies, J. & Rose, J. (eds.): *Drumlin Symposium*, 81–86. A. A. Balkema, Rotterdam.

Smalley, I. J. & Unwin, D. J. 1968. The formation and shape of drumlins and their distribution and orientation in drumlin fields. *Journal of Glaciology,* **31**, 337–390.

Smalley, I. J. & Warburton, J. 1994. The shape of drumlins, their distribution in drumlin fields, and the nature of the sub-ice shaping forces. *Sedimentry Geology,* **91**, 241–252.

Stokes, C. R. & Clark, C. D. 1999. Geomorphological criteria for identifying Pleistocene ice streams. *Annals of Glaciology,* **28**, 67–74.

Stokes, C. R. & Clark, C. D. 2001. Palaeo-ice streams. *Quaternary Science Reviews,* **20**, 1437–1457.

Stokes, C. R. & Clark, C. D. 2002. Are long subglacial bedforms indicative of fast ice flow? *Boreas,* **31**, 239–249.

Tavast, E. & Raukas, A. 1982. *The bedrock relief of Estonia.* Valgus, Tallinn, 194 pp. (In Russian)

Trenhaile, A. S. 1971. Drumlins: their distribution, orientation and morphology. *Canadian Geographer,* **15**, 113–126.

Trenhaile, A. S. 1975. The morphology of a drumlin field. *Annals of the Association of American Geographers,* **65**, 297–312.

Van der Meer, J. J. M. 1983. A recent drumlin with fluted surface in the Swiss Alps. *In* Everson, E. B., Schlüchter, Ch., Rabassa J. (eds.): *Tills and Related Deposits: Genesis, Petrology, Application, Stratigraphy,* 105–109. A. A. Balkema, Rotterdam.

Weertman, J. 1968. Diffusion law for the dispersion of hard particles in an ice matrix that undergoes simple shear deformation. *Journal of Glaciology,* **7**, 161–165.

Wentworth, C. K. 1936. The method of moments. *Journal of Sedimentary Petrology,* **6**, 158–159.

Whittecar, G. R. & Mickelson, D. M. 1979. Composition, internal structures, and an hypothesis of formation for drumlins, Waukesha County, Wisconsin, USA. *Journal of Glaciology,* **22**, 357–370.

Wysota, W. 1994. Morphology, internal composition and origin of drumlins in the southeastern part of the Chełmno-Dobrzyń Lakeland, North Poland. *Sedimentary Geology,* **91**, 345–364.

Zakrzewska Borowiecka, B. & Erickson, R. H. 1985. Wisconsin drumlin field and its origin. *Zeitschrift für Geomorphologie Neue Folge,* **29**, 417–438.

Zelčs, V. & Dreimanis, A. 1997. Morphology, internal structure and genesis of the Burtnieks drumlin field, Northern Vidzeme, Latvia. *Sedimentary Geology,* **111**, 73–90.

Zur Mühlen, L. 1910. Der Soitz-See, seine Entstehung und heutige Ausbildung. *Sitzungsber der Naturf. Gesellschaft bei der Kais. Univ. Jurjeff,***18**, 39 pp.

Zur Mühlen, L. 1912. Der geologische Aufbau Dorpats und seiner nächsten Umgebungen. *Sitzungsb. Naturf. Gesellschaft Kais Univ. Jurjeff,* **21**, 68 pp.

SUMMARY IN ESTONIAN

Liustikualused protsessid voorte kujunemisel — Saadjärve voorestiku näide.

Klassikalised voored (Menzies 1979a) on piklikud ovaalse põhijoonisega seljandikud, mis on tekkinud aktiivse liustikujää all kulutus- ja kuhjetegevuse toimel. Voorte proksimaalne ots on kõrge ja järsk ning distaalne ots laugelt madalduv. Voorte pikitelg näitab liustikujää liikumise suunda. Enamasti paiknevad voored rühmiti, moodustades voorestikke. Voorestikes on voored tavaliselt orienteeritud kas paralleelselt või hajuvad lehvikutaoliselt voorestiku distaalosas, viidates liustikukeele radiaalsele laialivalgumisele. Üksikutes voorestikes esineb aga ka voorte koonduvust distaalosa suunas.

Liustikualuste protsesside olemus ja kulg on määratud liustiku termiliste ja hüdrauliliste tingimuste ning aluspinna/aluspõhja litoloogilis-geotehniliste omaduste omavahelise vastasmõjuga, mis omakorda määrab settematerjali reoloogilised iseärasused. Lähtuvalt nende tingimuste varieeruvusest ajas ja ruumis, on põhjust arvata, ning millele viitavad ka enamik andmeid, et voored kui liustikualuse protsessi tulem, ei ole kõikjal ühtmoodi tekkinud. Voorte suuruse, kuju ja siseehituse erinevused, ning voorte ja voorestike paiknemisiseärasused on viinud suure hulga tekkehüpoteeside väljakujunemiseni. Neid võib jagada kolme põhirühma lähtudes põhimõttelt erinevast interpreteerimise lähtekohast: (1) pehmete liustikualuste setete deformatsioon (Smalley & Unwin 1968; Smalley & Piotrowski 1987; Boulton 1987; Menzies 1979b, 1989; Hart 1997; Hindmarsh 1999), (2) vanemate setete erosioonilis-eksaratsiooniline künd (Whittecar & Mickelson 1979; Krüger & Thomsen 1984; Krüger 1987; Iverson 2000) ning (3) liustikusulavete (glatsiofluviaalne) erosioon või setete kuhjumine (Shaw 1983, 2002; Shaw & Sharp 1987; Shaw *et al*. 1989).

Käesolev dissertatsioon käsitleb voorte kujunemist ja selle protsessi dünaamikat kontrollivaid võimalikke parameetreid Saadjärve voorestiku näitel lähtuvalt voorte morfoloogiast, siseehitusest ja aluspinna geoloogilis-geotehnilistest omadustest. Autori poolt on uuritud Saadjärve voorte morfoloogiat, siseehitust (artiklid II, IV ja V), setete struktuurseid-tekstuurseid omadusi ning glatsiotektooniliste deformatsioonide levikut (artiklid I, III ja IV), ning analüüsitud aluspõhja/-pinnase omaduste ja settematerjali (moreeni) reoloogia mõju voorte tekkeprotsessi dünaamikale (artikkel IV). Esitatakse Saadjärve voorestiku võimalik tekkemudel ja hinnatakse kohaliku, nn. Saadjärve jäävoolu dünaamika iseärasusi Hilis-Weichseli jäätumise ajal.

Saadjärve voorestik ehk Vooremaa moodustab Pandivere aluspõhjalise kõrgustiku lõunanõlvalt algava loode-kagusuunaliselt kulgeva reljeefi suurvormi, mis madaldub ja aheneb distaalses suunas Devoni platooni (Joonised 1 ja 2). Reljeefi iseloomult on tegemist tüüpilise voorestikuga, kuid voorestiku kitsenemine ja voorte koondumine e. konvergents distaalosa suunas viitab liustiku eripärasele voolule Pandivere kõrgustiku taga.

Voored koosnevad Kesk- ja Ülem-Pleistotseeni liustikusetetest — moreenidest ja neid üksteisest eraldavatest liustiku sulavee setete kompleksidest. Erivanuseliste moreenide levik viitab sellele, et voorestiku piirkond on olnud setete kuhjealaks mitmete jäätumiste perioodidel. Voorte vanemad tuumikud pärinevad tõenäoliselt Hilis-Weichseli voorestamisprotsessi eelsest mitmekesise iseloomuga liustiku- ja liustiku sulavee tekkelisest pinnamoest. Mõnede voorte siseehituse põhjal võib oletada ka varasemat voorestatud reljeefi ja voorte akretsiooni (artikkel II).

Saadjärve voorte morfoloogia ja suurus on väga varieeruv, kuid eriilmeliste voorte pindalalises jaotumises on täheldatud juba varem kindlaid seaduspärasusi (Rõuk 1974b). Voorte morfomeetrilise analüüsi tulemusena (Tabel 1) võib eraldada valdavalt suurte laiade ja laugete lagedega voorte piirkonna voorestiku põhjaosas ning väikeste piklikumate ja kitsamate voortega piirkonna voorestiku lõunaosas (Joonis 3). Voorte morfomeetria ja pindalalise asetuse muutumine viitab erinevustele liustiku dünaamikas, milles olulist tähtsust etendasid lokaalse aluspõhja/-pinna hüdrogeoloogilised ja settematerjali (moreeni) geotehnilised omadused (artikkel IV). Efektiivne liustiku sulavee äravool läbi vett hästi läbilaskva aluspinna (S_1rk ja glatsiofluviaalsed liivad-kruusad) ja madal poorivee rõhk liustikualuses süsteemis tingis settematerjali suurema vastupidavuse erosioonile ja seega suurte voorte kujunemise voorestiku põhjaosas. Voorestiku lõunaosas oli sulavee äravool takistatud (vett mitteläbilaskvate D_2nr kivimite ja vanemate moreenide tõttu), mistõttu tekkis liustiku/aluspinna piirile veega küllastunud kiht (veekile) põhjustades nii liustiku liikumiskiiruse suurenemise kui ka settematerjali intensiivsema ärakande ning väiksemate voorte tekke. Voorestiku distaalosas mõjutasid liustiku liikumiskiirust juba oluliselt aluspõhja reljeefi tõus ning võimsamad Peipsi ja Kesk-Eesti jäävoolud, mis surusid nende vahele jääva Saadjärve jäävoolu kokku. Õhukese ja passiivse jää tingimustes kujunes voorestiku ja Suur-Emajõe oru vahelisele alale künklik moreenreljeef, tähistades Saadjärve jäävoolu distaalset servaasendit (artikkel III).

Saadjärve voorestiku kujundas Skandinaavia jääkilbi Ida-Balti liustikukeele iseseisev nn. kohalik Saadjärve jäävool Hilis-Weichseli jäätumise ajal umbes 12,5 ka BP. Esitatud liustiku dünaamiline mudel koos voorestamisprotsessil kuhjunud moreeni tekstuursete omadustega (lõimis, deformeerumise aste ja veeriste orientatsioon) vastab voorte tekke deformatsioonilisele hüpoteesile.

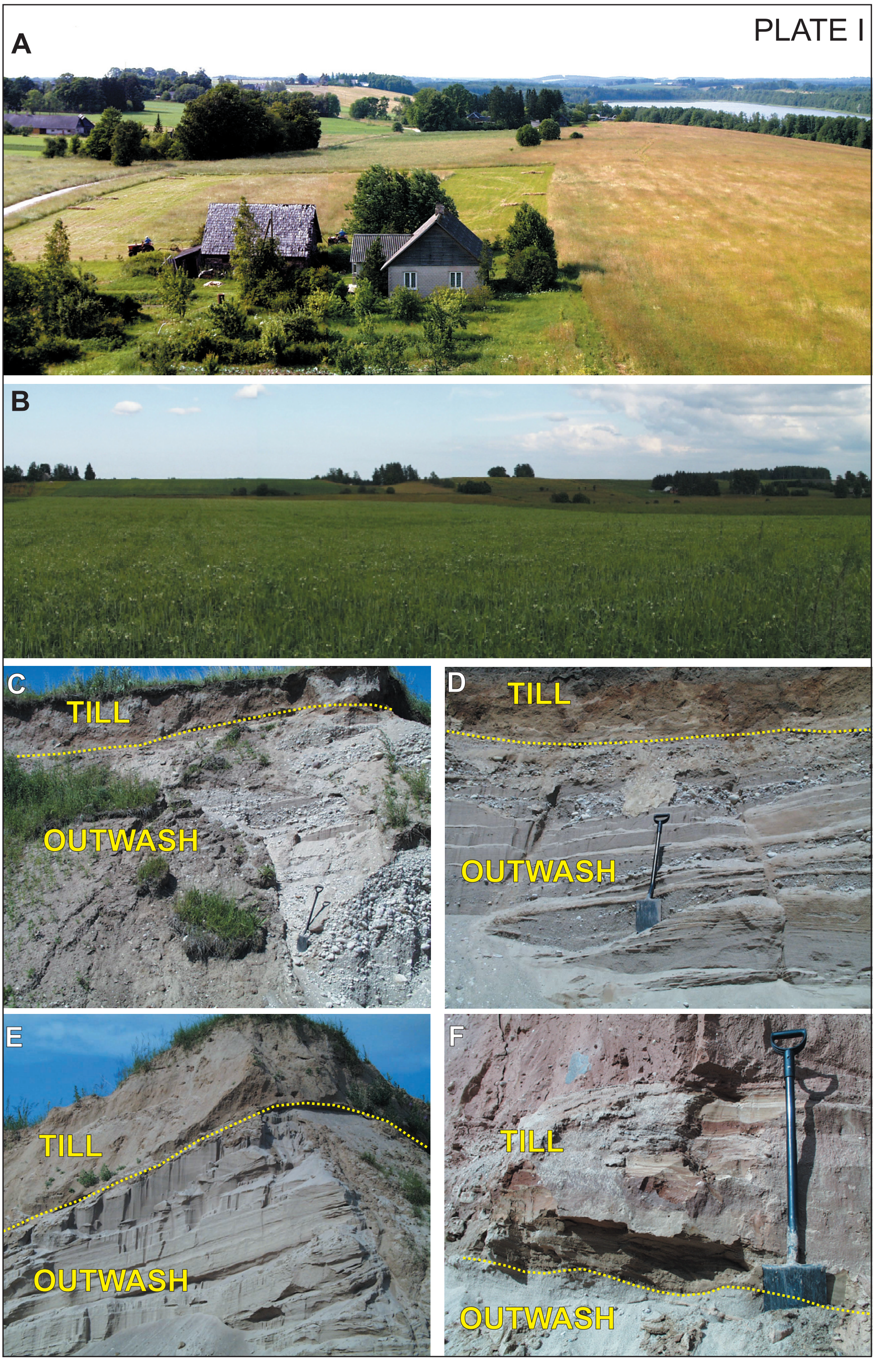

PLATE I. Morphology and the internal composition of drumlins. Site locations in Fig. 3. A – Undulated drumlinised relief. View to the north-west along the drumlin; B – Strongly elongated drumlin: 3.5 km long, 500 m wide, and 15 m high; C and D – Diffuse contact between the drumlin-forming till and underlying outwash sediments (pits 1 and 4); E – Sharp till/outwash boundary (pit 6); F – Sharp undulated contact between stratified till (melt-out?) and outwash sediments (pit 8).

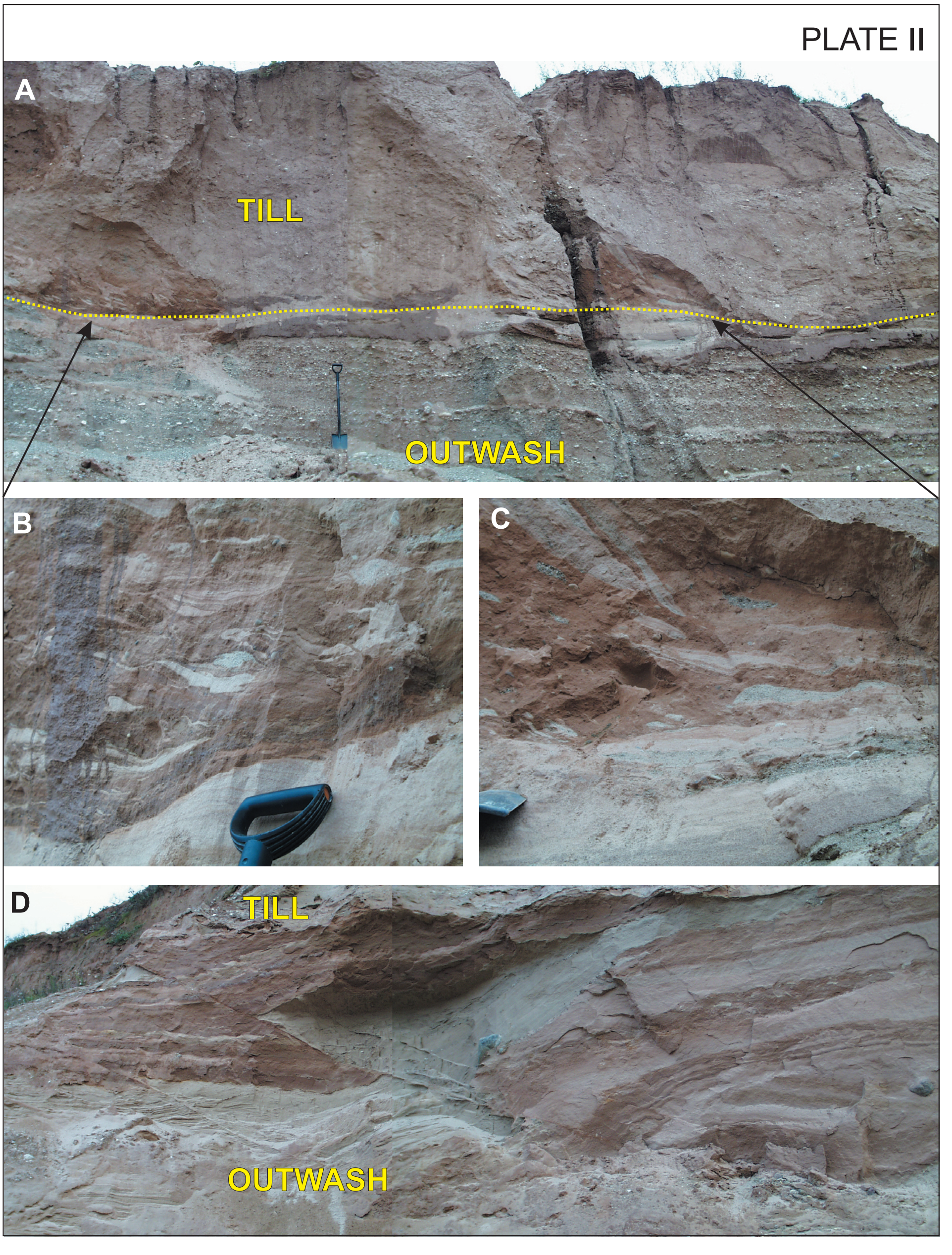

PLATE II. Deformed subglacial sediments in drumlin (pit 8). Site location in Fig. 3.
A – Contact between the drumlin-forming till and underlying outwash sediments; B and C – Ductile deformation structures in the contact between the drumlin-forming till and underlying outwash sediments. The till contains contorted lenses and pockets of the underlying outwash sand; D – Deformation structures in drumlin due to ice-induced shear.

PUBLICATIONS

Rattas, M. and Kalm, V. 2004.
Glaciotectonic deformation patterns in Estonia.
Geological Quarterly, **48** (1), 15–22.

Reprinted for this thesis with permission by the Polish Geological Institute.

Rattas, M. and Kalm, V. 2001.
Lithostratigraphy and distribution of tills in the Saadjärve Drumlin Field, east-central Estonia. P*roceedings of the Estonian Academy Sciences, Geology*, **50** (1), 24–42.

Reprinted for this thesis with permission by the Estonian Academy Publishers.

Rattas, M. and Kalm, V. 2001.
Glaciotectonic deformation pattern in the hummocky moraine in the distal part of the Saadjärve Drumlin Field, east-central Estonia.
Slovak Geological Magazine, **7** (3), 243–246.

Reprinted for this thesis with permission by the Slovak Geological Magazine, Geological Survey of Slovak Respublic, Dionyz Stur Publishers, Bratislava.

Rattas, M. and Piotrowski, J. A. 2003.
Influence of bedrock permeability and till grain size on the formation of the Saadjärve drumlin field, Estonia, under an east-Baltic Weichselian ice stream.
Boreas, **32** (1), 167–177.

The article accepted for publication in Boreas reprinted for this thesis by permission of Taylor & Francis AS.

Raukas, A., Kalm, V., Karukäpp, R. and **Rattas, M.** 2004.
Pleistocene Glaciations in Estonia.
In: Ehlers, J. & Gibbard, P. (eds.). *Quaternary Glaciations – Extent and Chronology, Part 1: Europe,* 83–91. Elsevier, Amsterdam.

Reprinted for this thesis with permission by Elsevier Science Publishers.

CURRICULUM VITAE

MARIS RATTAS

Personal Information

Date and place of birth:	17.02.1965, Kuressaare, Saare County, Estonia
Citizenship:	Estonian
Current Address:	Institute of Geology, University of Tartu Vanemuise 46, 51014 Tartu, Estonia Phone: +372 7 375 815 Fax: +372 7 375 836 E-mail: mrattas@ut.ee

Educational Background

1983 Leisi Secondary Scool, Saare County
1988 University of Tartu, diploma degree in geology
1997 University of Tartu, MSc in applied geology

Professional Experience

1988–1997 Geologist, Geological Survey of Estonia,
1997–1999 Project Leader, Geological Survey of Estonia,
1999–2002 Senior engineer, University of Tartu, Institute of Geology
since 2002 Research scientist, University of Tartu, Institute of Geology,

Main scientific interest

Glacial geology and geomorphology

CURRICULUM VITAE

MARIS RATTAS

Isikuandmed

Sünniaeg ja koht:	17.02.1965, Kuressaare
Rahvus:	eestlane
Aadress:	Tartu Ülikooli geoloogia instituut Vanemuise 46, 51014 Tartu, Eesti Tel.: +372 7 375 815 Faks: +372 7 375 836 E-post: mrattas@ut.ee

Hariduskäik

1983 Leisi Keskkool, Saare mk.
1988 Tartu Ülikool, geoloogiainseneri diplom
1997 Tartu Ülikool, MSc rakendusgeoloogia erialal

Teenistuskäik

1988–1997 geoloog, Eesti Geoloogiakeskus OÜ
1997–1999 osakonnajuhataja, Eesti Geoloogiakeskus OÜ
1999–2002 vaneminsener, Tartu Ülikooli geoloogia istituut
alates 2002 teadur, Tartu Ülikooli geoloogia istituut

Peamine uurimisteema

Glatsiaalgeoloogia ja geomorfoloogia

DISSERTATIONES GEOLOGICAE UNIVERSITATIS TARTUENSIS

1. **Пээп Мянник.** Конодонты в верхнеордовикских и нижнесилурийских отложениях Эстонии. Тарту, 1992, 355 с.
2. **Elvi Tavast.** Fennoskandia kilbi lõunanõlva ja sellega piirnevate alade aluspõhja reljeef. Tartu, 1992, 357 lk.
3. **Kaarel Orviku.** Characterisation and evolution of Estonian seashores. Tartu, 1992, 19 p.
4. **Анатолий Молодьков.** ЭПР-анализ скелетного вещества моллюсков в хроностратиграфических исследованиях позднего кайнозоя. Тарту, 1992, 33 с.
5. **Jaan Lutt.** Late- and postglacial deposits on the Estonian shelf. Tartu, 1993, 31 p.
6. **Reet Karukäpp.** Gotiglatsiaalne morfogenees Skandinaavia mandriliustiku kagusektoris. Tartu, 1997, 181 p.
7. **Argo Jõeleht.** Geothermal studies of the Precambrian basement and Phanerozoic sedimentary cover in Estonia and Finland. Tartu, 1998, 125 p.
8. **Jüri Nemliher.** Mineralogy of Phanerozoic skeletal and sedimentary apatites: an XRD study. Tartu, 1999, 134 p.
9. **Kalle Kirsimäe.** Clay mineral diagenesis on the Lower Cambrian "Blue Clay" in the northern part of the Baltic Paleobasin. Tartu, 1999, 113 p.
10. **Jüri Plado.** Gravity and magnetic signatures of meteorite impact structures. Tartu, 2000, 87 p.
11. **Olev Vinn.** Morphogenesis and phylogenetic relationships of Clitambonitidines, Ordovician Brachiopods. Tartu, 2001, 127 p.
12. **Leho Ainsaar.** The middle Caradoc facies and faunal turnover in the late Ordovician Baltoscandian palaeobasin: sedimentological and carbon isotope aspects. Tartu, 2001, 109 p.
13. **Oive Tinn.** Early Ostracode evolution and Palaeoenvironmental application in the Ordovician of Baltoscandia. Tartu, 2002, 145 p.