Quaternary studies in the northern and Arctic regions of Finland
Edited by Antti E.K. Ojala
Geological Survey of Finland, Special Paper 40, 97–111, 2005.

THE UNIQUE MORAINE MORPHOLOGY, STRATOTYPES AND ONGOING GEOLOGICAL PROCESSES AT THE KVARKEN ARCHIPELAGO ON THE LAND UPLIFT AREA IN THE WESTERN COAST OF FINLAND

by
Olli Breilin[1)], Aarno Kotilainen[1)], Keijo Nenonen[1)], Matti Räsänen[2)]

[1)]*Geological Survey of Finland, P.O. Box 96, FIN-02151, Espoo, FINLAND*
[2)]*Department of Geology, FIN-20014, University of Turku, FINLAND*
E-mail: olli.breilin@gtk.fi, aarno.kotilainen@gtk.fi, keijo.nenonen@gtk.fi, matti.rasanen@utu.fi

European Union

Breilin, Olli, Kotilainen, Aarno, Nenonen, Keijo & Räsänen, Matti, 2005. The unique moraine morphology, stratotypes and ongoing geological processes at the Kvarken Archipelago on the land uplift area in the Western coast of Finland. *Geological Survey of Finland, Special Paper 40*, 97–111, 18 figures.

The Kvarken Archipelago is situated in the centre of the Fennoscandian glacioisostatic land uplift area, with an overall net uplift rate of 8 to 8.5 mm per year. At a maintained uplift rate Finland and Sweden will become connected with a land bridge across the Kvarken strait in about 2500 years. The Bothnian Bay will then become the largest freshwater lake in Europe.

The rapid land uplift gains approximately 100 hectares of new land emerging from the Baltic Sea annually at the Kvarken archipelago, Western low topography coast of Finland. The Kvarken Archipelago is characterized by extensive moraine ridge topography and a shallow brackish sea (= low salinity 4–5 per mil). The area includes approximately 7000 islands and islets and a total shoreline of approx. 3000 kilometres. The bedrock is eroded to a peneplain already during the late Proterozoic thus forming unique platform for the study of rapid isostatic land uplift and its effects on geological and coastal processes as well as the biological successions of plant communities.

The Quaternary deposits on top of crystalline bedrock is composed of moraine formations, dating back to the last deglaciation. The major geomorphologic feature, which makes the Kvarken Archipelago area extraordinary, is the spectacular De Geer moraine fields, deposited during the gradual deglaciation of the continental ice sheet. The De Geer moraines are exceptionally abundant, well formed and representative and frequently appear in large fields within the area. Also, hummocky moraines and other types of transversal moraine ridges occur.

At the modern sea bottom in the Kvarken Strait, where the moraines have not yet been exposed to wave and current activity, the moraines have their original form created by the inland-ice. Owing to the ongoing land uplift process these are rising above the sea surface, as further invaluable geological records. Finland has made application of The Kvarken Archipelago to UNESCO`s World Heritage Committee on January 2005 to be nominated as a World Heritage object on Natural criterion (i):"be outstanding examples representing major stages of the earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiographic features".

Key words (GeoRef Thesaurus, AGI): archipelagos, geomorphology, glacial features, moraines, De Geer moraines, hummocky moraines, stratotypes, uplifts, marine geology, Quaternary, Merenkurkku, Kvarken, Finland

Introduction

The Kvarken Archipelago has undergone a long sequence of geological processes. What we can see today is one part of the geologic evolution of the earth's crust: crystalline bedrock from ancient times and overburden representing young geologic processes as a heritage of the ice age. Ongoing geologic processes are rapidly and invariably changing the face of this unique area over the course of a human's lifetime.

The glacial events and formations of the Quaternary ice age have built up the unique landscape and landforms of the Kvarken Archipelago (Fig. 2). The long lasting erosion and peneplanation of the Precambrian bedrock form a peculiar platform for the dynamic, ongoing geological processes. Since the early days of glacial geology, the Kvarken area has been the focus of scientific research dealing with postglacial land uplift, moraine morphology and deglaciation.

The Northern Kvarken is the narrowest part of the Gulf of Bothnia in the northern Baltic Sea, connecting Finland's Ostrobothnia (Pohjanmaa) and Sweden's Västerbotten. The distance from the Finnish to the Swedish coast is 80 km, with only 25 km between the outermost islands (Fig. 1). Northern Kvarken also forms a submarine sill, which separates the Bothnian Sea in the south from the Bothnian Bay in the north. The Kvarken Archipelago is situated at the eastern part of the Northern Kvarken. There are more islands than at any other archipelago in the Gulf of Bothnia. However, only few islands are located along the Swedish coast.

The bathymetry of this area has changed considerably since the last deglaciation, mainly due to the relatively strong land uplift. At present, the Northern Kvarken is very shallow (0–25 m) and shoaly, but during and just after the last deglaciation (around 10 000 years ago) it was submerged 250 – 280 meters. The area includes 6,550 islands and a total shoreline of 2,840 kilometres, a large number of peninsulas and bays, and extensive stony seashores in the Kvarken Archipelago area. The land increase in the area is about 100 ha/year based on calculations from 1:20 000 scale digital base maps of different ages. The highest hill peak (17.5 m a.s.l.) is situated on Replot Island.

During the last glaciation, the Northern Kvarken was located close to the centre of the Weichselian ice sheet, which reached ~2800 m thickness during the glacial maximum (Svendsen et al 2004). The islands of the region are smooth, glacially eroded, low rocky islands, which are characterized by till boulders on the shores. Also typical for the very special landscape of the Kvarken area are boulder-rich ridges so-called De Geer moraines. On the Swedish side of the Northern Kvarken, the shoreline is steeper and the archipelago smaller with just a few islands. The landscape in

Fig. 1. Location of the proposed world heritage area (Ollqvist & Rinkineva-Kantola 2004).

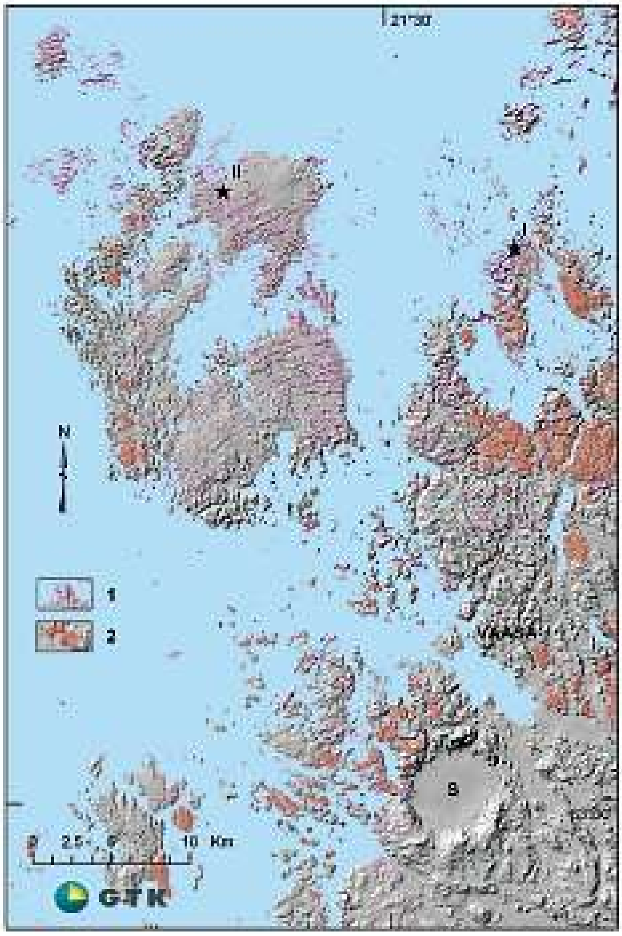

Fig. 2. The diverging of the de Geer moraine and large transversal moraine ridge clusters in the north shown by geographical elevation model. The Söderfjärden meteorite impact crater (S) is shown near Vaasa in the southern part of the image. 1 = de Geer moraine and large transversal moraine ridge, 2 = hummocky moraine. Star dots I and II = locations of excavations on moraine ridges (see Figs. 6 and 7) (Compilation: M. Paalijärvi).

Swedish side is dominated by streamlined till ridges, drumlins and flutings and elevated shore deposits, shingle field on shore slopes though De Geer moraines occur there too but more sparsely.

The World Heritage application of The Kvarken Archipelago is stated by arguments of outstanding universal value for the understanding of how glacial and deglaciation processes form a landscape. The Kvarken Archipelago is also the most representative area in the world for studying moraine archipelagos and the land uplift phenomena. The High Coast World Heritage and the Kvarken Archipelago represent complementary examples of post-glacial uplifting landscapes (Ollqvist & Rinkineva-Kantola 2004, Breilin et al. 2004) (Fig. 1).

As a complement to the High Coast World Heritage Site, The Kvarken Archipelago is proposed to the World Heritage List based on Natural criterion (i):"be outstanding examples representing major stages of the earth's history, including the record of life, significant ongoing geological processes in the development of landforms, or significant geomorphic or physiographic features" (Ollqvist & Rinkineva-Kantola 2004, Breilin et al. 2004).

Glacial formations

The most widespread surficial and seafloor sedimentary deposit in the Kvarken area is glacial till and its moraine formations. Till consists of varying amounts of boulders, stones, gravel, sand, silt and

GEOLOGICAL FEATURES OF THE KVARKEN ARCHIPELAGO

QUATERNARY DEPOSITS

- Quaternary deposits consist of young mainly glacial sediments approx. 13 000 – 10 000 BP years old. Maximum thickness up to 50 m, average 5 m.
- Complex deglaciation pattern with several ongoing ice-flow stages.
- Main soil types are glacial till, boulder fields and marine/littoral sediments and young organic deposits like gyttja and peat bogs.
- Typical glacial formations are De Geer moraines and large traversal "Rogen type" moraines, which form large moraine fields with hundreds of formations. Also, some hummocky moraine fields and minor drumlins occur.
- Rapid glacial isostatic land uplift (8 – 8.5 mm/year) and new land emerges from under the sea with an area of 100 ha/year.

BEDROCK

- The hard crystalline bedrock belongs to the Precambrian Svecofennian schist belt.
- The bedrock consists mainly of gneiss, diatexite, granites and diabase.
- The history of bedrock contains 11 different phases, aging from 1,9 Ga to 520 Ma.
- Palaeozoic sediments began to deposit on the eroded Precambrian peneplain 520 million years ago.
- The main part of these sediments is also missing (due to peneplanation erosion processes).

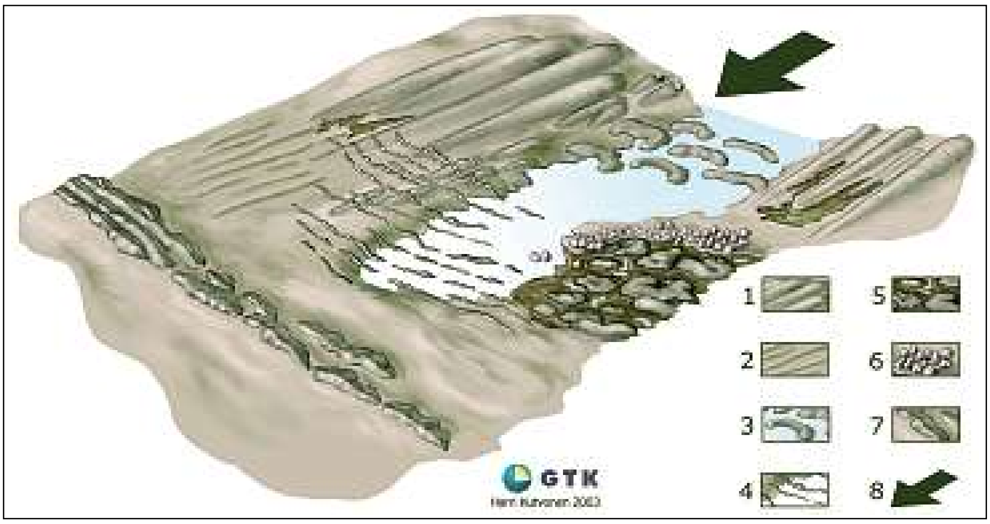

Fig. 3. Schematic figure of the moraine formations in the Kvarken area. 1. Drumlins, 2. Flutings, 3. Large transversal moraines (Rogen type), 4. De Geer moraines, 5. Hummocky moraines, 6. Boulder-rich surface, 7. End moraines, 8. Latest ice flow direction (Drawing: H. Kutvonen).

clay. Till generally lies directly on the bedrock and largely follows its surface configuration. Till also commonly forms surficial configurations like various moraine ridges and hummocks (Fig. 3). Numerous De Geer moraines are a specific feature of the Kvarken Archipelago. The best area to study De Geer moraines is in the Björkö Svedjehamn area (Fig. 4).

Moraines parallel to the ice direction

A drumlin is the oval-shaped streamlined ridge formed beneath an ice-sheet as it moved over the terrain. Drumlins and drumlinoid formations are often found in groups and the ridges may extend for several kilometers. Drumlins are composed mainly of basal till or lodgement till. Fluting ridges are either depositional or erosional small glacial features on the basal till surfaces, indicating the last ice flow direction.

Both drumlins and flutings form a small field at Norra Vallgrund where the younger transversal moraines cover the streamlined parallel moraine forms. In the Swedish side of the Kvarken both drumlins and flutings are the major moraine forms on till areas.

Fig. 4. Helicopter view of the De Geer Moraines. Björkö Svedjehamn. (Photo: A. Hämäläinen, 2000)

Moraines parallel to the ice margin

End moraines belong to this class and may either be large or small, short or long. The end moraines were formed along the ice margin and often have an asymmetrical shape with a gentle stoss-side and a steeper lee-side. A closely related type of moraine, the De Geer moraine, occurs in clusters in lowland areas (Fig. 4). Earlier, it was thought that the moraines were formed at the ice margin and were a type of end moraine. De Geer moraines are most commonly till ridges up to 5 m high, from 10–50 m wide and a couple of hundred meters long. In rare instances, the height exceeds 5 m and length 1000 m. The moraines occur at 40 – 300 m intervals in large groups, mostly in low-lying landscape areas. The Replot and Björkö areas in the Kvarken Archipelago are the best examples of clusters of De Geer moraines in Finland (Aartolahti 1988).

In the Kvarken Archipelago area, the amount of De Geer moraine ridges is greatest and they occur in very compact formation swarms. The width of the formations is often over 50 m and the formations are symmetrical (Laaksonen 1994). In some areas, the formations seem to be related or deposited on top of drumlin forms and other hummock moraine forms like large transversal Rogen type ridges. In the Märaskär and Köklot areas, De Geer moraines are deposited on top of larger Rogen type moraine formations and the long axis of both moraine formations forms a network pattern in the terrain and archipelago. Laaksonen (1994) put forward a competing hypothesis of stabile laminar basal flow of ice as an explanation of the wave like pattern and symmetric forms of the De Geer moraines and swarms. It is evident that both De Geer moraines, transverse basal till ridges (Rogen type moraines or ribbed ridges) and radial streamlined moraine ridges (drumlins) occur in the same area of Replot and Björkö islands. There may also be a connection between the clusters of De Geer moraines and tectonic features (Lundqvist 2000).

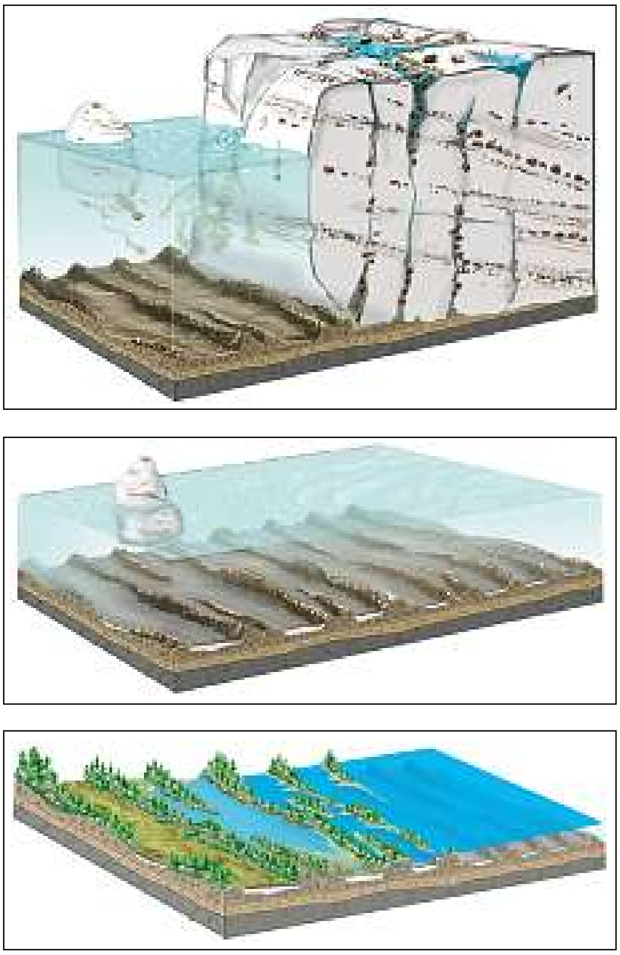

Fig. 5. The suggested formation of De Geer moraines (Drawings: Harri Kutvonen).

The De Geer moraine formation were first described in Sweden by De Geer (1889) and called De Geer moraines by Hoppe (1957) or washboard moraines by Mawdsley (1936). In the case of the Kvarken Archipelago, the water depth during deglaciation and formation of the moraine ridges was 250–280 m. According to the current moraine genesis explanation, the moraine ridges were formed in the crevasses running parallel to the ice margin in sub -aquatic conditions. Huge icebergs calved at the ice front and the De Geer moraine reflects the probable position of the retreating ice margin (Fig. 5).

Hummocky moraines

Hummocky moraines principally occur in valleys and in flat-lying areas. Hummocky moraines are irregular and non-oriented formations, usually 5–20 m high, and form a mosaic of lakes, tarns, and peatlands. The moraines were deposited in the Kvarken area beneath the melting and thinning glacier front in sub-aquatic conditions. Material in these formations is usually washed and coarse grained till (melt out till). Most of the hummocky moraine formations were deposited in the final stage of the last deglaciation. In a way, they witness the non-oriented deposition character of till material during the formation of De Geer moraines. In some localities, the texture of the faulted and fissured glacier front can be seen in the hummocky relief, sometimes resembling ring-ridge type of deposition like in Pulju moraines or ribbed moraines in Northern Finland (comp. Sarala 2003, 2004 and Johansson & Nenonen 1991). Some hummocks are just heaps of till that were deposited, squeezed or that flowed in a crevasse or cavity beneath the melting glacier.

A Rogen moraine is a type of hummocky moraine or ribbed moraine characterized by ridges, that are irregular in detail but largely at right angles to the direction in which the ice was moving (comp. Lundqvist 1989, Hätterstrand 1997 and Sarala 2003, 2004). Rogen type moraines are often composed of basal till or lodgement till and deposited clearly in sub glacial conditions probably in the same zones as the drumlins. Transversal basal till ridges occurs in swarms and often inside drumlin fields. Some Rogen type moraine formations in the Kvarken area have developed elongated tails parallel to the last ice flow directions, thus showing a relationship to the drumlin forming processes. Rogen-like transversal moraine formations occur in the Köklot, Mickelsörarna and Valsörarna areas.

The drumlins and large transversal moraine ridges (Rogen type) were formed below the ice sheet, some 200 – 700 km inside ice margin. At that time, huge ice lobes filled the Bothnian Bay area and the ice flow was roughly south-southeast as shown by striations and drumlin orientations on maps (comp. Bargel et al. 1999). The term hummocky moraine is used to describe all kinds of moraine hummocks. Cuts in the moraines and documentations of the sections give tools for a more detailed classification. In recent investigations, new evidence of complex ice flow directions have been discovered (Geonat 2004). Therefore, the Kvarken Archipelago might become one of the key areas for understanding the Early- and Mid- phases of Weichselian glaciation.

One striking phenomenon in the Kvarken Archipelago is the boulder rich till surfaces even in shallow sea areas, like in the Ikmo Lillön area, Halsön Island and the Bergö Gaddarna rocky islets. Some of the boulders are huge erratics transported by flowing glacier ice or floating icebergs in the Ancylus Lake. The granitic rock types are susceptible to intensive cubic cracking and thus large boulders and erratics are easily carried by the glacier from rock outcrops and possible preglacial inselberg or tor like bedrock formations. This boulder rich undulating moraine terrain is an example of glacioaquatic and subaquatic till deposition and represents the youngest till deposit and moraines in the area.

Structure of the De Geer moraine and large transversal moraine ridge at Björköby and Köklot

Three representative moraine formations in the GEONAT research area were chosen for further studies. The Björkö Skagback De Geer moraine formation represents a well-shaped prominent higher moraine ridge with a smooth proximal side and steeply dipping distal side. Two test pits and one trench were excavated in this formation. The Björkö Ohls De Geer moraine formation represents a lower moraine ridge were the proximal and distal sides are both smoothly dipping (location II in Fig. 2). One study trench was excavated in this formation. Both De Geer ridges are located within the Björköby De Geer moraine field where the terrain is covered with numerous higher and lower moraine ridges at less than 100- meter intervals. The third chosen formation at Köklot Furuskäret represents larger, more prominent transversal moraine formations of Rogen type (location I in Fig. 2). De Geer moraine formations are on a transversal position and overlie the larger Köklot moraines especially north from Köklot in the Mickelsörarna area.

Three test pits were excavated in the formation at Köklot. The cuttings and trenches in the Björkö Skagback and Björkö Ohls De Geer moraine formations revealed that both lodgement till and melt out till are present in the formations. The till fabric in

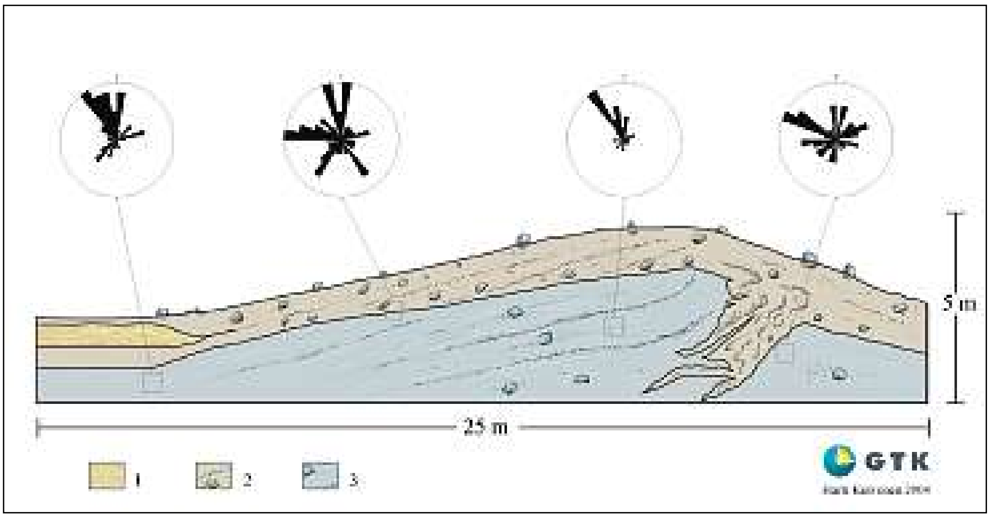

Fig. 6. Schematic cross section from test pit excavated in the low-lying De Geer moraine Björkö Ohls. Ice flow direction from left to right in drawing. 1= sandy loam, 2= melt out till with deformation structures and 3= basal till with some deformation structure (location II in Figure 2, Drawing: H. Kutvonen)

both moraine types showed relatively good preferred orientation along the latest ice flow direction though some fabric analyses also showed transversal peaks or were not oriented (Fig. 6).

The structure of the till material shows that shearing and deformation was present during the depositional process. Shear planes, glaciotectonic folds, thrust structures and good preferred orientation in the till fabric shows the presence of actively flowing ice and deposition in a subglacial environment. The texture of the till material is a matrix supported in the lodgement type till and both the matrix and clast were supported in the melt out till type, which also shows sorting of sand and gravel material. The sorting and coarser texture of the melt out till type demonstrates the presence of water in the depositional process. The petrographic composition of the till types in the Björkö formations shows quite similar transport conditions in both formations and moraines and results are typical of subglacial basal tills.

Results of the excavations of the larger Köklot Furuskäret moraine formation differ considerably from the Björkö formations. The till type in the Köklot formation is of a melt out type. The structure of the till shows sorting, sandy wrappings under and over stones and boulders, abundantly sorted sandy and gravelly lenses, bed and layer structure in till and some folding and bending of the sorted layers (Fig. 7). The till fabric is poorly oriented. One fabric analysis shows a northerly fabric, which coincides with younger northerly striations and De Geer moraines deposited by a northeastern ice flow. The moraine in the Köklot formation is over consolidated and was clearly deposited in subglacial conditions. The petrographic composition differs clearly from the Björköby area showing abundant granites and porfyric granodirites in the ice flow direction.

The studied moraine formations in Björkö and Köklot are clearly of subglacial and subaquatic origin (comp. Benn & Evans 1998). The Björkö De Geer moraine formations shows actively flowing, deforming and pushing behavior of the ice edge rather than the melting, loading and convoluting, crevasse fill phenomena of subglacial ice crevasses (Fig. 8). The depositional environment indicates sub marginal formation of parallel moraine ridges at a calving ice margin (comp. Aartolahti 1995 and Linden et al. 2004). The Köklot large transversal moraine formations show abundant subglacial melting, glacial loading, consolidating of melt out till and probably reactivation of the glacier sole. The Köklot formations probably have a complex origin and there are still riddles to be solved

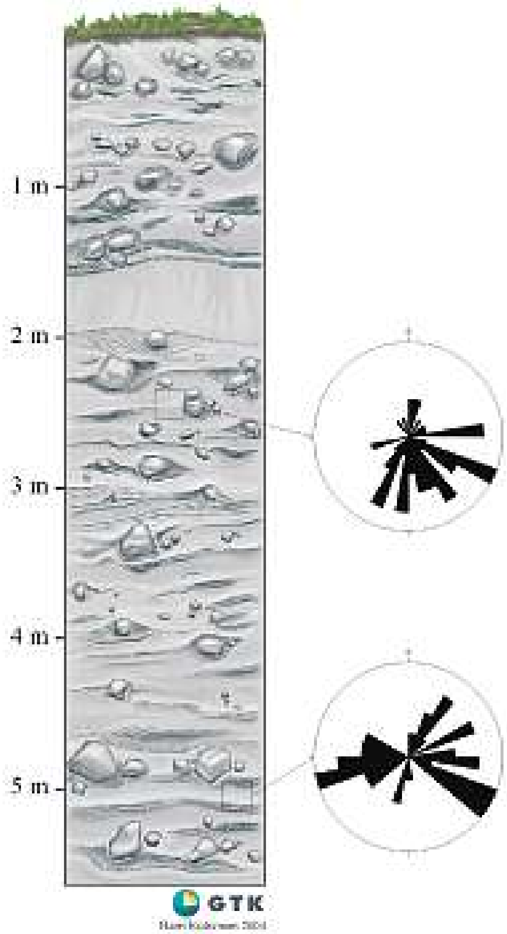

Fig. 7. Schematic profile and photograph from the test pit excavated in large transversal moraine ridge in Köklot. The length of the red knife grip is 10 cm (location II in Fig. 2) (Drawing: H. Kutvonen). (Photo: J. Ojalainen, 2003).

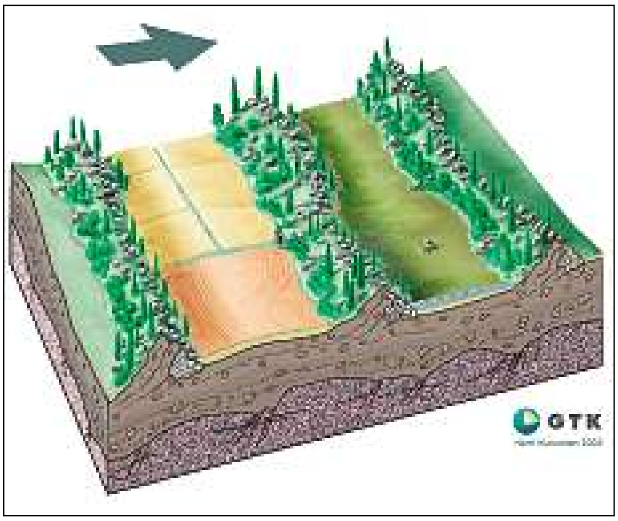

Fig. 8. Schematic picture of the De Geer moraines in the Björkö area. Arrow indicates the last ice flow direction, which is perpendicular to the De Geer moraine ridges. Wedge-like brown basal moraine in the formations illustrates shearing and pushing behaviour of ice edge. Gray moraine inclusions illustrate the melt out facies of the basal till at the distal side of moraine formations (Drawing: H. Kutvonen).

in these formations (comp. Benn & Evans 1998 and Aartolahti 1995).

Fig. 9. Svedjehamn gyttja site and example of the gyttja sample. Blue areas in sample shows vivianite – mineral, which is typical for till covered organic deposits. (Photo: J. Ojalainen, 2004)

Svedjehamn gyttja

Excavations at Svedjehamn, Björköby in the northern part of the archipelago discovered a new till covered organic deposit under a 3 – 4 meter thick till cover (Matti Räsänen, personal communication) (Fig. 9). A test pit was excavated at the De Geer moraine's distal site. Later also several sediment core drillings where made to the spot. The till cover over the organic deposit is composed of a sandy till of melt out type. After preliminary laboratory investigations, the organic deposit is interpreted to be gyttja deposited in fresh water conditions. Pollen flora is mainly *Betula*, representing interstadial conditions of Early- or Mid-Weichselian stages (Matti Räsänen, personal communication). The gyttja is just a few meters above the present sea level and is in the lowest topographic position compared with any other till covered organic deposit in Ostrobothnia (Nenonen 1995). This deposit is clear evidence of a much lower sea level stage in the Bothnian Bay area before the last glacial maximum (see Fig. 10). Drillings and earth penetrating radar surveys where made in the location during fall 2004. A detailed study of the biostratigraphy and litostratigraphy of Svedjehamn Gyttja is under work in the University of Turku.

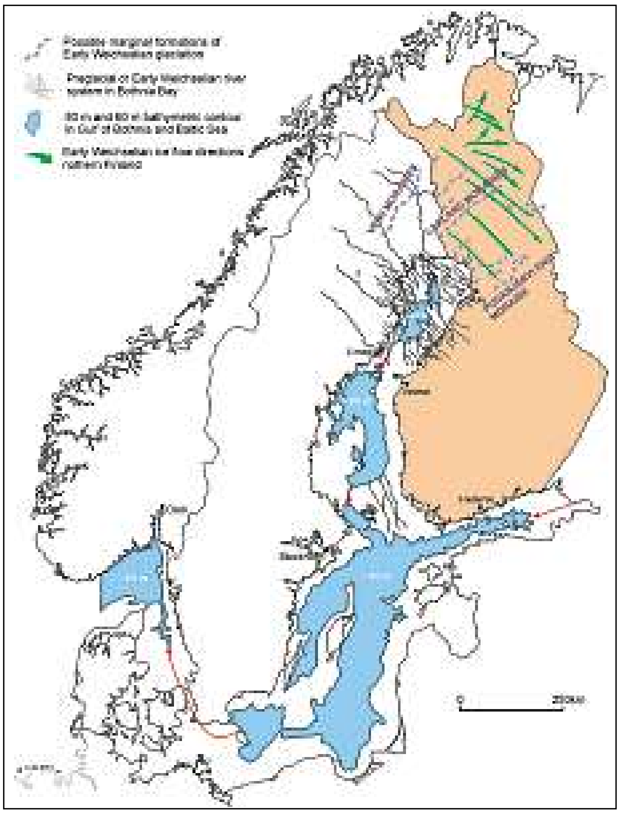

Fig. 10. Bothnian Bay and Baltic Sea area during Weichselian interstadials (Nenonen 1995).

Complex Ice flow pattern in the Kvarken Archipelago

Based on field observations, the phenomena of weak glacial erosion and complex ice flow pattern in the Kvarken Archipelago are strong (Geonat 2004). Evidence of these phenomena is formed in different phases of glaciations. Part of striae and the Svedjehamn organic layer could be of Mid or Early Weichselian age. Field observations of several boulder fields show that rock types are local and in many cases boulder fields are interpreted as erosional remains. This supports the theory of weak glacial erosion in the Kvarken area.

Glacial striaes

On fresh outcrops, glacial striaes are clearly seen in shore areas of thousands of islands and islets (Fig. 11). Faceted, polished surface also appear in some outcrops. Based on field observations of these glacial striae (Fig. 12), ice flow direction has been between 330° – 80° degrees. In the same outcrops, the angle of different directions could be nearly 90° degrees. Also, a direction near 360° degrees has been observed. In some outcrops, the youngest and oldest directions are not same through the area (Geonat 2003, 2004). In some outcrops, the youngest direction is 40° – 65° and in some outcrops 335° – 360°.

Geomorphology

De Geer moraines and large transversal moraine ridges are the main formations of the Quaternary deposits in the Kvarken Archipelago. The direction of the longitudinal axis of moraine formations is complex, which supports the complex glacial striae directions (Figs. 2 and 8). Moraines overlying each other can be seen in some areas. The angle of overlying formations could be up to 90° degrees in northeast parts of the Mickelsörarna area of the archipelago. On the Swedish side, the deglaciation morphology is different. The main feature is a large and intensive drumlin field, which continues from the mainland to the sea bottom (Geonat 2003). The morphology of the sea bottom changes rapidly from drumlin fields to De Geer and large transversal moraine fields approximately 5 km east of Holmö Island on the Swedish coast.

Fig. 11. Crossed glacial striaes (350° – 65°) on a bedrock outcrop on Storskäret Island. Direction of the GPS receiver is 65°. (Photo: O. Breilin, 2003)

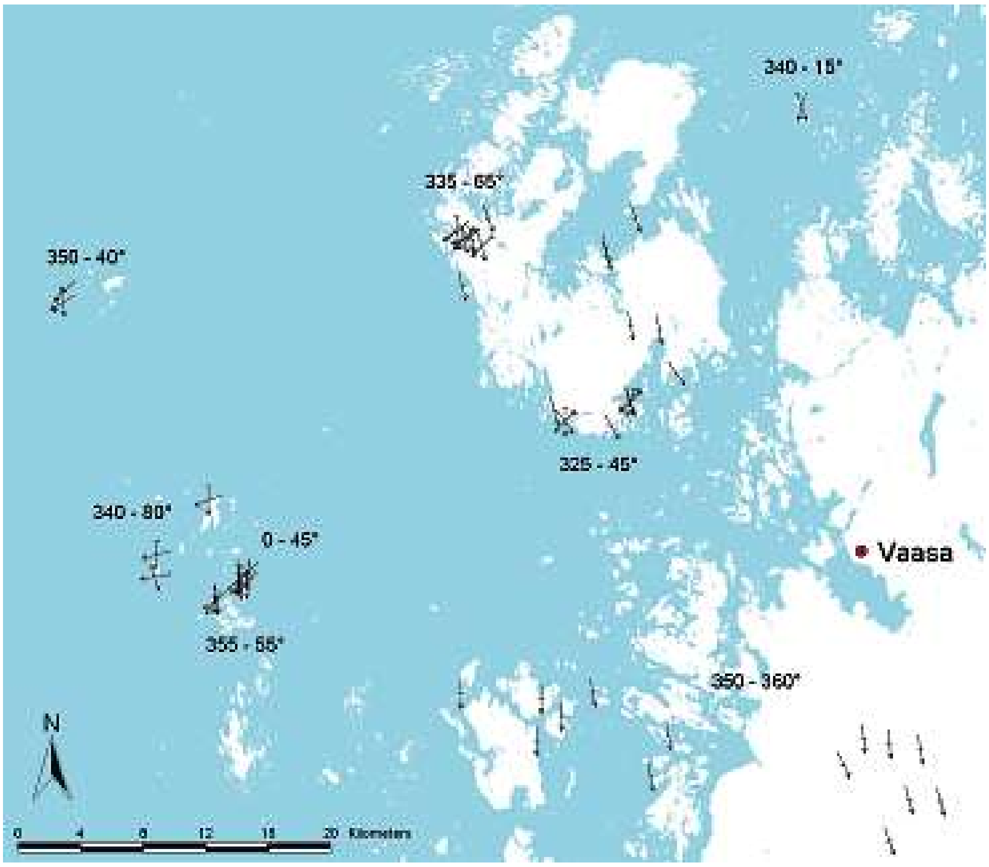

Fig. 12. Location and direction of glacial striations at Kvarken Archipelago (Compilation: J. Ojalainen, Geonat 2003).

Land uplift – historic, present and future

Land uplift studies have a long and respectable history in Finland and Sweden. Changes in shoreline during a human lifetime can be easily observed and had been noticed early. The writer Zachris TOPELIUS depicted late 19th Century the land uplift thus:

"Most noticeable are the effects of this, partly still unexplained, phenomenon. The land rises from the sea, the sea flees, shores are exposed, and the slope is moving forward. Where in days of old ships were sailing, now hardly a ship can travel; where once the fisherman cast his net, now his cows go grazing on the coastal meadow. Banks and rocks appear out of the water, of which no sea chart has had knowledge before; banks expand into islets, these grow together and connect with the mainland. Beaches expand; harbours dry up, seaports must move after the fleeing sea. Every generation of men, new arable land rises from the sea, every century grants Finland a kingdom" (Edlund 1893).

One encounters many a re-owned scientist's name in the field of land uplift research, like the Swede Gerard DE GEER who proved land uplift to be a residual rebound phenomenon from the ice age Finnish geologist Wilhelm RAMSAY, who separated conceptually the isostatic land uplift and the eustatic change of sea level from each other (The Finnish Geodetic Institute, http://www.fgi.fi/yleis/historia_eng.html).

The total depression of the earth surfaces is calculated at 800-1000 m (Taipale & Saarnisto 1990, Eriksson & Henkel 1994, Kakkuri & Virkki 2004). It is assumed that the land uplift will continue some 10 000 to 12 500 years in the Kvarken area and it will still probably result in 100-125 m of isostatic land uplift (Kakkuri 1991). So the uplift will continue until the depression of the geoid is reversed or the next oncoming glaciation begins to load and submerge the Earth's crust in the Kvarken area. The sub-aquatic Kvarken area is a shallow sill with a maximum water depth of 30 m. According to the shore level displacement curve, the sill will be just a strip of water in about 2 500 years (Figs. 13 and 14).

The land uplift had already begun during the melting and thinning of ice 15 000 years ago during the glacial retreat from the Baltic area. During the first

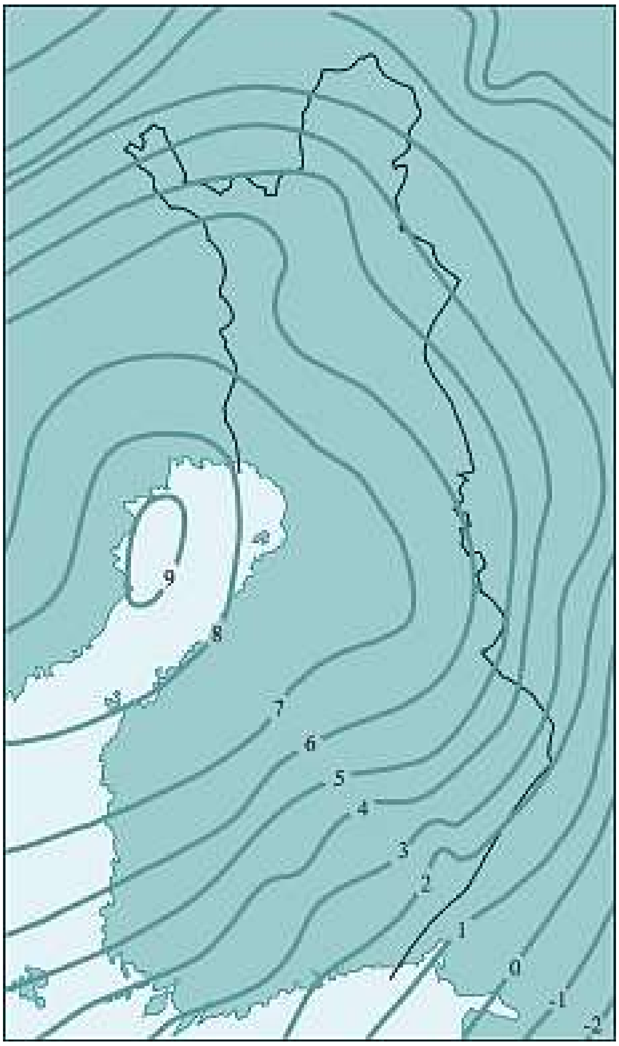

Fig. 13. Present isobases of land uplift (mm per year) in Eastern and Central Scandinavia (Alalammi 1990).

thousand years, the land uplift in the deglaciated areas was calculated to be up to 10 m in 100 years or 100mm/ year (Saarnisto 1981). According to the latest Weichselian ice sheet LGM models, the maximum thickness of the ice had been approximately 2 800 m (Svendsen et al. 2004).

The isostatic land uplift creates not only new land but also many practical problems for the northern Kvarken area. All old harbours are, at present, dry land. The Vaasa-Korsholm harbour that was founded in 12th century is situated 10 km inland from the present Vaskiluoto harbour that was founded in 1890. New land emerges from the shallow sea at a rate of several hectares for individual villages per year. For example, in Replot and Björkö villages 35 hectares of land emerges annually (Palomäki 1988). In the proposed Kvarken Archipelago world heritage area new land emerges from the sea approximately 100 ha annually (Geonat 2004, Ollqvist & Rinkineva-Kantola

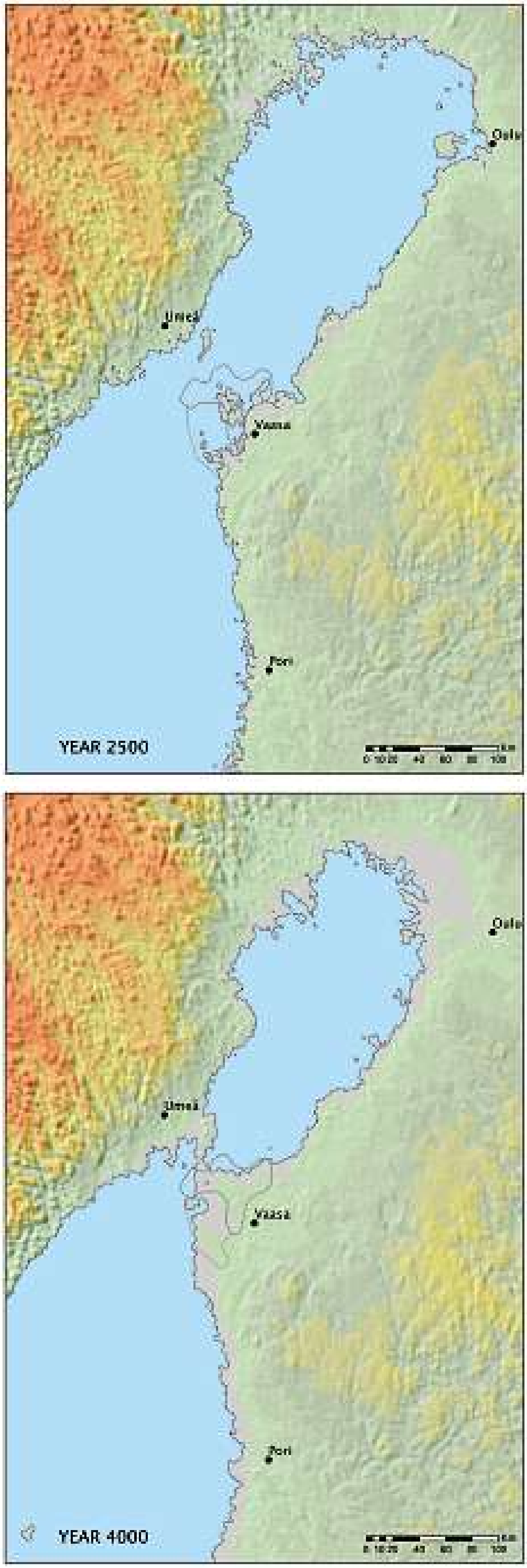

Fig. 14. Future of the Bothnian Bay which is the northern part of the Baltic Sea (DEM Seifert et al. 2001, processing: H. Virkki).

2004). It is estimated that the total new land gain is approximately 7 square kilometres along the Finnish coast (Kakkuri & Virkki 2004).

Also, the construction of deeper harbour basins and canals is a continuous struggle against sea and marine routes that are becoming shallower. A typical phenomenon is summer cottages and their boat shelters lying far inland from the present day shallow shoreline of many low lying islands and peninsulas along the Finnish side of the Kvarken area (see Osala 1988). The land virtually rises from the shallow sea during the span of a human's lifetime. At first, some elongated boulder rich ridges and reefs emerge and seabirds begin nesting there, then the moraine ridges grow together to form elongated bushy moraine islands and finally close into small lagoons. The new soil is fertile and plant cover appears to become established on the shores almost immediately. As land uplift continues, the lagoons become separated from the sea and develop as freshwater ponds or "fladas" and lakes that occasionally get saline intrusions of flooding water from the sea during stormy days. As the vegetation occupies the freshwater ponds wetland development begins, which continues to form raised peatlands in a span of thousand years.

The current relative uplift is about 8.0 mm on the Finnish side of Kvarken area and about 8.5 mm on the Swedish side according to the current postglacial land uplift information from three precise surveys in Finland (Ekman 1996, Mäkinen & Saaranen 1998) (Fig. 13). On the basis of gravimetric surveys of the Geodetic Institute, the Fennoskandian land uplift is associated with some mass flow in the deep mantle layers of the Earth. When, for example, the land uplift in the Vaasa area in relation to the centre of the Earth is approximately 10 mm/y, gravity has diminished in 26 years (0.24×10×26 microgals), or about 0.06 milligals. (The Finnish Geodetic Institute, http://www.fgi.fi/yleis/historia_eng.html)

Marine geology of the Kvarken Archipelago

The narrowest part of the Gulf of Bothnia, Kvarken area, forms a submarine sill (25 m) that separates the Bothnian Sea in the south from the Bothnian Bay in the north. The Kvarken Archipelago also includes areas outside the sill where greater depths occur sparsely (~83 m at maximum). Due to the relatively rapid land uplift, the bathymetry of the Kvarken Archipelago has changed dramatically since the last deglaciation. The majority of the Kvarken Archipelago is very shallow (0–25 m) and shoaly. The fairways are shallow, boulder-rich, and mostly less than 10 meters deep. During, and just after the last deglaciation (around 10,000 years ago), the archipelago was submerged more than 200 m.

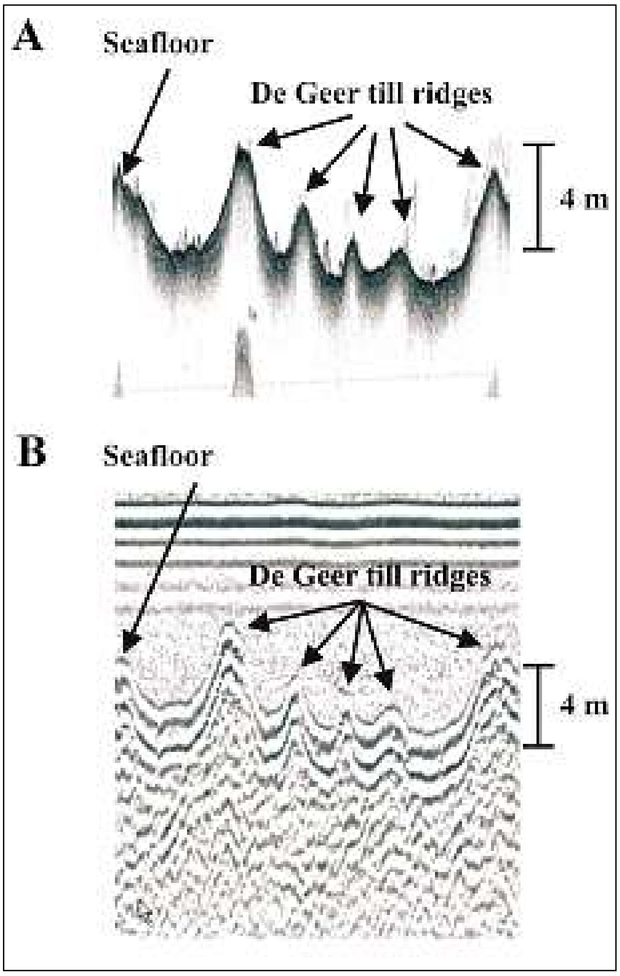

Fig. 15. Echosounding (A) and acoustic reflection profiles (B) of De Geer moraines (Compilation: A. Reijonen).

Seafloor geologic information was obtained using acoustic-seismic investigation methods and sediment sampling. Acoustic-seismic methods used include echo sounding (MeriData MD 28 kHz transmitters); single-channel seismic reflection (Electro Magnetic implosion type sound source, ELMA, 400–700 Hz, depth resolution of ± 2 m) and side scan sonar (Klein SA 350, 100 kHz) surveys.

The seafloor morphology is characterised by tectonic lines in Vaasa granite, and hummocky and De Geer moraines. The crystalline bedrock is similar on both sides of the Northern Kvarken and thus it is assumed that this is true also for the sea area, although no actual data are available (Winterhalter 2000). Sedimentary rocks exist on the seafloor of the Bothnian Sea and the Bothnian Bay but the rocks have not yet been found in the Kvarken Archipelago. However, Lower Cambrian sedimentary rocks occur in the coastal area (Söderfjärden), close to the city of Vaasa.

The entire Baltic Sea basin has undergone several

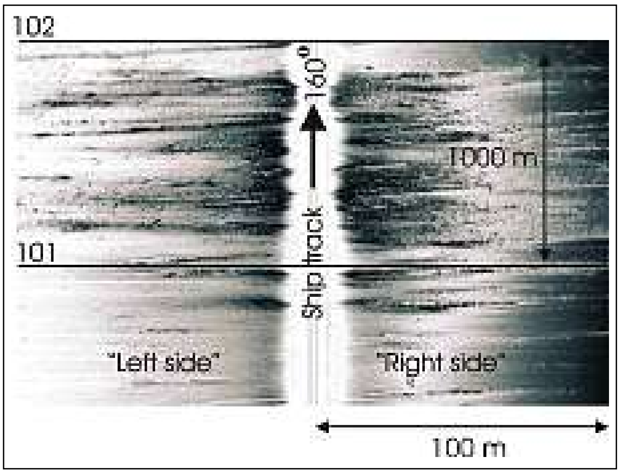

Fig. 16. Side-scan sonar profile of De Geer moraines. Side-scan sonar presents the seafloor on both sides of the vessel and produces images resembling aerial photographs.

Fig. 18. Splitting the sediment core onboard r/v Geola. White line in Figure indicates the onset of the Litorina Sea stage in lithostratigraphy. (Photo: J. Hämäläinen, 2003).

glaciations during the Late Pliocene and Pleistocene (the past ~2.7 million years). During this time, the Kvarken and Baltic Sea areas have been repeatedly subjected to glacial erosion and accumulation. However, information on possible interglacial deposits in the present marine area is still very scarce. From earlier geological stages, there are indications of land uplift in the Bothnian Bay area of 100 m above present level, and a lowering of the ocean sea level would have changed the hydrography of the whole area.

The Bothnian Bay and the entire Baltic Sea were isolated from the ocean during the Early and Mid-Weichselian sub stages, 115 000 – 50 000 years ago, when the ocean level was lower than it is today and the area was undergoing uplift after the Saalian and Early Weichselian glaciations (Lundqvist 1992, Lundqvist & Robertsson 1994, Nenonen 1995). Old preglacial river channels, tens of metres deep, have been found on the seafloor of the Bothnian Bay and the Bothnian Sea as extensions of present-day rivers (Tulkki 1977). The channels extend to the central parts of the marine area, to a depth of 80 m below present sea level, thus showing the probable ancient shoreline (Fig. 10).

The seafloor consists mainly of till. Due to strong currents and wave action, varved clay and postglacial clay sediments are often absent. Postglacial clays and gyttja-clays cover the sea floor only in basins, protected from current activity (Ignatius et al. 1980). According to the available data, the thickness of the Quaternary deposits in the Kvarken area is relatively low.

The geomorphologic feature that makes the Kvarken Archipelago unique is the occurrence of spectacular De Geer moraines (Aartolahti et al. 1995). These moraines also occur on the seafloor in the Kvarken Archipelago (e.g. Nuorteva 1988, Reijonen 2004) (Fig. 15 and 16).

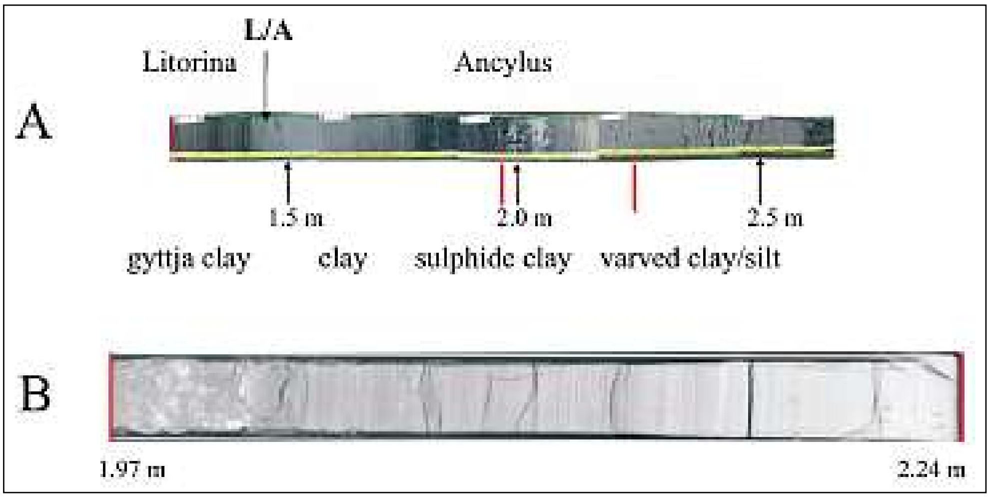

Fig. 17. Early Holocene lithostratigraphy in vibrohammer core MGTK-2003–14 of the Kvarken Archipelago (A). The onset of the Litorina Sea stage is indicated by L/A in Fig.. X-ray radiograph of sulphide clays and varved clays (1.97–2.24 metres below seafloor, red bars in Fig. A) is shown in Fig. B (Compilation: A. Kotilainen).

The glacial morphology of the seafloor has not undergone coastal deformation, as is the case with land areas. In the marine area, it is possible to study the nature of glacial features more or less in the state they were formed (Winterhalter 1972).

Despite the sparse occurrence of glacial and postglacial clays in the Kvarken Archipelago, the Ancylus Lake and the Litorina Sea stages of the Baltic Sea are relatively well represented in submarine sediments of sheltered basins as shown in Figures 17 and 18. However, the latest history of the Baltic Sea is rarely recorded in submarine sediments of the Kvarken Archipelago.

Acknowledgements

We are very grateful to funding organizations and steering group members of Geonat – project of opportunity to write this paper: European Union (Interreg IIIA Kvarken Mitt-Skandia), Regional Council of Ostrobothnia / Saini Heikkuri-Alborzi, Vaasa town / Harri Nieminen, municipality of Korsholm / Pertti Malinen, Metsähallitus Western Finland Nature Heritage Services / Kari Hallantie, K.H.Renlunds foundation / Professor Carl Ehlers and Geological Survey of Sweden / Dr Naz Ahmed Shaikh and Anders Elhammer. Especially we thank you Susanna Ollqvist and Leena Rinkineva-Kantola of intensive work and encouraging support to geology in the Kvarken Archipelago World Heritage preparatory project and to Professor Matti Saarnisto of accepting the manuscript. We are also grateful to Harri Kutvonen from GTK who prepared many of the illustrations. The authors will thank you Hanna Virkki, Miikka Paalijärvi and Tapio Väänänen of GIS-services. Also we thank you the captain and staff of GEOLA – vessel. Finally we thank you our colleagues in GTK Jyrki Hämäläinen, Jukka Ojalainen, Sakari Kielosto, Niko Putkinen, Anu Reijonen, Seppo Töllikkö and Janne Tranberg, who made great part of field observations.

REFERENCES

Aartolahti, T. 1988. Maanpinnan muodot, Landytans former. In: Osala, T. (ed.), Vaasan saaristo, Vasa skärgård. Vaasa: O&G Förlaget/O&G Bolaget, 26–36.

Aartolahti, T. 1995. Glacial geomorphology in Finland, In: Ehlers, J., Kozarski, S. & Gibbard, P. (eds.), Glacial Deposits in North – East Europe. Rotterdam: A.A.Balkema Publishers, 37–50.

Bargel, T., Huttunen, T., Johansson, P., Jokinen, S., Lagerbäck, R., Mäkinen, K., Nenonen, K., Olsen, L., Svedlund, J.-O., Väänänen, T. & Wahlroos, J.-E. 1999. Maps of Quaternary geology in central Fennoscandia, sheet 2: glacial geomorphology and palaeohydrography. Scale 1:1 000 000. Espoo : Trondheim : Uppsala: Geological Survey of Finland : Geological Survey of Norway : Geological Survey of Sweden.

Benn, D.I. & Evans, D.J.A. 1998. Glaciers and glaciation. London: Edward Arnold, 734 p.

Breilin, O., Kotilainen, A., Nenonen, K., Virransalo, P., Ojalainen, J. & Stén, C.-G. 2004. Geology of the Kvarken Archipelago. Geological Survey of Finland, unpublished report, 47 p.

De Geer, G. 1889. Änmoräner i trakten mellan Spånga och Sunbyberg. Geologiska Föreningens i Stockholm Förhandlingar 11, 385–397.

Edlund, G.W. (ed.) 1893. Finland in the 19th century as presented by Finnish writers and artists in words and pictures, Helsinki 1893. [in Finnish]

Ekman, M. 1996. A consistent map of the postglacial uplift of Fennoscandia. Terra Nova 8, 158–165.

Eriksson, L. & Henkel, H. 1994. Geophysics. In: Fredén, C. (ed.), Geology – National Atlas of Sweden, 76–101.

Geonat 2003. Unpublished fieldwork results of the Geonat-project. Geological Survey of Finland and Department of Geology, University of Turku.

Geonat 2004. Unpublished fieldwork results of the Geonat-project. Geological Survey of Finland and Department of Geology, University of Turku.

Hoppe, G. 1957. Problems of glacial morphology and the Ice Age. Geografiska Annaler 39, 1–18.

Hätterstrand, C. 1997. Ribbed moraines in Sweden-distribution pattern and paleoglacial implications. Sedimentary Geology 11, 41–56.

Ignatius, H., Kukkonen, E. & Winterhalter, B. 1980. Pohjanlahden kvartäärikerrostumat. Geologinen tutkimuslaitos, Tutkimusraportti 45. [in Finnish]

Johansson, P. & Nenonen, J. 1991. Till stratigraphical studies in the Pulju area in northern Finland. In: Autio, S. (ed.), Geological Survey of Finland, Current Research 1989–1990. Geological Survey of Finland, Special Paper 12, 131–134.

Kakkuri, J. 1991. Planeetta Maa. Ursan julkaisuja 42. Helsinki: Tähtitieteellinen yhdistys Ursa, 184 p.

Kakkuri, J. & Virkki, H. 2004. Maa Nousee. In: Koivisto, M. (ed.), Jääkaudet. Helsinki: WSOY, 168–178.

Laaksonen, K. 1994. De Geer-moreenien syntymalleista. Terra 106, 25–34.

Linden, M., Möller, P., Adrielsson, L. & Kljaer, K. 2004. Subglasial formation of De Geer moraines, northern Sweden. Geologiska Föreniges i Stockholm Förhandlingar 126, 123 p.

Lundqvist, J. 1989. Rogen (ribbed) moraine-identification and possible origin. Sedimentary Geology 62, 281–292.

Lundqvist, J. 1992. Glacial stratigraphy in Sweden. Geological Survey of Finland, Special Paper 5, 43–59.

Lundqvist, J. & Robertsson, A-M. 1994. Glacials and Interglacials. In: Fredén, C. (ed.), Geology, National Atlas of Sweden, 120–124.

Lundqvist, J. 2000. Paleoseismicity and De Geer Moraines. Quaternary International 68, 175–186.

Mawdsley, J.B. 1936. The wash-board moraines of the Opawica-Chibougamau area Quebec. Transaction of the Royal Society of Canada 30, Ser. III, 9–12.

Mäkinen, J. & Saaranen, V. 1998. Determination of post-glacial land uplift from three precise leveling in Finland. Journal of Geodesy 72, 516–529.

Alalammi, P. (ed.) 1990. Atlas of Finland. Folio 123–129: Geology. Helsinki: National Board of Survey, Geographical Society of Finland, 58 p.

Nenonen, K. 1995. Pleistocene stratigraphy and reference sections in southern and western Finland. Geological Survey of Finland, Miscellaneous Publications, Ph.D. Thesis, 205 p.

Nuorteva, J. 1988. Akustisilla luotausmenetelmillä saatu kuva merenpohjan kvartäärikerrostumista. Geologian tutkimuskeskus, Tutkimusraportti 82, 32 p. [in Finnish]

Ollqvist S. & Rinkineva-Kantola, L. (eds.) 2004. Nomination of the Kvarken Archipelago for the inclusion in the World Heritage list. Metsähallitus Western Finland Natural Heritage Services, West Finland Regional Environment Centre, Regional Council of Ostrobothnia, Vaasa, 85 p.

Osala, T. 1988. Vaasan Saaristo – Vasa Skärgård. Vaasa: O&G Förlaget, 424 p.

Palomäki, M. 1988. Maankohoaminen, Landhöjningen. In: Osala, T. (ed.), Vaasan Saaristo, Vasa Skärgård, Vaasa: O&G Förlaget/ O&G Bolaget, 37–65.

Reijonen, A. 2004. Vedenalaisten moreenimuodostumien monimuotoisuus Merenkurkussa. University of Helsinki, Department of Geology, Unpublished M.Sc. Thesis, 102 p. [in Finnish]

Saarnisto, M. 1981. Holocene emergence history and stratigraphy in the area north of the Gulf of Bothnia. Annales Academiae Scientiarum Fennicae. Series A. III. Geologica – Geographica 130, 42 p.

Sarala, P. 2003. Ribbed-moreenit – jäätikön liikesuunnan poikittaiset indikaattorit (Summary: Ribbed moraines – transverse indicators of the ice flow direction). Geologi 55, 250–253. [in Finnish]

Sarala, P. 2004. Deglaciation pattern and glacial dynamics of the southern Finnish Lapland. In: Mansfeld, J. (ed.) The 26th Nordic Geological Winter Meeting, January 6th – 9th 2004, Uppsala, Sweden, abstract volume. GFF 126, p. 124.

Seifert, T., Tauber, F. & Kayser, B. 2001. A high-resolution spherical grid topography of the Baltic Sea revised edition. Proceedings of the Baltic Sea Science Conference 2001, Stockholm, 25–29.

Svendsen, J.I., Alexanderson, H., Astakhov, V.I., Demidov, I., Dowdeswell, J.A., Funder, S., Gataullin, V., Henriksen, M., Hjort, C., Houmark-Nielsen, M., Hubberten, H.W., Ingólfsson, Ó., Jakobsson, M., Kjær, K.H., Larsen, E., Lokrantz, H., Lunkka, J.P., Lyså, A., Mangerud, J., Matiouchkov, A., Murray, A., Möller, P., Niessen, F., Nikolskaya, O., Polyak, L., Saarnisto, M., Siegert, C., Siegert, M.J., Spielhagen, R.F. & Stein, R. 2004. Late Quaternary ice sheet history of northern Eurasia. Quaternary Science Reviews 23, 1229–1271.

Taipale, K. & Saarnisto, M. 1990. Tulivuorista jääkausiin: Suomen maankamaran kehitys. Porvoo: WSOY, 416 p. [in Finnish]

Tulkki, P. 1977. The bottom of the Bothnian Bay. Geomorphology and sediments. Merentutkimulaitoksen julkaisuja 241, 5–89.

Winterhalter, B. 1972. On the geology of the Bothnian Sea, an epeiric sea that has undergone Pleistocene glaciation. Geological Survey of Finland, Bulletin 258, 66 p.

Winterhalter, B. 2000. Sedimentary rocks underlying the Gulf of Bothnia. In: Lundqvist, T. & Autio, S. (eds.), Description to the bedrock map of central Fennoscandia (Mid-Norden). Geological Survey of Finland, Special Paper 28, 76–79.