APPENDIX 1

GEOLOGY OF THE KVARKEN ARCHIPELAGO

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GTK

The Geology of the Kvarken Archipelago - report is an appendix (appendix 1) to the application for nomination of the Kvarken Archipelago to the World Heritage list (Ollqvist & Rinkineva-Kantola 2004).

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CONTENTS

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. 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. Northern Kvarken also forms a submarine sill, which separates the Bothnian Sea in the south from the Bothnian Bay in the north. Situated at the eastern part of the Northern Kvarken is the Kvarken Archipelago, where there are more islands than at any other place in the Gulf of Bothnia. However, only few islands are located along the Swedish coast.

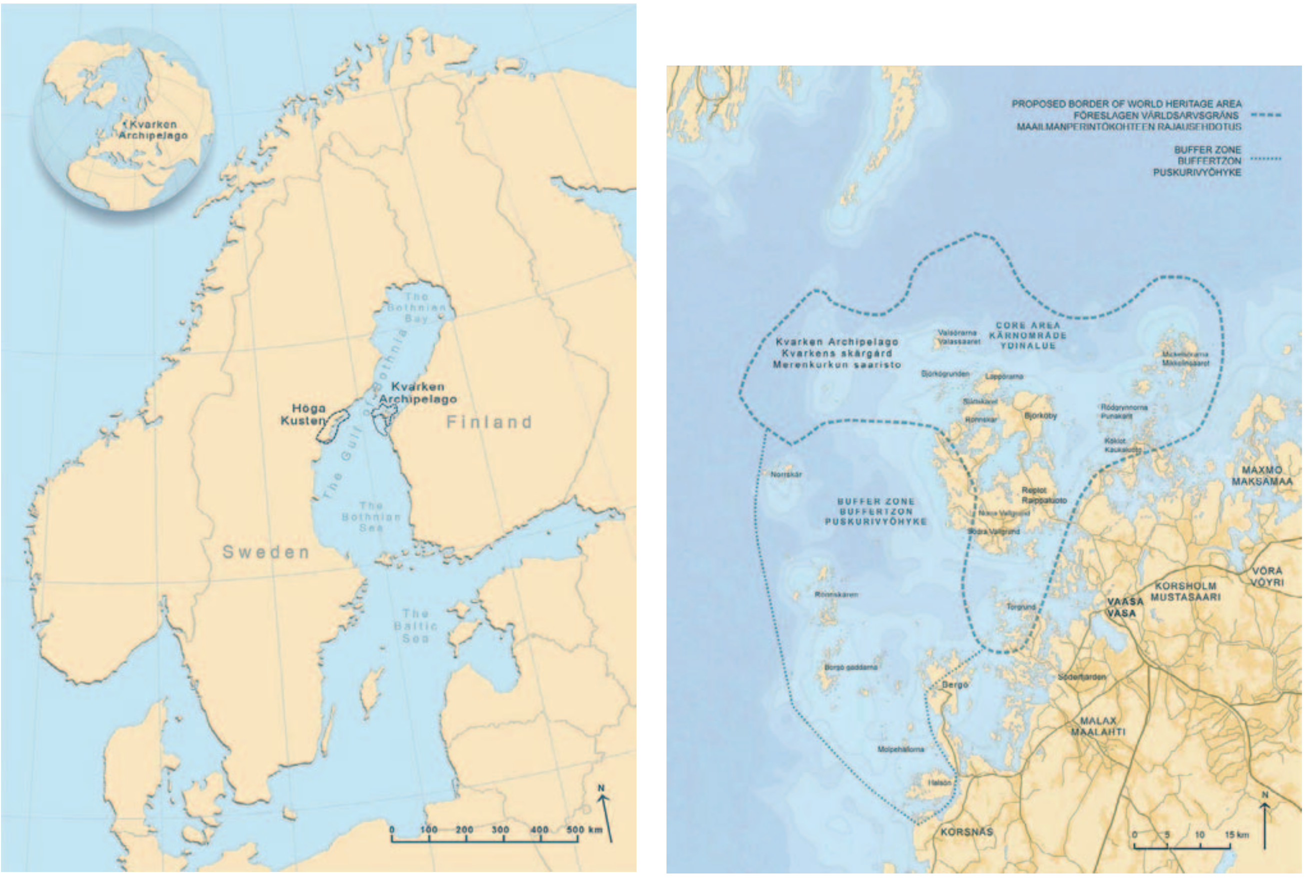

Figure 1. Location of the proposed world heritage area (Ollqvist & Rinkineva-Kantola 2004).

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. Today, there are about 7000 islands and islets, a large number of peninsulas and bays, and extensive stony seashores in the Kvarken Archipelago area. The total shore length is about 3000 km and 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, or 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.

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 100 m, average 10 m.
- Complex deglaciation pattern with several active ice-flow stages.
- Main soil types are glacial till, boulder fields and marine/littoral sediments and young organic sediments like gyttja and peat.
- Typical glacial formations are De Geer moraines and large traversal “Rogen type” moraines, which form large moraine fields with thousands of formations. Also, some hummocky moraine fields and minor drumlins occur.
- Rapid glacial isostatic land uplift (8 – 9 mm/y) 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).

Quaternary deposits

The Earth's youngest period, the Quaternary, which has lasted for 2.6 million years, is characterized by alternating glacial and interglacial stages. The term Quaternary deposit in Finnish geologic stratigraphy refers to the loose overburden on the surface of the Earth. Most of the Quaternary deposit were formed during and after the latest, Weichselian glaciation, some 13 000 – 10 000 years ago in the Kvarken area. At that time, the depth of the ancient Baltic Sea in the Kvarken area was approximately 250 – 280 m.

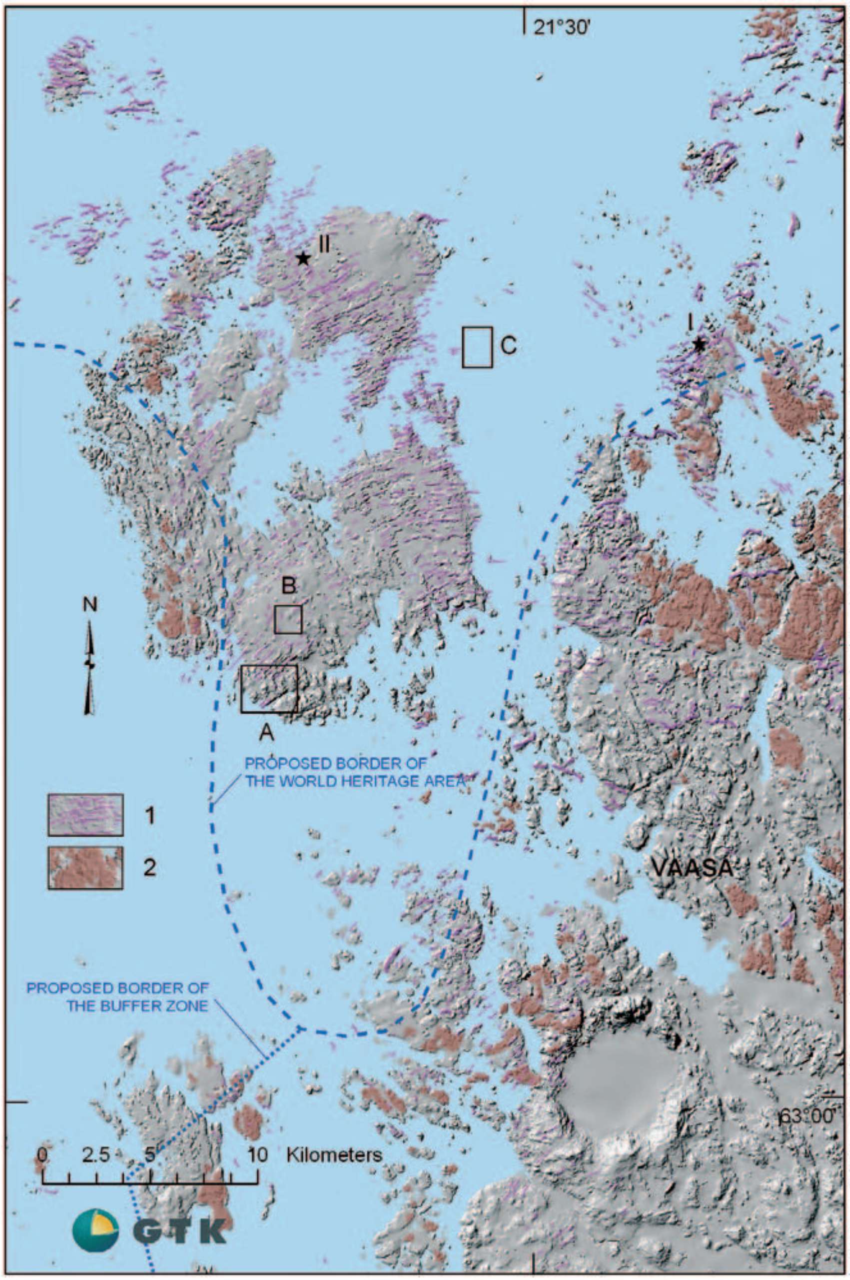

Figure 2. The diverging of the de Geer moraine and large transversal moraine ridge clusters in the north shown by geographical elevation model. The Söderfjärden meteorite impact crater is shown near Vaasa in the southern part of the image.
1 = de Geer moraine and large transversal moraine ridge, 2 = hummocky moraine, A = location of a map of different moraine fields (Figure 3). B = location of the Storslätmossen peat bog (Figure 17). C = location of the marine geological map (Figure 28). Star dots I and II = locations of excavations on moraine ridges (Figure 10 and Figure 12), (compilation Miikka Paalijärvi).

The classification of Quaternary deposits according to genesis and the environment in which they were formed consists of two main groups: glacial and postglacial. An ice sheet or its melt water formed glacial deposits. This group includes till, glaciofluvial sediments, and glacial clay. Postglacial deposits (clay, silt, gyttja, peat, marine/littoral sediments) were formed independently of the melting of an ice sheet.

Geologic mapping of Quaternary deposits

The detailed settings and composition of Quaternary deposits and formations is surveyed by geologic mapping of Quaternary deposits to a 1:20 000 scale. The mapping is based on interpretation of aerial stereo photographs and revisions from the field. Also, digital processing and digital 3D interpretation is used. The size of the area of one soil type is 2 hectares minimum and mapping depth is one meter based on the use of a steel stick. By excavations, drillings, laboratory analysis and geophysical surveys, more detailed information of texture and structure of different formations is investigated. Quaternary deposit formations like eskers, drumlins, De Geer moraine ridges, and hummocks are mapped with special consideration. Special features like potholes, caves, kettle holes, and raised beaches are documented. Some extra observations of striations, road or gravel pit cuttings are also done along with the mapping. An example of a detailed Quaternary deposit map is shown in Figure 3 where the De Geer moraines form a tight field with 100 to 200 meter intervals between separate formations.

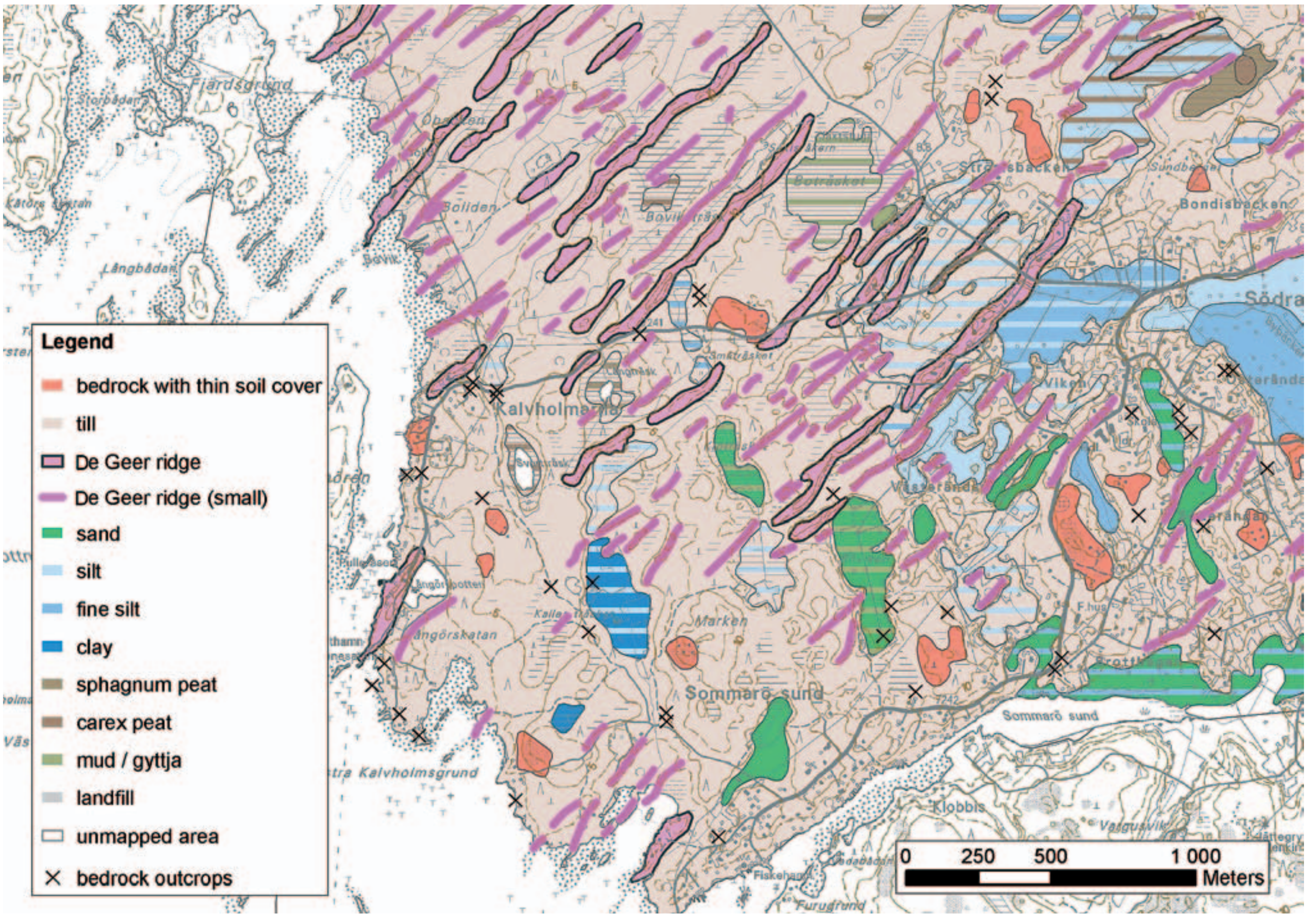

Figure 3. An example of Quaternary deposits map from Replot (location A in figure 2, compilation Jukka Ojalainen).

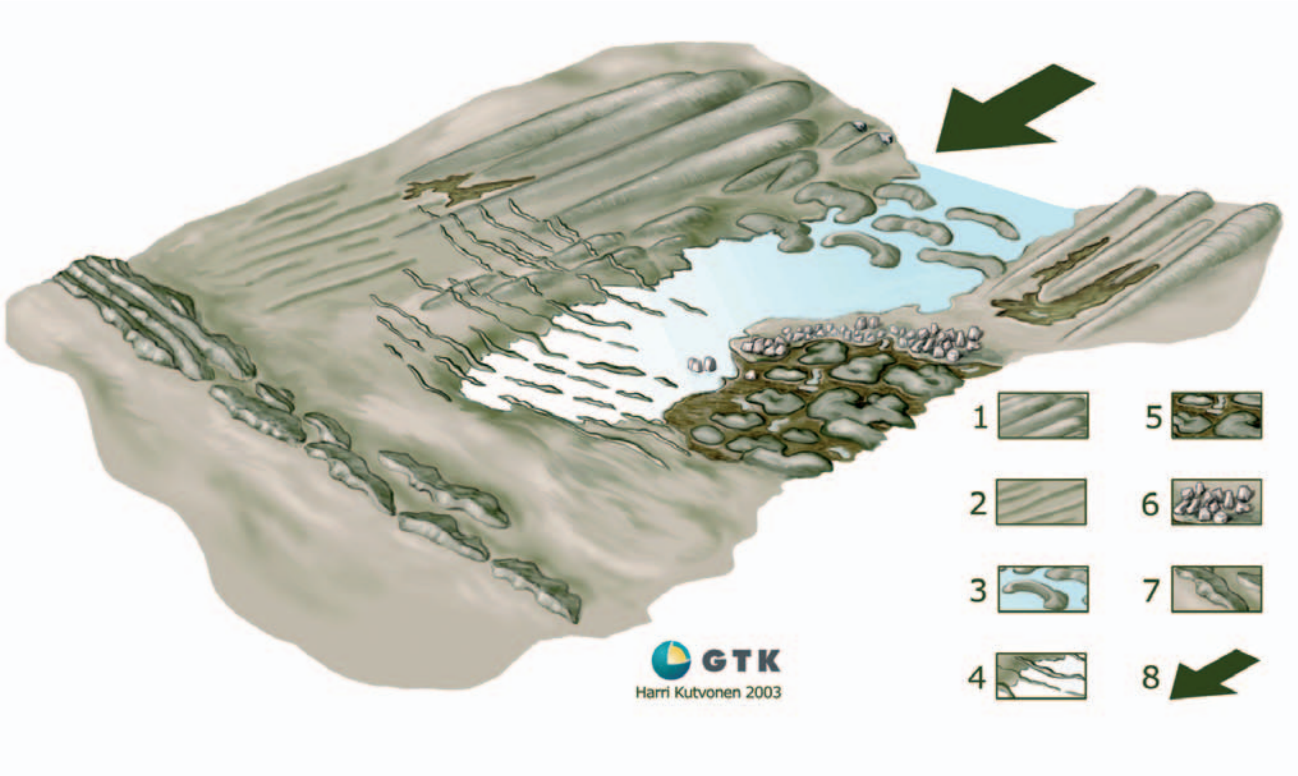

Figure 4. Schematic figure of the moraine formations in the Kvarken area. 1=Drumlins, 2=Flutings, 3=Large transversal moraines (Rogen type), 4=De Geer moraines, 5=Hummocky moraines, 6=Boulder-rich surface, 7=End moraines, 8=Latest ice flow direction (drawing Harri Kutvonen).

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 clay. Till generally lies directly on the bedrock and largely follows its surface configuration. Till also commonly forms its own surficial configurations like various moraine ridges and hummocks (Figure 4). 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 (Figure 5).

Moraines parallel to the ice direction

A drumlin is an oval-shaped 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 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.

Figure 5. Helicopter view of the De Geer Moraines. Björkö Svedjehamn (photo Arto Hämäläinen 2000).

Figure 6. Typical shape of De Geer moraine ridge, proximal side on the right (photo Jukka-Pekka Palmu 2002).

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 (Figures 5 and 6). 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).

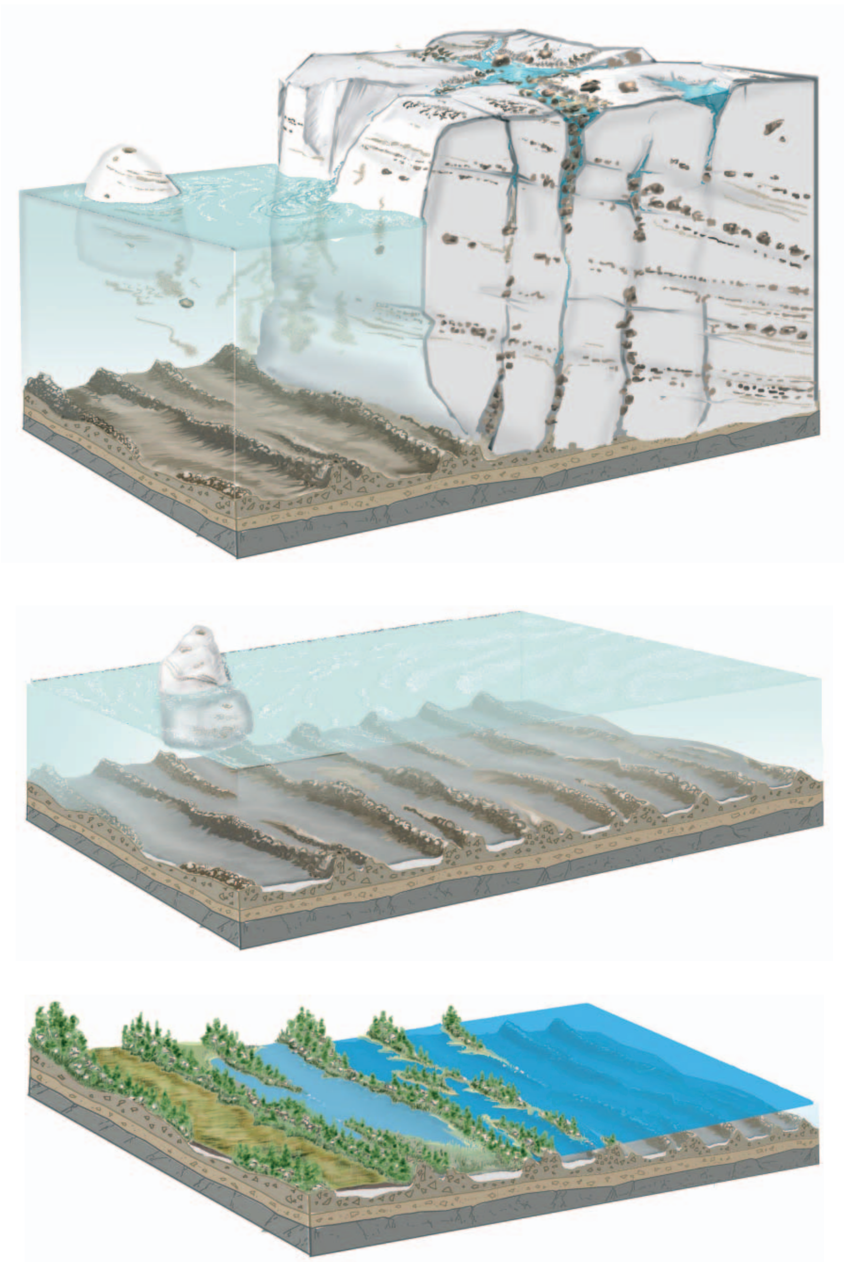

Figure 7. The origin and genesis of De Geer moraines (drawings by Harri Kutvonen 2003).

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 log 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) 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). 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 (Figure 7).

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 of till material during the formation of De Geer moraines (unclear). In some localities, the texture of the faulted and fissured glacier front can be seen in the hummocky relief. 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, characterized by ridges that are irregular in detail but largely at right angles to the direction in which the ice was moving. 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 20 – 200 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 Iskmo Lillön area, Halsön Island and the Bergö Gaddarna rocky islets (Figure 8). 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 glaciomarine subaquatic till deposition and represents the youngest till deposit and moraines in the area.

Figure 8. View of a rocky terrain in Korsnäs Archipelago (photo Hans Hästbacka).

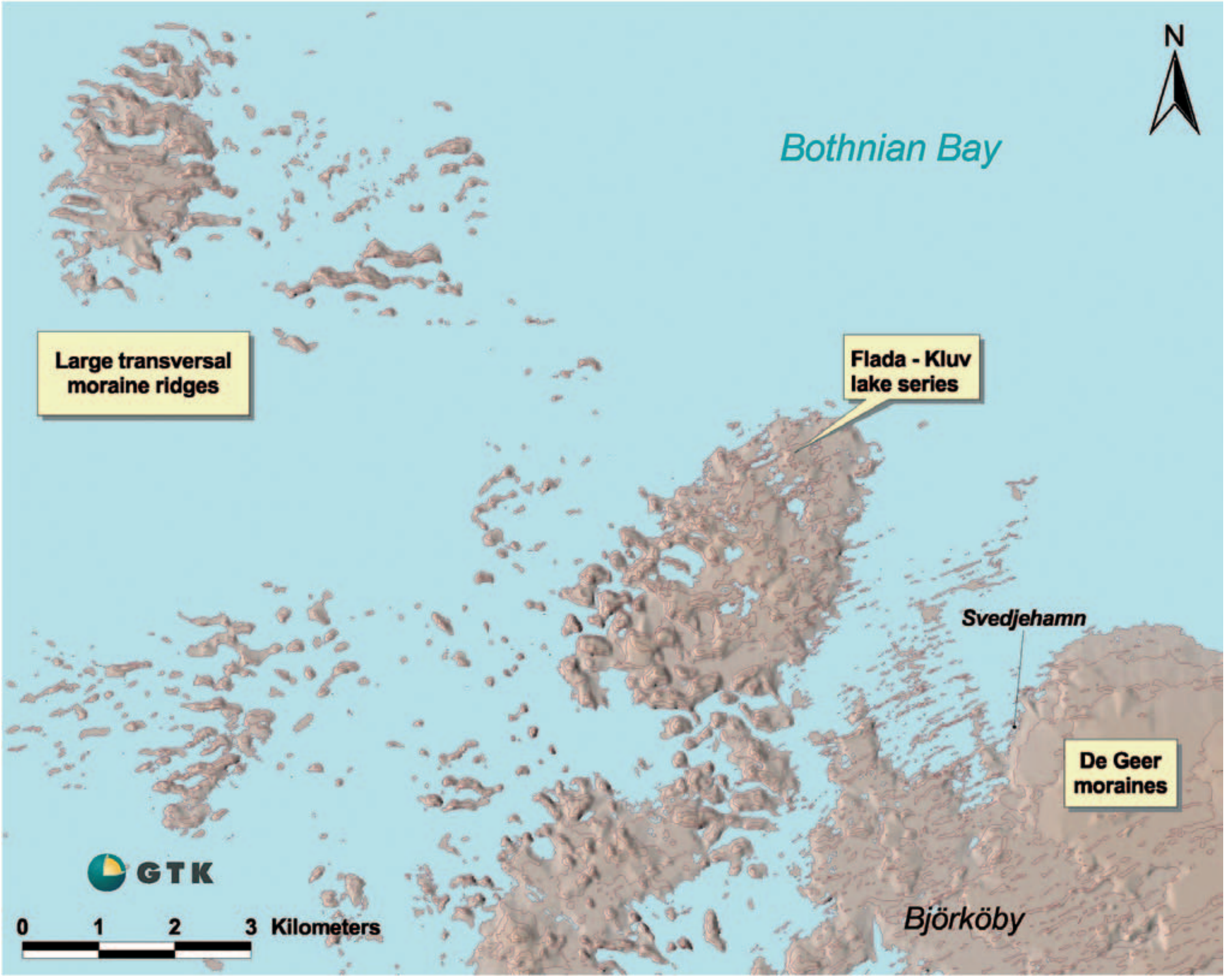

Figure 9. Shaded relief map from the northwest part of the Björkö Island showing an example of the De Geer moraines, large transversal moraine ridges and the Flada – Kluv lake series. Shape of the large transversal moraine ridges is sometimes winding, which is clear evidence of the complexity of the deglaciation pattern of the area (DEM National Land Survey of Finland, processing Olli Breilin).

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 Figure 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 Figure 2). De Geer moraine formations are on a transversal position and overlie the larger Köklot moraines especially north from Köklot in the Mickelsörarna area.

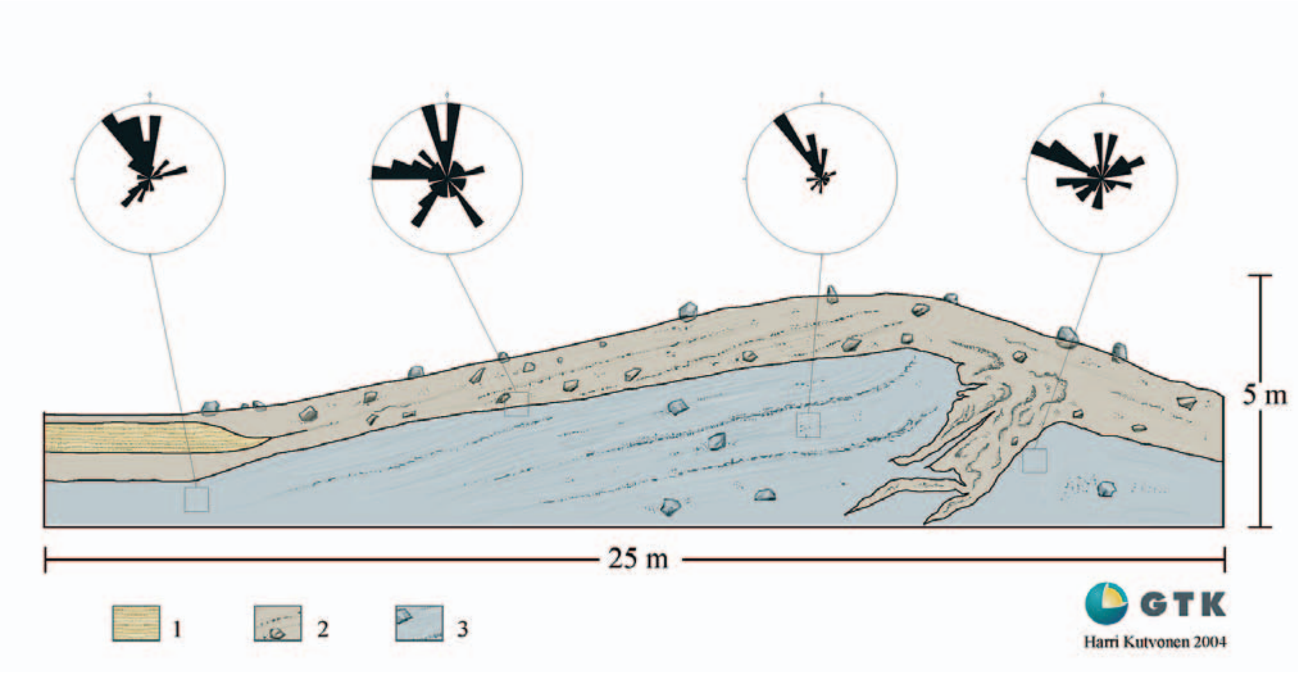

Figure 10. Schematic cross section from test pit excavated in the low-lying De Geer moraine Björkö Ohls (see Figure 11). Ice flow direction from left to right in drawing. 1= sandy loam, 2= melt out till with deformation structures and 3= basal till with some deformation structure (location II in Figure 2, drawing Harri Kutvonen).

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 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 (Figure 10).

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 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 (Figure 12). 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.

Figure 11. Excavation of the De Geer moraine at the Björkö Ohls formation. Test pit is situated across the De Geer moraine. Photo was taken from proximal to distal side of the moraine (photo Jukka Ojalainen 2003).

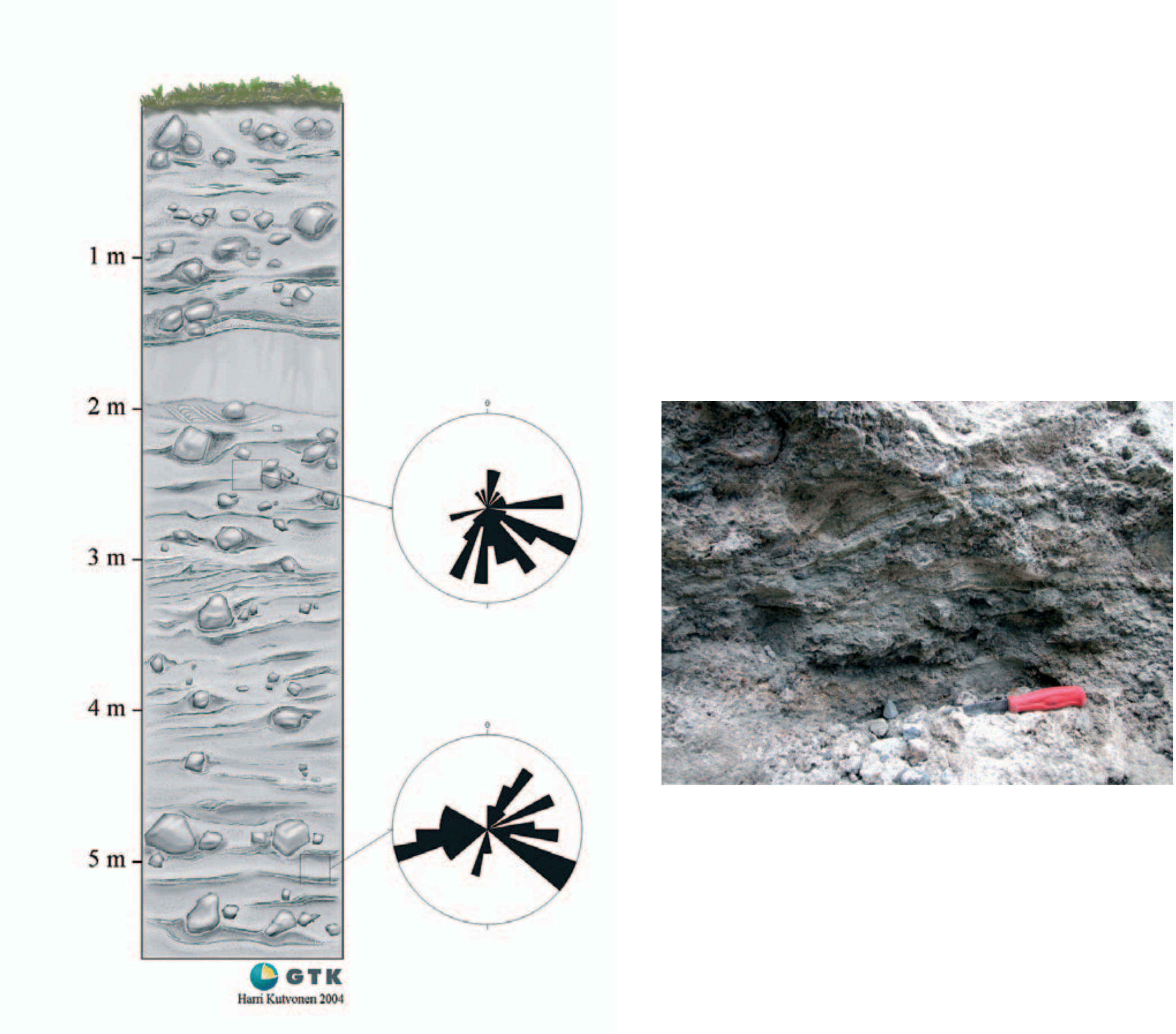

Figure 12. Schematic profile and photograph from the test pit excavated in large transversal moraine ridge in Köklot. The length of the red knife grip is 10 cm (location I in Figure 2), (drawing Harri Kutvonen, photo Jukka Ojalainen 2003).

The studied moraine formations in Björkö and Köklot are clearly of subglacial and subaquatic origin (comp. Benn and Evans 1998 p. 512-514). 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 (Figure 13). 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 in these formations (comp Benn and Evans 1998 p. 437-447 and Aartolahti 1995).

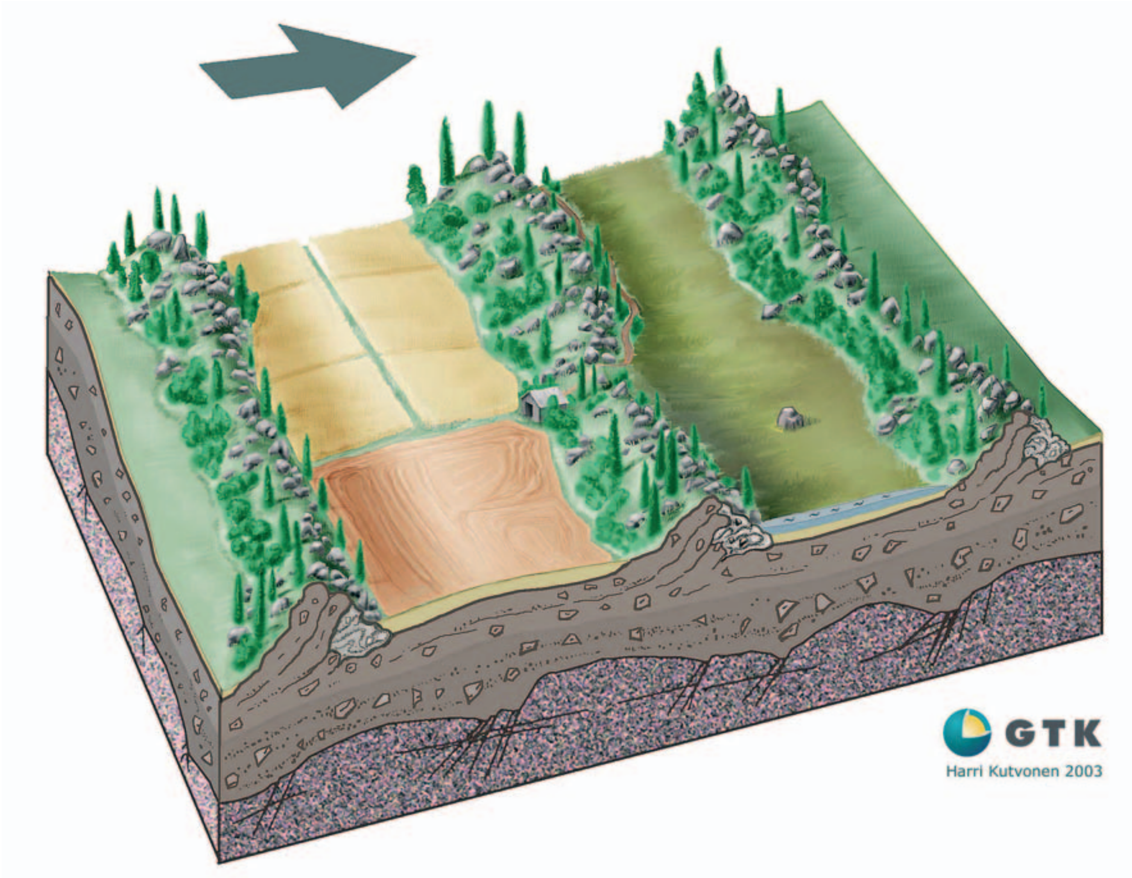

Figure 13. Schematic picture of the De Geer moraines in the Björkö area. Arrow indicates the last ice flow direction, which is perpendicular to the De Geer moraine ridges. Wedge-like brown basal moraine in the formations illustrates shearing and pushing behaviour of ice edge. Gray moraine inclusions illustrate the melt out facies of the basal till at the distal side of moraine formations (drawing Harri Kutvonen).

Figure 14. Example of Svedjehamn gyttja sample. Blue areas in sample shows vivianite – mineral, which is typical for till covered organic deposits (photo Jukka 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 pers. com.). A test pit was excavated at the De Geer moraine's distal site. The till cover over the organic deposit is composed of a sandy till (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 pers. com.). 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. This deposit is clear evidence of a much lower sea level stage in the Bothnian Bay area before last glacial maximum (see Figure 26).

Glaciofluvial deposits and varved glacial sediments

Glaciofluvial sediment consists of boulders, stones, gravel and sand that has been transported, sorted and deposited by melt water from the inland ice. Glaciofluvial sediment is stratified in layers with one or several particle sizes and the particles are usually rounded.

The shape of the deposits depends on the environment in which they were formed. The melt water in the inland ice formed strongly flowing rivers in tunnels emerging at the margin of the ice. The finer material, silt and clay, was deposited at greater distances from the mouth of the subglacial river. Few glaciofluvial eskers appear in the Kvarken area on land or seafloor in the Mickelsörarna area. Eskers are a long, ridge-shaped glaciofluvial deposit that was formed in a tunnel in the continental ice sheet.

Figure 15. Littoral wave washing and sea ice pushing with glacial isostatic land uplift have enclosed a fisherman's old boat harbour (photo Olli Breilin 2004).

Glacial clay

During the melting of the continental ice sheet, the finest particles of glaciofluvial origin, clay, were dispersed in the sea and in large lakes. These particles formed clays with varying properties.

In freshwater, the particles remained suspended for long periods and sedimentation took place slowly. Depending on the seasonal changes in the melting of the ice, and thus in the flow of water, there was a regular change in the rate of sedimentation. During the spring and summer, the flow of water in the glacial rivers was great and large amounts of clay and silt particles were transported. The supply of sediment during autumn and winter was, on the other hand, low. Thus, a thicker and a thinner layer together formed an annual varve. The winter layer is usually darker in colour than the summer layer and has higher clay content. Dropstones and other iceberg-transported material are occasionally found in clay profiles.

In saline water, the sedimentation of clay took place faster on account of the electrolytic properties of the saline water and consequently, there is no clear varve pattern. In the peneplain of Ostrobothnia, the clay sediments make the terrain really flat as smaller valleys and the roughness of the glacially sculptured terrain are covered and filled. The youngest layers of the marine strata are muddy clays that make the soil fertile. Thus, most of the clay and mud areas are cultivated fields and pastures forming the cultural landscape “the archipelago of thousands barns” that is typical of the Vaasa region.

Figure 16. Top part of a large transversal moraine ridge has been submerged under the sea. Due to strong littoral wave washing, the fine sediments are washed away and copples and boulders remain (photo Olli Breilin 2004).

Postglacial sediments

Land uplift exposed older deposits to the influence of wave washing and there was a more or less complete re-stratification. Wave-washed material was deposited along and close to shorelines as shingle, gravel and sand with decreasing particle size away from the shore. Alluvial sediments are deposited as banks along the reaches of the river or as a delta at the river mouth.

The youngest sediments and deposits in the Kvarken Archipelago area are shallow peatlands and recent mud/clay deposits. Most of the peat deposits are less than one meter deep. The first stage in the Kvarken area peatland development is minerotrophic sedge peat accumulation, which is rich in herb plant subfossils in strata and luxurious vegetation on the surface. On peatlands more than 1000 years old and located 10 m above sea level, Sphagnum peat is dominate and the peatlands are of raised bog type. At Replot Island, the peat bog growth is very fast, with two meters of peat build up in less than 900 years.

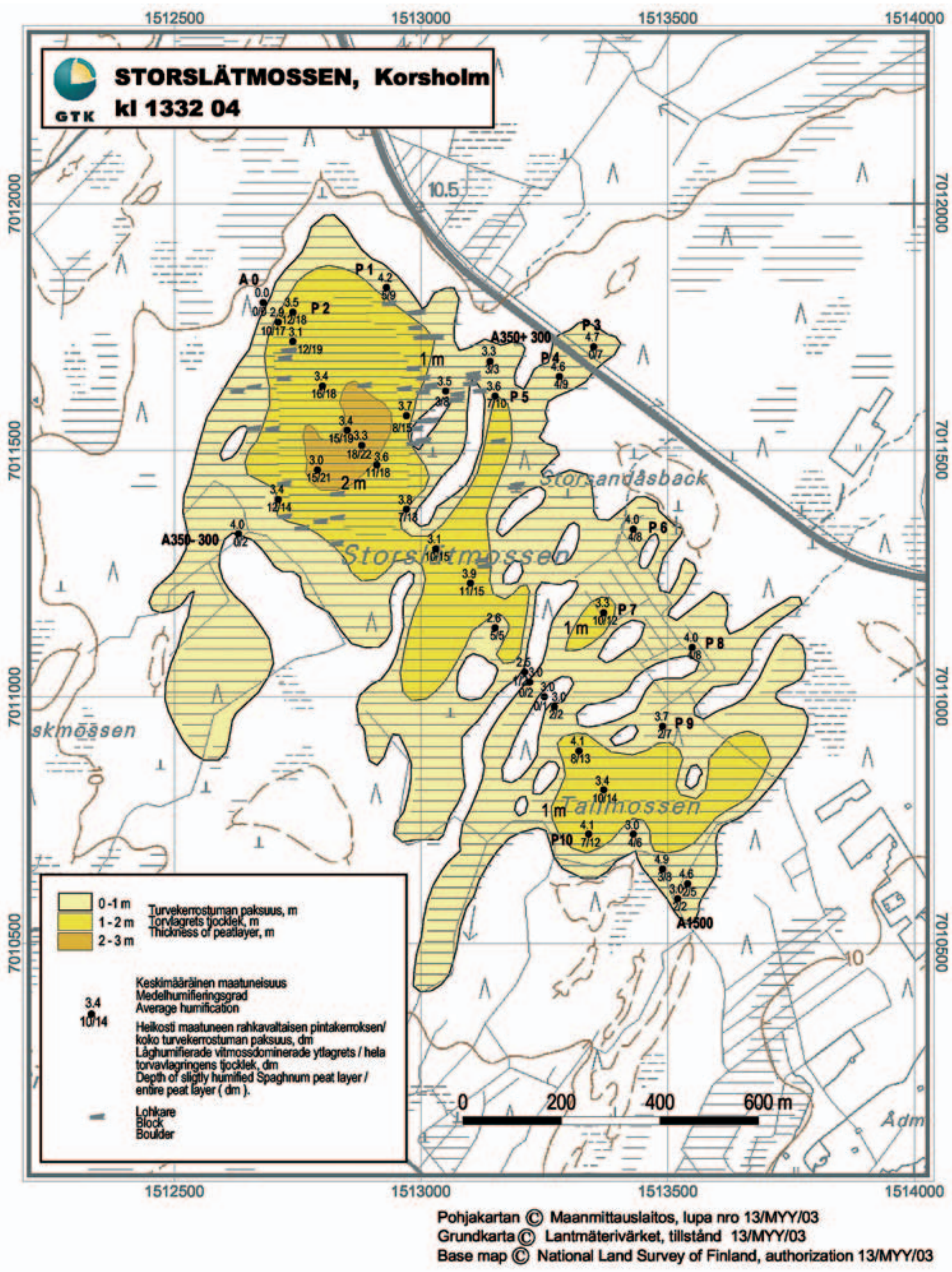

Figure 17. Map of the Storslätmossen peat bog, which is the largest and deepest peat bog on the island of Replot. The location of the map is marked with B in figure 2 (GTK).

An outstanding example of organic deposits is the Storslätmossen Sphagnum bog, which is situated in the western part of Björkö Island near Södra Vallgrund (Figures 17 and 18). In the lower profile, the peat consists of Carex and in upper profile Sphagnum moss. At the bottom of the peat layer (2,4 m), the calibrated C-14 age is 819 +/- 25 years B.P. The bottom of the bog is currently approximately 8,6 m.a.s.l. This means that the area has emerged from the Bothnian Bay Sea approximately 1200 years ago (Figure 24). Based on peat age and the thickness of the peat layer, the annual peat growth rate has been 3 mm, which is a record peat growth rate in Finland.

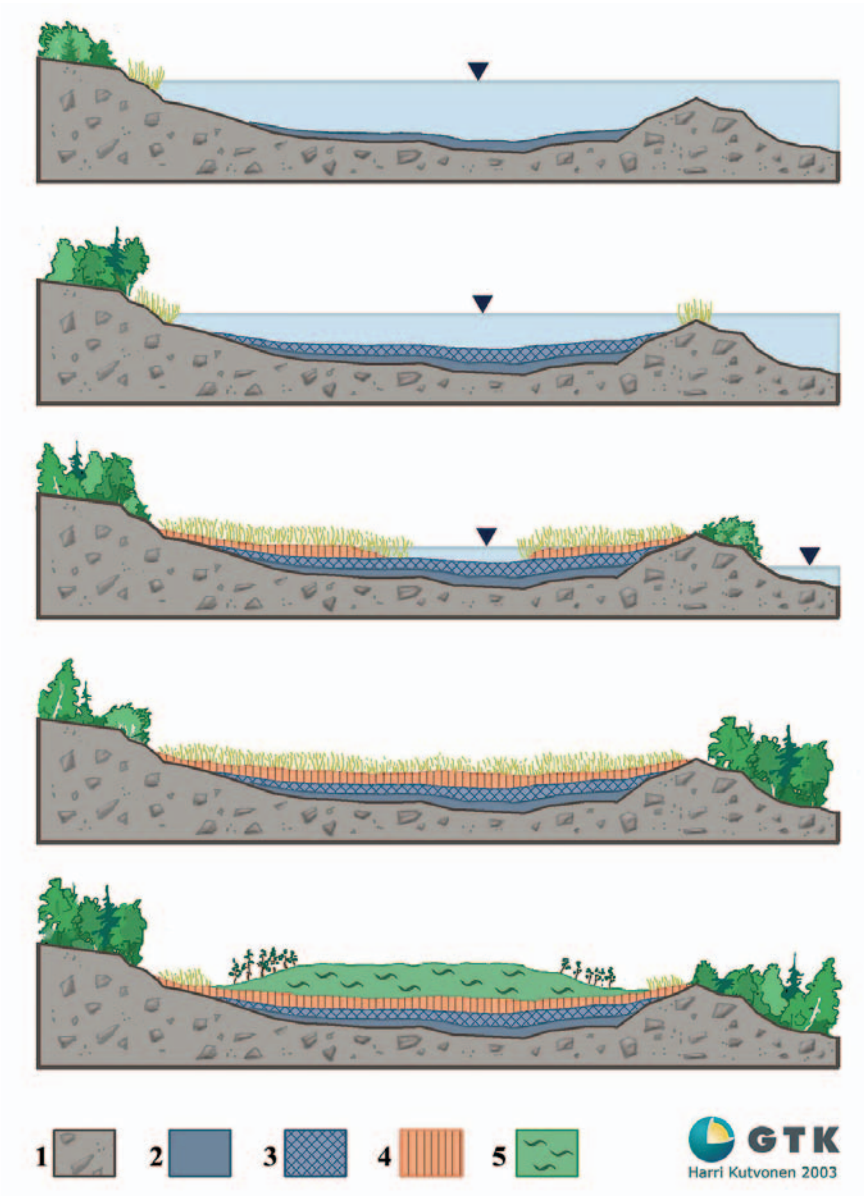

Figure 18. The evolution of the Storslätmossen peat bog. A schematic picture of different phases of the peat bog development on Replot Island. Legend: 1) till, 2) silt and clay, 3) gyttja, 4) Carex peat, 5) Sphagnum peat. (Drawing Harri Kutvonen and Carl-Göran Stén).

One very rare example of peat forming processes can be followed on Lappörarna Island. Small lakes and ponds (Flada – Kluv lake series) become separated from the sea and peat-forming plants gradually fill the ponds with peat moss finally occupying the depression. The whole island is in a pristine natural stage and as such, a very valuable natural area. In Lappörarna, the postglacial history of the Baltic Sea area can be experienced on a small scale as a powerful ongoing dynamic process (Figure 9).

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 (Figure 19). Faceted, polished surface also appear in some outcrops. Based on field observations of these glacial striae (Figure 20), ice flow direction has been between 330° – 80° degrees. In the same

Figure 19. Crossed glacial striaes (350° – 65°) on a bedrock outcrop on Storskäret Island. Direction of the GPS receiver is 65° (photo Olli Breilin 2003).

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 (Figure 9). 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.

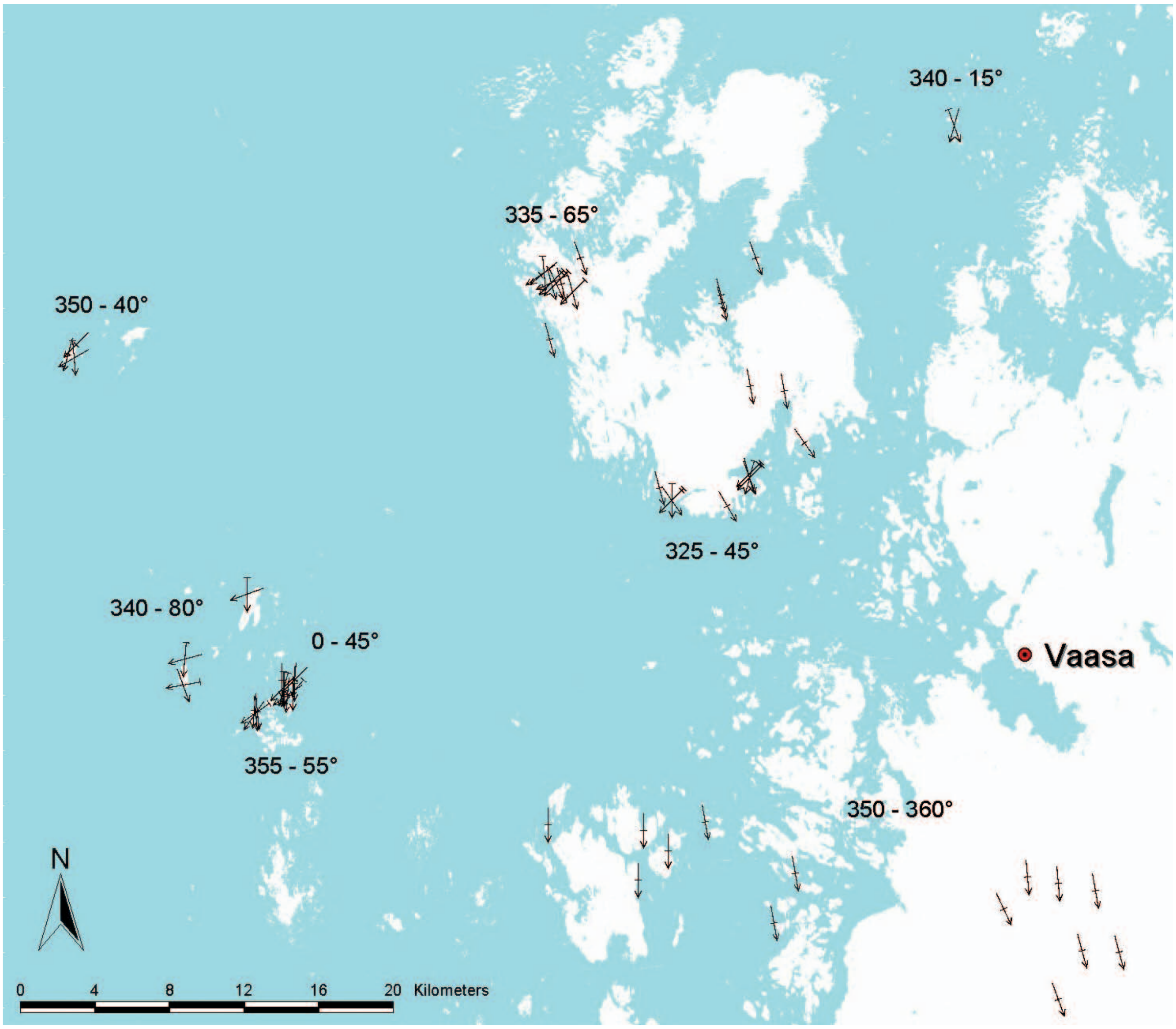

Figure 20. Location and direction of glacial striations at Kvarken Archipelago (compilation Jukka Ojalainen, Geonat 2003).

Deglaciation and development of the Baltic Sea

The heavy load of the approximately 2 800 meters of thick ice depressed the Earth´s crust at least 800 m below its present position (Svendsen et al 2004). As soon as the pressure started to decrease, the crust began to slowly rebound. The highest situated traces of the shoreline (the highest shoreline) are at different altitudes throughout Scandinavia, depending on how deep the crust was depressed, how much the sea had risen, and the time when the area became ice-free. During deglaciation, low-lying areas were covered by seawater (Figure 21). The nearest supraglacial areas are in the Lauhavuori Mountains in southern Ostrobothnia, where the highest shoreline is 203 m.a.s.l. and in the High Coast area on the Swedish east coast, where the highest shoreline is 293 m.a.s.l. Based on these observations, the depth of the sea was approximately 250 – 280 m at the Kvarken Archipelago just after deglaciation. The Baltic Ice Lake and Yoldia Sea stages never reached the Kvarken Archipelago area due to the continental ice sheet. In recent years, research on the last phases of glaciations has been conducted to construct a new deglaciation model (Lunkka et al 2004).

Ancylus Lake stage 10 700-9 000 years ago

The Ancylus Lake stage lasted from 10 700 to 9 000 years ago. The lowest clay strata are glacial clays with clear varved texture, typical of the sedimentation in a glacial basin. Fracturing of the floating ice front and calving of icebergs were typical of glacial lacustrine conditions during the beginning of the Ancylus Lake stage. According to current concepts, deglaciation still continued in the Kvarken area during the Ancylus Lake stage. The sediments that were deposited in the Kvarken area were mostly homogenous gray clays and black sulphid bearing clays. The highest shorelines on the Ostrobothnian side of the Kvarken area are all from the beginning of the Ancylus Lake stage between 190-210 m.a.s.l. (Glückert et al 1993).

It was earlier thought that the De Geer moraines and their clusters were also deposited in an annual deglaciation rhythm. Later studies, especially varved clay chronology, showed that deglaciation at beginning of the Ancylus Lake stage in the Kvarken area was rapid, between 200-500 m annually. Thus, moraine ridges that occur in intervals less than 100 m imply the formation of several moraine ridges in a single year (Zilliacus 1987, Aartolahti et al 1995).

Litorina Sea stage 8000 years ago – present stage

At the end of Ancylus Lake stage, rising global ocean level resulted in an opening through the Danish straits to the ocean causing fresh water conditions to gradually become brackish. In the sedimentary record, the onset of the Litorina Sea stage is defined over the whole Baltic Sea area. In the clay strata, the arrival of brackish water at the transition to the Litorina Sea stage is marked by an exceptionally sharp litostratigraphic boundary, indicating a dynamic change in the hydrographic conditions of the Baltic Sea. The widely spread greenish mud rich in organic matter, methane gas and saline diatom flora was deposited on the bottom of Litorina Sea. Today, these sediments are the most fertile agricultural areas in the coastal land of the Bothnian Bay area. All ancient shore marks and beach deposits on the Finnish side of Kvarken area date back to the Litorina Sea stage less than 7000 years BP (Winterhalter et al. 1981).

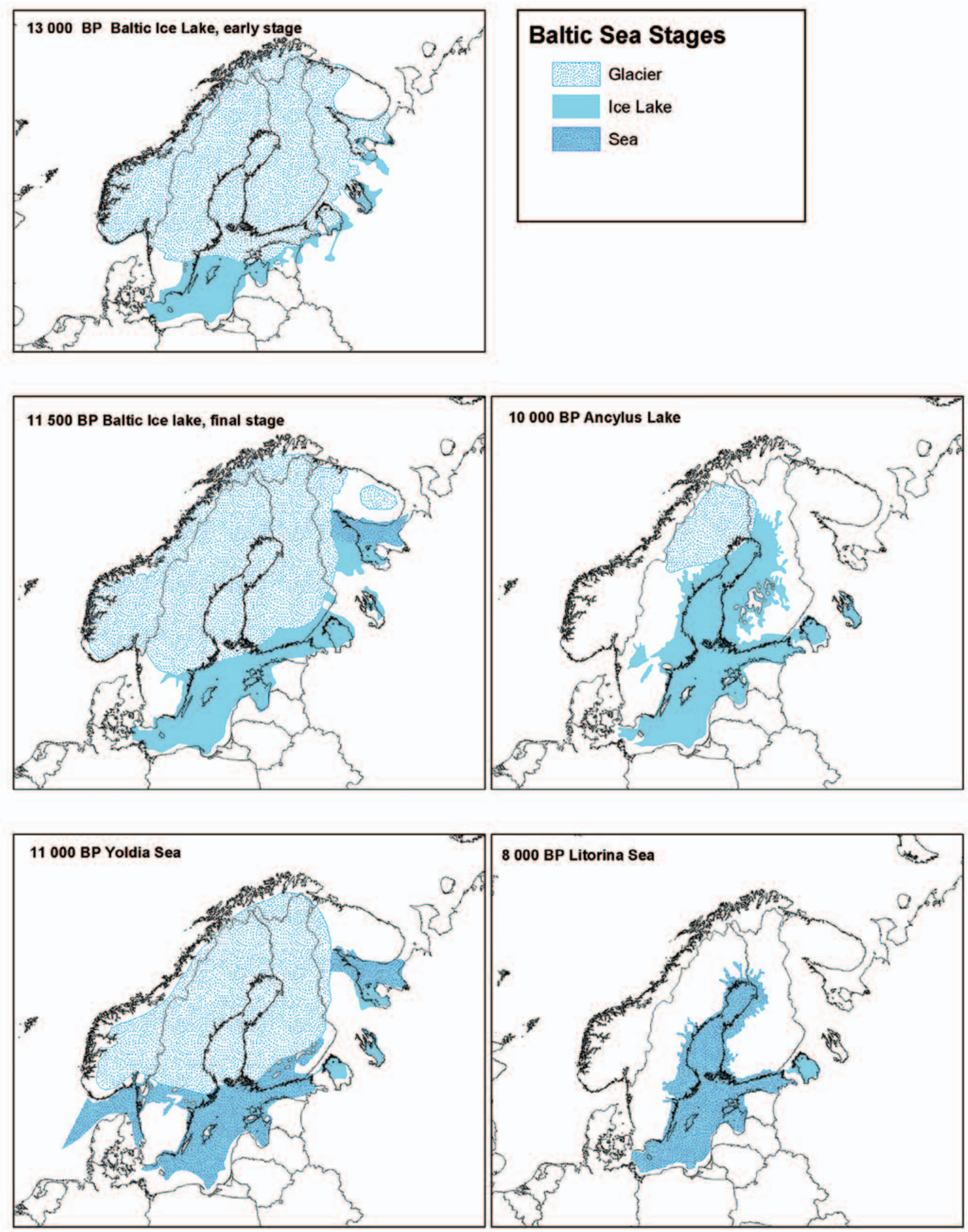

Figure 21. Evolution of the Baltic Sea (Saarnisto 2003, drawing Olli Sallasmaa).

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 renowned 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 (Figures 22 and 23).

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

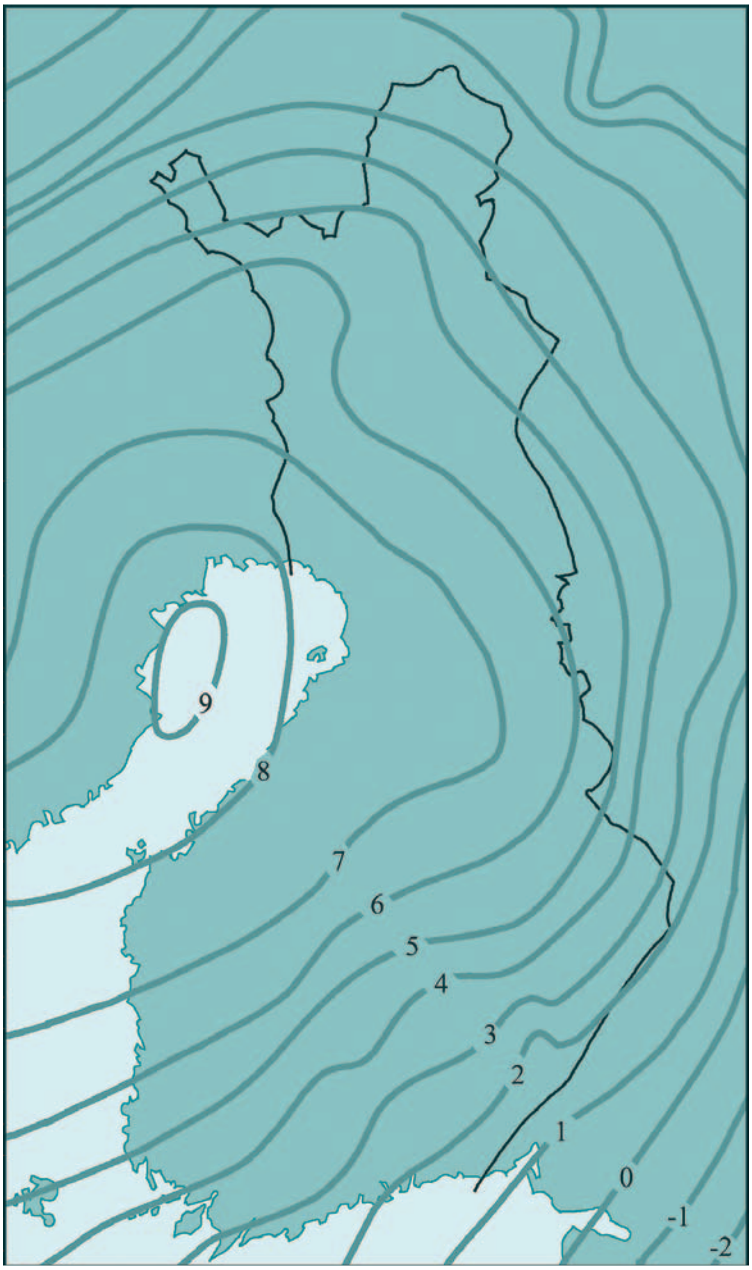

Figure 22. Present isobases of land uplift (mm per year) in Eastern and Central Scandinavia (National Board of Survey 1990, drawing Harri Kutvonen)

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.

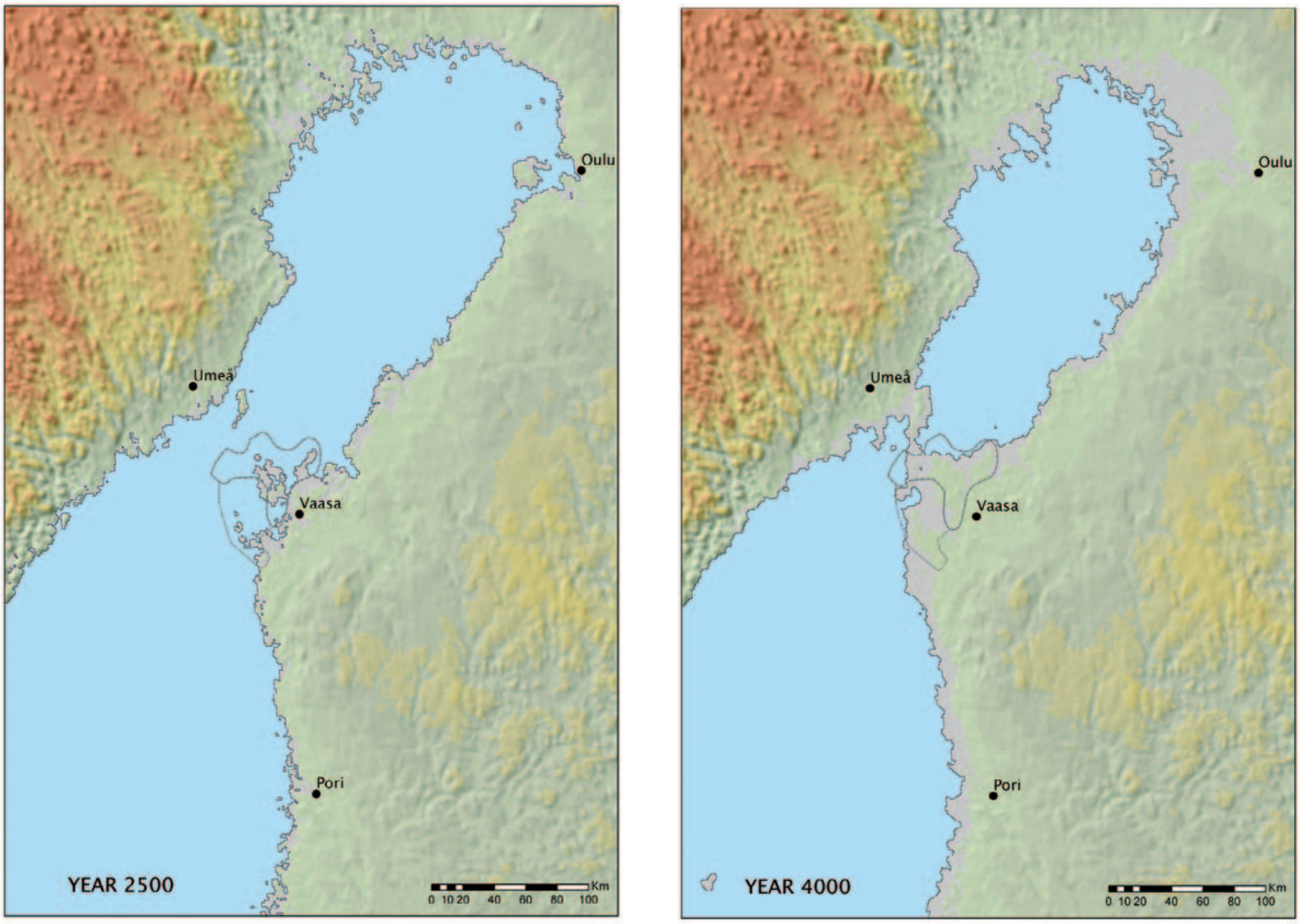

Figure 23. Future of the Bothnian Bay, the northern part of the Baltic Sea. (DEM Seifert et al 2001, processing Hanna Virkki).

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) (Figure 22). 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 micrograls), or about 0.06 milligals (The Finnish Geodetic Institute, http://www.fgi.fi/yleis/historia_eng.html).

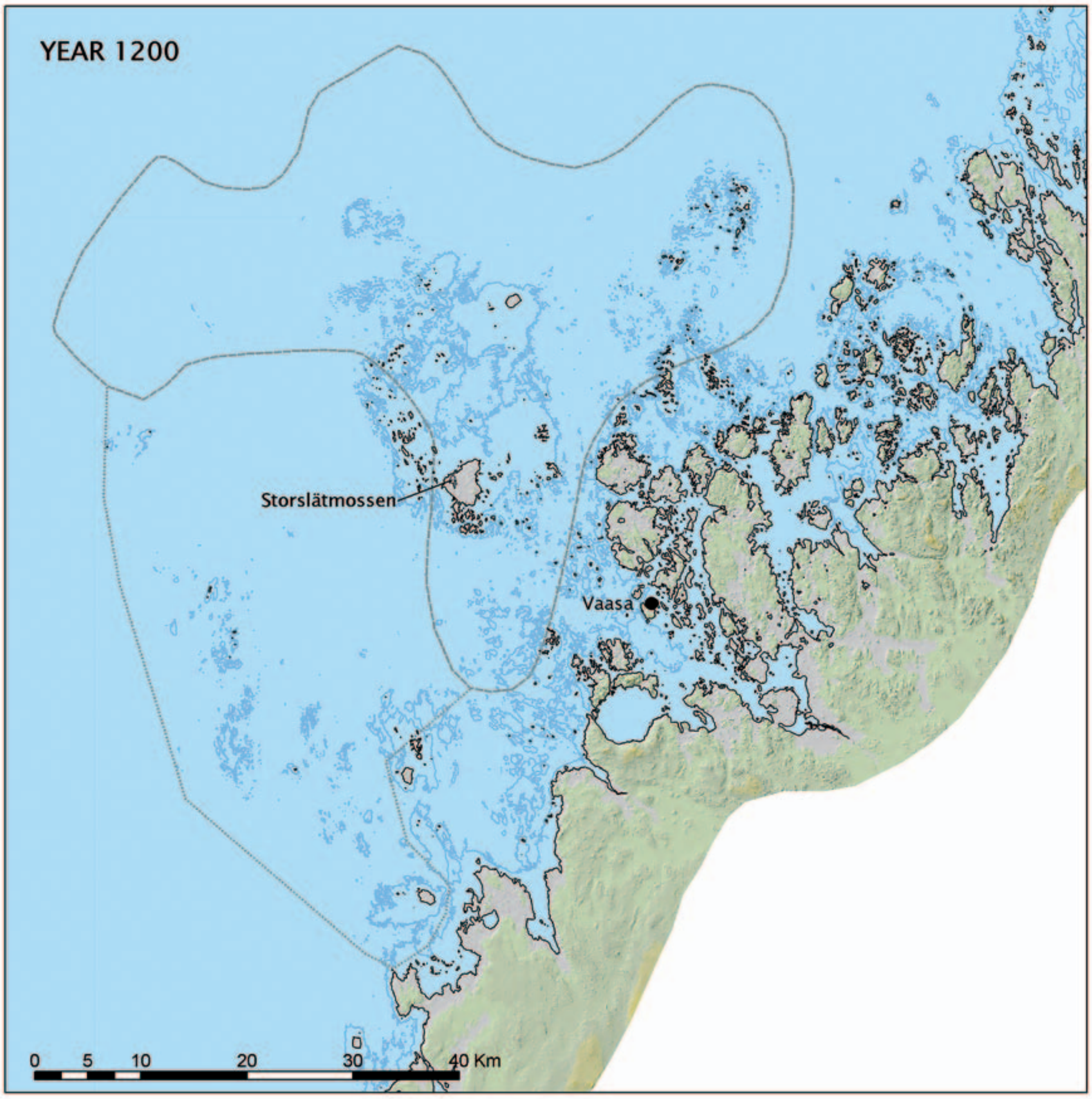

Figure 24. Map showing the shoreline when Storslätmossen – peat bog started to grow (Figure 17). The present shoreline is also shown with a darker line (DEM Seifert et al 2001, processing Hanna Virkki).

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). 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.

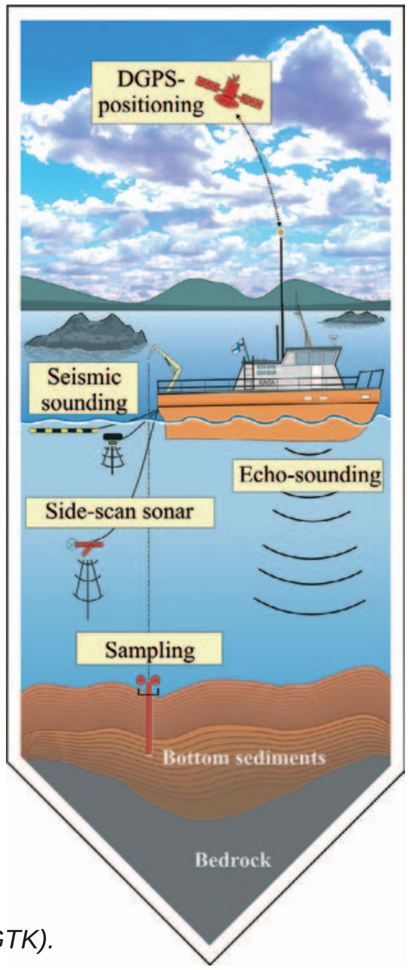

Figure 25. Marine geological survey methods (GTK).

Seafloor geologic information was obtained using acoustic-seismic investigation methods and sediment sampling (Figure 25). 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 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 has undergone several 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 and 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 (Figure 26).

The seafloor consists mainly of till. Due to strong currents and wave action, varved clay and post-glacial 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.

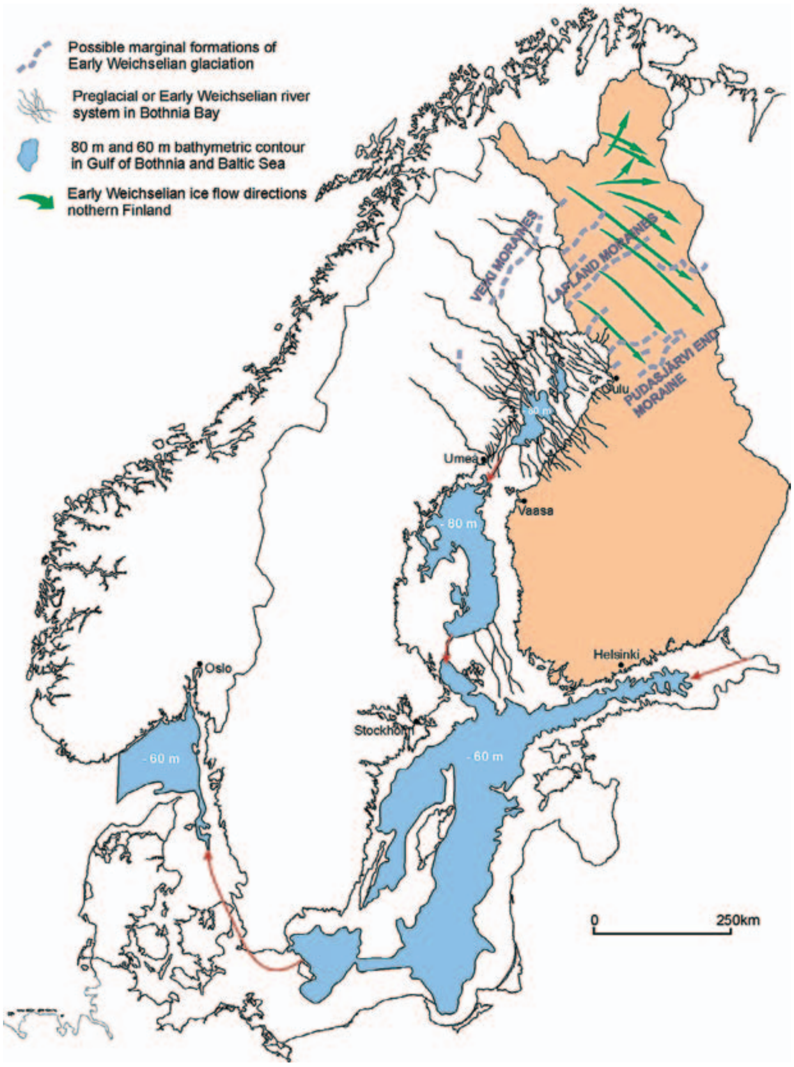

Figure 26. Bothnian Bay and Baltic Sea area during Weichselian interstadials (Nenonen 1995).

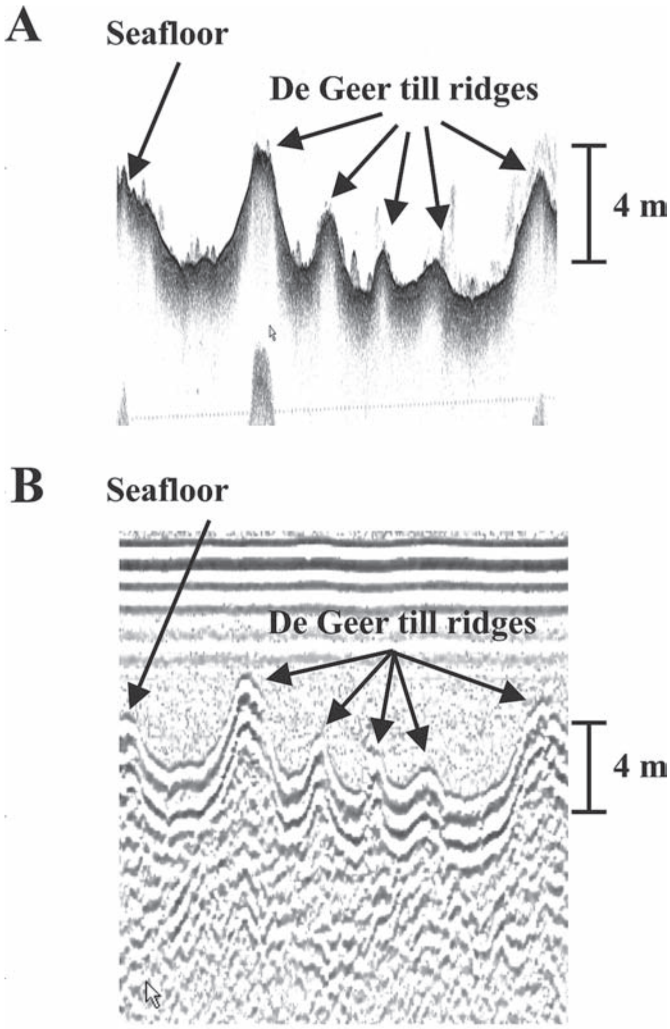

Figure 27. Echosounding (A) and acoustic reflection profiles (B) of De Geer moraines (compilation Aarno Kotilainen).

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 (Nuorteva 1988, Reijonen & Kotilainen 2004, Figures 27 and 28).

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 post-glacial 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 29 and 30. However, the latest history of the Baltic Sea is rarely recorded in submarine sediments of the Kvarken Archipelago.

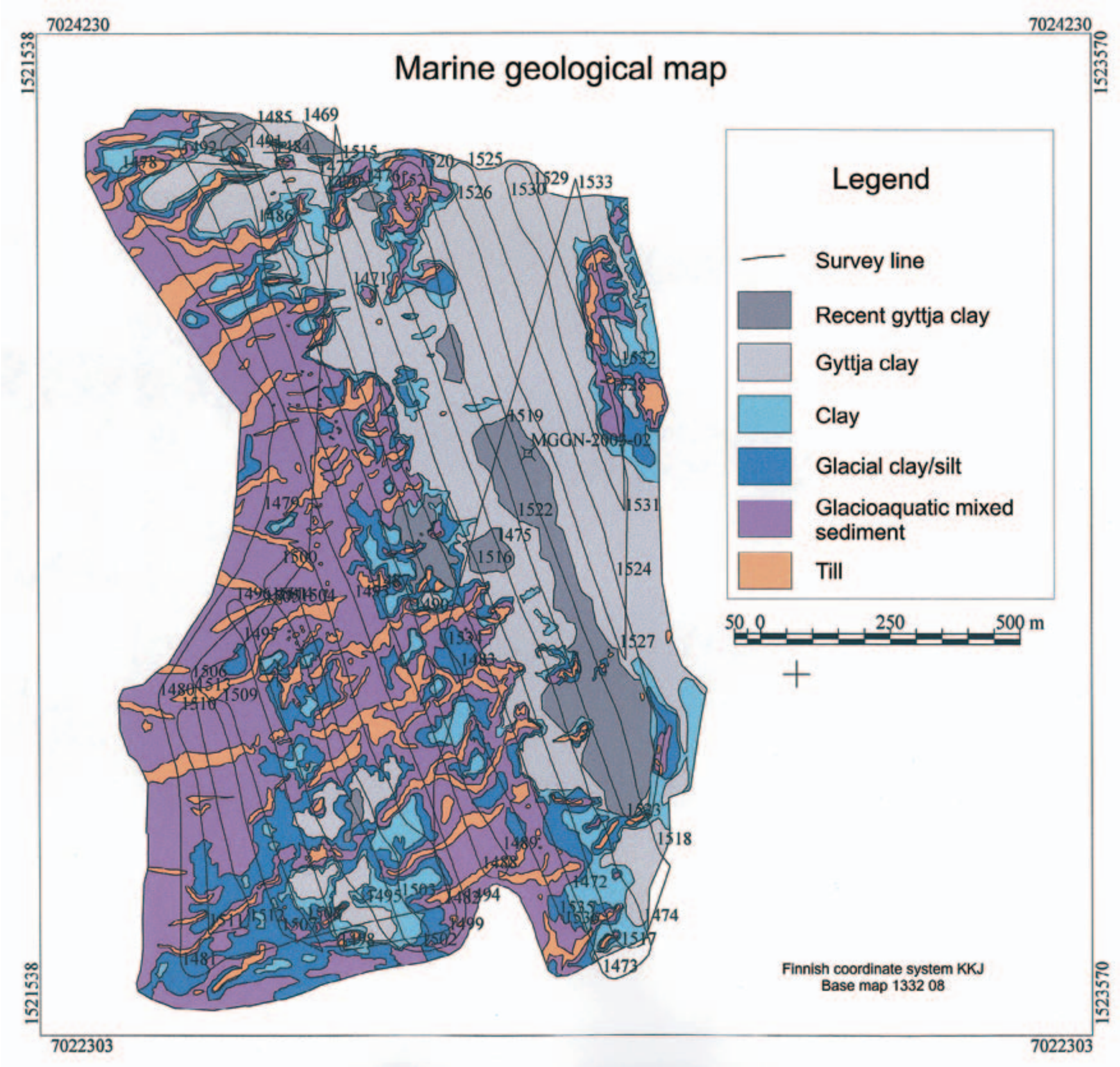

Figure 28. Example of Quaternary deposit map from sea area (water depth of 5 –12 m) of the Kvarken Archipelago (Reijonen & Kotilainen 2004). Location of the map is indicated by C in Figure 2.

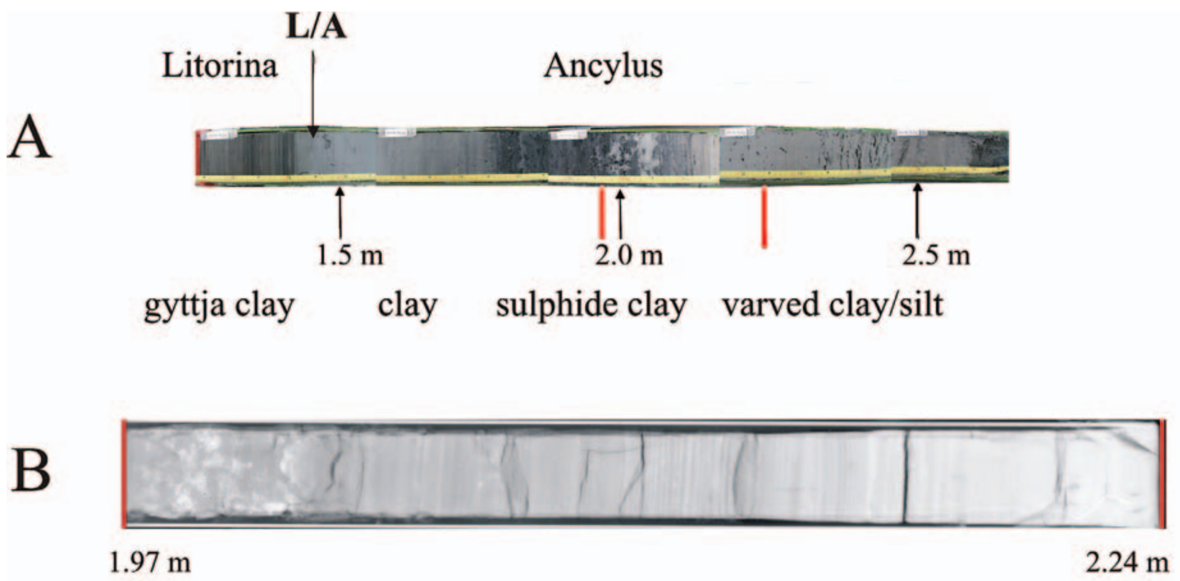

Figure 29. Early Holocene litostratigraphic in vibrohammer core MGTK-2003-14 of the Kvarken Archipelago (A). The onset of the Litorina Sea stage is indicated by L/A in figure. X-ray radiograph of sulphide clays and varved clays (1.97-2.24 metres below seafloor, red bars in figure A) is shown in Figure B. (Compilation Aarno Kotilainen).

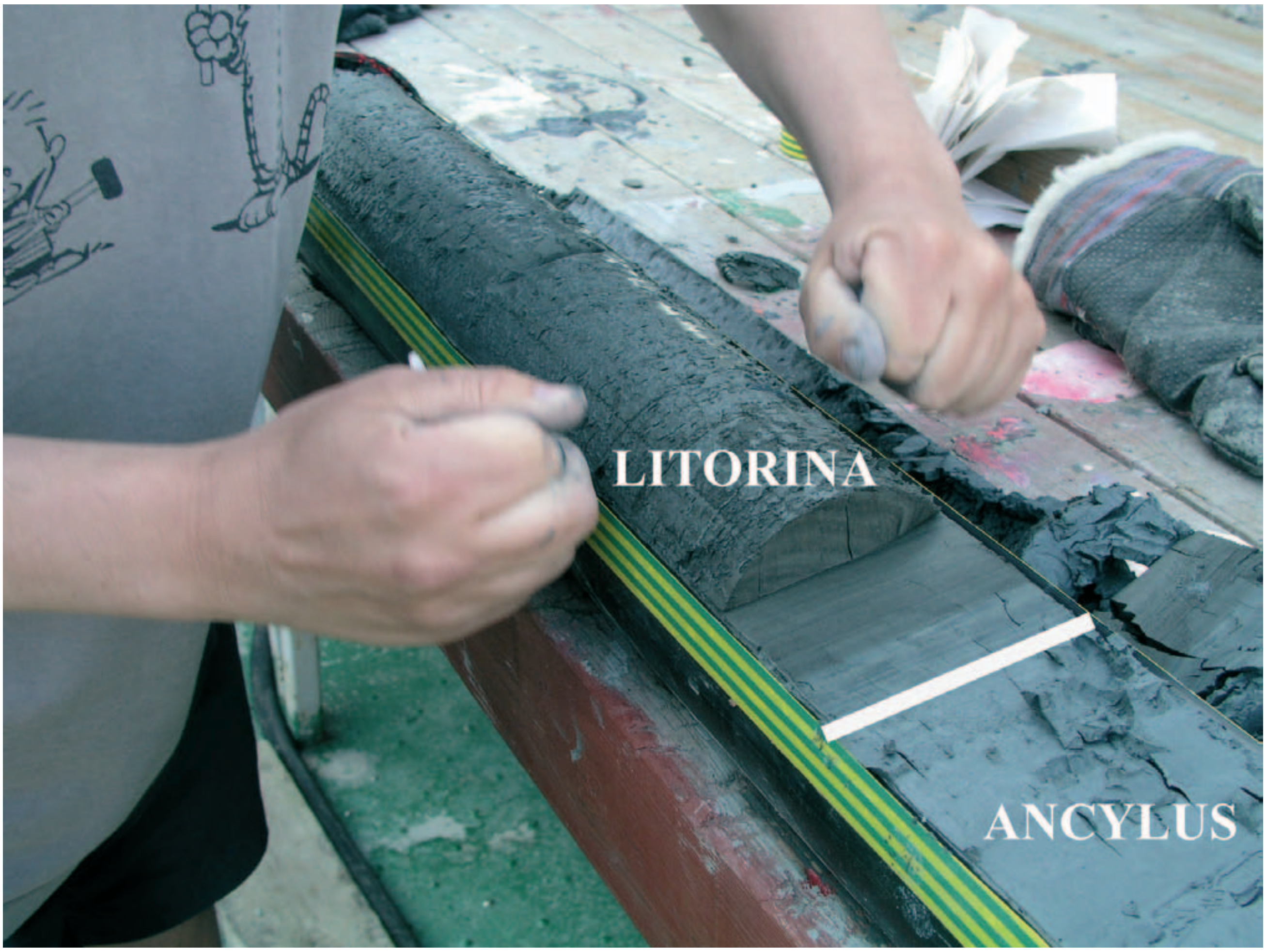

Figure 30. Splitting the sediment core onboard r/v Geola. White line in figure indicates the onset of the Litorina Sea stage in lithostratigraphy (photo Jyrki Hämäläinen 2003).

Bedrock geology

Geologic history of the Kvarken area

The bedrock of the Kvarken area belongs to the Precambrian Svecofennian schist belt and is composed of ancient, hard crystalline rock, which developed during the 700 million year (Ma) time period starting at the Paleoproterozoic, 2000 Ma ago and ending at Mesoproterozoic, c. 1300 Ma ago. On the eroded and peneplane surface of Precambrian crystalline rocks, Paleozoic sediments were deposited 520 Ma ago. The Paleozoic sedimentary blanket was eroded away over the last 500 million years to the present. Evidence of this sedimentation still can be seen in the Söderfjärden meteorite impact basin, where a pile of Paleozoic sedimentary rocks (Cambrian) tens of meters thick was preserved from erosion.

The geologic history of the crystalline rocks in the Kvarken area starts with the turbiditic sedimentation of sand and mud beds on a seafloor with an unknown basement. Volcanic rocks, lavas and pyroclastites were deposited as interbeds and minor constituents within the turbidites. Subsequently, during orogenic movements 1880 Ma ago (Svecofennian orogeny), the sedimentary pile sank about 15 kilometers deep into the earth's crust, recrystallized into mica gneisses, veined gneisses and amphibolites and also partly fused into granodioritic melt (diatexites). Around 1800 Ma ago, a post-orogenic thermal pulse produced granitic magma expressed as small plutons in the western part and as minor felsic dikes and pegmatites in the eastern part of the Kvarken area. After a period of magmatic quietism that lasted for about 200 Ma, rapakivi magma aroused, intruded and crystallised as batholites in upper parts of the crust about 1570 million years ago. The felsic rapakivi magmatism was accompanied by mafic magmatism, expressed as diabase dikes (Sub-Jotnian) and gabbros intruding the bedrock. The boulders of quartz-feldspar porphyries that one can see in the coastal area around Vaasa are considered as near surface equivalents to the rapakivi magmatism. These porphyries are also seen in the moraines on the bottom of the Bothnian Sea near the Kvarken area. Around 1270 million years ago, a set of olivine diabases (Post-Jotnian) intruded the crust and this was the last rock-forming event of the crystalline basement in the Kvarken area (Suominen 1991).

The Svecofennian orogenic belt had already lost much of its mountainous grandeur during the Mesoproterozoic time. This is indicated by thick, 1400 – 1200 Ma old, red Jotnian sandstone deposits within the Svecofennian schist belt in Satakunta and Muhos, in Finland and in Nordingrå, Gävle, Dalarn and Småland in Sweden. Extensive distributions of Jotnian sandstone (Figure 31) have also been verified on the bottoms of the Bothnian Sea and the Bothnian Bay, around the Kvarken area. Small boulders of red sandstone are frequently seen in the Finnish coastal area near Vaasa and further inland. After the intrusions of Post-Jotnian dikes 1270 Ma ago, there is no record of significant magmatic activity in the Svecofennian area. Stable tectonic conditions were now established and until the beginning of the Paleozoic era 540 Ma ago, uninterrupted erosion and sedimentation (e.g. 600 Ma old, grayish Lauhanvuori sandstones, Finland) continued and flattened the Svecofennian surface to a peneplain.

During the Cambrian, 520 million years ago, a meteorite impact created a basin on the Earth´s surface in the southeast corner of the Kvarken area (Lehtovaara 1992). The Söderfjärden impact crater has provided a shelter for the Cambrian sediments, unique to an extensive land area within the Svecofennian schist belt, against erosion and abrasion until present time.

Figure 31. Ripple marks in bedding plane of a Jotnian sandstone boulder in Storskäret (photo Petri Virransalo 2003).

Existence of Lower Cambrian siltstone in the Bothnian Sea and comparable seismic velocities of this siltstone with velocities in the Bothnian Bay, north of the Kvarken area is evidence that Söderfjärden belonged to a once widespread Cambrian sedimentary strata (Axberg 1980, Winterhalter 2000). Also, sandstone erratics found in many places in western Finland have similarities to the sandstones at Söderfjärden (Laurén et al. 1978).

Structure of the bedrock

At the time of orogeny, sedimentary rocks deformed under plastic conditions. Therefore polyphase fold structures are common in gneisses. Bedrock later deformed rigidly causing jointing and faulting. A huge shear zone (the Merenkurkku shear) runs from the south of the Söderfjärden crater northwest towards the Kvarken area. According to seismic reflection data, the thickness of the Earth's crust in the Kvarken area is over 50 kilometers (Korja et al. 2001).

Precambrian crystalline rocks

Supracrustal rocks

Mica gneisses, veined gneisses, diatexites (Figures 32 – 34). In the Kvarken area, mica gneisses, veined gneisses and diatexites have a common origin as turbiditic sediments, sand and mud deposited on an ancient sea floor. Subsequently, varying metamorphic conditions caused recrystallisation, partial melting and, in an ultimate case, total melting of these sediments to produce the crystalline rocks seen presently on the Earth's surface. Concretions, round nodules, which were produced at the time of sediment consolidation, are common in metasediments.

Figure 32. Open fold in veined mica gneiss, Molpehällorna (photo Petri Virransalo 2003).

Figure 33. Mica gneiss fragments in even grained diatexite at Vaasa (photo Petri Virransalo 2003).

Figure 34. Example of coarse grained diatexite, Vaasa granite at Norrskär. In the middle of the picture is feld-spar twin (photo Petri Virransalo 2003).

Mica gneisses are the least metamorphosed Precambrian metasediments in the Kvarken area. They are light gray in color and show clear primary bedding structures. Scant veining is common. An increase in vein generation and in grain size alters the mica gneiss to veined gneiss. Bedding structures are still observable. In addition to the main mineral constituents, quartz, plagioclase, biotite and garnet are frequently seen in these rocks. Cordierite, sillimanite and pyroxene occur together with increasing metamorphism.

Graphite and sulphide schists occur as interbeds within the mica and veined gneisses. These rocks are eroded deeper than the surrounded gneisses and are rarely seen in outcrops. In geophysical maps, the graphite and sulphide schists can be traced as long and narrow anomalies, which display the general structures of the gneiss complex.

The diatexites are coarse grained, often feldspar porphyritic rocks that have an igneous looking appearance and granodioritic composition (Figure 34). These rocks are often called Vaasa granites. Relics of partly melted mica gneisses, fragments of arkosic calc-silicate beds and calcareous concretions in some areas refer to the host rock. Garnet is an appreciable mineral component and together with biotite and cordierite, it occasionally exists as small dark restite ‘drops’. In terms of migmatite classification, the diatexites can be regarded as schollen migmatites with floating ‘rafts’ of veined gneiss in homogeneous granodioritic neosome. Zonation from mica gneisses to veined gneisses and further to diatexites is found in some areas.

Most of the Kvarken area in Finland, including the archipelago, is covered solely by geologic mapping carried out during the early 20 th century with a map scale of 1:400 000 (Saksela 1934, Laitakari 1942). As a result, for the major part of the Kvarken area only a very generalized geologic picture can be presented and the above-mentioned rock divisions of mica gneisses, veined gneisses and diatexites cannot be shown accurately on the map. In the Vaasa area, there are several large in production and abandoned aggregate rock quarries in diatexites.

Quartz-feldspar gneisses. Due to the gently or nearly horizontally dipping beds, the quartz-feldspar gneisses in the southeast part of the Kvarken area covers areas wide enough to plot on a map. The feldspar gneisses occur as light colored interbeds in the mica gneiss usually with gradational contacts. Bedding is a common primary sedimentary structure, but grading has also been noted (Nykänen 1960b).

Amphibolites in the Kvarken area are basaltic and andesitic volcanogenic rocks that occur as narrow tongue-like interbeds within the mica- and veined gneisses. These greenish, hornblend-bearing schists have a metamorphic striped and foliated appearance but in some places pyroclastic and pillow lava structures are still recognized (Figure 35).

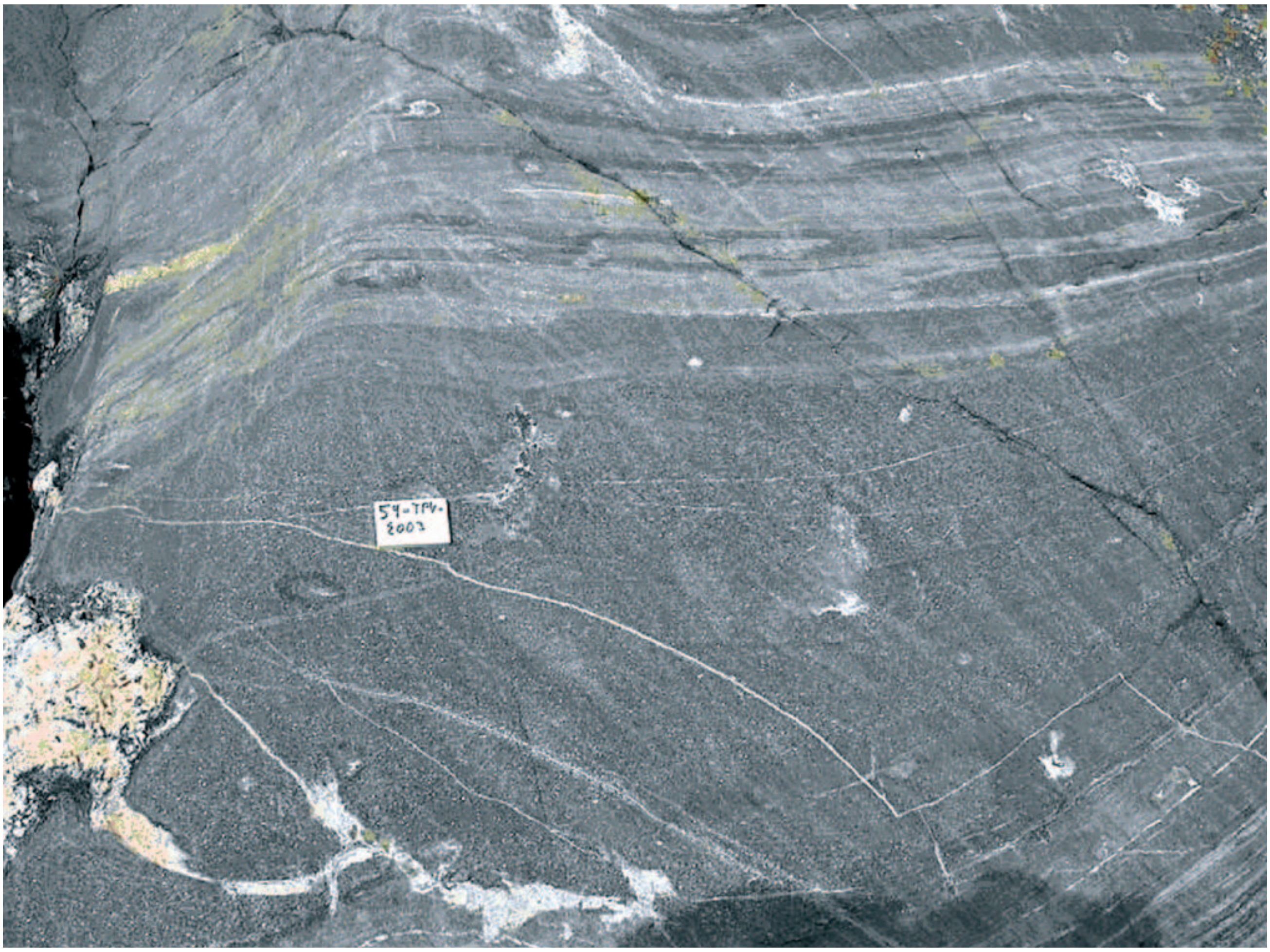

Figure 35. Deformed pyroclastic structure in mafic metavolcanite at Rönnskär (photo Petri Virransalo 2003).

Deep seated rocks

Granites and pegmatites. Coarse grained, reddish or white pegmatites are common in the areas occupied by mica and veined gneisses. Pegmatites usually form conformable bodies, but occasionally crosscut the gneisses. Red granites in the southeast corner of the Kvarken area intrude mica gneisses and their deformation structures. The granites are mediun to coarse-grained rocks with a texture of both even grained and porphyritic. About ten kilometres outside the Kvarken area in the southeast, a zircon dating from a cross cutting, post-kinematic granite shows an age of 1800 Ma. In the area of Rödgrynnorna islands southeast of Replot, there is red porphyritic coarse-grained granite often with magmatic flow structures (Figure 36). This granite was quarried as dimension stone in the 19th century and was used in many buildings in the Vaasa area. An age determination this rock is forthcoming.

Grandiorites. In the southeast of the Kvarken area, in Mope, there are grey, medium grained and foliated grandiorites, which typically have breccia fragments of mica gneiss near the contact (Figure 37). In the inner parts of intrusion, the grandiosity is homogenous and carries enclaves, typical for intrusive bodies. One boulder of rare orbicular grandiorite or tonality is found in Replot. The boulder is now situated on the yard of the Headquarters of Geological Survey in Espoo (Laitakari and Lahti 1984).

Figure 36. Magmatic flow structure in coarse post-kinematic granite, Rödgrynnorna (photo Petri Virransalo 2003).

Gabbros. The Tistronskär gabbro, south of Replot, is exposed only on a few small islands. On the geologic map, this magnetic gabbro is traced from an anomaly pattern on the geophysical map. The dimensions of this subaqueous anomaly are 1 x 13 kilometres. Geochemically, the Tistronskär gabbro is quartz monzonitic in composition and has slightly alkaline chemical characteristics. The age of the gabbro is not known, but rapakivi magmatism as a possible source cannot be excluded.

Ultramafites. In connection with ore exploration, the diamond drilling at Korsnäs has revealed tens of meters of thick, conformable horizons of ultramafites in mica gneiss (Nykänen 1960 a, b). The ultramafites are medium grained hornblendites, pyroxenites and serpentinites. Under the sea at Oravainen, there is a nickel deposit in metadunite. Ultramafic rocks are found as boudinaged fragments in mica and veined gneisses as well as in diatexites in the Kvarken area. These fragments originate from ultramafic magma that intruded the sedimentary deposits before the main phase of deformation.

Dike rocks

Feldspar porphyrites. At the beach in Vaskiluoto, a camping site in the city of Vaasa, dikes of light red feldspar porphyrite intrude mica gneiss. The dikes range from a few centimetres to five meters in thickness. Feldspar phenocrysts occur even in the thinnest dikes. There appears to be no prevalent direction to the dikes, which crisscross in mica gneiss and also brecciate it. Radiometric dating on the zircon gives an age of 1800 Ma to the dike.

Figure 37. Quartz vein in even grained granodiorite, Särkimo (photo Petri Virransalo 2003).

Post-Jotnian diabases (Figures 38 – 40). The Post-Jotnian dark diabases in the Kvarken area form voluminous sills and dikes, which in the Vaasa Archipelago run in a mostly north- northwest direction and are nearly horizontal. The diabases are unmetamorphosed and have an ophitic texture typical of diabases even in fine-grained variations. Contacts with migmatites are crosscutting, but no contact metamorphism is recognized. In diabases, there is a meter or so of fine-grained chilled margins showing that intrusion happened in hybabyssal conditions near the ancient surface of the earth. As olivine is a common constituent in the Post-Jotnian diabases, these diabases are called olivine diabases. In Post-Jotnian diabases in the Rönnskär area, there is often narrow feldspar, carbonate and amphibole veins and roundish weathering structures. Radiometric age determination of the olivine diabase from Molpe, Korsnäs gives an age of 1268±13 Ma to this rock (Suominen 1991).

Paleozoic rocks

Söderfjärden sandstone and the Söderfjärden meteorite crater. The Söderfjärden meteorite crater, 10 kilometres south of Vaasa, is a more or less circular depression, which has a diameter of 6 kilometres and shows a discontinuous rim 30-40 m in height (Laurén et al. 1978). Based on gravimetric studies and drilling, the crater has an uplifted central part in its basal topography. The age of the impact has been set at 520 Ma, the time only shortly before sediment deposition (Anneli Uutela pers. com.).

Sandstone and siltstone make up 250 m thick sedimentary strata in the lower part of the depression and are overlain by glacial overburden 80 m in thickness. The sedimentary rocks have been dated micropaleontologically to the Lower Cambrian (Tynni 1978).

Figure 38. Ophitic structure in olivine diabase, Rönnskär (photo Petri Virransalo 2003).

Figure 39. Roundish weathering structure in olivine diabase, Rönnskär (photo Petri Virransalo 2003).

Figure 40. Feldspar and amphibole combined vein in olivine diabase, Strömmingsbådan (photo Petri Virransalo 2003).

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