Technical Report

TR-04-25

The amount of glacial erosion of the bedrock

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November 2004

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Abstract

The purpose of this study is to estimate an upper bound for the average erosion of fresh bedrock that can reasonably be expected during a glacial period or a single glaciation. The study is based on the assumption that clastic sediments, formed by Scandinavian ice erosion during the Quaternary period, still exist within the formerly glaciated area or its periphery. The volume of these sediments thus constitutes the maximum average glacial erosion of bedrock within this area. This volume is calculated by estimating the thickness of the minerogenic Quaternary from well data in Sweden and Denmark and from seismic measurements in adjacent sea areas.

The average thickness of the Quaternary deposits and other reogolith in the investigated area was estimated to 16 m. Assuming that the whole volume is the result of glacial erosion of fresh bedrock this corresponds to 12 m depth. However a great part of the sediments may consist of glacially redistributed Tertiary regolith. As the amount of Tertiary regolith is uncertain the estimated maximum average glacial erosion rate in fresh bedrock is uncertain, and assuming that the total sediment volume is the result of glacial erosion leads to an overestimation of the glacial erosion depth. Considering this, the average glacial erosion during a full glacial period has been estimated to between 0.2 m and 4 m. If the extremes in the made assumptions are excluded the glacial erosion during a glacial cycle can be estimated to about 1 m.

Sammanfattning

Syftet med denna studie är att skatta en övre gräns för den genomsnittliga erosionen av berggrunden under en glacial cykel eller enskild glaciation. Studien bygger på antagandet att de minerogena sediment som bildats under kvartärperioden genom inlandsisarnas erosion av berggrunden finns kvar inom det område som tidigare varit nedisat. Volymen av de kvartära sedimenten i detta område kan därmed användas för att gränssätta den maximala genomsnittliga glaciala erosionen i området. I detta arbete har volymen beräknats genom att statistiskt bearbeta data avseende jorddjup i Sverige och Danmark och i angränsande hav. På land har detta skett med hjälp av brunnsdata och i havsområdena med utgångspunkt från resultat av seismiska mätningar. Medelvärdet av jorddjupet i det undersökta området har bestämts till 16 m. Om hela volymen antas utgöras av eroderat fast berg motsvarar det ett djup av 12 m, vilket således är en skattning av den maximala genomsnittliga erosionen av berg under kvartärtiden.

Under tertiärtiden täcktes eller utgjorde övre delen av berggrunden av regolit ner till ett djup av ca 10 m eller mer. Genom de första inlandsisarna kom den prekvartärt vittrade berggrunden att eroderas bort, omlagras och inkorporeras i de kvartära avlagringarna. Under senare nedisningar har glacialerosionen haft en alltmer motståndkraftig yta att bearbeta varvid erosionen minskat i omfattning.

Även om den prekvartära regoliten inkorporerats i de kvartära sedimenten genom glacialerosion är dess ursprungliga bildning knuten till andra klimatförhållanden än kvartärtidens. Syftet med detta arbete är att försöka gränssätta glacialerosionen i fast berg. Det tidigare uträknade erosionsdjupet av berget minskas därför med ett belopp som antas motsvara volymen av den prekvartära regoliten.

Medeldjupet av den glaciala erosionen av berggrunden har mot bakgrund av detta skattats till mellan 0,2 m och 4 m under en hel glacial cykel. Om extremerna i gjorda antagen exkluderas kan den genomsnittliga erosionen under en glacial cykel skattas till ca 1 m.

Contents

1 Introduction

1.1 Objective

Theories and hypotheses regarding processes of glacial erosion are discussed in detail in glaciological literature but as yet there is no answer to the essential question of how much bedrock is eroded during a glacial phase. The aim of this project is to attempt to answer this question by estimating an upper bound for the average amount of bedrock erosion in Sweden during a glaciation phase.

1.2 Method

Glacial erosion forms mineral particles, which give rise to deposits of till, glaciofluvial sediments and clay. The particles in till are usually transported less than 10 km from the source areas. The distance of transport for glaciofluvial material may be somewhat longer but is usually less than 20 km. Clay and silt particles are transported in suspension in melt water, which may reach relatively long distances, but ends as soon the melt water reaches a large basin. Fine-grained particles, that reached the Baltic during deglaciation phases, were thus trapped within this basin. When suspended sediment entered seawater during deglaciation phases it was deposited very quickly due to aggregate formation and deposited close to the ice border. Fine-grained particles were thus trapped in the Kattegat and the Skagerrak when melt water entered this sea area.

The basic assumption in the estimation of bedrock erosion is that the bulk of inorganic detrital (minerogenic) sediments formed by glacial erosion throughout the Quaternary still exist within the formerly glaciated area or its periphery. The volume of minerogenic sediments within this area, is consequently the result of glacial erosion within the same area. It follows that, it is possible to estimate the average glacial bedrock erosion by estimating the thickness of minerogenic Quaternary deposits. Detailed information about the thickness of Quaternary sediments exists in the form of well data for land areas in Sweden and Denmark and seismic measurements in adjacent sea areas. The information from this area represents a major sector of the formerly glaciated area, from the glacial centre to the periphery.

1.3 Contradictory opinions regarding the amount of glacial erosion of the bedrock

Boulders and stones from Finland and Scandinavia have been carried hundreds of kilometres from its origin, as far as Britain, Germany and Poland. Such indications of the long transportation of glacial debris has been assumed to be general and if it were reversed transported sediments could fill up the basin of the Baltic Sea, all the lakes in Scandinavia, with enough left over to add a 25 m thick layer to the surface of the entire Scandinavian peninsula /Hansen, 1894/. This assumption is contradicted by the observation that glaciers carry only a minor proportion of their load far beyond the place where it is picked up, so that there is a close relationship between the composition of glacial coarse-grained sediments and that of the local bedrock /Lidén, 1975; Svantesson, 1976/.

The formation of fjords has been ascribed to a huge rate of glacial erosion, which could amount to more than 1,900 m over the whole Quaternary period /Andersen and Nesje; 1992/. However, investigations of bedrock morphology indicate a very low rate of glacial erosion of the bedrock /e.g. Johansson, 2000/. Land forms and ventifacts in their original positions, which survived the erosive impact of the last continental ice sheet in the Norrbotten area, show that the rate of glacial erosion in this area has been very low during the main part of the Weichselian /Lagerbäck, 1988a; Lagerbäck, 1988b; Lagerbäck and Robertsson, 1988/.

The above examples illustrate the difficulty of estimating glacial erosion. Further the possibilities to investigate the basal parts of inland ice sheets in field are very limited. During recent years hypotheses concerning glacial abrasion have been developed, for example by /Boulton, 1974/ and /Hallet, 1979; 1981/. These address the question of erosion mechanisms, but they give little information on the rate of erosion. Textbooks by /Drewry, 1986/ and /Menzies, 1995/ discuss the mechanism of glacial erosion. The introduction to glacial erosion given in sections 2.1 to 2.4 is mainly derived from these publications.

1.4 Geological development during the Tertiary and the Quaternary periods

The distribution between land and sea in Scandinavia during the Tertiary period can be assumed to have been quite similar to the present distribution. However, there may have been a narrow channel over southern Jylland, which connected the Baltic to the North Sea during this time /Binzer and Stockmarr, 1994/.

During the Tertiary and the Early Quaternary periods a regolith layer covered the superficial part of the bedrock. This regolith included alluvial sediments, rock debris of different kinds and also saprolite. Saprolite is a weathering mantle formed by chemical weathering and consists of deeply decomposed parent rock usually with a clayey kaolinitic composition. Grus is a particular form of saprolite, which predominantly consists of sand and gravel and which generally not has a kaolinitic composition. The time span most suitable for deep kaolinitic weathering was the Mesozoic up to the Upper Cretaceous period, while grus most probably was formed between Pliocene to Early Pleistocene /Lidmar-Bergström et al.1996/.

Weathering mantles are very widespread in central, western, and northern Europe /Migón and Lidmar-Bergström, 2001/. They often form thick near-surface residual deposits in excess of 50 m. In Sweden the kaolinitic saprolite is most common in the southern part and the thickness of the saprolite is estimated to 10 m or somewhat more by /Lidmar-Bergström et al. 1996/. Grus is realtively abundant in southern Sweden but is also known from rest of the country. Most of the grus profiles are unconformably overlain by till and these are usually only a few meters thick, yet others are as much as 15 m /Lidmar-Bergström et al.1996/.

The clay mineral kaolinite can usually be traced in both till and glacial clay. This indicates that material weathered prior to the Quaternary period is included in these sediments /Brusewitz, 1982; Stevens et al. 1987; Engdahl, 1997/.

The last 2.5 million years (Ma) of earth history is designated the Quaternary period or Pleistocene. This period is characterised by a climate, which successively became colder. At the end of the period inland ice sheets repeatedly covered Scandinavia. According to /Jansen and Sjöholm, 1991/, based on ice-borne deposits in the Norwegian Sea, the major Pleistocene glaciations in Scandinavia started about 2.5 Ma ago but became more intensive1 Ma ago. About 800,000 years ago the dominant periodicity of global glaciations changed from about 40,000 years long cycles to about 100,000 years long cycles. For the Scandinavian development three about 100,000 years long glacial periods are well known, the Elterian, the Saalian and the Weichselian, while earlier evolution is uncertain. Between the glacial periods there were short periods with climatic conditions similar to the present, the Holsteinian and Eemian interglacials. The latest glacial, the Weichselian, started about 115,000 years ago and ended 11,000 years ago. The ice coverage during the Weichselian was smaller than during the previous glacials, as shown in Figure 1-1. The maximum extension of the ice occurred in some regions during the Elsterian and in other region during the Saalian, Figure 1-1. The Scandinavian ice coalesced for a time with the independent British glaciers.

Warmer fluctuations during the glacial periods reduced or completely melted the ice sheet. Such warm periods are called interstadials. As a rough estimate there have been three periods of glaciation and thus two interstadials during each ice age /cf Houmark-Nielsen, 1987/.

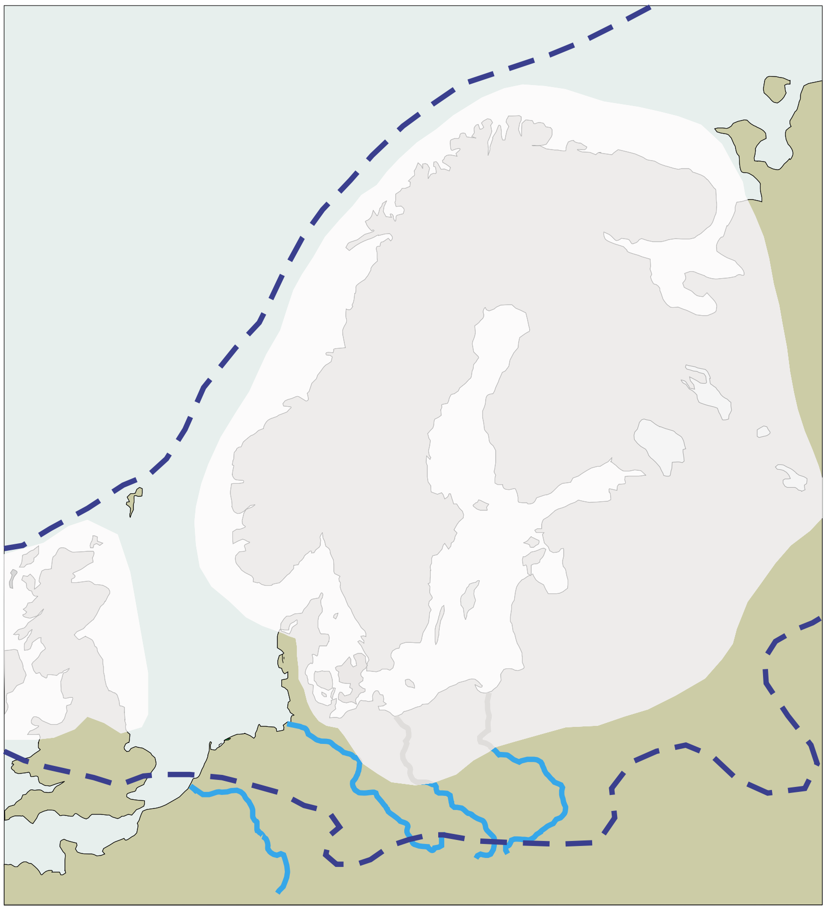

Figure 1-1. *Extension of the Quaternary glaciations. The covered white area represents the maximum extension of the Scandinavian ice during the Weichselian. The dark blue line shows the overall maximum extension, which in some regions occurred during the Elsterian and in some regions during the Saalian.*

2 Glacial erosion

In this chapter processes of glacial erosion are described and discussed. Observations of glacial erosion and its extension in time and space are accounted for. The intention is to summarise different views on glacial erosion and shed a light on how they have evolved over time as dating and modelling techniques have improved. The intention is also to support the basic assumption in this study that glacial eroded sediments still remains within the former glaciated area.

2.1 Introduction

Erosion and denudation results from the action of: the sun, wind, rain, frosts, running water, moving ice and the sea. In addition, water has a slow solvent action on rocks. To be effective, the process of erosion includes both weathering and the transportation of the weathering products.

Only bare bedrock is considered available for bedrock erosion. The sun, wind, rain, frosts, running water, moving ice and the sea do not affect the bedrock surface if sediments cover it.

Glacial erosion is usually regarded as the main erosion process in Scandinavia during Quaternary time. However, as great parts of Scandinavia were not covered by ice during long periods of the Quaternary other agencies should not be neglected.

Weathering by granular disintegration affects exposed bedrock during ice-free conditions. /Swantesson, 1992/ has estimated the postglacial weathering of bare bedrock surfaces in southern Sweden during the Holocene to be less than 2 cm. As sediments cover most bedrock surfaces, the average postglacial erosion can be assumed to be of minor importance to this issue.

Bedrock in contact with water is exposed to solvent action. Chemical analyses of river discharge are used to quantify the amount of dissolution. It should be emphasised that these measurements reflect weathering of the bedrock only to a small degree, the main component being derived from chemical weathering of the surrounding sediments. If weathered sediments are transported out of the investigated area the loss will result in an underestimation of sediment thickness and thus of bedrock erosion. However, in this study this potential loss of sediment volume is regarded as negligible.

The glacial erosion process is highly complex as it depends on material properties of ice and rocks, ice dynamics, thermodynamics, friction and lubrication, chemical effects and subglacial hydrology. As knowledge is incomplete in each of these fields the physical process of erosion cannot yet be accurately described.

Glacial erosion consist of several mechanisms – loosening of rock fragments, including fracturing and crushing; evacuation of fragments from the bedrock and their entrainment in the ice. There are three main processes of glacial erosion: plucking, abrasion and the action of subglacial water including dissolution. Plucking can be described as joint-block removal from the bedrock. Abrasion is the process whereby bedrock is scored by debris carried in the basal layers of the glaciers. This means that glaciated bedrock are smoothed by abrasion and roughened by plucking. Another obvious difference between the two is that abrasion occurs mainly at stoss surfaces whereas plucking mainly occurs at lee surfaces.

Despite the local importance of erosion caused by subglacial waters, for example in the formation of potholes, it is usually considered to be volumetrically subordinate to abrasion and plucking. The discussion of glacial erosion will thus focus on the effects of abrasion and plucking.

2.2 Plucking

The lee sides of bumps on glacier beds typically comprise of irregular, fractured surfaces. Such surfaces are presumably the result of plucking, the process by which basal ice fractures the bed and dislodges rock fragments. Stresses caused by the ice load and high water pressures may cause failure in some rocks. Pressure may significantly increase when clast edges at the ice sole impinge on bedrock. In this way features such as chattermarks (Sw. parabelriss) and crescentic gouges (Sw. skärformiga brott) are formed. The formation of crescentic gouges includes loosening of small rock fragments, while the formation of chattermarks only induces fracturing. Observations at the lee sides of bedrock hummocks indicate that the formation of chattermarks may be an important factor for the plucking process. Close to the zones where plucking has occurred, abundant chattermarks may exist, associated with fissures perpendicular to the ice movement as shown in Figure 2-1. These observations indicate that normal stress at the glacier bed may be sufficient to cause failure in some rocks. However, the main part of the crushing is most probably due to the presence of pre-existing weakness such as joints, cracks and foliation, but also due to reduced hardness of the rocks as the result of pre-glacial weathering. These qualities reduce the amount of stress necessary to loosen bedrock particles from the bedrock.

Figure 2-1. *Chattermarks close to the surface where plucking has occurred.*

2.3 Abrasion

Glacial abrasion by an ice containing debris is often likened to a piece of sandpaper rubbing the bedrock. The effect of the rubbing depends mainly on the velocity of the basal ice, the quantity and grain size composition of the subglacial debris and the hardness contrast between the debris and the bed. This analogy leads to the idea that pure ice does not abrade. However, /Budd et al. 1979/ have shown by laboratory studies that pure ice will abrade and that the abrasion increases as velocity and stresses increase. These results suggest that ice alone may be an effective agent of erosion. The studies indicate a possible wear of several mm per year. However such laboratory experiments can seldom be directly compared to the harsh natural conditions under glaciers.

Glacial abrasion is manifested by the formation of striation but also by a polishing effect of some bedrock surfaces. The abrasion forming the striation is due to large stress differences localised beneath ice–entrained rock fragments in frictional contact with bedrock. Abrasion produces fine debris, ranging from silt to coarse sand, whereas plucking produces larger rock fragments.

/Mattsson, 1962/ has pointed out glacial imprints on the same rock surface from several glacial events as an indication of a generally low rate of glacial erosion. Striation on the same bedrock surface but from different glaciations may show that the total abrasion has only been of the order of a few mm, even though the surface has been abraded during multiple glaciations.

The genesis of well-polished bedrock surfaces has not been highlighted as a specific phenomenon in the literature concerning abrasion. This phenomenon is not as common as ordinary striated bedrock surface, but ought to attract more attention. Such well-polished or shiny surfaces are assumed to reflect a more total abrasion due to wear by very fine-grained debris or by clean ice. An ordinary striated bedrock surface reflects wear by single large clasts, while the rest of the bedrock surface may be rather rough. That actually means that only a minor part of the surface has been abraded and the contribution of abrasion to the total amount of erosion is low.

2.4 Evacuation and entrainment

Once bedrock has been weakened by fracturing, or if such fracturing already exists, it is necessary to remove the loose material in order to achieve effective erosion. High water pressure may be one of the main factors for opening fractures and starting evacuation. Entrainment of particles into the ice is expected to be due to regelation, which means refreezing of meltwater above and in the lee of bedrock undulations. In addition to entrainment at the bed, debris is also incorporated at the ice sheet surface where nunataks pierce the ice cover.

2.5 Distance of glacial transportation

In the peripheral parts of the formerly glaciated area, for example in Germany and Denmark, it is well known that erratic boulders exist, which originally came from the central part of the glaciated area. These boulders clearly indicate that glacial transport can be very long but it should be taken into account that such boulders most probably advanced in stages during several glacial phases. The existence of these erratics is one of the main arguments for the idea that most of the sediments from former glaciations are deposited in the peripheral parts. What is not taken into account in this context is that these boulders are most likely transported englacially or at the surface of the ice, rather than at the base. That means not only that transportation may have occurred in the upper, most rapidly moving part of the ice but also that it probably occurred during cold based conditions and thus cannot be linked to the erosional phases of the glaciation. They do comprise an increment of the total glacial transportation but its relative significance is very small.

Till is often dived into two main types, ablation and basal till. Ablation tills are formed near the ice front during deglaciation. The grain size distributions are generally very coarse, with angular clasts. Ablation till can generally be described as a juvenile till, which means that it is freshly formed following "cracking". Ablation till is generally entirely composed of local bedrock types, which indicates a transport distance of the order of hundreds of meters. Ablation tills are the best sedimentological evidence for the existence of glacial erosion of the bedrock.

One of the physical differences between basal till and ablation till is the grain size distribution. Basal till generally has a much lower gravel content. The gravel is crushed during transport and transformed into sand and silt, while stones and boulders are more resistant to crushing /Påsse, 1997/. Coarse particles in basal till are usually abraded and much more rounded than in ablation till.

/Lidén, 1975/ investigated transport distances in basal till in the Uppsala region by petrographic counting. He found a very strong relationship between the coarse material in till and the local bedrock. He also estimated the dilution of the local bedrock. Considering the < 20 mm clasts, about 60% could be derived from local bedrock within about 3.5 km. Following transport of about 6.5 km only 20% of the material was not of local origin. /Svantesson, 1976/ made a similar investigation from Gotland and derived somewhat different results. Most tills in Gotland comprise less than 50% of the local Cambro-Silurian rock types. This is remarkable, considering that the nearest outcrop of Precambrian bedrock is 50–80 km north and north-west of the area. The till in Gotland has another property, which is worth mentioning, namely high clay content, which is not derived from the local calcareous bedrock. That indicates that the clay was most probably derived from older Baltic deposits. /Hansen, 1965/ point out that Danish tills and glaciofluvial sediments may contain more than 50% $CaCO_3$, by weight which clearly indicates the close relationship of these sediments to the local bedrock.

/Salonen and Glückert, 1992/ have investigated the dispersal of boulders in southern Finland and have calculated the mean average transport to be about 4 km. However, both till and glaciofluvial sediments from the Salpaussälkä zone showed more than twice this transport distance.

The transport of minerogenic clasts created by glacial erosion, is in some cases extended by glaciofluvial transport. The maximum glaciofluvial transport distance of coarse-grained particles is not known in detail but is generally assumed to be less than 20 km. Glaciofluvial transport is limited by the possible length of drainage tunnels and the material is deposited close to the ice margin. Fine-grained material, transported in suspension, can be transported by fluvial transport until the running water reaches a great lake or the sea.

2.6 Redeposition of sediments

The idea mentioned in the introduction that the entire glacial deposit constitutes glacial erosion of the bedrock from a single glacial period probably originates from observations of recent advancing glaciers where huge end moraine ridges have been pushed up at the glacier snouts. In this idea the advancing glacier is compared to a bulldozer, which effectively cleans the landscape. However, frontal push moraine would have reached enormous heights if this process were active during the growth of a Scandinavian ice sheet. The height of such push moraine can be calculated from the volume of available material for a given length of advance. Assuming an ice sheet advance of 10 km, a sediment thickness of 5 m and an angle of repose of 25° the push moraine height would be about 215 m, or 265 m if assuming an angle of repose of 35°.

It should be an urgent task for research to examine how pre-existing sediments are glacially eroded and redeposited. A section exposed during road construction at Holmagärde /Påsse, 1992a/ is given as an example illustrating redeposition. The section contents a nearly complete Eemian deposit including marine clay and gyttja, but also organic-rich fluvial deposits. Parts of the Eemian sequence are preserved as short strata in a sequence which can be regarded as more or less in situ. Other parts of the Eemian sediments are enclosed in till and distributed in the direction that the ice moved during the Early Weichselian. Gyttja, clay and the other Eemian sediments exist as lumps, generally in sizes of < 5 dm^3, within this till as shown in Figure 2-2. These lumps are found with decreasing frequency in the ice movement direction at least 200 m away from the original source. This sequence shows that redeposition was an active process. The conclusion is that glacial erosion of sediments occurs by breaking up small parts of the pre-existing sediments, some of which are transported very short distances. At this specific site the redeposited sequence was preserved from further erosion and redeposition during the Middle and the Late Weichselian glaciations.

Another example of redeposition is located at Snickarkullen in the county of Västra Götaland /Lind, 1983/. At this site lumps of diatomite, which most probably was formed during the Holstainian interglacial, are incorporated in a huge deposit of Late Weichselian glaciofluvial sediment.

Figure 2-2. *Lumps of redeposited Eemian clay (light spots) in Weichselian till at Holmagärde, SW Sweden.*

Redeposition is also indicated by the existence of redeposited microfossils. /Heinonen, 1957/ performed a thorough investigation of microfossils in basal till and also in Baltic clay. He showed that the tree pollen count can reach > 9,000 and non- tree pollen > 3,000 in 10 g of basal till. Heinonen concluded that the microfossils originate from older sediments deposited before the tills were formed.

/Miller, 1977/ used redeposited Quaternary and Pre-Quaternary microfossils for stratigraphic investigations in both tills and fluvial sediments within the Alnarp valley in Skåne. /Klingberg, 1998/ made biostratigraphic investigations of Late Weichselian clays on the Swedish West Coast. At a site named Åbrå, in the vicinity of Göteborg, there is Late Weichselian clay dated by radiocarbon to about 10,600 years BP and containing Late Weichselian foraminifera. However, the pollen content of this clay is undoubtedly redeposited as it mainly consists of interglacial species, most probably of Eemian age.

2.7 Rate of glacial erosion

/Drewry, 1986/ has compiled estimates of erosion rates based on measurements of sediment discharge in meltwater streams at recent glaciers. These suggest that erosion rates range from 0.07 to 30 mm/y. It should be noted that these estimates can only be representative for a deglaciation phase. /Boulton, 1974; 1979/ made direct measurements of abrasion at Breidamerkurjökul using plates fixed to the bedrock beneath the ice and estimated the abrasion to between 0.2 and 4 mm/y.

Glacial erosion is a known phenomenon, however the rate of glacial erosion over a full glacial cycle can be overestimated if not considering that glacial erosion is only effective during special conditions whose extension vary both in time and space over a glacial cycle. The first condition is that a warm based ice sheet must cover the bedrock. The second condition is that bedrock can only be eroded if not covered by a layer of debris or sediment. These conditions limit both the time available for erosion and its spatial extent.

2.7.1 Time during a glacial cycle available for erosion

A late Quaternary glacial period has a duration of about 100,000 years. During this period the peripheral parts of the maximum glaciated area can be assumed to be covered by ice for less than 10,000 years, while more central parts may be ice covered for 50,000 years. The time of ice coverage can be investigated by means of glacial modelling /e.g. Näslund et al. in press/.

Investigations by /Lagerbäck, 1988a; 1988b/ have shown that the Early Weichselian glacial landscape in the northernmost part of Sweden escaped significant erosion, despite being ice covered during two later glaciations. This area was covered by ice for a relatively long period, but despite that the glacial erosion has been very weak. This is because the ice sheet was cold based most of the time and erosion is restricted to periods of warm based conditions.

At places where cold based conditions prevail during a glaciation the time available for glacial erosion is limited. By means of modelling /Näslund et al. in press/ calculated the total distance of basal sliding that occurred at different places during the Weichselian glaciation. The calculated values of total basal sliding distances are low in the central and peripheral parts and high in a zone in between these areas. This indicates that glacial erosion may have been relatively weak in the central and peripheral parts and stronger in the intervening area. This could explain observed differences in the distribution of sediment thickness.

2.7.2 Spatial limits for erosion

The hypothesis that the minerogenic sediments formed by glacial erosion remain within the glaciated area implies that sediments covered the bedrock even during the glaciations and thus inhibited glacial erosion of fresh bedrock. Such sediment coverage is self-generated. When debris formed by glacial erosion is deposited on the bedrock it will shield the bedrock surface for further erosion. The total bedrock area covered by sediments may have changed gradually during the glaciations, but is assumed to have been in the same order of magnitude as during unglaciated periods. This limits the area accessible to glacial erosion to about 10% of the total surface.

Sediments more easily cover horizontal than vertical surfaces. This means that vertical bedrock surfaces are more susceptible to glacial erosion. Compared with horizontal surfaces, vertical surfaces also exhibit vertical joint systems to a high degree. For these two reasons, vertical bedrock surfaces are assumed to be most susceptible to glacial erosion.

/Påsse, 1990/ has demonstrated how a pre-existing layer of till can protect a bedrock surface from glacial erosion. At an exposure at Himle in south-western Sweden two different beds of till were deposited on the gently sloping side of a small bedrock hummock, as shown in Figure 2-3. Below the lower till bed only one direction of striae was observed, while there were two distinctly different directions of striae on bedrock directly below the younger till bed.

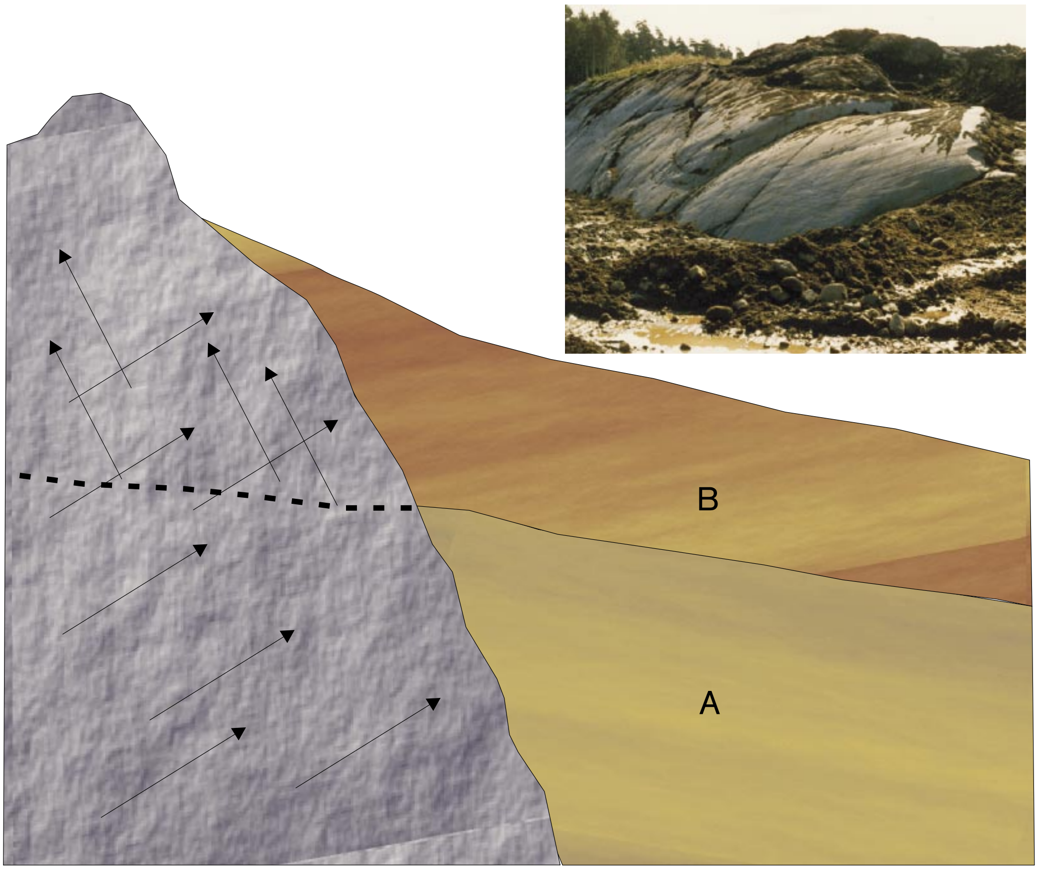

***Figure 2-3.** Pre-existing layer of till protecting a bedrock surface from glacial erosion at Himle, SW Sweden /Påsse, 1990/. At the right top of the figure there is a photo of the site. Striae and till stratigraphy are explained in the drawing. The oldest till (A) covered the lower part of the bedrock summit, where only one direction of striae exists. During the next glaciation only the upper part of the small bedrock summit was exposed for abrasion. A divergent direction of striae was formed on that surface. The upper part of the summit was later covered by till (B).*

2.7.3 Estimates of glacial erosion from observations of bedrock morphology

A long-term perspective on glacial erosion is presented by /Lidmar-Begström, 1997/, and summarised in this section. According to /Lidmar-Begström, 1997/ the relief of the Fennoscandia shield is made up of three types of palaeosurface; the sub-Cambrian peneplain, sub-Mesozoic etch-surfaces and plains with residual hills developed during the Tertiary. The main erosion processes during the Tertiary were probably stripping of old kaolinitic saprolites, lateral retreat of slopes, valley incisions and renewed etching. Remnants of gravelly saprolites, most probably of pre-Quaternary origin, are quite common in south-eastern Sweden.

/Lidmar-Begström, 1997/ estimates total erosion below the peneplain level of the sub-Cambrian peneplain at 20–30 m. The first lowering of the relief was caused by stripping of the original thin kaolonitic saprolite. As remnants of Late Tertiary or Early Pleistocene saprolites are common in some areas, their weathering to gravel is assumed to have lowered the relief by at least 10 m. Glacial erosion in this area may thus account only for 5–10 m. /Lidmar-Begström, 1997/ gives rough estimates of the amount of glacial erosion at small Mesozoic residual hills. The summits of these hills show signs of heavy glacial erosion, while there is evidence for only 20–30 cm of glacial erosion at the hillsides. The thickness of the gravelly saprolites within the Tertiary relief is at least 10 m and probably more /Lidmar-Bergström et al. 1996/.

Glacial erosion is divided into three types by /Lidmar-Begström, 1997/. Channeled glacial erosion within basins or valleys may amount to 50 m in southern Sweden and up to 200 m at a few sites in the highlands of northern Sweden. Glacial erosion of the pre-Quaternary saprolites may amount to 10–50 m. Ice sheet erosion in fresh bedrock may amount to some tens of metres but there are areas with no glacial erosion at all.

/Johansson et al. 2001/ has investigated inherited landforms and the glacial impact to bedrock morphology in south-western Sweden. They conclude that reshaping of the sub-Cambrian flat bedrock surfaces is negligible, while glacial impact is more evident in dissected parts of the peneplain and within hilly sub-Mesozoic surfaces. Glacial erosion is more effective where the initial relief is high, both for abrasion and plucking. However, plucking occurs only a maximum of 20 m below the hill summits. /Johansson et al. 2001/ concludes that the magnitude of the Pleistocene glacial erosion is considerably less than the palaeorelief amplitude in the entire area.

2.8 Transport and deposition of glacial eroded material

There are three different stages in the transport and deposition of the material involved in glacial erosion. First is the glacial stage, during which mineral particles are transported under or within the ice. Second is the deglaciation stage, characterised by the formation of some till types, glaciofluvial sediments and glacial clay. The third stage occurs during ice-free interglacial and interstadial periods, when redeposition of glacially eroded material occurs.

2.8.1 Transport during glacial stages

The transport direction of glacially eroded material may have changed through time due to different glacial developments. The predominant ice movement directions during the Late Weichselian glacial are pointed out in Figure 2-4, which also indicates the position of the ice divide during the Weichselian maximum. The glaciated area west of the ice divide is remarkably smaller than that to the east. The two different parts of the ice sheet could be considered as separate glaciers. Glacial erosion west of the ice divide produced particles, which were mainly transported towards the Atlantic Ocean. The glacial erosion estimated in this work, is due to the "East Scandinavian" ice. However, glacial erosion in the southern part of the "West Scandinavian" ice did contribute to some of the material that was transported via Skagerrak to Jylland.

2.8.2 Transport during the deglaciation phase

The transport distance of the mineral clasts created by glacial erosion, were in some cases extended by glaciofluvial transport during deglaciation. The maximum glaciofluvial transport distance is not known in detail for coarse-grained clasts, but is generally assumed to be of the order of only a few kilometres. The distance is limited by the possible length of drainage tunnels. Glaciofluvial deposition by definition always occurs close to the ice margin.

Fine-grained material is transported by running water until it reaches a great lake or the sea, where calm conditions allow the particles to settle. When clay particles reach sea water they flocculate and settling occurs relatively rapidly. Most fine-grained particles which reached the sea during deglaciation stages, were thus deposited close to the ice margin.

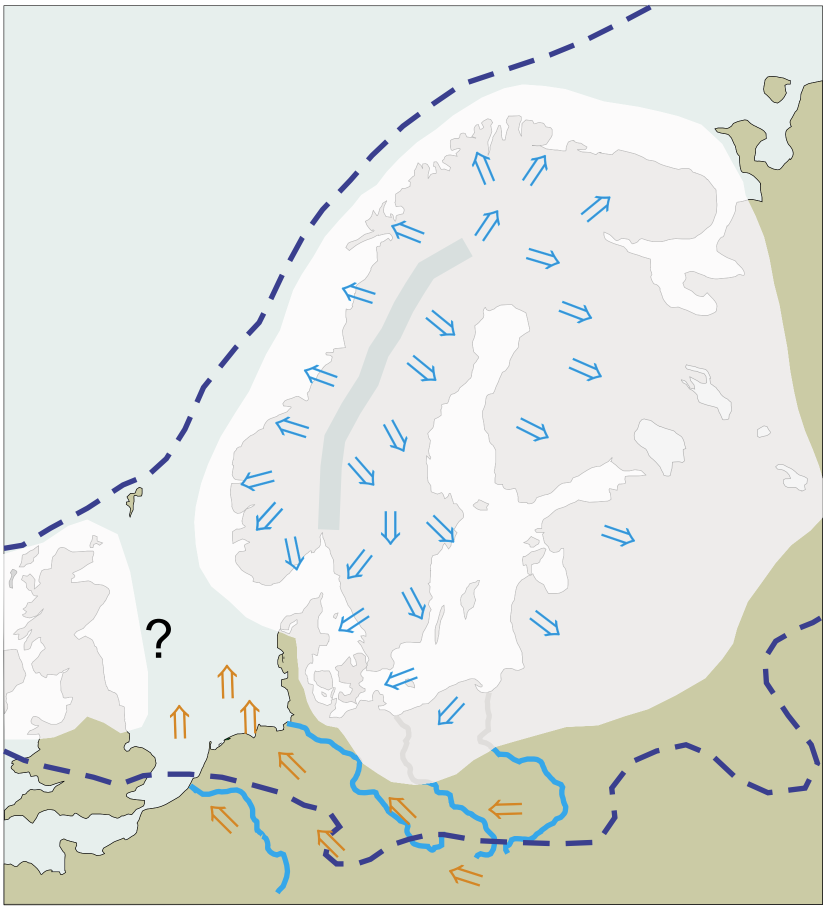

Figure 2-4. *Transport directions during the Late Weichselian glacial. Blue arrows indicate the direction of glacial transport. Orange arrows indicate directions of fluvial transport outside the ice front. The position of the ice divide during the Weichselian maximum is indicated by a thick light blue line.*

During the main part of the Late Weichselian deglaciation stage the Baltic Sea basin was fresh water and similar conditions most probably prevailed during other deglaciation phases. The deposition of clay particles in fresh water is slower than in seawater, but most of the clay particles that reached the Baltic were nevertheless deposited within the basin. If the fine-grained particles were transported out from the Baltic, they would have entered marine water within the Kattegat and been trapped in its southern part.

Some debris may have been lost during deglaciation from the sector investigated here due to transport by icebergs moving northwards. The existence of south Scandinavian erratics including flint in Halland County /Påsse, 1992b/ proves that this occurred during deglaciation. However, the amount of material transported by iceberg from southern Scandinavia seems to decrease rapidly north of Halland so that most of the material transported by icebergs was probably deposited within the Kattegat.

2.8.3 Transport during ice-free conditions

During parts of the interstadials, periglacial conditions are assumed to have prevailed over major parts of Scandinavia. Wind erosion may have caused loss of fine-grained sediment from this area during such conditions.

Hitherto only loss of material from the formerly glaciated area has been considered as a source of error in calculating glacial erosion. However there is also transport of material into the area, which complicates the calculation. This emanates from rivers that enter the southern Baltic (Weichsel, Oder) and the southern part of the North Sea (Elbe, Weser, and Rhine) as shown in Figure 2-5. The provenance of material which is transported by these rivers, is partly from areas outside the formerly glaciated area. Glacial erosion and transport has affected the drainage basins for Elbe, Weser and Rhine. However, the glacial influence on these areas, especially the Rhine drainage basin, can be taken to be of minor importance seen over the whole Quaternary period. Instead there has been a more or less continuous fluvial transport, which has been a very large sediment supply to the North Sea basin.

/Eisma et al. 1979/ has estimated that about 25 million tons of suspended matter is currently supplied annually to the North Sea, mainly in the south. About 5 million tons of this matter is deposited south of Dogger Bank and about 3 million tons south-east of Helgoland in the German Bight. This leaves about 17 million tons to be deposited in the Skagerrak, Kattegat and the Norwegian Channel or to be transported into the Atlantic Ocean. At present there is a major depositional area between the Skagen Peninsula and the Djupa Rännan Trench off the Swedish West Coast /Fält, 1982/, which is fed by this material coming from the west. The huge Skagen delta (> 100 m) was formed in this area due to very high deposition rates. On the slope of the Djupa Rännan Trench, the rate of deposition is about 30 mm per annum according to /Fält, 1982/.

Sediments in the Skagen area have been closely investigated and dated by e.g. /Knudsen et al. 1996/ and /Sejrup and Knudsen, 1999/. These investigations show that most of the thick deposits were formed during ice-free conditions by current and longshore drift transport of material from the rivers entering the North Sea. The sediment in those deposits does not originate from erosion by the Scandinavian ice. The thickness of Quaternary deposits in those areas must thus be reduced in order to estimate the erosion due to the Scandinavian Ice.

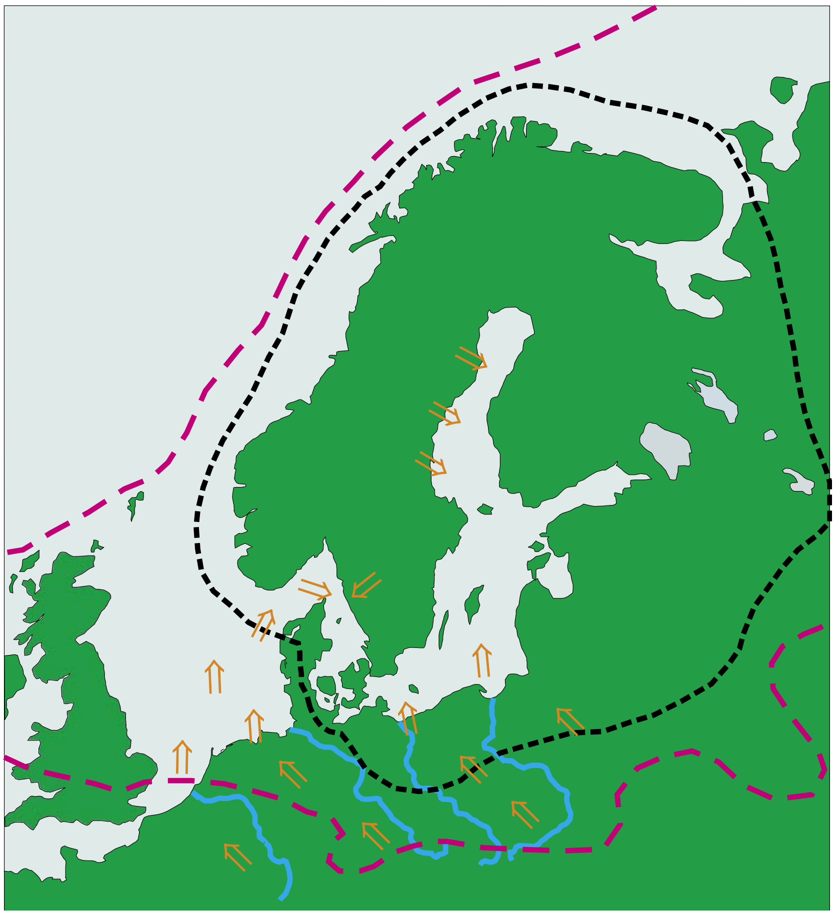

Figure 2-5. *Interglacial and interstadial transport directions of importance to this work. Fluvial transport has been a major contribution to sediment within the North Sea.*

3 Estimation of the thickness of Quaternary deposits

3.1 The investigated sector

Before estimating the amount of glacial bedrock erosion from the thickness of Quaternary deposits, some conditions need to be fulfilled. The area chosen for the calculation, should be large and should represent both central and peripheral parts of the formerly glaciated area. Another condition is that almost all of the clastic particles formed by glacial erosion, are actually deposited within the chosen area. Another important condition, which governs the choice of area, is that reliable information should be available concerning sediment thickness within the chosen area. A sector of the formerly glaciated area including Sweden, Denmark, Kattegat Sea and the main part of the Baltic Sea fulfils all of these conditions. The thickness of Quaternary deposits within the chosen sector has been calculated by a number of different methods. The investigation area has based on the used method to calculate sediment thickness been divided into five sections, see Figure 3-1.

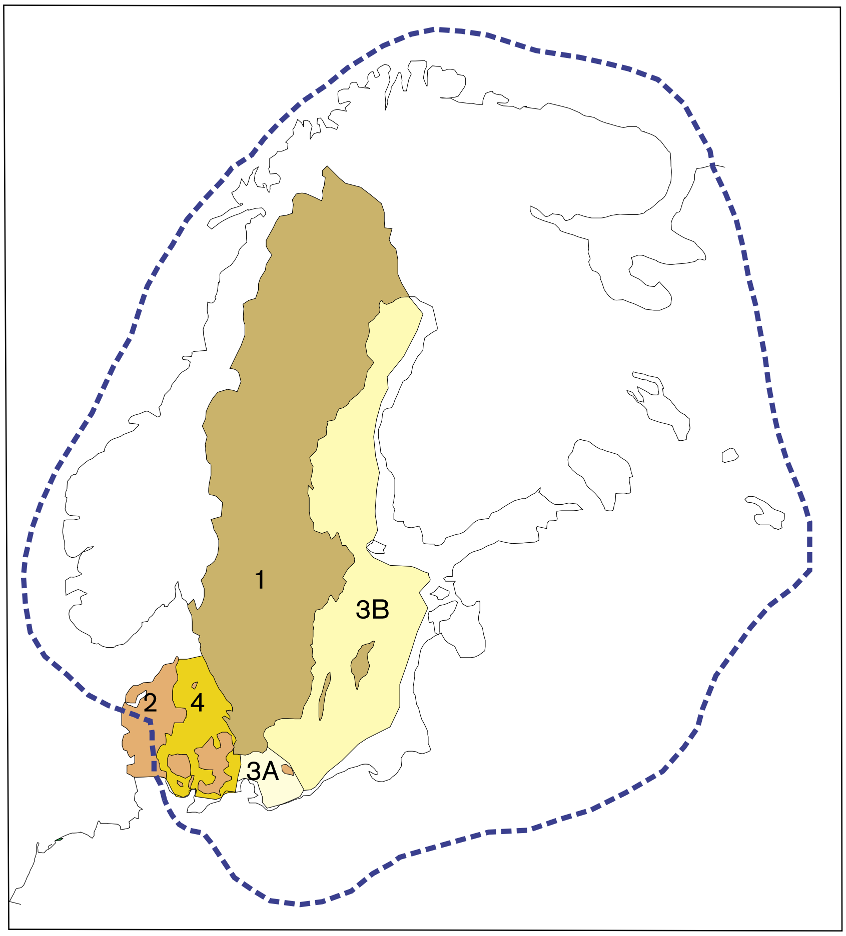

Figure 3-1. *The thickness of the Quaternary deposits has been calculated within a sector of the formerly glaciated area including Sweden, Denmark and adjacent sea areas. The dashed line shows the maximum extension of the Scandinavian ice sheet during the Weichselian glacial. The investigation area and the descriptions of the calculations are divided into five areas: 1 Sweden, 2 Denmark, 3A The southern part of the Baltic Sea, 3B The main part of the Baltic Sea, 4 The Kattegat Sea.*

3.1.1 The North Sea

The North Sea contents huge amounts of Quaternary sediments. There is a linear trough trending north- north-west down the centre of the North Sea in which maximum Quaternary thickness exceeds 1,000 m /Caston, 1979/. However, most of the North Sea has thickness < 300 m. During parts of the Elsterian and the Saalian periods the Scandinavian ice sheet extended over the North Sea area, Figure 1-1. Material deposited within the North Sea area thus ought to be included in the calculations. However, the North Sea sediments are almost exclusively composed of fine-grained marine or fluvial sediments, which are mainly due to river discharge into the North Sea (3.2.3). Purely glacial deposits seem to be extremely rare in this area, and it has thus been excluded from the calculations.

3.2 Estimation of thickness of the Quaternary deposits in Sweden

Well data from SGU well archive (Brunnsarkivet) has been used to make a map of the thickness of Quaternary deposits in Sweden, Figure 3-2. From this map the mean thickness was calculated. The well archive contains information from about 186,000 wells. The well data is somewhat unevenly distributed, which means that the accuracy of estimated sediment thicknesses differs within the country. The best accuracy is in densely populated areas where the number of wells is greatest. The information is especially scarce within the Scandinavian Mountain Range, which means that the accuracy within this area is low. Isolines of constant thickness have not been constructed for the western part of Jämtland county, south-western Skåne county and Gotland. However, mean values of sediment thicknesses were calculated for these areas. The calculated mean thicknesses and the area of each region are presented in Table 3-1.

The intervals used for interpolating the isolines in Figure 3-2 and the areas of each interval are presented in Table 3-2. There is an abundance of bare bedrock surrounding Lake Vänern. Due to this the interpolated sediment thickness in the whole Vänern basin was first estimated at < 1 m. However a more probable sediment thickness for Lake Vänern is 5–10 m, with an area of 5,585 km^2. To correct for this error the < 1m interval was reduced by 5,585 km^2, which was added to the 5–10 m interval. This correction is incorporated in Table 3–3, which also includes the results presented in Table 3-1.

The total volume of Quaternary deposits is calculated from the information presented in Table 3-3. The total volume divided by the total area of Sweden gives a mean value of 5.85 m for the thickness of Quaternary deposits for the whole country.

Table 3-1. Mean values for Quaternary deposit thickness calculated for areas not included in Figure 3-2.

	No of wells	Area (km^2)	Mean value of sediment thickness (m)
SW Skåne	9,080	6,042	14
W Jämtland	1,505	25,200	4.5
Gotland	4,947	3,112	1.8

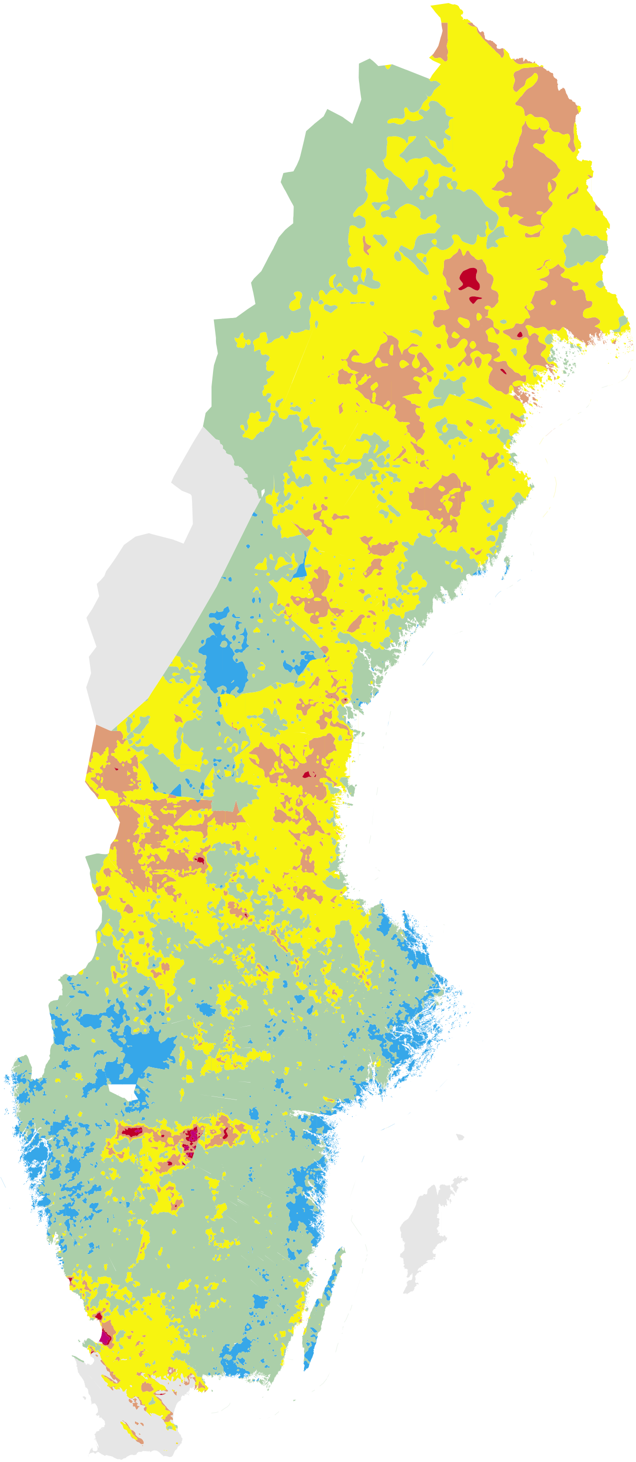

Figure 3-2. *Thickness of the Quaternary deposits in Sweden. Blue represents areas with thickness < 1m, green 1–5 m, yellow 5–10 m, pink 10–20 m, and red 20–30 m. The thickness distribution has not been calculated within the grey area. However, mean thickness values have been calculated for these areas, see Table 3-1.*

Table 3-2. Calculated areas for interpolated thickness intervals for Quaternary deposits in Sweden from Figure 3-2. Areas in the middle column are from statistical analysis of well data. Areas in the right column include corrected sediment thickness for Lake Vänern.

Interval (m)	Original area (km^2)	Revised area (km^2)
< 1	22,420	16,835
1–5	185,900	185,900
5–10	157,300	162,885
10–20	45,490	45,490
20–30	1,009	1,009
30–40	178	178

Table 3-3. Estimate of the thickness of Quaternary deposits in Sweden. The total volume is calculated from the statistical analysis. The total volume divided by the total area of Sweden gives a mean value of 5.85 m for the whole country.

Interval (m)	Mean value (m)	Area (km^2)	Volume (km^3)
< 1	0.5	16,835	8.4
1–5	2.5	185,900	464.8
5–10	7.5	162,885	1,221.6
10–20	15	45,490	682.4
20–30	25	1,009	25.2
30–40	35	178	6.2
SW Skåne	14.0	6,042	84.6
W Jämtland	4.5	25,200	113.4
Gotland	1.8	3,112	5.6
Total	5.9	446,651	2,612.2

3.3 Estimate of Quaternary deposit thickness in Denmark

/Binzer and Stockmarr, 1994/ have presented a map of the Pre-Quaternary surface topography of Denmark and surrounding sea areas. This map is based on well data from more than 200,000 wells and additional basic data have been derived from seismic mapping of the Danish Basin and shallow seismic mapping of Danish coastal waters. The latter information has been used for calculating sediment thickness in the Kattegat both in Denmark and Sweden (3.5).

The digital information, which was used for preparing the map of the pre-Quaternary surface topography of Denmark, was bought from GEUS for this project to estimate the thickness of the Quaternary deposits. A map was prepared from the digital information but the terms of purchase do not allow this map to be published. The map shows that extreme thickness exist at some places in the Skagen Peninsula, Läsö Island and along the North Sea coastal areas including the deep valleys at the western part of Jylland. Denmark has a total area of 43,069 km^2 of which 720 km^2 has a sediment thickness > 200 m and about 2,500 km^2 has a thickness < 150 m. Sediment thickness > 300 m have been recorded in Denmark. Figure 3-3 shows the distribution of recorded sediment thickness.

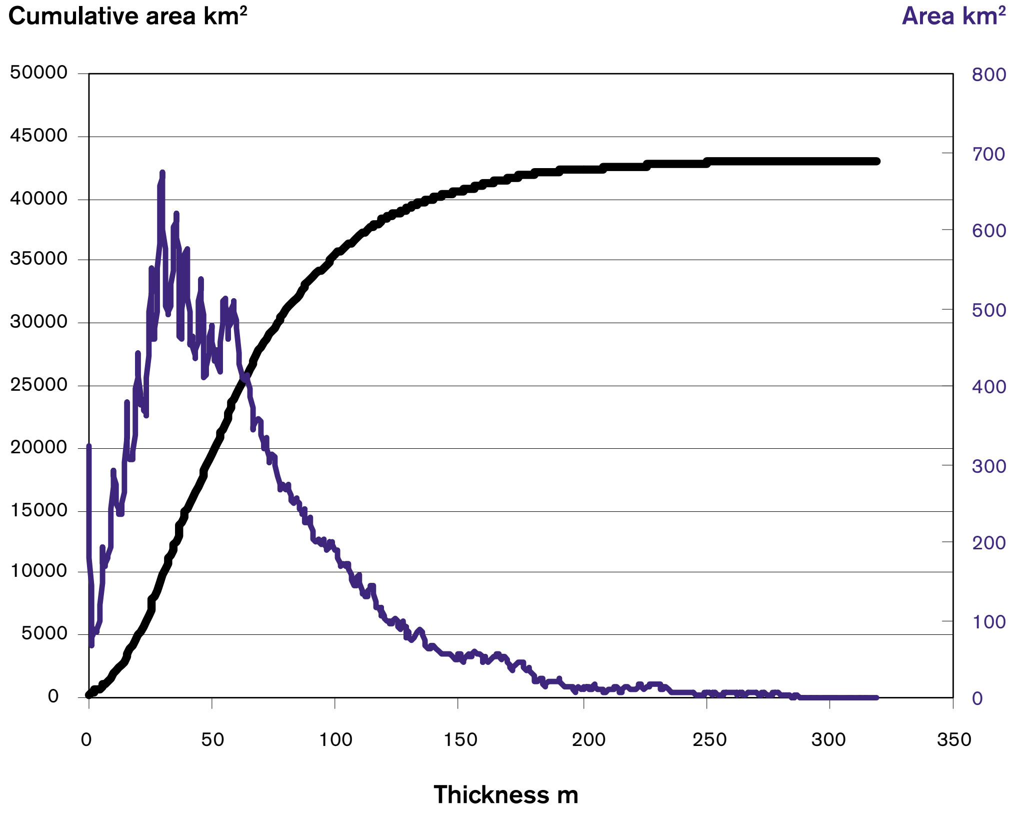

Figure 3-3. The blue curve shows the distribution of each recorded sediment thickness. The black curve records the cumulative thickness. A mean value of the thickness of Quaternary deposits in Denmark is calculated at 64.8 m from this information.

Based on this information the calculated total volume of the Quaternary sediments in Denmark is 2,790 km^3 and the mean thickness is 64.8 m. However, assuming that the thickest deposits in the western and northern parts of Jylland were formed mainly by non-glacial processes and originate from Germany or Holland means that the volume of Danish deposits used to estimate the glacial erosion ought to be reduced. A reduction of the estimated value by c 5 m seems likely.

The total volume of the Quaternary sediments in Denmark is estimated to 2,464 km^3 and in Sweden to 2,610 km^3. The volume of the Quaternary sediments in Denmark is thus on a par with the volume in Sweden, despite the area of Sweden being ten times larger than that of Denmark.

3.4 Estimate of thickness of Quaternary deposits within the Baltic basin

An estimation of sediment thickness within the Baltic basin was done by Per Söderberg at FOI. The thickness of Quaternary deposits was estimated along 8 profiles shown in Figure 3-4, based on published data and examinations of geophysical data from the Institution of Geology and Geochemistry at the University of Stockholm. The semiquantitative method used for examining the long profiles means that the interpretations are subjective. In order to calculate the average thickness of the deposits in the main part of the Baltic it was dived into two parts as shown in Figure 3-1. The mean thickness of the deposits in the southern part of the Baltic was estimated to 35 m, over an area of 24,585 km^2. The mean thickness in the main part of the Baltic was estimated to 17 m, over an area of 235,390 km^2. The calculated total volume of the sediments is 4,862 km^3, and the total area 259,975 km^2. The average thickness of the deposits within the Baltic was thus estimated to 18.7 m.

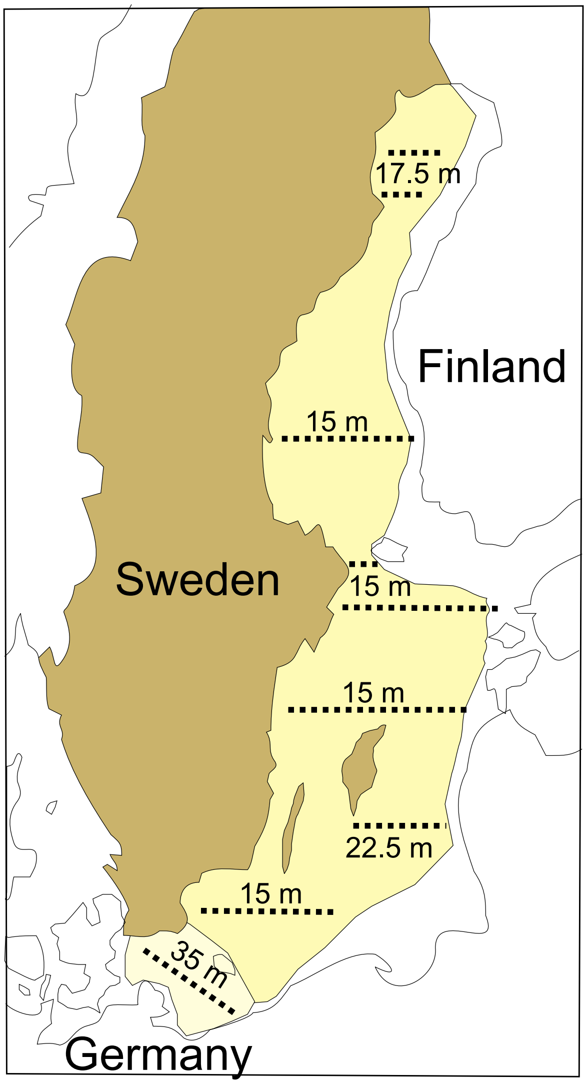

Figure 3-4. *Estimation of sediment thickness within the Baltic basin along 8 profiles based on published data and estimates from geophysical data from the Institution of Geology and Geochemistry at the University of Stockholm. The positions of the profiles are shown by dotted lines and the numbers show the estimated average thickness of the deposits.*

3.5 Estimate of Quaternary deposit thickness within the Kattegat

The thickness of deposits in the Kattegat area was calculated from information of the pre-Quaternary surface topography presented by /Binzer and Stockmarr, 1994/ and from a database of the present depth. There are some uncertainties in the results, but a comparison with the pre-Quaternary surface topography map, which was made for Denmark by GEUS, shows good agreement of sediment thickness between land and sea areas.

The diagram, which summarises the calculations for the Kattegat, clearly shows that the thickness distribution comprises two populations, Figure 3-5. One has thicknesses > 125 m whereas the main population has thicknesses < 125 m. This situation clearly reflects non-glacial transport of material from the North Sea, which at present time built up the Skagen delta. In the same manner as for land areas in Denmark the thickest sediments are assumed to be non-glacial and excluded from the calculations. The area with sediment thickness > 125 m is instead assumed to have "normal" thickness of glacial deposits.

An area of 37,935 km^2 was investigated in the Kattegat. The volume of the sediments was estimated to 2,421 km^3, which results in an average thickness of 64 m. If the non-glacial deposits are included the volume is 2,788 km^3, and the average thickness 73.5 m.

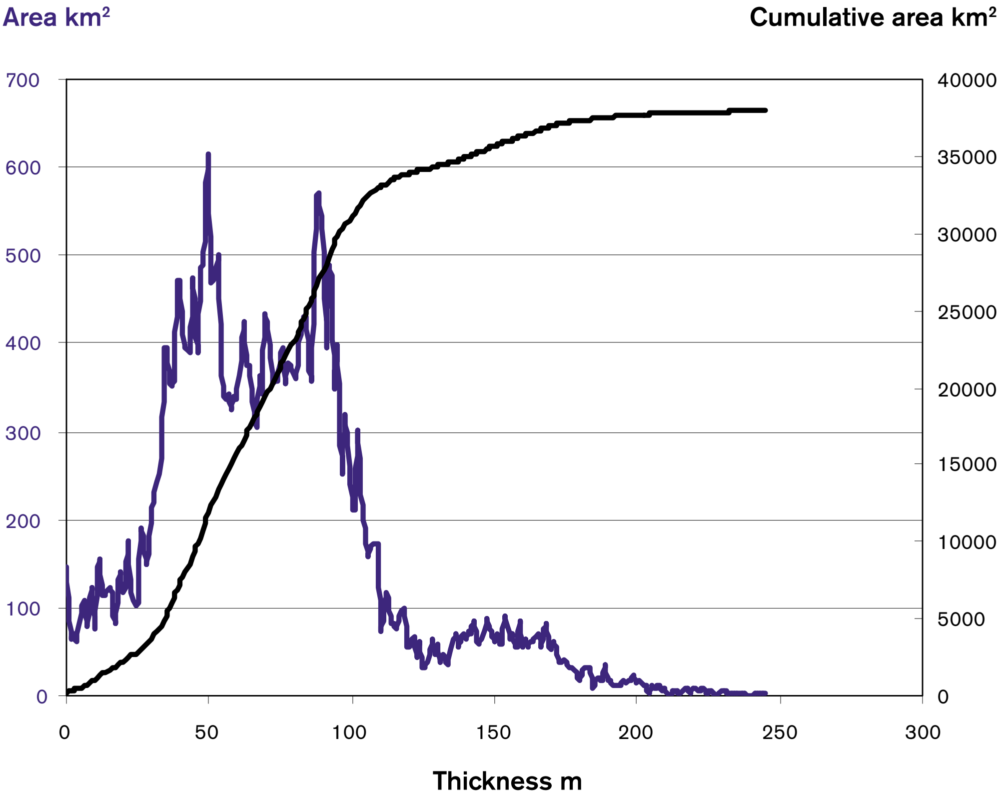

Figure 3-5. The blue curve shows the distribution of each recorded sediment thickness. The black curve records the cumulative thickness. The diagram clearly shows that the distribution is composed of two populations. Thicknesses > 125 m comprises one population whilst thicknesses < 125 m comprises the main population. This clearly reflects postglacial transport of material from the North Sea, which built up the Skagen delta.

3.6 Estimate of thickness of the Quaternary deposits within the investigated sector

The results of the different estimates of thickness of Quaternary deposits are summarised in Table 3-4. The total volume of Quaternary deposits within the investigated sector was estimated to 12,359 km^3 in an area of 787,630 km^2. These values give an average thickness of Quaternary deposits within the investigated sector of 15.7 m. If the non-glacial deposits in Denmark and within the Kattegat were included in the estimations the result would have been 16.6 m. A rounded value of 16 m can thus be assumed to be a reasonable upper limit for the average thickness of Quaternary deposits within the investigated sector.

Table 3-4. Estimates of thickness of Quaternary deposits within the different regions.

	Area (km^2)	Volume(10^3 km^3)	Thickness (m)
Kattegat Sea	37,935	2,421	63.8
Baltic Sea	259,975	4,862	18.7
Denmark	43,069	2,464	57.2
Sweden	446,651	2,612	5.8
Total	787,630	12,359	15.7

4 Estimation of depth of bedrock erosion

4.1 Conversion of sediment thickness to bedrock erosion

Different types of sediment have different porosity. Clay usually has porosity between 25 and 75%, the high value referring to unconsolidated sediments, while normal consolidated clays have porosity of 30%. Coarse grained sediment porosity ranges between 15 and 45%, high values refer to sorted sand and gravel, while the lower value refers to basal tills.

To convert the calculated sediment thickness to corresponding depth of eroded bedrock the difference in porosity between the solid rock and the sediments must be taken in to account. To simplify the conversion the sediments are assumed to be composed of approximately equal portions of clay and coarse-grained material. When estimating the depth of bedrock erosion the sediment thickness was reduced by an average conversion factor of 25% based on the assumption that the average porosity of clay is 30% and the average porosity of the coarse grained material is 20% as till is more common than sorted sediments.

The average 16 m thickness of Quaternary sediments generated in Scandinavia using this conversion factor represents an average 12 m erosion of the bedrock.

4.2 Amount of glacial erosion of the bedrock

The objective of this study is to estimate an upper bound for the average amount of bedrock erosion during a glacial cycle. The study is based on the assumption that the sediments formed by glacial erosion throughout the Quaternary time still exist within the formerly glaciated area or its periphery. Even if processes of glacial erosion are described and discussed in chapter 2 the intention is not to give a complete description of the complex glacial erosion but merely to estimate to which average depth it possibly can have eroded the solid bedrock in Scandinavia.

For glacial erosion to occur coverage of a warm-based ice sheet is required. The extent of this condition varies in time and space over a glacial cycle. Further the amount of erosion depends on the characteristics of the substratum. Consequently the amount of glacial erosion can be assumed to be extensive in some areas while insignificant in others. This study only gives an estimation of the average bedrock erosion. However in combination with dynamic ice sheet modelling and/or geological surveys the results are considered to be useful as a basis for making simple estimations of bedrock erosion in specific areas.

By the basic assumptions of this study the complex problem of estimating the amount of glacial erosion of the bedrock during a glacial cycle is limited to two questions. The first is to determine how great part of the estimated sediment volume that can be assumed to be the result of glacial erosion of solid bedrock and the second is to determine the number of glacial cycles that have caused the erosion.

If the total volume of sediments is assumed to have been generated by glacial erosion of fresh bedrock, the average amount of glacial erosion during a glacial cycle can be calculated given that the number of glacial cycles during the Quaternary is known. Alternatively, if the total volume of sediments is assumed to include initial glacial erosion of the Tertiary regolith, the regolith, must be subtracted from the sediment volume in order estimate the rate of glacial erosion of fresh bedrock. As in the first case the number of glacial cycles during the Quaternary must be known.

It is generally accepted that three 100,000–120,000 years long glacial cycles – the Elsterian, the Saalian and the Weichselian – have occurred in Scandinavia. The three glacial cycles all include a glacial maximum corresponding to the last glacial maximum about 20,000 years ago. Each of these glacial cycles includes several ice sheet advances and retreats. Consequently each glacial cycle consist of several glaciations. Since the estimated sediment thickness constitutes the average in the maximum formerly glaciated area only the average amount of erosion per full 100,000–120,000 years long glacial cycle has been estimated.

According to /Jansen and Sjöholm, 1991/ the major Pleistocene glaciations of Scandinavia started about 2.5 million years ago but became more regular and intensive 1 Ma ago. If this conclusion is correct that should imply that there have been about 8–10 glacial cycles similar to the three mentioned above during the Quaternary.

The regolith formed during the Tertiary period was stripped away by the first Quaternary glaciations and included in the Quaternary deposits. The amount of this initial erosion can be assumed to have been greater than the erosion during later glaciations, when only "fresh" bedrock was eroded. /Lidmar-Bergström, 1997/ suggests that the glacial erosion of the pre-glacial regolith correspond to 10 m of bedrock.

Since both the number of glacial cycles and the thickness of the regolith are uncertain the average amount of bedrock erosion during a glacial cycle has been estimated for alternative cases. The alternative cases are based on the assumptions that the estimated sediment thickness of 16 m corresponding to 12 m bedrock is the result of either 3 or 8–10 glaciations and;

- erosion of 12 m bedrock only,
- erosion of pre-glacial regolith corresponding to 10 m and erosion of 2 m bedrock,
- erosion of pre-glacial regolith corresponding to 5 m and erosion of 7 m bedrock.

The average amount of bedrock erosion during a glacial cycle corresponding to the resulting 6 cases are accounted for in Table 4-1.

Table 4-1. Average amount of bedrock erosion during a glacial cycle.

Depth of erosion	3 glacial cycles	8–10 glacial cycles
Bedrock erosion only	4 m / glacial cycle	1.2–1.5 m / glacial cycle
10 m regolith and 2 m bedrock	0.7 m / glacial cycle	0.2–0.25 m / glacial cycle
5 m regolith and 7 m bedrock	2.3 m / glacial cycle	0.7–0.9 m / glacial cycle

The glacial erosion during a full glacial cycle has thus based on the assumptions in this study been estimated to be between 0.2 m and 4 m. Considering the assumptions behind the different estimates the average glacial erosion of bedrock during a full glacial cycle can be assumed to be about 1 m, and 4 m can be regarded as an upper bound for the average amount of bedrock erosion during a 100,000–120,000 years long glacial cycle of the Quaternary.

Due to regional and local factors the amount of glacial erosion can vary significantly between different areas and places. It has been pointed out earlier that sediments covering the bedrock ought to inhibit glacial erosion (2.7.2). That would mean that the bedrock in glacial peripheral areas most probably has been less eroded than more central areas. That would also mean that calculating the erosion depth based on the total area is somewhat misleading. Assuming erosion occurred in 10% of the whole area and thus low or no erosion took place in 90% of the area, results in an erosion depth in exposed areas that is 10 times higher than the estimated average depth i.e. 10 m during a glacial cycle. In the same way 40 m can be regarded as an upper bound for glacial erosion in exposed areas.

5 Conclusion and discussion

5.1 Conclusion

The average thickness of sediments in the maximum area exposed to glaciation during the Quaternary has been estimated to represent 12 m erosion of bedrock. This estimate is considered to be fairly reliable, provided that the loss of material from the formerly glaciated area out of the investigated area is negligible. Calculations of the amount of glacial erosion of bedrock per glacial cycle are less certain, however, the rate of erosion can be constrained within an interval if the number of glacial cycles and the portion of pre-glacial regolith in the sediments are known. The glacial erosion during a full glacial cycle has thus been estimated to 0.2–4 m. 4 m is believed to be an upper bound for the average amount of bedrock erosion during a glacial cycle. If the extreme cases are excluded the glacial erosion during a full glacial cycle is estimated to be about 1 m.

5.2 Discussion

The erodibility of the bedrock has most probably decreased through the Quaternary period, as the regolith was successively removed, but also as accessible fresh bedrock material for plucking decreased through the repeated glaciations.

Even if glacial overprinting is obvious in most parts of the Scandinavian landscape, the basic landscape is much older. /Lidmar-Bergström, 1997/ has presented a rough estimate of glacial erosion in the Precambrian basement based on geomorphological observations. She distinguishes the estimates of glacial erosion of Tertiary saprolites from ice sheet erosion of fresh bedrock. The glacial erosion of saprolites is estimated between 10 and 50 m and glacial erosion of fresh bedrock is estimated at some tens of metres.

In spite of the totally different approaches in this study and the work of /Lidmar-Bergström, 1997/ referred to above, a common conclusion is that the glacial erosion in Scandinavia can in general be assumed to be low. This assumption is confirmed by several arguments presented in chapter 2 and summarised below.

Deposits covering the bedrock surfaces inhibit glacial erosion. This obstruction to erosion is seldom discussed but is here pointed out as one of the main reasons for low rates of glacial erosion. The sediment cover is self-generated. When debris formed by glacial erosion (or redeposition) are deposited on the bedrock this will shield the bedrock surface from further erosion.

Glacial abrasion is manifested by the formation of striation but also by a polishing effect of some bedrock surfaces. Striation on the same bedrock surface but from different glaciations indicate that the total abrasion has generally only been of the order of a few millimetres even if the surface has been abraded during several glaciations (2.3).

Normal stress at the glacier bed may reach a maximum value of 45 Mpa. Unconfined compressive strength of rocks lies in a range well above this value and solid crystalline basement is thus not significantly affected by this stress (2.2). Nevertheless the ice load may be sufficient to cause failure in some rocks due to pre-existing weakness such as joints, cracks and foliation and also to reduced hardness of the rocks due to pre-weathering.

Plucking is thus restricted to these weaknesses and occurs preferably on the lee-side of small hills or roches moutonnées. /Johansson, 2000/ has demonstrated that plucking only occurs 20 m below subglacial hill summits, whilst hills may rise 80 m above the surroundings. This is most probably due to a less effective entrainment by regelation at lower levels of the hills.

As was shown by /Johansson et al. 2001/ the shape of glacial erosional landforms is strongly controlled by the inherited relief. The small amount of glacial erosion is also indicated by the preservation of regoliths in sheltered positions /cf Lidmar-Bergström et al.1996; Johansson, 2000/.

6 Acknowledgements

The author is indebted to four colleagues for their assistance with estimating the thickness of Quaternary deposits. Jonas Gierup (SGU) and Magnus Åsman (SGU) handled the Swedish data from SGU and Leif Andersson (SGU) handled the Danish data from GEUS, both the onshore and the offshore data. Estimation of sediment thickness within the Baltic basin was done by Per Söderberg at FOI.

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ISSN 1404-0344
CM Digitaltryck AB, Bromma, 2004