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TECHNICAL COMMUNICATION

The Generation of the Foundation for the Skagen Spit, North Jutland, Denmark, by the Action of Ice and Geomechanical Forces Combined with Glacial Eustacy

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ABSTRACT

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This paper explains how the huge marine foreland, the Skagen Odde at the northern top of peninsula Jutland, Denmark, was initially formed by ice masses moving from north and east during the late phases of the last glacial age. These ice masses pushed existing deposits around and brought with them new material from Norway and Sweden.

Ice-ages have occurred in various geological periods. During the last half million years, their largest magnitudes were in the northern countries of Canada, Greenland, Iceland, Scandinavia, the Balticum, the U.S.A. and the USSR. The latest glaciation took place 16,000–24,000 years BP with a rapid advance in Scandinavia ~20,000 BP. The large quantities of materials from Norway, Sweden and Finland moved south and westward. Most of Denmark was covered with ice, but the westernmost part of the Jutland peninsula was ice free but overworked by meltwater deposits. In the final withdrawal phase, commencing about 16,000 BP, the glaciers left enormous bottom and marginal moraines in Denmark. Following the final withdrawal of the ice (13,000 BP in Jutland), a glacial rebound started. Simultaneously, sea level rose due to the increasing temperatures and melting of ice encroaching upon the rebound. Today, the two movements up and down are almost equal in northernmost Jutland while sea level rise has the lead south and east of here. Glacial rebounds still are strong on the Scandinavian peninsula.

ADDITIONAL INDEX WORDS: *Marine foreland, ice-ages, moraines, glacial rebound.*

INTRODUCTION

With the ocean free of ice, the newly born shores were subjected to wave action of increasing magnitude as ice vanished and sea level rose causing erosion and longshore material transport building up land at the same time. The result of the battle between nature's forces ultimately became a spectacular coastal geomorphological development, one of the largest marine forelands in the world, the Skagen Odde (Spit) extending out from Jutland in or towards the deep Norwegian Trench on softer marine deposits.

THE LATE AND POST GLACIAL STAGE

We know little about the time-related thickness and movement of the ice which came from Norway and Sweden. All we see are the results of its actions in the form of marginal and bottom moraines of materials ranging from clays to rocks up to 10–20 tons. The ice cap exerted immense pressures on the ground. Following the melting of the ice, isostatic rebounds (uplifts) took place which still continue on the Scandinavian peninsula. In Denmark and in southern Sweden, uplifts have now been overtaken by sea level rise. The Danish *zeroline* for relative movements of sea and land seems to be located in the Hirtshals-Frederikshavn area (Figure 1). From here and north, the isostatic uplift has the upper hand. It is about 10 mm per year in the northern part of Sweden and in Finland while in the southernmost Swedish province, Skaane, sea level rise is leading.

In the northern part of Denmark, older arctic Marine Yoldia clays (from earlier glacial periods)

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and interglacial (before latest glacial period) Emian (interglacial) clays have a thickness up to 150 meters (STRAND PETERSEN, 1985b). The younger Yoldia shorelines are found up to 60 meters above present sea level (14,000–15,000 BP). This indicates a much higher sea level relative to land at about 11,000 BP when glacial pressures had vanished while the glacial rebound still was relatively small.

Using the balance equation:

$$\begin{aligned}&\text{PAWT (Past Sea Level Elevation)}\\&\quad + \text{GR (Glacial Rebound)}\\&\quad = \text{PRWT (Present Elevation)}\end{aligned} \qquad (1)$$

with a recorded shoreline elevation of 60 m above MSL today, one arrives at a water table of minus 70 meters (11,000 BP) and a 130 meter glacial rebound. If rebound is less, rise of water table is also less. Equation 1 has two unknowns.

HOW THICK WAS THE GLACIAL ICE COVER?

The thickness of the ice during the melting period is unknown; but over the Norwegian mountains, the ice cap was probably a dome on the top of the mounds. Comparison with Iceland glaciers, (BJÖRNSSON, 1986), Svalbard glaciers (DOWDESWELL *et al.*, 1986) and conditions in the Antarctic (CRABTREE and DOAKE, 1986), one arrives at a thickness of <300 m at the Norwegian coast, and undoubtedly less when ice moved out over the deep (60–700 m) Norwegian Trench (Figure 1). The latest advance of the ice from Norway started ~20,000 BP (STRAND PETERSEN, 1985b). This late phase of glaciation lasted only a few thousand years.

Mammoths were roaming the northern Jutland 13,000 BP (STRAND PETERSEN, 1984a) so the ice must have disappeared before that time. From the Norwegian coast, ice thickness must have decreased gradually (compare conditions on the West Antarctic) (CRABTREE and DOAKE, 1986). From purely mechanical considerations, it is unlikely that the ice reached the bottom of the 600–700 m deep Norwegian Trench, which is a fault line, but it may have done so—for a shorter period—in the easternmost section of the Trench north and northeast of Skagen (Figure 1).

Further towards the West after passing the 50–60 km wide trench, the ice ran aground on relatively steep slopes on the Danish side. The rather rapid advance of the ice about 20,000 BP was probably by thinner ice than in the earlier glacial periods. It probably floated across the deepest parts of the Norwegian Trench. Compare similar conditions in the Ross Sea, Antarctica and on Svalbard in the Arctic (*cf.* Figure 4).

We have only little data on the time development of glacial rebound. It is still about 10 mm/year in the north and northeast Scandinavia and in the order of 2.5 mm/year on the Swedish west coast and in the Oslo Fjord. One may assume that it is of the same order of magnitude or somewhat less in the northern part of Jutland including the province of Vendsyssel (Figure 1). In the early melting periods, it was probably much larger. Yoldia Sea shorelines are found at Frederikshavn (Figure 1) at elevation 60 m above present sea level.

As mentioned above, Equation 1 with sea level 70 m below present gives a glacial rebound of 130 m which corresponds to an average rise of 10 mm/year over 13,000 years. This matches with the present records for north and northeast Scandinavia. Shorelines at Frederikshavn 7,000 BP are now located 15 m above MSL. With a rebound of about 40 m (5,000 × 0.004 + 2,000 × 0.010) one arrives at a MSL 25 meters (40 m minus 15 m) below present. This corresponds to the period when areas of the North Sea during the Boreal (land) period were dry. STRAND PETERSEN (1985b) states that "it has been possible to establish an early Atlantic transgression to a height of −25 meters around 7,800 BP in the northern Denmark". It seems less likely that glacial ice has been grounded in the deep finger of the Norwegian Trench extending from north to south towards the town of Skagen (Figure 1). The Skagen Spit has for a period of at least 1,000 years or more extended out into the trench where depths may have been 100–200 meters. We know that the Skagen Spit is founded upon marine deposits without limestone as is usually found at about 200 m depth as it normally is south of Skagen. The lack of proper soil mechanics investigations based on core-borings makes it difficult to determine whether the ice has rested on the bottom or—in case—if it was there long enough to leave a still lasting influence on the depth versus pressure relation to prove that it certainly was there!

If it actually was—for a while—we may find a "bump" in the (pressure versus depth) diagram proving that the subsoil has a "memory". This was revealed in many cores in the North Sea during drillings for oil and gas. Deep core borings have now been undertaken at Skagen as a part of

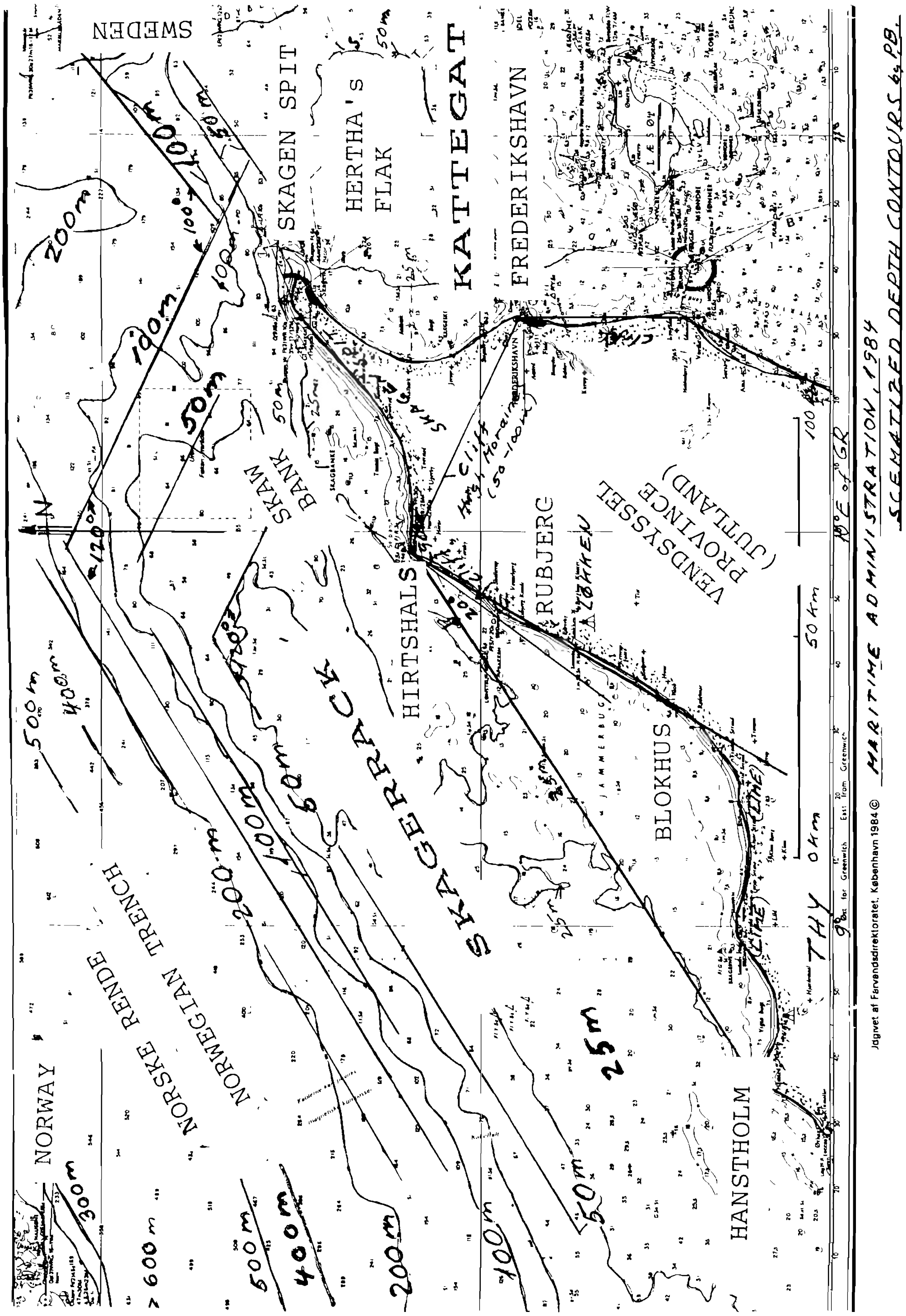

Figure 1. The Skaggerack.

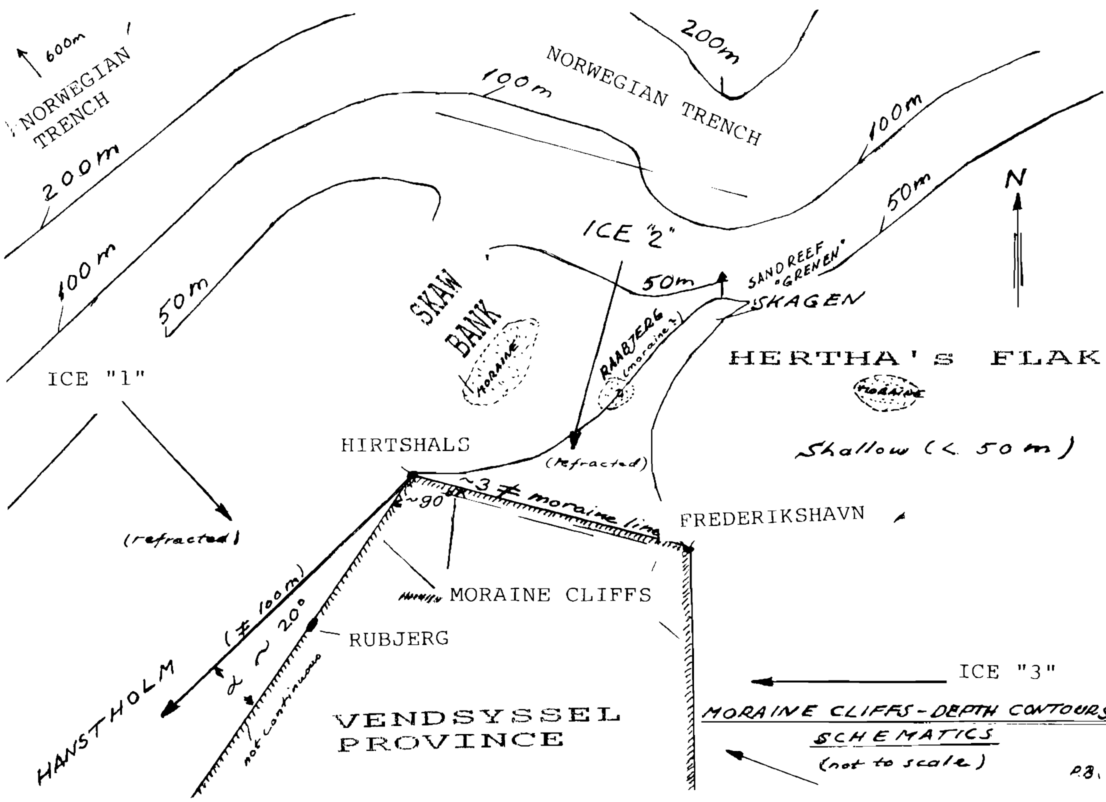

Figure 2. Moraine cliffs and depth contours schematics.

the Skagen Odde project. The soil may not have forgotten the ice! Some seismic movements may, however, also be associated with the Norwegian Trench. When the ice finally melted down to a relatively thin layer, it kept exerting pressures on the marginal moraines it had generated but in a much smaller scale dropping glacial materials in front of the moraines which it had built.

ICE PUSH-UPS OF MORAINES

The ice in its final movements pushed up or deposited the large marginal moraines which we now find as shore cliffs elevated on the top of Yoldia Sea deposits on the west, north and east side of Vendsyssel (JESSEN, 1936).

These cliffs are very distinct lines which in part found their slopes during the Atlantic Period occurring 7,000–4,000 years BP when the world sea level during short periods apparently was up to 3–5 meters above present. At that time, the isostatic uplift had not progressed up to today's level. The old shorelines in the northern Vendsyssel are now by glacial rebound elevated 10–20 meters above present MSL.

The following is an attempt to explain the directional configuration of the old marginal moraines. Figure 1 was reprinted from the Hydrographic Map of the Skagerrak (Danish Hydrographic Service). Figure 2 is a schematics extracted from Figure 1 showing the direction of the old moraine shore cliffs, at some places islands, and various depth contours in the Skagerrak.

The 50 m, 100 m and 200 m depth contours have been rectified in Figure 2. The moraine cliffs shown in the schematics are very distinct lines. Their lower parts were finally formed during the Littorina (Atlantic) Period when sea level in the oceans was above present. Elevations of the moraines are 40 to 90 meters above MSL at present.

The line Blokhus–Løkken–Rubjerg–Hirtshals continues north in the offshore Skaw Bank, which may be the remains of a marginal moraine. Comparing Figures 1 and 2, it may be observed that:

(1) Depth contours 50 m, 100 m and 200 m in the western section are largely parallel to the line Hirtshals–Hanstholm and only deviate about 20 degrees from the line Blokhus–Hirtshals which is not a continued moraine.

(2) The nearly 90 degrees corner at Hirtshals–Rubjerg, 120 degrees for Hirtshals–Hanstholm, correspond to the 120 degrees corner for the 100 m depth contour or the 200 m contour.

Following the corner, the multi-cliff line Hirtshals–Frederikshavn is largely parallel to the 100 m and 200 m depth contours running about 50 km towards the east-northeast followed by a 100 degree turn making the 100 m contour run northeast 40 km towards Sweden. The moraine cliffs demonstrate a late phase in the glaciation stage 16,000–14,000 years ago.

The similarity of the configurations and directions of these marginal moraines and the depth contours lends itself to a physical explanation relating forces to configuration. The ice movement seems to have refracted, its propagation being dictated by the depth contours and by what was land at that time.

The Norwegian Trench undoubtedly also existed during the glacial period when it was covered with ice of unknown thickness. Geophysically and mechanically, it is unlikely that the ice has been in moving contact with the bottom across the deepest part of the trench. No forces were available to lift the ice up several hundred meters following a dip into the open-ended ocean trench during the late Weichsel phases. The ice probably floated across the deep trench during that period. Experimentally, it may be assumed that the ice during the late glacial period was in contact with the bottom at the break in slope at 300 m depth at present on the Norwegian side (200 to 230 m during the glacial stage) and at 100 to 150 m on the Danish side. The ice moved down the Norwegian mountains under high pressure after which it floated on water across the 50 km wide section of the Skagerrak (70–100 m to be added to obtain sea level today).

The ice movement "refracted" and tended to become perpendicular to the depth contours, a common phenomenon (BRUUN, 1983). The ice movement had two main directions, as indicated in Figure 2, perhaps separated by some hundreds or a few thousands of years. Finally the ice propagated from a more easterly or even southeasterly directly generating the moraine south of Frederikshavn. In Denmark, the ice ran aground on glacial and interglacial deposits of earlier date and pushed up moraines and finally generated the marginal moraines which we observe as the very distinct shore cliffs elevated above sea level on the northern and eastern frontier of Vendsyssel due to the glacial rebound overpowering the sea level rise until recently. On the western, less distinct frontier, erosion due to high exposure has eroded the moraine cliffs. These movements, of course, have been irregular. What we see today is the ultimate result as of 1990.

MECHANICAL EXPERIMENT

Figure 3 is a schematic showing a cross section of Skagerrak with an ice cover 200 m thick on the Norwegian side and 50 m thick on the Danish side. The 200 m is an arbitrary figure based on Antarctic Ross Sea, Svalbard, Iceland, Norway and Greenland experiences. The ice is assumed to be in contact with the bottom at 200 m depth (270 m today) on the north side and 50 m depth (about 120 m today) on the Danish side. If this is true, the ice must have melted down in thickness by 150 m across the Skagerrack. An arbitrary figure for glacial movement of 1 m per day is now chosen. It is high compared to Alpine glaciers (which are in a trough with high friction) and low compared to some glaciers in Greenland.

To move 50,000 meters will take 50,000 days; during that time, the ice is assumed to melt 150 meters or 3 mm per day. This figure does not sound unrealistic. Assuming during the late glacial stages that the evaporation equalled snowfall, all melting would have to be from the bottom. But most melting or evaporation may also have been from the top, preserving glacial materials for build-up! Ice at the bottom of the glacier would melt at zero plus degrees (it is under high pressure) while water temperature might have been one plus degree in water of salinity about 3‰ decreasing going east until finally the ice (possibly including saline bottom ice) was in contact with the bottom in the easternmost section. This, of course, is speculative.

The melting of ice generated rivers which carried materials to the sea where coarser particles were deposited in the nearshore and finer particles were carried further offshore for deposition. With the Skaggerack ice-covered, there is perhaps

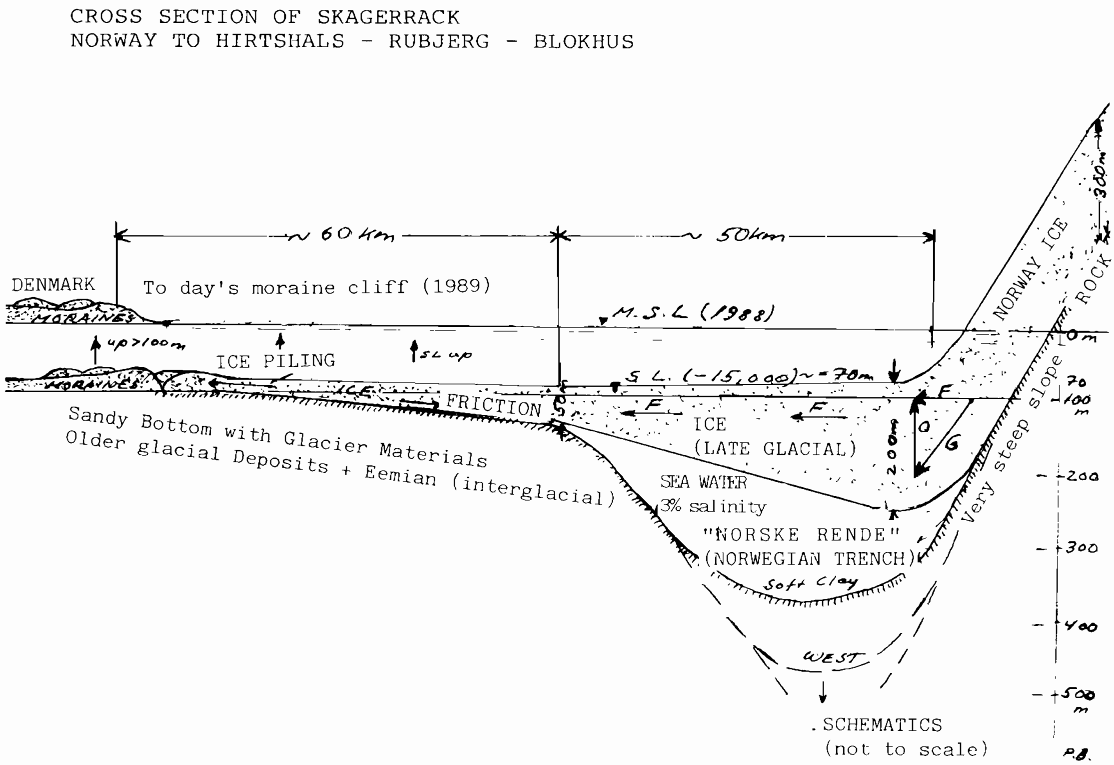

Figure 3. Cross section of the Skaggerack during late glacial stage.

a chance that a circulation like the one shown in Figure 4 for the west Antarctic Ice Shelf may have occurred (GROSSWALD, 1989). According to Grosswald, such current-generated benches could be formed some 500–900 meters below sea level when the ice cap gradually decreased in thickness. Similar conditions could have existed in the Skagerrack. Referring to the figure caption of Figure 4, the material moved by such currents, however, is so small that it suspends easily. There is no proof that such action—of any magnitude—has worked on the coastal Skaggerack platform off the Danish coast.

ICE SHELF IN TOUCH WITH BOTTOM SOIL OF JUTLAND

We shall now look at the situation when the ice cap moved back and forward in the late glacial and past glacial period. Let us assume that the ice shelf was 50 meters thick when it touched the bottom of what later became the northern part of Jutland. At a depth of around 45 meters, the floating ice shelf will be in contact with the bottom and it will plow its way into the slope, pushing the soil in front of the ice where it eventually will pile up. This is shown in Figure 5.

The resistance from the soil can be split up into three components: (1) The earth pressure E′ from the soil being piled up on the front of the ice, (2) The earth pressure E″ from plowing into the bottom, (3) The additional surcharge from the soil displaced in front of the ice will result in additional earth pressure E‴ at the lower part of the ice front. We can calculate the magnitude of the different earth pressures described above. The formulae for the earth pressures are as follows (kN/m):

$$E' = \frac{1}{2}(3H')^2 \cdot \gamma \cdot e',$$

$$E'' = \frac{1}{2}H'^2 \cdot \gamma \cdot e'',$$

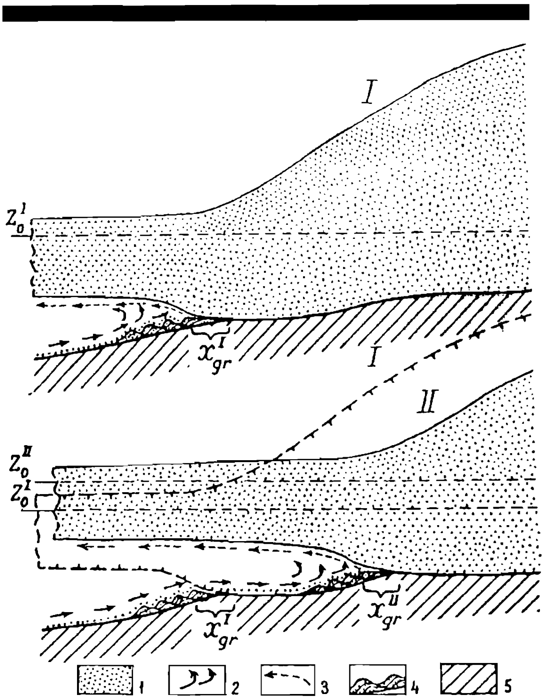

Figure 4. Formation of ice-erosional benches and abutting zones of ridge-and-hill moraines associated with rise in sea level and step-like retreat of an ice shelf grounding line, Z_0^{I} and Z_0^{II}, consecutive positions of sea level: X_{gr}^{I} and X_{gr}^{II}, zones of diurnal migrations of grounding lines: I and II, consecutive stages of icesheet retreat. Legend (1) glacier ice, (2) water circulation beneath the ice shelf (relatively warm and saline water), (3) the same (relatively cold and fresh water), (4) submarine accumulations of glaciomarine sediments, and (5) bedrock (GROSSWALD, 1989).

$$E''' = 3H' \cdot H' \cdot \gamma \cdot e''',$$

$$E = E' + E'' + E'''$$

where H' is the plowing depth, $3H'$ is the estimated piling up height, γ is the unit weight of submerged soil (kN/m^3), e' is the earth pressure coefficient for the displaced soil—the soil which is piled up on the front of the ice—e'' is the earth pressure coefficient valid in the soil of height H' (the bottom soil), e''' is the coefficient valid due to the surcharge on the bottom part of the soil.

To get an idea of the magnitude of these earth pressures resisting the ice, let us assume: $H' = 10$ meters, $\gamma = 10\ kN/m^3$, $e' = 0.8$, $e'' = 2.0$, $e''' = 2.0$. See Figure 5. The result of the calculation is: $E' = 3.6$ MN/m, $E'' = 1.0$ MN/m, $E''' = 6.0$ MN/m, a total of $E = 10.6$ MN/m. This shows that the ice shelf is able to push very large quantities of soil, thus acting effectively in the formation of moraines.

When the ice shelf is plowing the bottom of the sea, friction will develop at the ice/bottom interface. Pushed by external forces, the ice moves until the friction and the earth forces develop resistance against a movement. Large masses of soil will then be pushed around and end-moraines will be deposited in front of the ice cap. It can be shown that for an ice shelf, 50 meters thick, a force of approximately 1,000 kN per meter width of ice front will initially build up. This will initiate the plowing up of bottom soil. While the ice cap is moving further into the slope, the force will slowly increase until soil is piled up in front of the ice eventually reaching values of a magnitude of 10,000 kN per meter width and even more as the ice penetrates further into the slope. The upper limit will be reached when the ice starts to fail in compression. It is, however, not likely that this will happen as very high local pressures can be absorbed by the ice.

Eventually the ice cap will be forced to follow the contours of the ground and this results in cracking and decomposition of the ice. A zone in front of the shelf will be a chaotic mass of broken up ice. In the summertime, the ice will partially melt and water will flow in many directions. The water will erode and deposit finer materials below and in the front of the ice shelf. The thickness of the ice shelf will gradually decrease with time during the transition to warmer periods. The development described above may be seen in the Bovbjerg cliffs marginal moraine on the West Coast.

Ice islands continued moving towards the shores of the Skagen Spit slowly decreasing in thickness. Finally the Skagerrack was covered with polar sea ice and, a period as described in the following, with ice pilings on the shores now dominated by ice forces acting directly on the beaches and shores. When an ice sheet moves into a gently sloping beach, we know that different scenarios may develop depending on the conditions in which the ice is moving towards the beach. The ice likely will be broken up in smaller pieces which will pile up on the beach; we call that ice piling.

It is possible to formulate an equation which may tell us how the pattern of the ice piling will be. Such an equation could be as shown below (TRYDE, 1973, 1977).

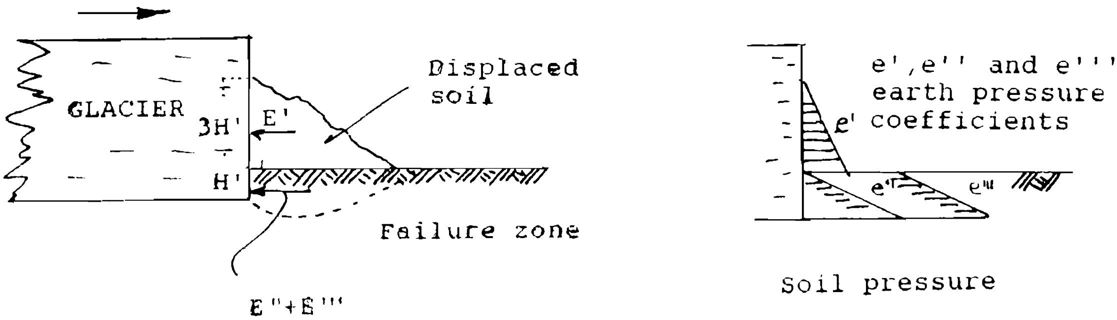

Figure 5. Glacier moving into the bottom soil.

$$y/e = (\tan \beta/12)((1 + \mu \cot \beta)/(1 - \mu \tan \beta)) \cdot \langle (r_c e/H') + 6\text{–}7/(r_c e/H') \rangle \quad (2)$$

We assume that the coastline is straight and that the ice is moving perpendicularly towards this line (a two dimensional case): y is the "length" of the ice piece (in the direction of movement), e is the ice thickness, β is the angle between the coastal plane and horizontal, μ is the friction coefficient between the ice and the shore material, r_c is the uniaxial compression strength of the ice, H' is the total wind shear force on one meter of the ice sheet, extending a certain length out from the shore. As H' is a function of the wind velocity squared and as all the other parameters may be known for a certain locality with known wind data, we are able to determine the "size" of the ice pieces in the ice piling. See Figure 6. (Units: m, kPa, kN/m.)

Small pieces of ice are likely to appear, for low

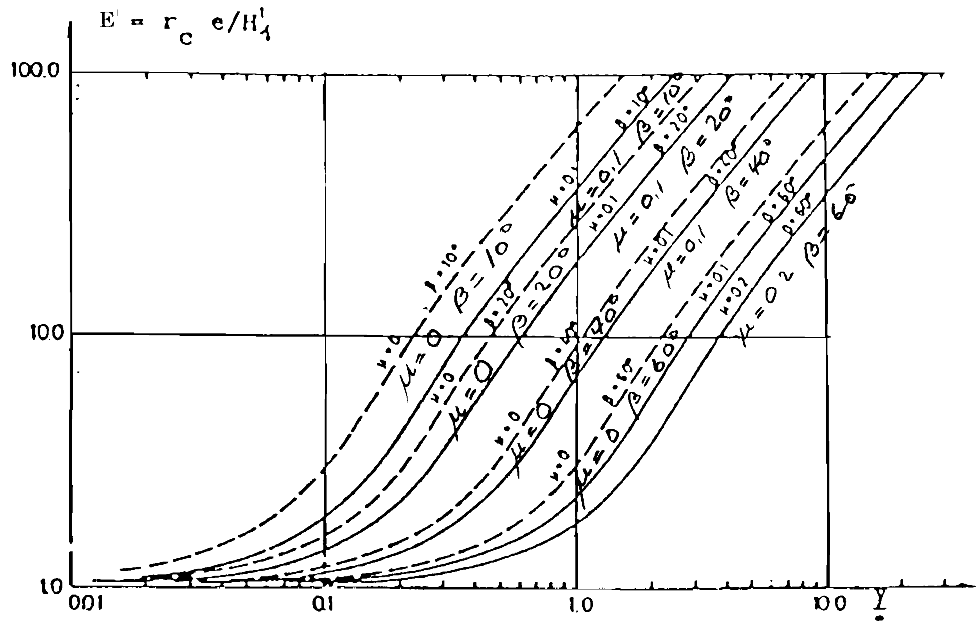

Figure 6. y/e as a function of E_1, β and μ.

values in the case of a gentle sloping beach, for an ice of small thickness and strength, and for large wind velocities. In that case, we are at the left part of the curves in Figure 6, y/e yields small values.

Larger values of y/e appear for steeper beach profiles, for cases with greater friction coefficients, and for moderate wind velocities. At the right part of the curves, we obtain large pieces of ice; as a matter of fact, the ice sheet may just be pushed unbroken up on the beach until it is at rest. This tool enables us to describe the possible scenarios which may develop. This leads to the determination of the ice forces acting on the beach or at least the level magnitude.

The maximum force (per meter) will be $r_c e$ and the minimum only 25% or less of that. The most likely force will be approximately 25% of $r_c e$. A numerical realistic value for r_c = 1,600 kPa and e = 0.5 m is:

$$H' = 0.25 \cdot 1{,}600 \cdot 0.5 = 200 \text{ kN/m} \quad (3)$$

This force will act partly on the beach material and/or partly on any object located on the beach. We may also have a plowing effect of loose material deposited on the beach resulting in pile up of material and ice.

Ice pilings are known to grow to great heights in their destructive actions on structures. The ice may even "overtop" the ice piling and cause destructions further inland. The heights that ice pilings may reach are estimated from the following empirical formula (TSANG, 1973).

$$h = u/30 \cdot \sqrt{(2L \sin\beta)/(g(1 + \mu \cot\beta))} \quad (4)$$

u is the wind velocity, and g is the acceleration of gravity, all in the SI units (see below).

The type of onshore ice pilings and their effects on the shore has been analysed on the Arctic coasts of Alaska and Canada (KOWACS and SODHI, 1988).

As an example with: wind velocity u = 20 m/sec, L = fetch = 20,000 m, u = 1, β = 12 degrees (1: 5), sin β = 0.1, cot β = 4.7 we obtain:

$$h = 20/30\sqrt{(2 \cdot 20{,}000 \cdot 0.2)/(9.81 \cdot (1 + 4.7))}$$

$$= 8 \text{ meters}$$

i.e. an ice piling 8 m high.

DID ICE INFLUENCE THE DEVELOPMENT AFTER THE GLACIAL STAGE?

No doubt the influence of the ice was considerable during the late glacial period. Ice continued carrying materials to the area as is witnessed by submerged reefs like the Herthas Flak and the Skaw Bank (Figure 1). The ice's damping effect on the waves caused relatively little erosion by sea forces as known from arctic areas today (BRUUN, 1987). During the following periods, ice probably always occurred during the winter time—perhaps not during the Atlantic Period. Ice piled up on beaches and moved some material around, but with little or no effect on the coastal geomorphological development. Ice, however, may have contributed to the erosion of barren cliffs by thawing and freezing and ice "gauging" has undoubtedly occurred offshore as known from Beaufort Sea shores in Alaska. With the vanishing of the ice, large free fetches for wave action developed causing erosion and littoral drifts. The ultimate result was the formation of the Skagen Spit as a high marine foreland growing north over or towards the Norwegian Trench and Norway.

CONCLUSION

The large marginal moraine systems between Frederikshavn and Hirtshals and perhaps south of Hirtshals and between Frederikshavn and south of Saeby were built up by glaciers during repeated advances and retreats by ice moving first from the north and northeast and later from the east and southeast. This took place over a period extending for 1,000–3,000 years when ice forces and glacial eustacy combined, gradually lowering the elevations of the marginal moraines, and working hand in hand "to generate the land". The question of whether the ice during the late phase of glaciation ever rested on the (deep) sea bottom for a longer or shorter period of time where the town of Skagen is now located remains unanswered. Core borings to 250–300 meters' depth at Skagen undertaken now may reveal weak glacial rebounds. For the future welfare of the town this, of course, is of major importance, should the sea level increase in the near future. Settlings, however, are apparent.

ACKNOWLEDGEMENTS

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LITERATURE CITED

BJÖRNSSON, H., 1986. Surface and bedrock topography of ice caps in Iceland. *Annals of Glaciology,* International Glaciological Society, 8 (1985), 1921.

BRUUN, P., 1983. Ice behavior at free end obstructions comparisons with wave and sediment conditions. Helsinki, Finland: *Proceedings POAC,* 87.

BRUUN, P., 1987. Glacial eustacy versus sea level rise: Its effect on shore stability in the Arctic. Fairbanks, Alaska: *Proceedings POAC,* 87.

DOWDESWELL, J.A., *et al.,* 1986. Digital mapping of the Nordostlandet Ice Caps from airborne geophysical investigations. *Annals of Glaciological Society,* 1986, 51–58.

GRABTREE, R.D. and DOAKE, C.S.M., 1986. Radio-echo investigations of Ronne Ice Shelf. *Annals of Glaciology,* International Glaciological society, 8, 37–46.

GROSSWALD, M.G., 1989. Submerged shorelines on glaciated continental shelves: Solving the puzzle. *Journal of Coastal Research,* 9(1), 113–121.

JESSEN, AXEL, 1936. Vendsyssels geologi, D.G.V., V. Räkke, No. 2. Copenhagen, Denmark: C.A. Reitzel.

KOWACS, AUSTIN and SODHI, DEVINDER S., 1988. *Onshore ice pile-up and ride-up: Observations and theoretical assessment,* Reprint: Arctic Coastal Processes and Slope Protection Design, Technical Council on Cold Regions Engineering Monograph, American Society of Civil Engineers, *TCCR Practice Report.*

STRAND PETERSEN, K., 1984a. Stratigraphical position of Weichselian tills in Denmark. O.G.V. Reprint 4-1984, *Striae,* 20, 75–78.

STRAND PETERSEN, K., 1985b. The Late Quaternary history of Denmark. *Journal of Danish Archaeology,* 4, 7–22.

STRAND PETERSEN, K., 1985c. Late Weichselian and Holocene marine transgressions in Northern Jutland, Denmark. D.G.V. Reprint 10, *Eiszeittalten und Gegenwart,* 35, 71–78.

TRYDE, P., 1973. Ice piling—Correction for eccentricity of horizontal force and face friction. Technical University of Denmark, Institute of Hydrodynamics and Hydraulic Engineering, *Progress Report #28* (April), pp. 27–29.

TRYDE, P., 1977. Ice forces. *Journal of Glaciology,* 19 (81).

TSANG, GEE, 1973. *Ice piling on lakeshores with special reference to the occurrences on Lake Simcoe in the spring of 1973.* Burlington, Ontario: Canada Centre for Inland Waters, Inland Waters Directorate, Scientific Series #35.