Observations of sea ice influence on the littoral sediment exchange, North Zealand, Denmark

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In 1985 and 1986 monthly surveys of sediment volumes were carried out on a sandy beach and its nearshore platform at the north coast of Zealand. Both winters in the research period had temperatures below average, and consequently abundant sea ice formations. 'Ice winters' in open Danish waters occur statistically about 1/3 of the winters. The appearance of sea ice resulted in marked loss of sediment from the whole littoral zone, but by far the largest net erosion could be detected on the nearshore plane. An important factor is assumed to be the interaction of waves with the icefoot and ice pile-ups. For the beach itself, ice-glazing of the beach surface and interstitial frost in the foreshore sediments caused wave erosion within and just off the swash zone due to variations of the percolation parameter. This dynamic was observed during both the freeze-up and thaw-up periods. On the backshore, wind-derived forms characterized the winter beach, but here the net sediment budget was less affected.

Keywords: *Coastal geomorphology, Sea ice, Icefoot, Sediment volume.*

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In arctic and sub-arctic regions frost and sea ice affect the coastal geomorphology both directly and indirectly. The appearance of fast ice, or drift ice, eliminates or reduces the waves, and polar coasts are therefore classified as low-energy coasts. Directly, sea ice may interact with the coast by erosion, deposition or protection of the forms.

In the initial freeze-up phase, spray water may glaze the morphology, and snow and icefoot formations will preserve the beach forms. Drifting ice floes contain an enormous energy and may plough furrows in the sea bed and groove the beach with resulting ice-pressed ridges. Suspended sediment in the wave swash may be interbedded in the icefoot and ice floes rafting frozen sediment may be thrown up on to the beach and add materials to this part of the littoral zone.

During the last few decades many works have appeared on the role of ice in coastal geomorphology, and comprehensive reviews have been elaborated by John and Sugden (1975), Dionne (1976,1979), and Kovacs and Sohdi (1980).

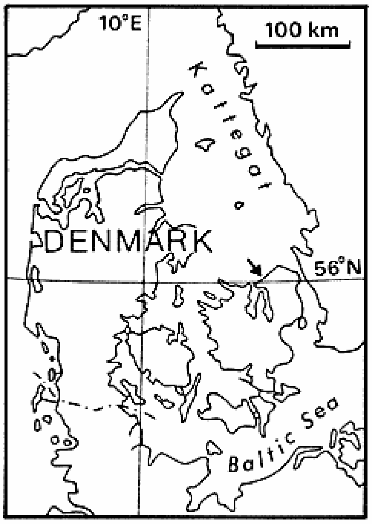

Fig. 1. Location of the study area on the north coast of Zealand.

The vast majority of ice-coast observations are made at high latitudes and in polar regions, but Reinson & Rosen (1982) and Gordon & Hansom (1985) indicate that sea ice may influence the coastal geomorphology considerably below the subarctic as well.

Great Britain and the western Sovjet Union are characterized by a maritime and a continental temperate climate, respectively. Denmark (56°N.lat., 12°E.lon.) is situated in between, and the average temperature of January is about -0.1°C. Westerlies predominate and bring mild and humid air-masses from the relatively warm ocean currents penetrating the North Sea. This means that marginal oscillations in climatic conditions decide whether the Danish sea waters freeze or not. Even though winters with extensive sea ice occur aperiodically in Danish sea waters, recent coastal research has shown that "ice-winters" may interfere in the development of the coastal profile.

It is striking that the majority of the investigations and observations concentrates on the influence of ice on the beach morphology. But how is the interaction with the nearshore zone? Dionne (1968, 1969, 1973, 1979, 1981 and 1984) describes in detail ice action and the morphological consequences on tidal flats at St.Lawrence estuary. Apart from his works observations off the coastline are sparse, and those who have seen the dramatic environment in periods when ice floes crunch and scrape against each other, understand the reluctance to make observations in this area.

The present investigation revealed that icefoot and ice pile-up on the nearshore sea ice interacted with the nearshore wave regime during open water conditions. Morphologically this meant a general lowering of level on the inner nearshore terrace. The field observations also

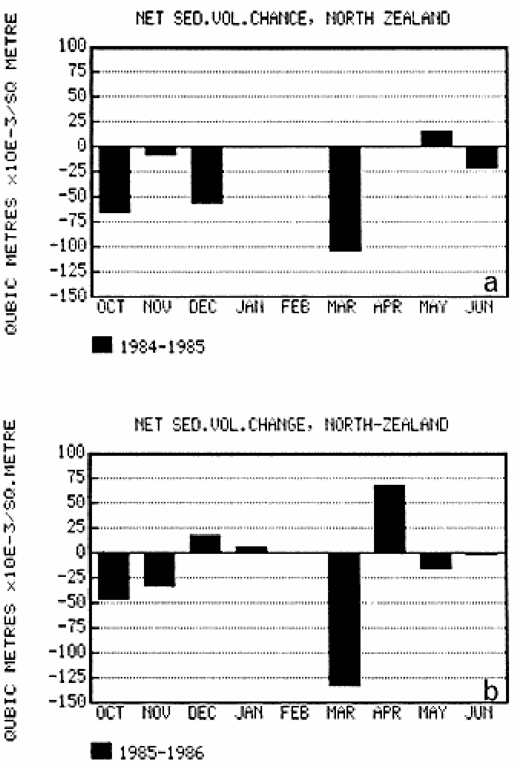

Fig. 2. Bar charts showing net sediment volume changes for consecutive surveys before, during, and after the ice-winters 1984-85 and 1985-86. Survey dates in 1984-85 were: 25/10, 21/11, 20/12 – 1/4, 9/5 and 20/6. In 1985/86: 25/10, 14/11, 11/12, 22/1 – 20/3, 28/4 and 20/5.

showed that frost in the beach sediments and the glazing of the beach face prevented percolation in the swash zone and thereby increased the littoral sediment exchange close to the shoreline.

PHYSICAL ENVIRONMENT ALONG THE NORTH COAST OF ZEALAND

The linear and aligned coast of North Zealand is created in glacial till and meltwater deposits interrupted by stretches of postglacial marine sediments. The coastline retreats and the coastal scenery are characterized by cliff erosion with an offshore wavecut platform. Large areas of the nearshore zone expose pavement and clay, but in many places the surface is superimposed by thin layers (0.1 to 2 m) of fine sand. Beach sediments range from sand to cobbles, and the amount of mobile material changes in time and space.

Due to cyclons moving from west to east frequent storms hit the coast during the months of autumn. Normally the storm situations are associated with a rise in sea-water level of more than 1.5 m (astronomic tide is only 0.2 m).

Limited fetches restrict the wave parameters, and wave periods exceeding 5 sec. are rare, and swell does not occur. Significant wave heights of 2 m are common and Hsmax = 3.5 m is recorded. Because of the predominating wind from west and northwest net longshore sediment transport is pronounced with a rate of about 40,000 m^3/year.

Kattegat, fig. 1, is not covered by fast sea ice every year. Only during winters when high pressures stabilize in the southern part of Scandinavia, the water cools down because the influence is cut off of the relatively warm North Sea water. Winters with sea ice formations are therefore aperiodic and named "ice-winters". According to the National Sea Ice Service (1987) sea ice formations at the north coast of Zealand have been recorded in 22 winters during the period 1929/30 to 1986/87.

Even during ice winters permanent, fast sea ice through all the winter months are rare. The wind direction changes very frequently and cause break-up of the sea ice; thus 3-6 m ridges of piled-up ice on the sea ice and along the coastline are the common picture.

FIELD METHODS AND -OBSERVATIONS

In connection with a small-scale beach nourishment pilot project (25,000 m^3), fig. 8, a number of follow-up investigations were carried out of the pumped in sand and the development of the adjacent coastal stretches. An important task was to determine the erosion rate of the deposited amounts of sand (mean grain-size of added material was 300 μ against the abt. 125 μ, which are natural for the area).

Through a 2-year period the nourished area was surveyed about once a month within a fixed section (300 x 75 m). The survey procedure was tachmetry of approximately 300 xyz-coordinates in fixed lines, and a modified computer program ("COMA") produced contour maps and calculated positive, negative, and net volumes and the areal redistributions since the preceding survey and to an initial reference surface.

The determinations of volume showed a "half-life" period of approximately one year and, without going into details, the erosion rate was found to be closely correlated to the variation in wave- and water level conditions between the individual surveys.

The total observation period lasted from April 1984 to September 1986 and thus comprised two winters, both of which developed into ice winters. During the first winter initial sea ice formations showed up at the end of December, and mid-January the sea was covered by fast ice. With exception of a few and brief periods when the ice broke up and drifted, the ice cover lasted until the middle of March, i.e. roughly for 3 months. In the winter of 1985-86 the sea did not freeze until mid-February and several periods occurred with ice drifting until the thaw set in towards the end of March.

The first survey (1 April, 1985) after the disappearance of the ice recorded a conspicuous drop in the total amounts of sediment as compared with the last survey before the sea was covered with ice (20 December, 1984), see fig. 2a. The high loss figures were first interpreted as a data collection error, since the wave activities were eliminated while the sea was covered with fast ice, and moreover did the brief ice-free periods not coincide with situations with strong onshore winds or storms.

The following ice winter (1985-86) the coastal development was closely followed. Total surveys of the ice-and snow-covered nourished area were impossible, and records of water levels and waves are missing. In return, the dynamic effect of the sea ice was closely observed and a few profile measurements were carried out which also included the ice and snow forms on the beach, cf. fig. 4.

RESULTS

When comparing the fluctuations in sediment volume within the study area during the two ice winters, it is conspicuous that marked losses of sediment were recorded for both winters, cf. fig. 2a and b. This development was surprising the more so because the calculations showed that during the same periods the net longshore material transport was weak or slightly southwest-going, i.e. opposite the usual direction for this area.

In absolute figures the loss was 3,680 m^3 for the 1985-winter and 4,700 m^3 for the 1986-winter. For comparison, it can be stated that an unusual severe gale in September 1985 "only" resulted in a net loss of 2,290 m^3.

It is astonishing that the losses in sediment are of the same magnitude for the two winters, although the duration of ice cover differed. Common for winters with sea ice formations is, however, the similar morpho-dynamic during the phases of freeze-up and thaw-up.

In spite of the limited observations it can tentatively be assumed that the morphological development just in these periods influence largely the net sediment exchange.

Comparison between loss of sediments and the study area's changing distribution of levels recorded for the two ice winters, fig. 3, clearly shows that the erosion mainly takes place on the nearshore; this was especially due for the winter 1985-86.

Simultaneously with this development the morphology of the beach displays a high degree of stability concerning the net material budget, which means that erosion and deposition only take place in a small scale or counterbalance each other in this part of the littoral zone.

To elucidate the question why so large quantities of sand are removed from specific subzones in the study area, its special morphological and dynamic conditions must be focussed upon, not only during the freeze-up and thaw-up phases, but also during the intermediate periods with sea ice.

The icefoot

At a time during the lowering of sea-water temperature the swash is freezing almost immediately when it hits the beach face, such as described in detail by Short & Wiseman (1974), and a so-called "slush icefoot" will be created (Wright and Priestly 1922). Typically, this develops during periods with calm wave conditions and relatively low

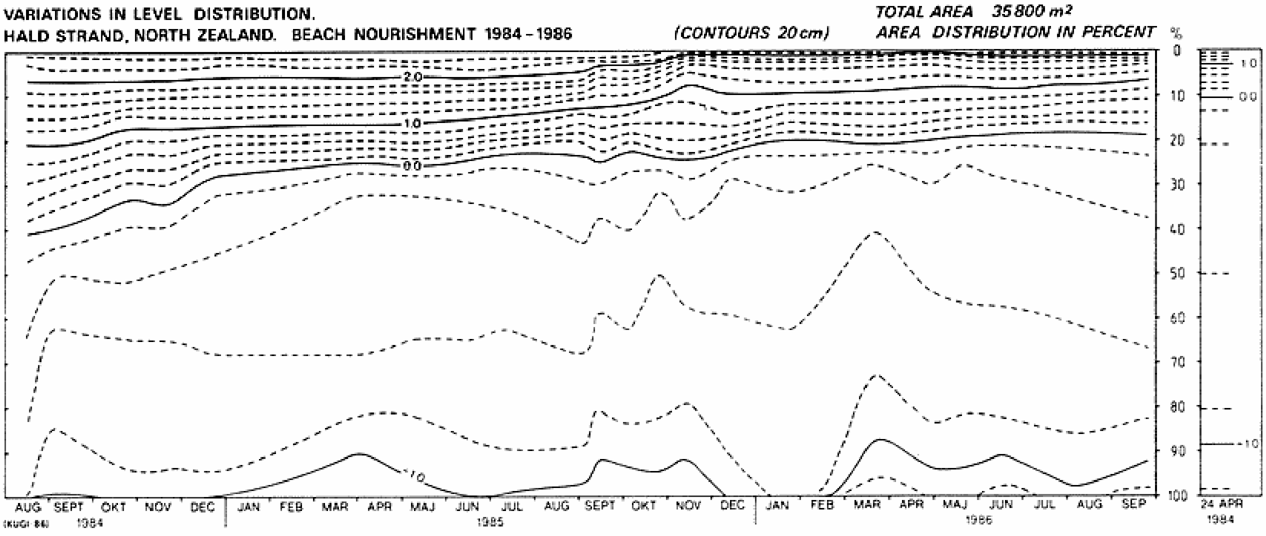

Fig. 3. Time series showing the development in the distribution of the different levels expressed in percentages of the total study area. The diagram is based on hypsographic calculations from the surveys and therefore reveals where and when general changes in the morphology take place. Minor and local alterations in the beach- and nearshore forms are filtered out.

Notice the landward movement especially of the contours below -0.2 m DNN (Danish Ordnance Datum) during the winter months, while the contours above this level simultaneously got a steady position. Apparently the -0.6 m contour is unaffected during Jan., Febr. and Marts 1985, maybe because nearshore was covered by fast ice even during periods, when the sea ice broke.

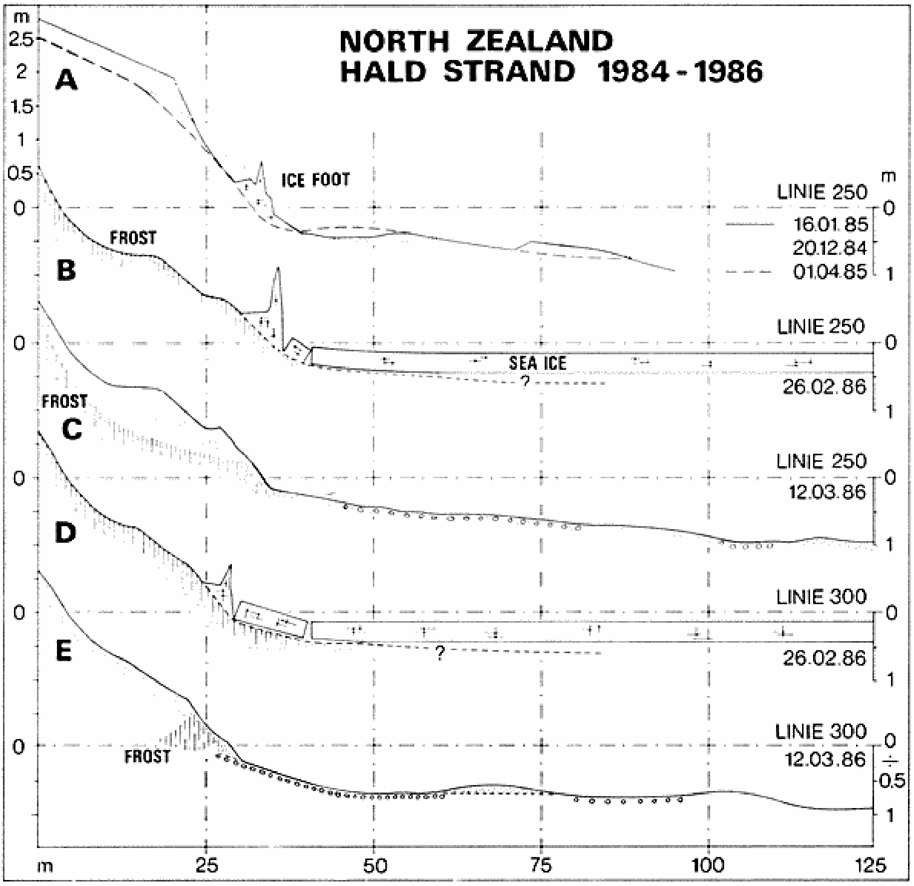

Fig. 4. Beach and nearshore cross sections in the study area during the months of winter and spring illustrating the dimensions of the sand-, snow-, and ice morphology.

water level; such situations are frequent during the winter because of the stable high pressures (which are also a precondition for sea ice formations in Danish waters) and normally these induce weak winds and low water-level, the latter also due to the cooling down of the sea water.

The icefoot is built up of wave wash, maybe filled with slush ice, and finally develops into a vertical ice wall, often with an overhang, fig. 5. The icefoot's growth continues during situations with high water level and wave wash-overs to heights of abt. 1-1.5 m, figs 9a and b. When sea ice has developed, the wave action will be eliminated, and the growth of the icefoot ceases. But during strong offshore winds, which may occur even in periods with lasting cold, the sea ice breaks up and drift away from the coast and the icefoot may continue to grow.

Foreshore erosion during freeze-up and thaw-up

When the frost period sets in the humid sand on the backshore will rapidly freeze, cf. fig. 9 a. The sea water's salinity in this part of Kattegat is abt. 20 ‰ and has not yet reached freezing point. The erosion in the swash zone's lower part will be intensified, because the amount of water in the backwash is not reduced due to the eliminated percolation in the upper part of the frozen foreshore. Formation of small cavities in the frozen surface can be observed, see fig. 6. Fragments of frozen sediment sheets, or even blocks, break off and disintegrate by the following swashes or they may be thrown up on the beach or are rafted away if the amount of ice embedded in the sediments is sufficiently large (interbedded ice/snow or as interstitial ice). If the freezing up coincides with a general lowering of the water level, several erosion steps on the foreshore can be seen. Each step may be 1-3 cm thick and reflects sediment lamina deposited during different dynamic conditions (different grain sizes and pore volumes, see fig. 6).

In the thaw-up phase the ice will first melt in the sediments of the backshore. After the disappearance of sea and icefoot there will still be frost for a short period within and just above the swash zone. The percolation in the upper part of the foreshore is therefore eliminated with a consequent relatively vigorous backwash; loose material immediately in front of the foreshore will be transported seaward, fig. 4 e and 9 f.

Deposition on the beach

Although the general net sediment exchange during the winter months is considered to be low, or slightly nega-

Fig. 5. Icefoot formation in an early phase (26/2 1986). The vertical wall facing the sea is created by slush ice in the swash zone. During break-up periods and open-water conditions the ice foot will grow higher, but maintains the vertical front. (Photo: N. Nielsen)

Fig. 7. Large dune formation on the backshore along the cliff foot, composed by alternating beddings of snow-, sand- and snow-sand mixture. The dune was built up during the winter 1985. (Photo: N. Nielsen)

tive, fig. 3, deposited sediments may locally develop forms on the beach.

Primarily the growth of icefoot is due to spray water from surging breakers, which is typical for coasts exposed to a non-tidal environment (Joyce, 1950). When the waves hit the more or less vertical front of the icefoot, large quantities of sediment will be suspended, and the sediment-loaded water washing over the icefoot may give this a dark colour. A typical transection of the icefoot will therefore show alternating layers of ice-filled sand and pure ice and snow, fig. 9 d.

Superimposed and within the icefoot there might, locally, be concentrations of sediment, deposited en bloc as fragments of frozen sediment sheets. During the freeze-up phase the waves cut into the ice-layered foreshore, and the broken off pieces of sediment are thrown up upon the icefoot, fig. 6 and fig. 9 b.

In the study area eolian activities influenced the surface of the backshore during both winters which to some extent disagrees with observations from Alaska (Short & Wiseman, 1974). Thus it was observed that only the upper sand layer was frozen, and in periods when the wind removed the snow, evaporation was sufficiently high to sublimate the ice and exposed the sand to wind transport. When the frozen sand layer disappeared, large deposits of sand were available for drifting. However, these deposits were limited to the central part of the backshore, because other non-marine processes also influenced the frost cementing of the beach. In particular, water extruding from the coastal cliff created a massive and stable body of ice due to the limited sun insolation at the foot of the north-facing cliff. The depth of the frost is unknown, but this area was the last to thaw in the spring.

Long tongues of sand extended from the backshore and over the icefoot, and locally even farther out on the sea ice. Along the coastal cliff a more than 1 m high dune was formed, fig. 7, composed of alternating layers of sand, snow and sand/snow mixture. Especially the latter were typical and thus emphasize the importance of snow as transporting agent, "niveo-eolic", such as described by Koster & Dijkmans (1987).

Nearshore erosion

The reason for the recorded loss of sediment on the nearshore in the winter months is primarily assumed to originate from the specific wave conditions induced by the

Fig. 6. Wave erosion in a partly frozen foreshore due to textural differences in the sediment laminae. The exposed and frosen sediment layers break off because of undercutting and are thrown up upon the beach. The fence is 1.2 m high. (Photo: N. Nielsen)

formation of the icefoot and ice pile-ups during open water phases.

Normally, the swash zone on a sandy beach is sloping 3-7 degrees and this zone acts as a buffer against the incident wave energy. According to Wright and Thom (1982) the gradient of the foreshore is of vital importance for the dynamics of the nearshore; steep foreshore slopes allow higher wave energy to be transported towards the coastline.

After formation of the icefoot, the foreshore is transformed into a vertical ice wall, and the incident wave energy is almost completely reflected. Even during moderate wave situations, the reflective conditions exist. On the inner nearshore the increased turbulence results in suspension of sediments affecting a zone, the size of which depends on the actual wave sizes. The amount of material available for transport is thus markedly increased.

During both ice winters a pronounced element in the coastal scenery were heaps of pack ice. Most frequently they were placed on the sea ice 100-150 m off the coastline and were observed as interrupted, 2-4 m high ridges parallel to the coastline. The location of the ice pile-ups corresponded to the position of the largest breakpoint bar, and as the water depth in this part of the coastal profile is only abt. 1 m, it is supposed that the ice pile-ups rested on the sea bottom. Between the icefoot and the ice pile-ups the sea ice was even and undisturbed, and no pile-ups were observed on the beach in the study area.

The stranded ice pile-ups formed almost vertical walls facing open water during the temporary break-up periods, and towards the end of the winter when the offshore sea ice had disappeared, this interim coastline was characteristic, fig. 8.

The diagram, fig. 3, displays the development in redistribution of levels in the investigation area. As it appears the nearshore off the -0.8 m contour is lowered, and it is assumed that the wave climate close to the ice margin has been extremely reflective, fig. 9 e, with a consequent intensification of the erosion – after the same model as described for the sea bottom along the icefoot.

Pack-ice disturbance of the sea bottom

When drifting towards shallow sea floors pressured pack-ice floes may affect the sediments of the sea bottom (Kovacs & Mellor 1974). Observations in the study area also indicated that pressure from large ice floes are able to push stranded ice pile-ups en bloc on the nearshore, maybe in combination with a rise in sea level.

Shortly after the sea ice disappeared, underwater observations by SCUBA equipments revealed that the wave-resistant abrasion platform paved with cobbles had evidently been disturbed in the same areas where ice pile-ups were recorded. This means that the ice is obviously capable of moving stones and blocks and thus expose the underlying till (clay, silt, sand, and gravel) which can now be eroded by waves and removed by currents. This observation leads to the conclusion that the level of the "solid" sea bottom – which is generally considered stable – is steadily exposed to erosion and, consequently, lowered.

Fig. 8. View towards northeast of the beach nourishment site in Marts 1985. Sea ice still covers the nearshore zone and creates an interim coastline in front of which ice pile-ups can be seen. (Photo: N. Nielsen)

CONCLUSIONS

During cold winters in Denmark – ice winters – sea ice is a morpho-dynamic parameter just as important as for higher latitude coasts. Frequent break-ups characterize sea ice formation in Danish sea waters why morphological consequences may be even greater in some respects.

The investigation at the north coast of Zealand demonstrated that a number of small-scale and local form modifications occurred on the beach during an ice winter, but for the sandy coast in question the changes in the overall beach morphology were short-termed, and significant alterations in the net material budget were absent.

The nearshore acted differently thereby that it showed a negative volume development. A reflective wave environment initiated by the icefoot and ice pile-ups (similar to what happens in front of a vertical sea wall) is suggested to be essential.

Concerning the Zealand north coast it is well known to coastal geomorphologists and -engineers that the amount and distribution of mobile sediments superimposing the abrasion platform change with an aperiodical rhythmicity during a number of years, but it is unknown why. Maybe the present study is a key to an understanding, but further investigations are necessary to verify the morpho-dynamic events in the littoral zone in ice winters to come.

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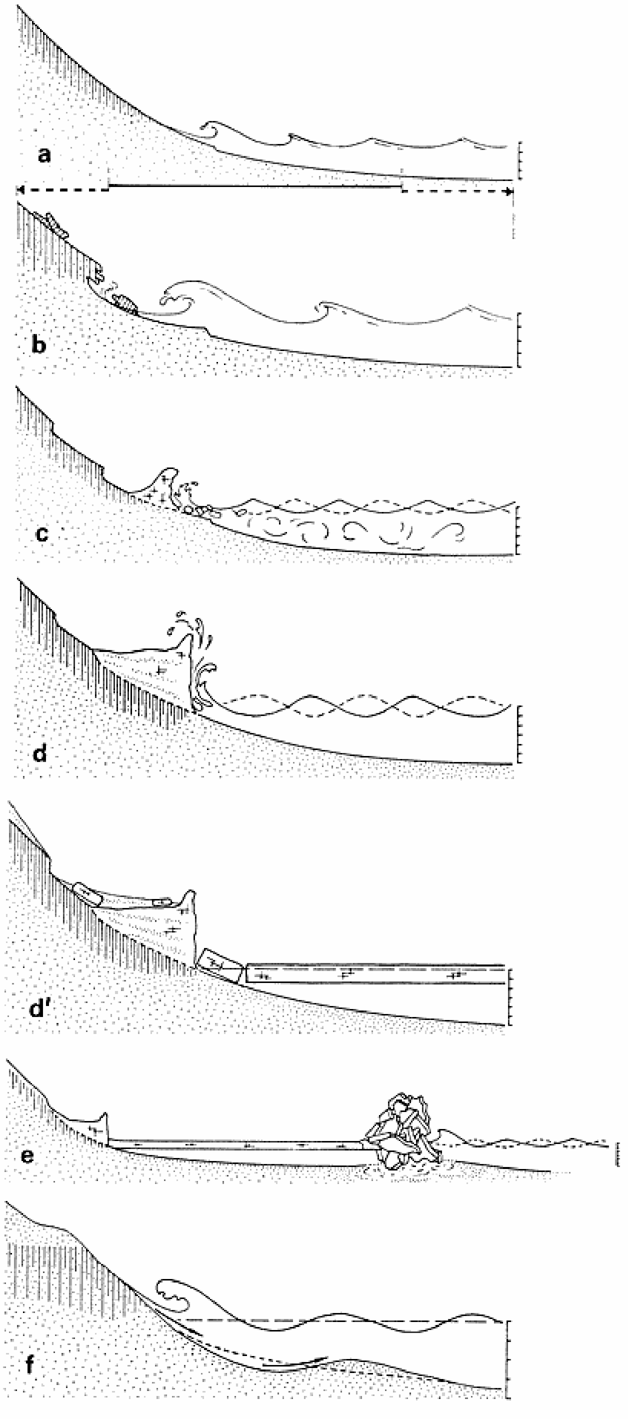

Fig. 9. Successive phases sea ice and frost interaction with beach and nearshore morphology, in principle.

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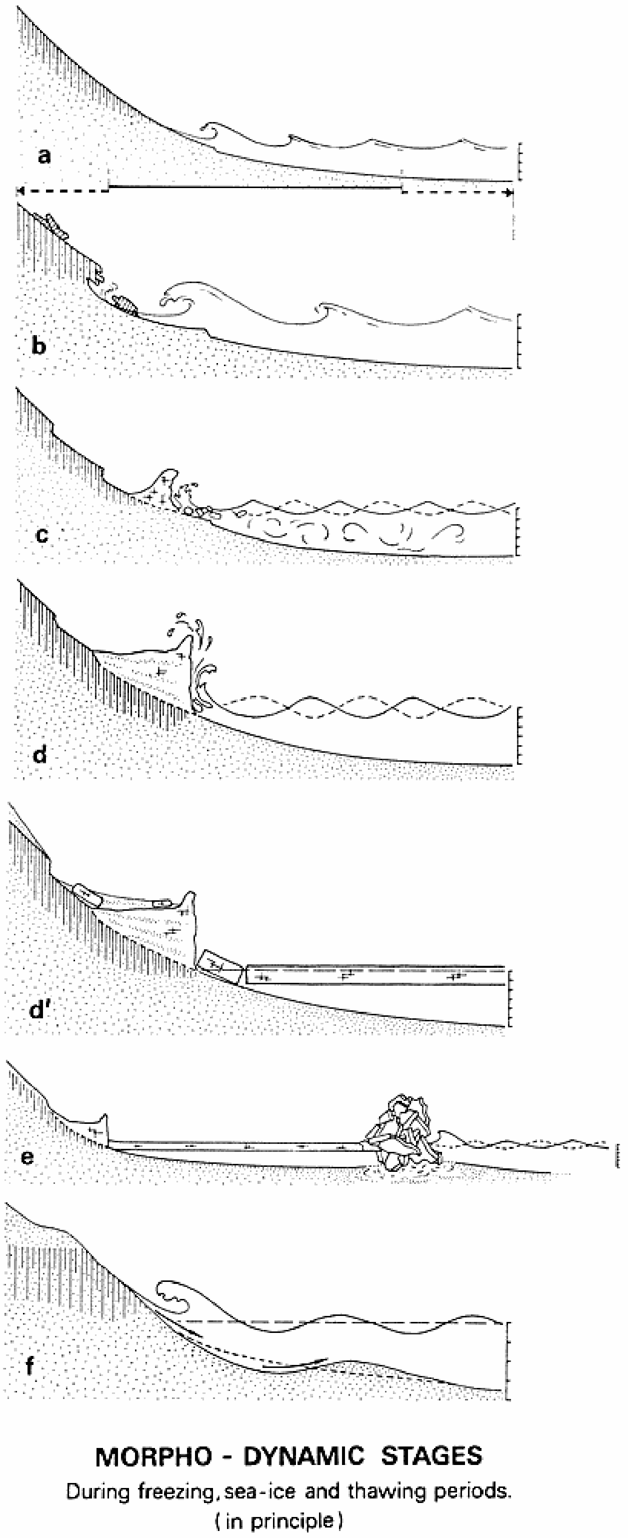

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The diagram, fig. 3, displays the development in redistribution of levels in the investigation area. As it appears the nearshore off the -0.8 m contour is lowered, and it is assumed that the wave climate close to the ice margin has been extremely reflective, fig. 9 e, with a consequent intensification of the erosion – after the same model as described for the sea bottom along the icefoot.

Pack-ice disturbance of the sea bottom

When drifting towards shallow sea floors pressured pack-ice floes may affect the sediments of the sea bottom (Kovacs & Mellor 1974). Observations in the study area also indicated that pressure from large ice floes are able to push stranded ice pile-ups en bloc on the nearshore, maybe in combination with a rise in sea level.

Shortly after the sea ice disappeared, underwater observations by SCUBA equipments revealed that the wave-resistant abrasion platform paved with cobbles had evidently been disturbed in the same areas where ice pile-ups were recorded. This means that the ice is obviously capable of moving stones and blocks and thus expose the underlying till (clay, silt, sand, and gravel) which can now be eroded by waves and removed by currents. This observation leads to the conclusion that the level of the "solid" sea bottom – which is generally considered stable – is steadily exposed to erosion and, consequently, lowered.

Fig. 8. View towards northeast of the beach nourishment site in Marts 1985. Sea ice still covers the nearshore zone and creates an interim coastline in front of which ice pile-ups can be seen. (Photo: N. Nielsen)

CONCLUSIONS

During cold winters in Denmark – ice winters – sea ice is a morpho-dynamic parameter just as important as for higher latitude coasts. Frequent break-ups characterize sea ice formation in Danish sea waters why morphological consequences may be even greater in some respects.

The investigation at the north coast of Zealand demonstrated that a number of small-scale and local form modifications occurred on the beach during an ice winter, but for the sandy coast in question the changes in the overall beach morphology were short-termed, and significant alterations in the net material budget were absent.

The nearshore acted differently thereby that it showed a negative volume development. A reflective wave environment initiated by the icefoot and ice pile-ups (similar to what happens in front of a vertical sea wall) is suggested to be essential.

Concerning the Zealand north coast it is well known to coastal geomorphologists and -engineers that the amount and distribution of mobile sediments superimposing the abrasion platform change with an aperiodical rhythmicity during a number of years, but it is unknown why. Maybe the present study is a key to an understanding, but further investigations are necessary to verify the morpho-dynamic events in the littoral zone in ice winters to come.

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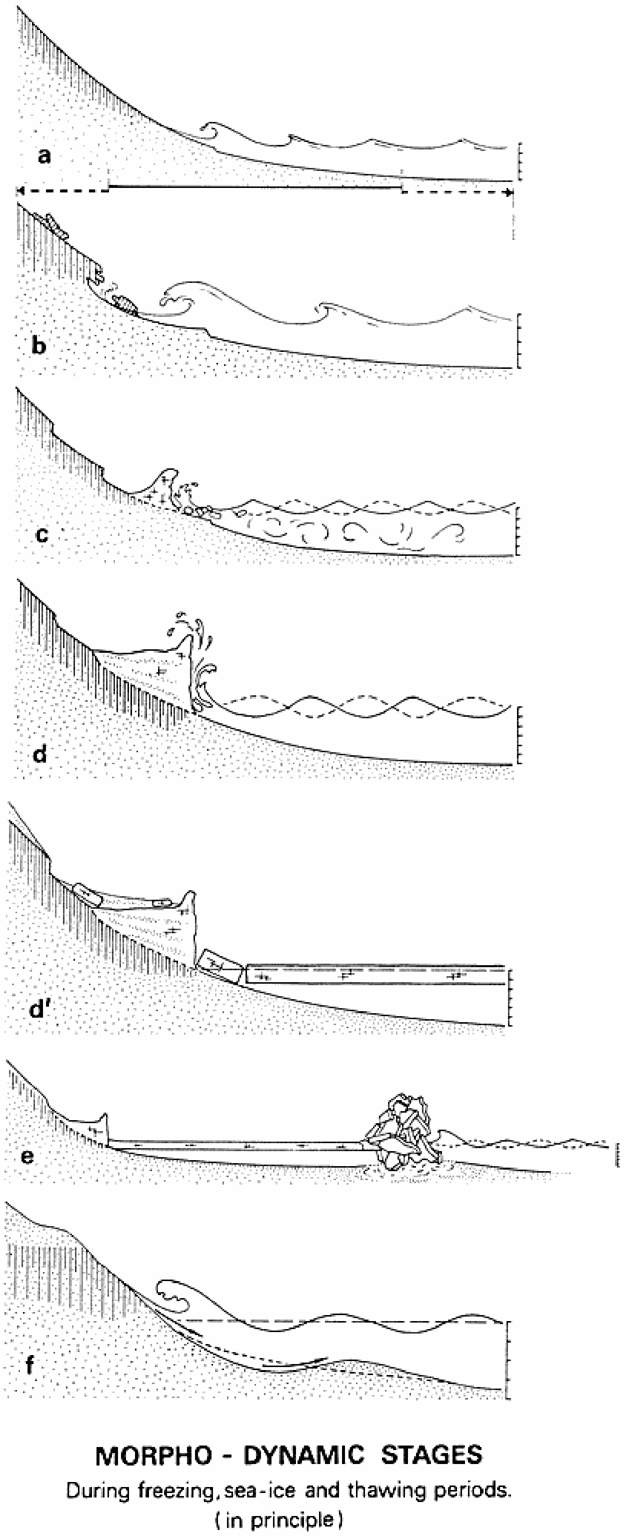

Fig. 9. Successive phases sea ice and frost interaction with beach and nearshore morphology, in principle.

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