DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 1997/5

Skagen Spit.
A general model for spit development.
Phase I

Jørgen O. Leth

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GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

GEUS

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List of Enclosures:

1. INTRODUCTION

With the object to develop a field analogue and establish a geological course sites for the use of Norsk Hydro, GEUS and Norsk Hydro have entered into a contract on a study of the Skagen Spit, the northernmost tip of Denmark.

The spit has developed during a relative short period from about 8.000 y. B.P. until today and is still prograding. Consequently, the Skagen Spit is excellent for studying the development of a coarse grained spit in three dimensions, the processes in relation to relative sea level changes and even the recent coastal sediment transport in time and space.

The study is divided into three phases: 1) a preliminary study based on existing data; 2) preparation of an analogue-model of Skagen Spit including field work and a proposal for a field course and 3) a field course in 1998.

The present report of phase 1 includes a preliminary study of the development of the Skagen Spit based on available published and unpublished data and a description of a general model of a coarse grained spit development. Furthermore, a programme for phase 2 is suggested at the end of the report.

2. GEOLOGICAL SETTING

The surface of the pre-Quaternary in the Kattegat is characterised by a topographic depression, 'The Kattegat Depression', with an approximately southeast-northwest trending axis (Fig. 1). The depression is wedge shaped with its apex close to the Swedish coast north of the Kullen Peninsula. Its width here is 50-75 km, and it increases to 125-150 km as measured across Vendsyssel to the Swedish coast north of Göteborg.

The depth increases north-westward in the depression from c. 100 m to c. 200 m. This embayment was connected to the North Sea and the North Atlantic to the Northwest and may be considered to have been a palaeo-extension of the Norwegian Trench. Contrary the Norwegian Trench the 'Kattegat Depression' during the Late Quaternary gradually has been infilled with almost 300 m sediments dating from the Late Saalian to the Holocene (Knudsen et al., 1996).

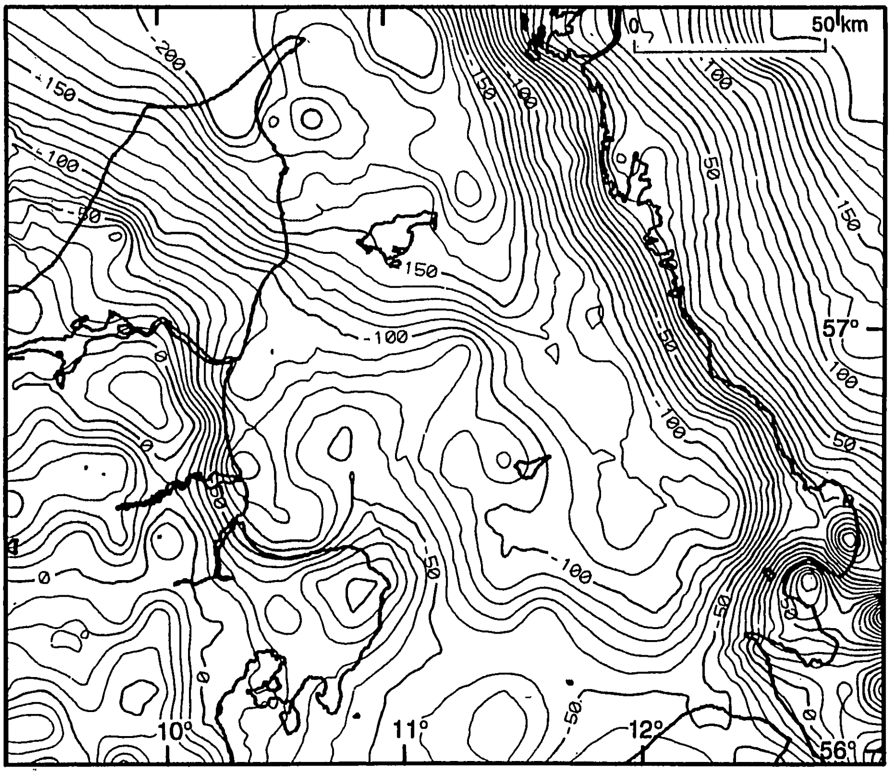


Figure 1. Morphology of the pre-Quaternary surface. Details omitted. Contour interval 10 m. (From Lykke-Andersen et al., 1993).

The Skagen Spit is located at the tip of Vendsyssel at the northernmost part of Denmark. It has developed from a line with the length of 30 km between Hirtshals in the west and Frederikshavn in the east (fig. 2) called The Base Line. A 40 km long west-coast line and a 35 km eastcoast line constitute together with The Base Line the triangle form of the spit, with a total area of about 400 km^2.

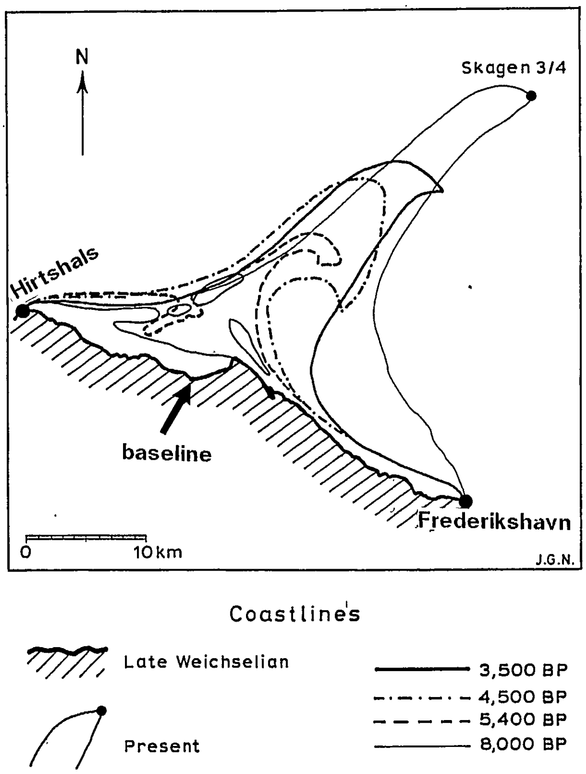


Figure 2. Map showing the stages of the Skagen Spit development after c. 8,000 y. B.P. indicating The Base Line between Hirtshals in the NW and Frederikshavn in the SE and the site of the Skagen 3/4 boreholes. Redrawn from Hauerbach (1992). (From Knudsen et al., 1996).

The morphology of Vendsyssel is composed of three major elements (fig. 3):

1) Weichselian glacial landscape, 2) late-glacial (Middle-Late Weichselian) marine plateau and 3) post-glacial (Flandrian) low-lying marine plains. The relative highlying glacial areas in Vendsyssel constitute the baseline of the Skagen Spit. These areas which northern termination is parallel to the axis of the 'Kattegat depression' probably have governed the initial growth of the spit.

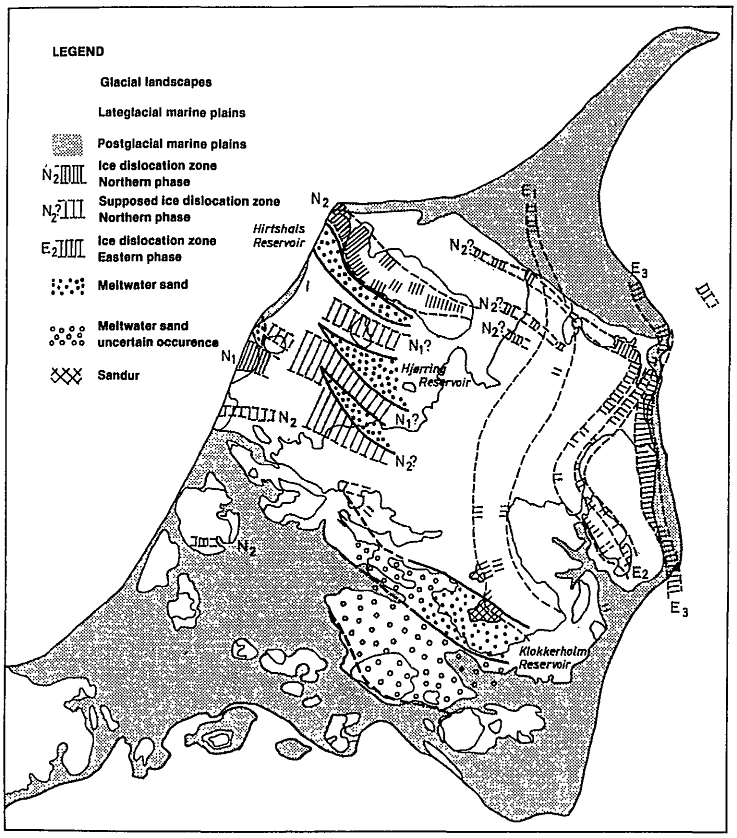


Figure 3. Geological map of Vendsyssel showing the three main types of landscapes (from Fredericia & Knudsen, 1990).

Due to the smelting of the ice cap in the Late Weichselian Vendsyssel was transgressed by the Younger Yoldia Sea (Petersen, 1985) depositing marine sand interlayered with clay (The Lower and Upper Saxicava Sand and the Younger Yoldia Clay). The Yoldia Clay today forms the highlying marine plateaus due to the isostatic rebound.

A geological map of the spit is presented in enclosure 9.

Two borings just north of the town of Skagen has been carried out in 1992 and 1993 (The Skagen 3 and Skagen 4 boreholes) (Fig. 4). They have penetrated 192 m of Quaternary deposits upon a base of Lower Createaceous non-marine sands. At the lower part of the core a full glacial-interglacial-glacial cycles of Late Saalian, Eemian and Early Weichselian ages is represented by c. 7 m marine sediments (185-178 m). Above this interval c. 46 m (178-132 m) Early-Middle Weichselian basin fill sediments are found deposited at the southern branch of the Norwegian Trench. The uppermost 132 m of the core represents marine deposits of Late Weichselian and Holocene age.

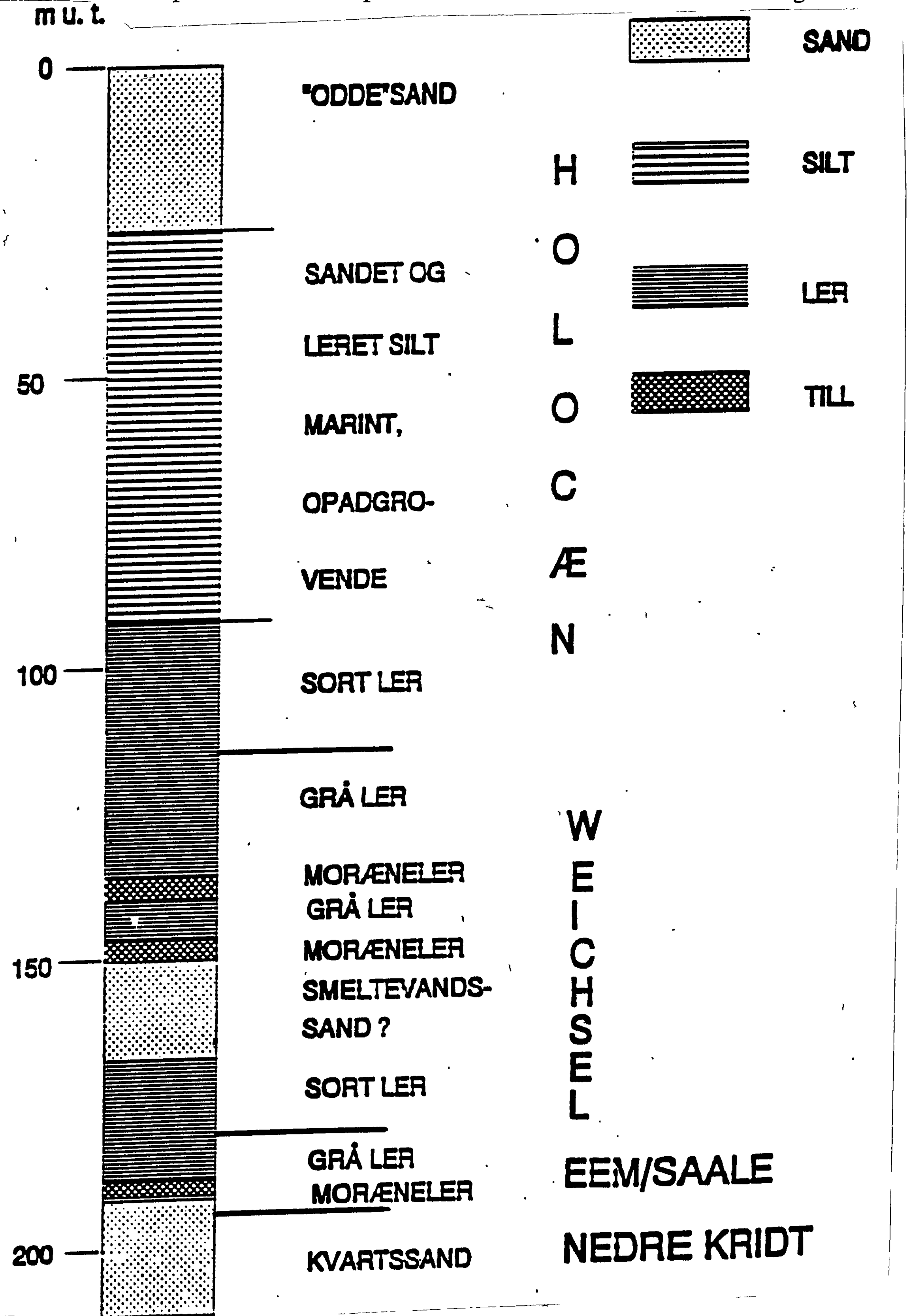


Figure 4. Core log of the Skagen-3 boring. From Bjørslev, 1993.

3. PALAEOCEANOGRAPHY

Due to variation in the influx of North Atlantic water the climate and oceanography in the Norwegian Sea and the North Sea have changed. The present surface current system in the North Atlantic has probably been the prevailing oceanographic setting in the Holocene. The migration of these water masses is reflected in the sedimentary record at the Skagen Spit.

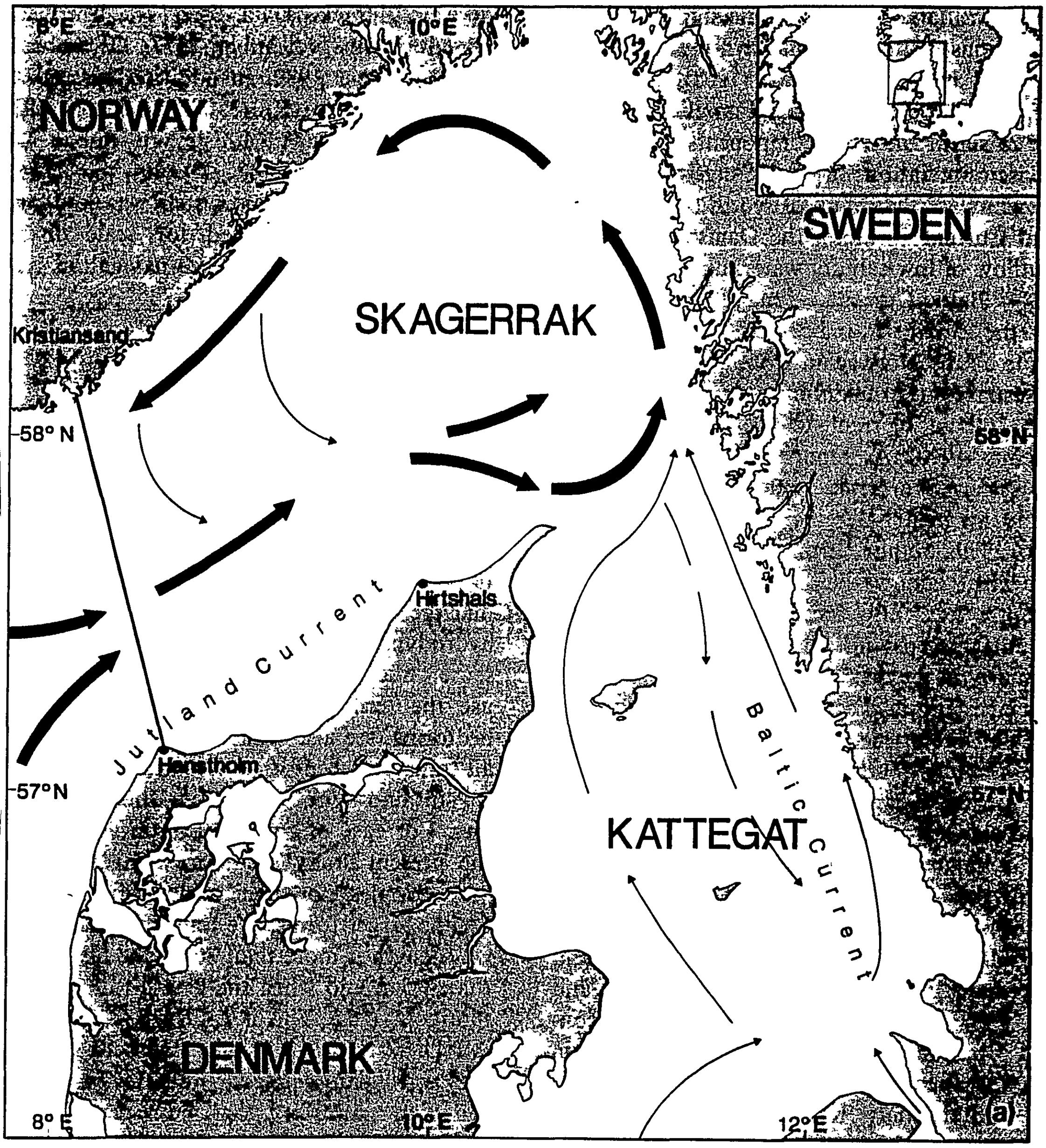
The present regional anti-clockwise circulation pattern in the Skagerrak can be divided into two main components: 1) influx of North Sea water (the Jutland Current) and 2) the outflow of low-saline water masses from the Baltic (the Baltic Current) mainly concentrated along the Swedish and Norwegian coast, to continue as the Norwegian Coastal Current. In the western Skagerrak another inflow maximum is found at greater depth, i.e. below 200 m (fig. 5).

After the rapid sea-level rise at the onset of the Holocene and the opening of the English Channel, a circulation pattern similar to the present came into existence (van Weering (1975). Nordberg (1992) suggested that the opening of the English Channel at about 8,000 y. B.P. led to the establishment of the North Sea current system. According to the latter author clear changes in the biostratigraphic and sedimentological variables are recorded in the Kattegat at about 4,000 y. B.P. This environmental change characterised by migration of temperate and cold-water species into the entire Kattegat-Skagerrak and NE North Sea suggest an increased inflow of the North Jutland Current-Norwegian Coastal Current and a small degree of mixing with Atlantic waters.

The establishment of the modern benthic foraminiferal faunas and areas of accumulation for fine-grained sediments in the Kattegat, and the present coccolith flora in the Skagerrak about 4,000 y. B.P. suggest that this was the date for the establishment of the modern surface current system in the Skagerrak-Kattegat (Nordberg, 1992). Similar observations suggesting a cooling event at this time was made by Jansen (1987) and Koc and Schrader (1990). Koc and Schrader (1990) suggested the change caused by a climatic deterioration at about 4,000 y. B.P.

Leth (1996) has from a study of the geological development at the Jutland Bank and the Little Fisher Bank, NE North Sea deduced, that the flooding of the widespread emerging glacial deposits in the latter area around 5,500 y. B.P. has governed the establishment of the coast-parallel current of the Jutland Current. After this time the tidal range might have been reduced to the present level (< 0.30 m at the Skagen Spit) due to interference between the North Sea amphidromic systems. A sedimentological change in the Skagen 3 Boring made Conradsen (1995) suggest that the Jutland Current is established around 5,500 y. B.P.

These hydrographically changes is closely related to the development of the Skagen Spit system. The understanding of the latter changes is very essential for the present analogue study.



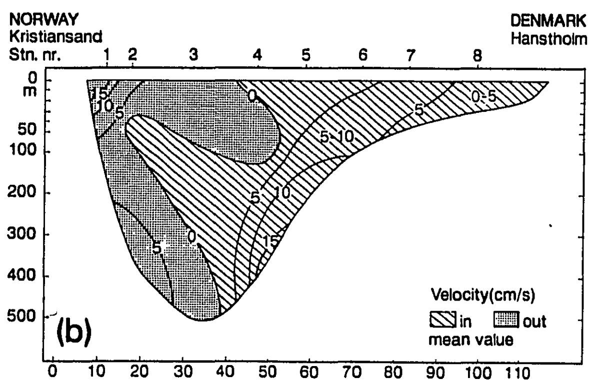


Figure 5. (a) Surface currents in the Skagerrak (Swansson, 1975). (b) Cross-section of the Skagerrak showing in- and outflow patterns (Rhode, 1987). From Kuijpers, 1993.

4. THE MORPHOLOGY OF THE SKAGEN SPIT

The Skagen Spit is dominated by two characteristic morphological elements: the 'ridge and swale system' and the aeolian deposits. The 'ridge and swale system' has build up on the marine foreland. Their structure makes up a conspicuous morphological pattern with a series of linear, parallel to sub-parallel ridges separated from each other by humid lowland peat deposits (in Danish 'Martørv') deposited shortly after the deposition of the beach ridges (fig. 7) aeolian dune formations cover during the coastal advance the stone ridges (fig. 6).

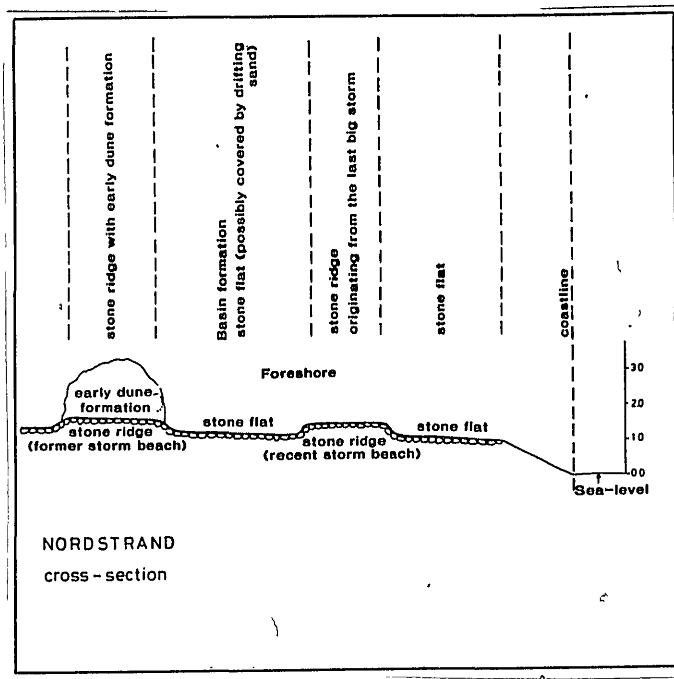


Figure 6. A cross-section of the area of coastal advance at Skagen Nordstrand (from N to S). Distance between coastline and early dune formation on top of former storm ridge is 100-200 m. From Hauerbach, 1992.

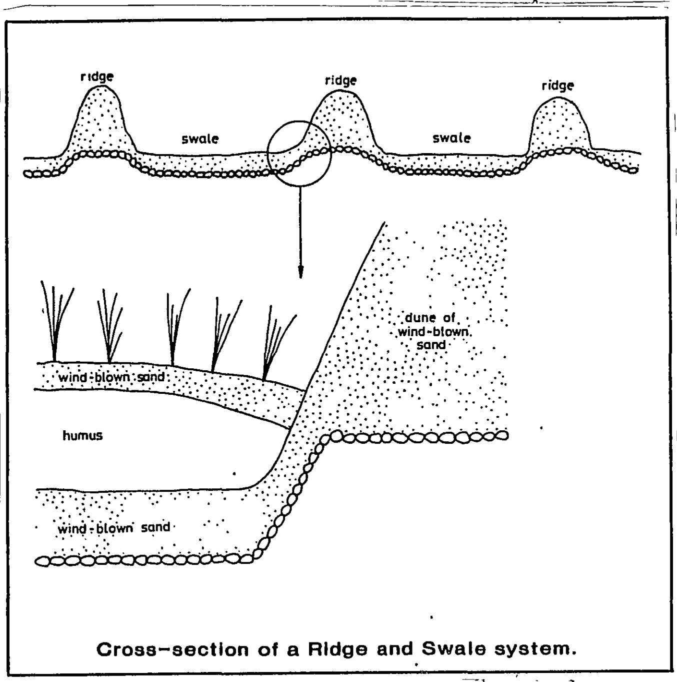


Figure 7. Cross-section through part of a 'ridge and swale system'typical of an area of coastal advance (like Skagen Nordstrand today). The system develops perpendicular to the coastline. The distances between the ridges may vary according to the frequency of storms i.e. increasing numbers of storms, the greater number and the higher concentration of beach ridges. From Hauerbach, 1992.

The conditions of generating the ridges are a frequent storm activity and an abundant sediment supply from the longshore coastal transport. Due to the decrease of the longshore current velocity at the end-point of the spit and the accomodation space here the sediment has been deposited. As a consequence of the isostatic rebound and regression during the Holocene in the Skagen Spit area the 'ridges and swales system' has been preserved.

The orientation of the ridges is seen from the enclosures 1, 2 and 9 (encl. 1: aerial photograph of the spit; encl. 2: morphological trends interpreted from the aerial photograph; encl. 9: geological map of the spit). It appears that the orientation of the ridges changes from the south to the Northeast. According to Jacobsen (1992) who did the analysing work of describing the morphological elements the following trends at enclosure 3 is the most conspicuous:

- south of Tversted the ridges are orientated S-N with the northernmost part turning NW

- a widespread 'ridge and swale system' surrounds the western part of the former lake, Gårdbo Sø. To the NE the trend has turned into a perpendicular direction to the lake. The level decreases against the lake. Around the lake the ridge contours are concordant to the shape of the former lake with a dip direction against the centre of the lake.

- along the eastcoast of the Skagen Spit the 'ridge and swale system' has a trend parallel to the coast of Ålbæk Bugt. The termination against the north is uncertain.

- the area from south of Kandestederne to Skagen Klitplantage the 'ridge and swale system' makes up a pattern with an E - W orientation at the west coast, turning south in the central part of the spit.

- at the tip, north of the town of Skagen, the orientation is E - W and parallel to the present north coast.

Large areas of the spit is super-imposed by aeolian deposits and, therefore, no beach ridge elements visible.

Interpretation of the morphology

From the above analysis of the morphology some of the processes and mechanisms in the development of the spit is discussed (Jessen, 1899, Schou, 1945 and Jacobsen, 1992).

Tversted - Kandestederne

The development at Tversted is interpreted as build up as a 'one-side initial cuspated foreland' (i.e. an extensive formation of marine foreland with spits and beach ridges growing from a land area until they coalesce). The growth is similar to the recurved spit's growth. From here the growth probably has continued as a tombolo development from a highlying ground at Kandestederne. The bending ridges and swales at this point suggest a growth as cuspated spits (Danish: 'krumodde') defining the observed curvature of the morphological elements at the map (enclosure 3). In addition, the grain size distribution decreases from the west to the east, supporting this interpretation.

Gårdbo Sø

However, the correlation between the development of the Tversted-Kandestederne area with the Gårdbo Sø area is uncertain. The level of the morphological system is dipping in the direction of the lake which is interpreted as originally a lagoon. The closing of the lagoon (today the Gårdbo Sø) is related to the isostatic rebound combined with a gradually infill of the lagoon with marine sediments. The structures closest to the lake has a dip direction against the centre of the lake.

The morphological elements bounding the lake at the eastern side is interpreted as barrier islands developed in Ålbæk Bugt on the lee-side of the large cuspated spit, which has developed between Tversted and Kandestederne.

North of the town of Skagen

The transition from the geomorphological structures of the cuspated spit growth to the east-west striking 'ridge and swale system' north of the town of Skagen represents a change in the hydrography in the Kattegat and/or a change of the relative sea level. It has caused a change in the depositional environment. The erosion at the eastcoast has governed the development of the rectilinear spit (Danish: retodde) with sand transport at both sides. The rectilinear spit axis bends to the east due to the less amount of sediment transport at this side (see the chapter 'Sediment transport and budget').

5. THE GRAIN SIZE DISTRIBUTION

In the light of the depositional environment and the geomorphological interpretation a general decrease in the grain size distribution from the west to the east would be expected for the Skagen Spit area. That means, there is a decreasing level of the coastal current energy at the lee-side of the northern part of the spit. Furthermore, it is expected that, due to erosion, coarse grained material will be reworked and even concentrated into coast-parallel layers at the eastcoast (Skriver, 1992). These can be seen at the eastcoast north of the town of Skagen.

The only available model of the lateral grain size distribution has been adopted from the hydrological model of the Skagen Spit area using geo-electrical sondings, a geo-radar profiles and well informations developed by Skriver (1992). The sedimentological pattern is presented in 5 profiles across the spit, deduced from the scattered wells throughout the area (fig. 8 and enclosures 4-8). The lateral lithological distribution is proved by sieve-analysis and by borehole logging. From this interpretations a gradual transition from the coarse grained to the fine grained deposits appears at a level about 5 meters deeper at the westcoast than at the central part of the spit. There is, however, a limited amount of sedimentological data from the eastern part of the spit.

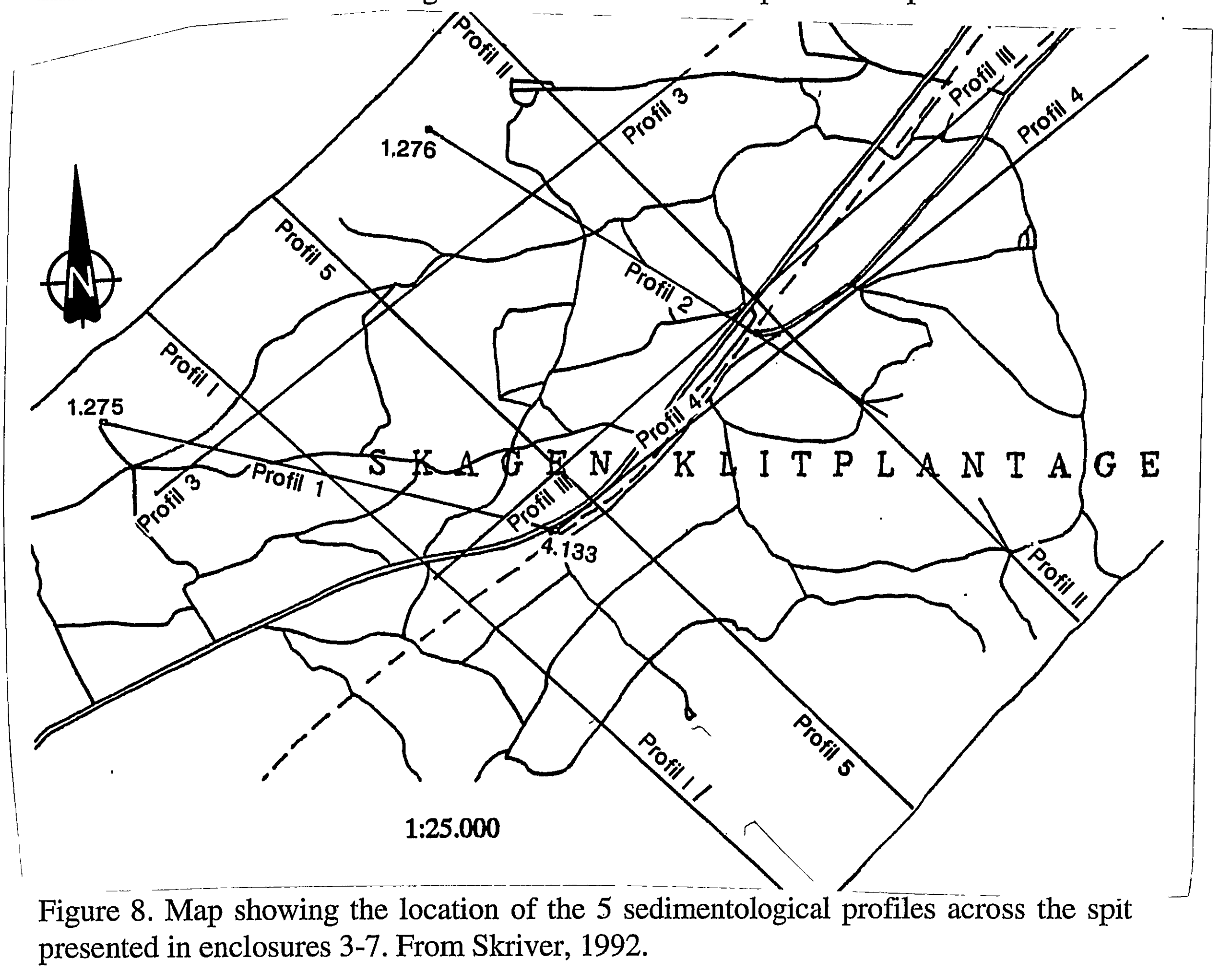


Figure 8. Map showing the location of the 5 sedimentological profiles across the spit presented in enclosures 3-7. From Skriver, 1992.

6. THE SKAGEN SPIT DEVELOPMENT AND THE ISOSTATIC/EUSTATIC CHANGES

Due to the Post Glacial isostatic rebound Vendsyssel was uplifted above the sea level followed by a regression. The amount of isostatic rebound since the termination of the Weichselian glaciation and the deposition from the Younger Yoldia Sea at 13,000-14,000 y B.P. deduced from tilted Holocene shorelines is estimated to be about 200 meters in the northern Jutland (Fig. 9). Isostatic uplift, however, probably has finished in the latter region. The isostatic rebound post 8,000 y B.P. at the spit base line is estimated to 35 m.

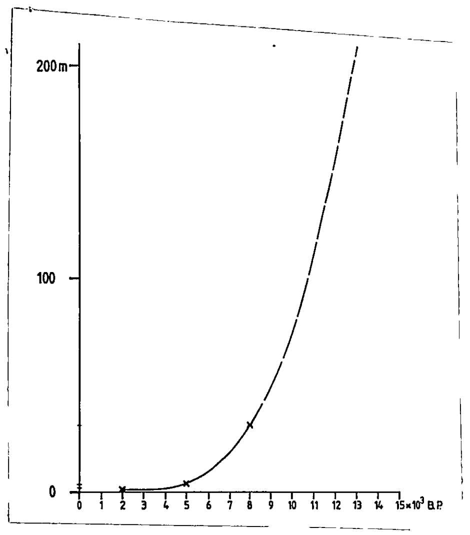


Figure 9. The difference in isostatic rises through time plotted with the curve extrapolated back in time. It indicates an isostatic rise between 13,000-14,000 y. B.P. At the other end the uplift can be regarded as expired at present (from Petersen, 1991).

The oldest Holocene deposits marking the marine transgression is described at the southern part of the Skagen Spit (the Tversted Å profile). A transition from peat to marine clayey gyttja marks a transition from terrestrial/limnic to lagoonal depositional environment. On the basis of datings of Cardium shells the marine gyttja has been dated to the Boreal between 8,280 - 7,820 y. B.P. (Petersen, 1991). These deposits are regarded as being part of huge Early Atlantic transgression with a sea level rise of 25-30 m, reaching its culmination about 7,000 y. B.P. Possibly a system of lagoons protected by high-lying offshore bars and sandbanks or partly submerged islands have existed at that time with the shore close to The Base Line (fig. 10).

The initiation of the of the spit system development has been studied and dated in a profile at Råbjerg Hvarre just north of Skiveren (Petersen (1991). The succestion of marine gyttja overlying well-sorted sand indicates a deposition not on a coast facing the North Sea, but rather as a part of a fjord system which opened against the east. The dating 6,850 y. B.P. refer to a time short after the culmination of the Early Atlantic transgression.

Due to the ongoing isostatic movement and the emergence of a ground at Råbjerg the initial growth has started. Regressive beach and shore deposits together with lagoonal deposits made the growth of the spit to còntinue. The southernmost outcrop at the coast of the beach ridge system occurs at Råbjerg Stene between Skiveren and Kandestederne (see map encl. 1). To the north of this point no signs of similar grounds have been observed indicating an hydrographic governed growth of the spit.

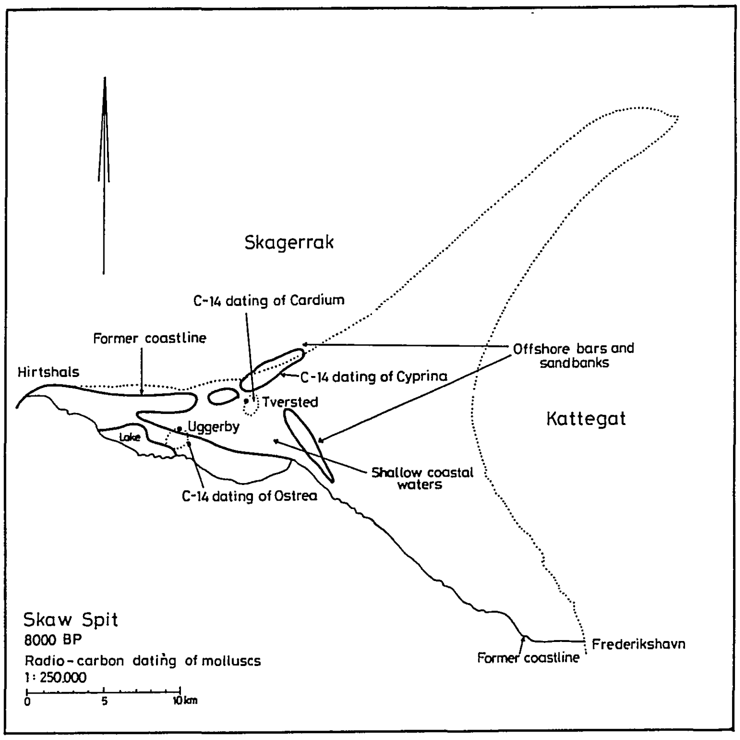


Figure 10. The map indicates the stage of the spit development by 8,000 y. B.P. Based on radiocarbon dating, aerial photography and examination of landforms and landscape. (From Hauerbach, 1992).

The coastal development due to isostatic movements of the Skagen Spit has been determined by measuring the levels of the ridges at the westcoast combined with datings of the peats (Hauerbach, 1992) formed behind the beach ridges in the 'ridge and swale system'. The palaeo-coastlines have been dated back to 5,500 y. B.P. with a coastal elevation of 12 m. The figures 11-14 below presents a series of palaeogeographical maps at different stages of the spit development.

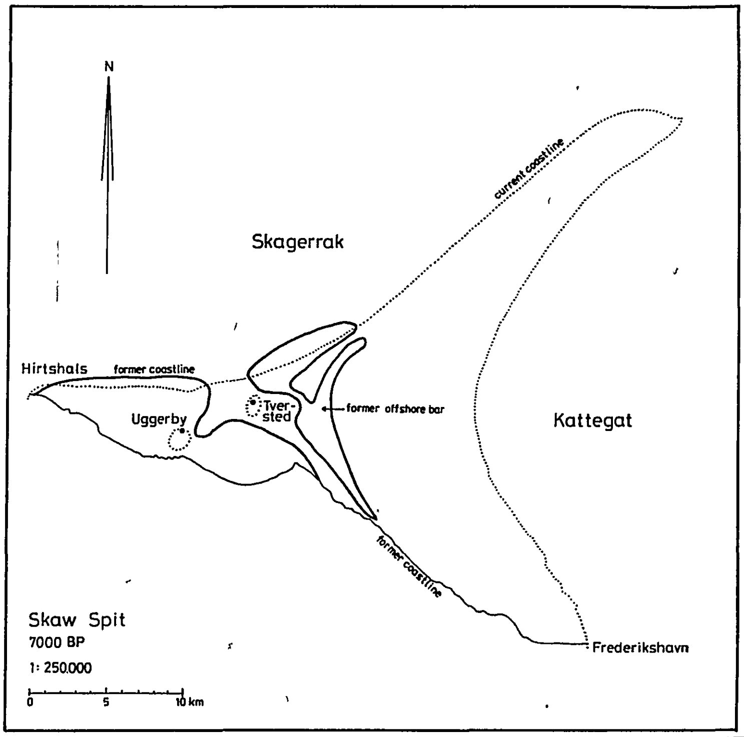


Figure 11. The map indicates the stage of development by 7,000 y. B.P. (from Hauerbach, 1992).

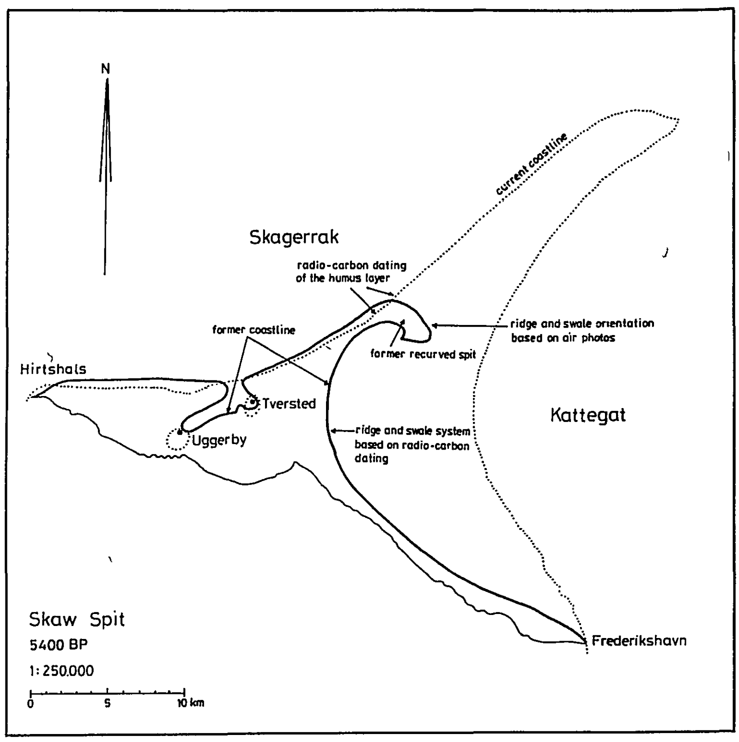


Figure 12. The map indicates the stage of development by 5,400 y. B.P. (from Hauerbach, 1992).

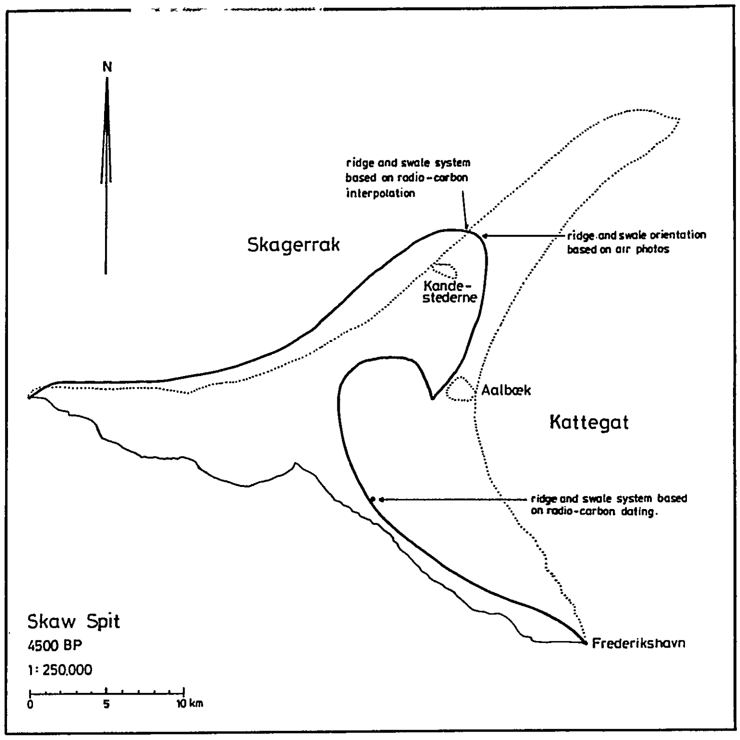


Figure 13. The map indicates the stage of development by 4,500 y. B.P. (from Hauerbach, 1992).

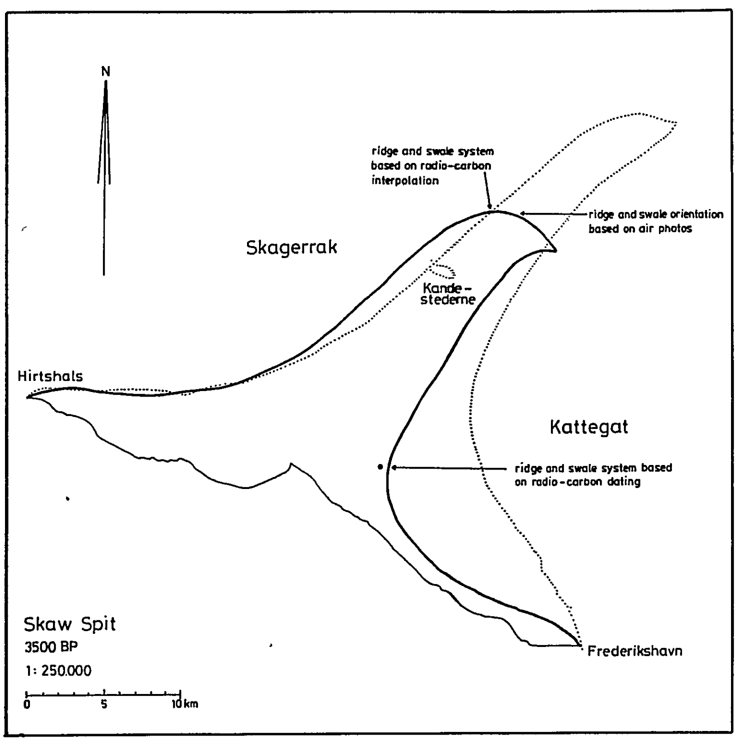


Figure 14. The map indicates the stage of development by 3,500 y. B.P. (from Hauerbach, 1992).

7. SEDIMENT TRANSPORT AND BUDGET

The growth of the Skagen Spit is a consequence of its position at the confluence of two major wave systems, The Skagerrak and the Kattegat. The wave climate at the Kattegat coast is mild compared to that found at the Danish West coast, due to relatively limited fetches found in the Kattegat. The northern coast today is accreting by up to 8 m/year (Foster & Jensen, 1990). Not all of the westcoast transport is deposited onshore as demonstrated by a very large offshore deposition area to the NE of the spit head (Foster & Jensen, 1990). The accretion bands can be seen clearly to the north of Skagen (fig. 15 and enclosure 3). They are nearly parallel, indicating that the coastline has maintained its present orientation for a considerable period. The offshore bathymetry is characterised by two main shore parallel bars (fig.15).

Figure 15. The two main offshore bars and the accretional bands at the north tip of the Skagen Spit. (Aero-map of 1986). From Foster & Jensen, 1990.

The south east coast is an area of moderate erosion. Though the total transport here is much smaller than the encountered on the westcoast, it is significant with respect to maintaining the the orientation of the spit. Looking at the development of the North Sea coast to the south and southwest of the Skagen Spit (fig 16) it appears, that the net longshore sediment transport north of the outlet of the Limfjord into the North Sea, in general, is in the direction of Skagen against the northeast.

Sediment budgets and the longshore transport variation from Tversted to Skagen Nordstrand has been compared with the fluctuations of the coast line from 1986 to 1992 by Hansen & Langballe, (1993). See enclosure 10. In addition to the Skagen Spitt it appears that deposition takes place at two points - at Råbjerg Hvarre and at Spirbakke. The net sediment transport capacity at Gl. Skagen (Station 1130, encl. 10) is in the latter period estimated to 1.092.733 m^3/year. The development of the coastal transport capacity at this station from 1954 until 1991 appears from table 1.

periode	energi-resultant KJ fra (°)	transport m^3/år mod 49°	transport m^3/år mod 229°	NETTO transport m^3/år (retning)	balance m^3/år
1954-64	42.915.324 (300°)	1.085.216	88.937	996.279 (49°)	-9.228
1964-69	58.425.576 (299°)	1.537.044	120.594	1.416.450 (49°)	-17.913
1969-75	62.442.124 (300°)	1.627.000	179.758	1.447.242 (49°)	-24.624
1975-81	49.227.612 (301°)	1.260.313	166.224	1.094.089 (49°)	-27.803
1981-86	48.122.928 (300°)	1.246.115	161.280	1.084.835 (49°)	-32.018
1986-91	41.755.280 (300°)	1.092.733	139.270	953.463 (49°)	-31.056

Table 1. The transport capacity at Gl. Skagen (station 1130) from 1954 to 1991. The largest transport is obtained at wind directions from 274° and 4°. The balance is estimated as the difference in net transport between stat. 1190 and 1130. From Hansen & Langballe, 1993.

The net longshore sediment transport at the south east coast between the town of Skagen and the tip is about 40.000 m^3/year due to a northgoing net transport.

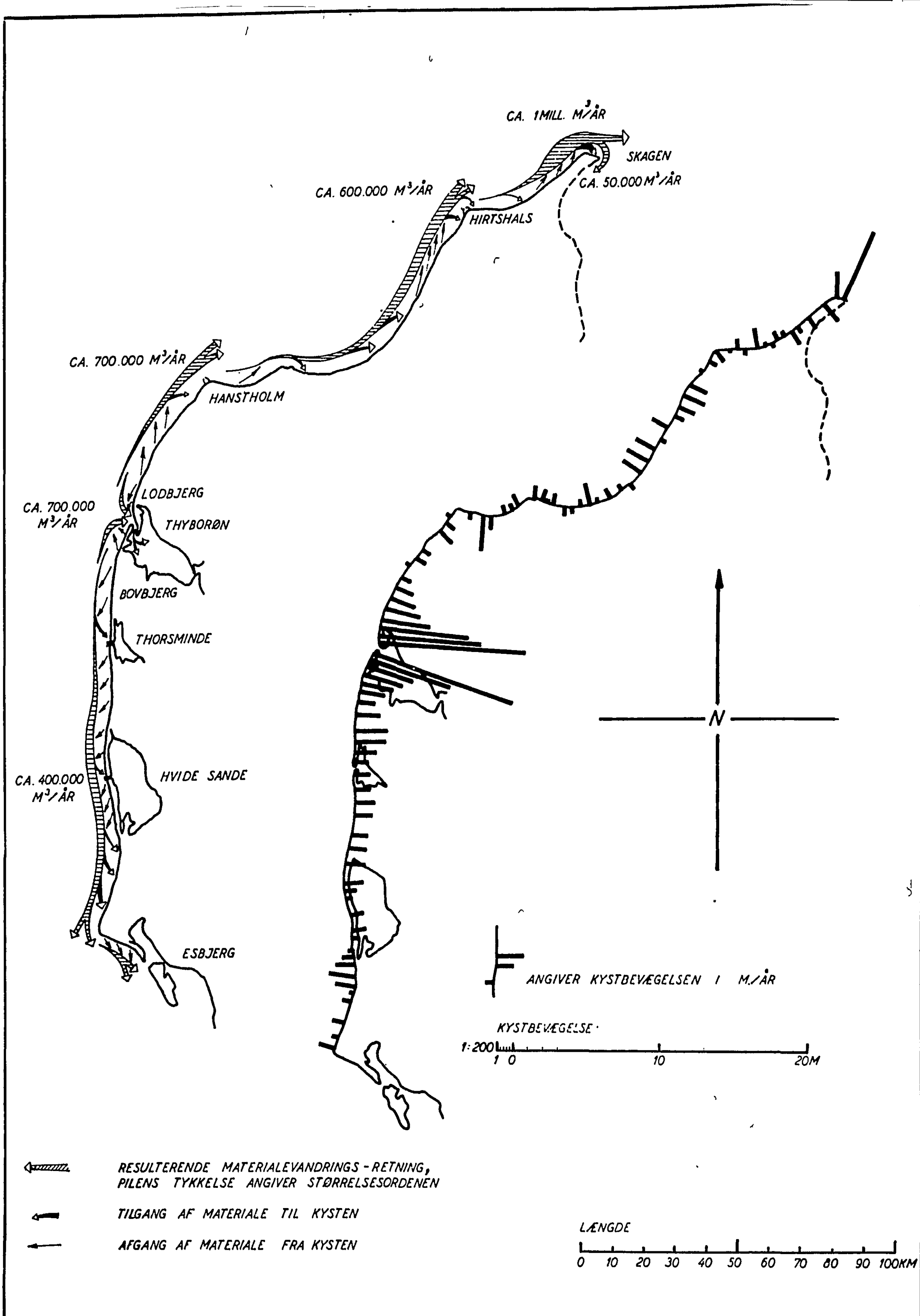


Figure 16. The left side: net sediment transport and direction at the westcoast of Jutland. Arrows indicate erosion of or deposition at the coast. The right side: Coastal displacement measured in mm/year. The database is averaged values from the century 1868-1968. From Nielsen & Nielsen, 1982.

The natural littoral transport capacity of the southeast coast today has been reduced by coastal protection works between 1970 and 1979. The most of the northgoing transport component arising mainly from small waves is today efficiently reduced by the breakwaters blocks. The southgoing transport component arises mainly from large amplitude, short duration waves, and therefore the breaker zone tends to be in front of the breakwaters. The transport pattern is thus relatively unaffected by their presence.
Figures 17 and 18 below illustrates the change in the sediment budget at the SE coast from the unprotected coast in 1961 to the protected coast during 1979-1989.

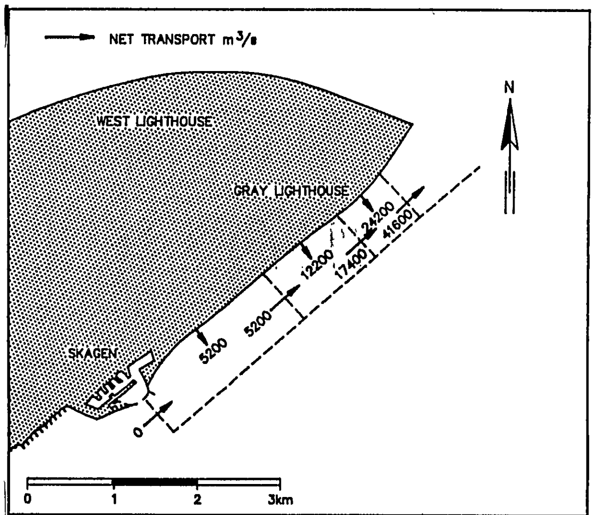


Figure 17. Sediment budget for the 1961-coast. From Foster & Jensen, 1990.

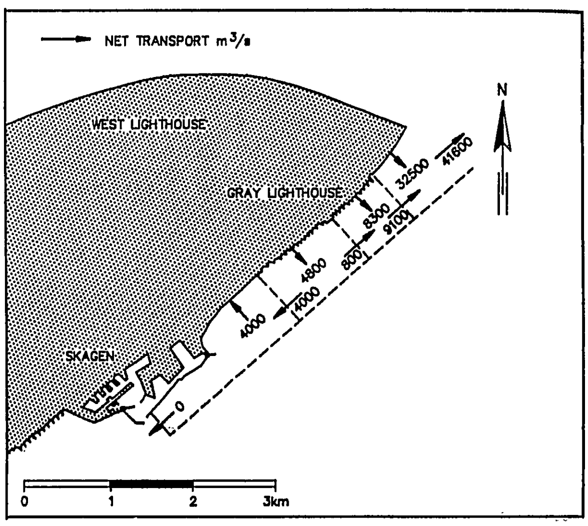


Figure 18. Sediment budget for the 1979-1989 coast. From Foster & Jensen, 1990.

During the Holocene the source areas for the longshore sediment transport supplying the Skagen Spit have changes. The one agent of sediment supply has derived from the coastal erosion at the west coast of Jutland like today (possibly some kilometres more westward than the present). Another agent might have derived as a result of coastal erosion of the subaerial archipelago of glacially deposits at the Jutland Bank and the Little Fisher Bank area (Leth, 1996). A predominately tidally influenced environment has until the time of flooding of the residual glacial islands mobilised huge amounts of sediment as a source for the later bed load/longshore transport against the north. Not until the time of flooding the hydrographical system like the present with the longshore Jutland Current has been established.

8. THE DEVELOPMENT OF A COARSE GRAINED SPIT-PLATFORM

Terminology of spit formation

A spit is a ridge or embankment of sediment attached to land mass at one end and terminating in open water at the other. It is younger than the land mass to which it is attached. According to Meistrell (1972) and Kumar & Sanders (1974) the 'spit-platform' is a large-scale primary sedimentary structure formed by sediment transport along the coast rising over the shelf but below the mean low tide. A 'spit' is a sediment ridge on the spit platform, partly elevated over mean low tide. The platform is established in advance of the spit formation.

Meistrell (1966, 1972) has demonstrated that sediment upon reaching deeper water at the end of a 'headland' beach was deposited in a successive series of foreset beds. This physical extension of the beach is the beginning of the platform structure. As the platform continued to increase in length three major characteristics occur: 1) the depth of the water above the platform remain constant irrespective of irregularities in the shelf topography, 2) the structure is basically composed of foreset and topset beds and 3) a spit ridge is formed on the top of the platform. Dynamically, in general, the growth of the spit and platform structure are inversely related and occur in alternating cycles. Thus, when the rate of the platform declines, the spit grows uniformly, whereas the platform grows uniformly, the rate of growth of the spit declines.

Nielsen et al. (1988) has developed a three-dimensional morphological-sedimentological model for coarse-grained spit systems prograding into deep water (fig. 19). The study is based on a Late Pleistocene coarse-grained spit-platform sequence in Vendsyssel, northern Jylland.

This model, however, describes mechanisms of deposition and spit platform structures similar to those acting at the time of development of the Skagen Spit system. Even the present depositional processes offshore the spit presumably can be described as a coarse-grained spit-platform progradation.

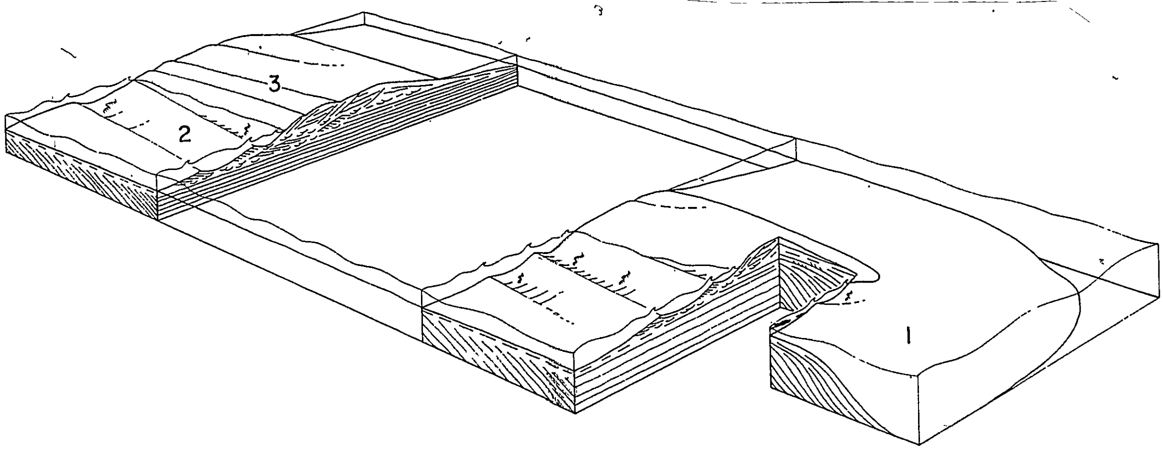


Figure 19. Dynamic three-dimensional morphological-sedimentological model for coarse-grained spit systems prograding into deep water: 1. Spit platform; 2. Oblique bar-trough system; 3. Spit, beach. From Nielsen et al., 1988.

In the constructive phase of the development of a spit system, obliquely incoming waves will create an oblique bar-trough system on the platform in the surf zone along the seaward side of the spit. Sand is transported forward to the edge of the platform by trough currents and migration of bars, while pebbles is transported in the swash-backwash zone along the spit coast. New giant-scale foresets are formed by avalanche down the steep platform front causing a progradation of the platform.

As a result of erosion of the mainland, the spit system will be eroded in the proximal end, as fast as the coast on the mainland retreats. Futher ahead along the spit there is a balance between erosion and deposition. Net deposition will occur where the coast begins to turn away from the sea and towards the bay. As a result of the bending of the coast, the waves will be refracted causing a reduction of the wave energy per unit length of the coast. At the same time there is an expansion of the coast-parallel currents over the platform, because the controlling effect of the subaerial spit gradually ceases. This combination causes high sedimentation on the platform along the end of the spit, implying that the 'refracted' bars will be wider and longer and the troughs shallower. This modification of bars and troughs will be more and more extensive, the more the spit coast bends away from the sea.

From the point on the spit coast where the bar-trough system begins to bend around the tip of the spit, and to the point where the bar-trough system is destroyed, the bars will migrate towards and weld onto the spit coast. In this manner successive bars will contribute to a seaward progradation of the spit tip. An idealised sequence for this part of the spit system will consequently consist of giant sandy foreset and topset overlain by sediments deposited in the bar-trough system. Gradually, as the bars migrate up to the shoreface, they will emerge and become swash bars, with swash-backwash lamination generated on their seaward side.

The water depth in which the spit system progrades and thus bottom topography, determines the thickness of the giant-scale cross-bedded foreset unit because the water depth over the top of the platform is relatively constant. The correct recognition of spit-platform sequences allows precise determination of sea-level and water depth at the time of formation.

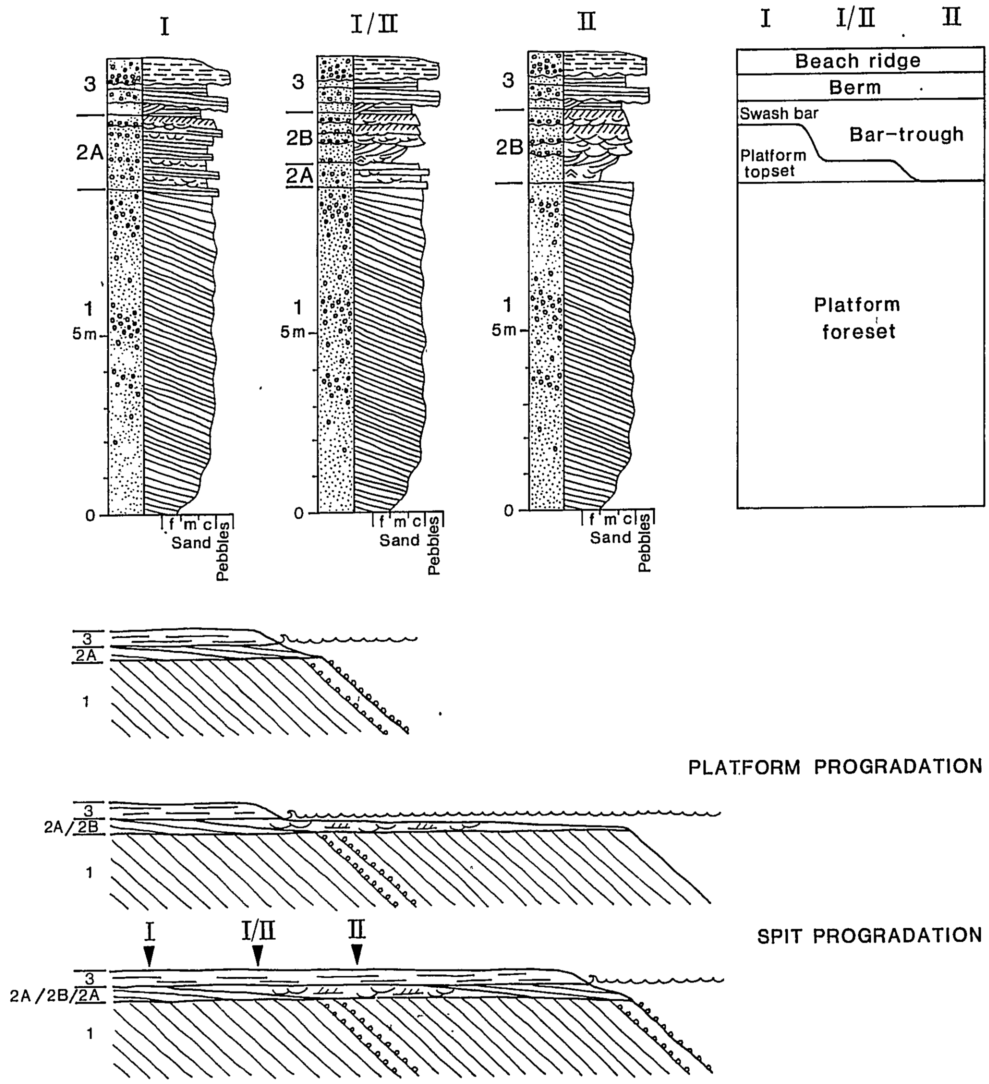


Figure 20. Dynamic model for coarse-grained spit-platform prograding into relatively deep water. Sequence I represents a situation where the spit has prograded almost to the end of the platform. The platform top is thus exclusively formed by the topset beds (unit 2A). Sequence II represents a stage of platform progradation with maximum distance from the end of the spit to the end of the platform. The platform top is thus in this case represented exclusively by the oblique bar-trough deposits (unit 2B). Sequence I/II marks a transitional stage where an oblique bar-trough system is being welded to the spit-beach and overlying the topset beds (unit 2A). Below is shown three consecutive states in platform and spit progradation showing the inversely related phases of platform and spit progradation.

An example from a georadar profile of the sedimentary structure of the Skagen Spit is presented in enclosure 11 and 12.

Enclosure 11 is an example from an area north of Gårdbo Sø. The georadar profile presents a cross-section through the spit-system. Well-developed inclining foresets with toplap and downlap indicating the platform foresets being formed by avalanching against the North is displayed. Erosion surfaces interrupting the foresets yields evidence of phases of erosion and/or changes in the direction of avalanching. The marine deposits is covered by in excess of 5 m aeolian sand (the topmost 5-6 m of the profile).

9. OBJECTS OF THE PHASE II STUDY - 'THE ANALOGUE-MODEL'

Mapping of the depositional sequences at the Skagen Spit in the light of the spit-platform progradation is one of the main goals of the second phase of the analogue study. By adding data on relative sea level changes and the depositional sequences, by studying the present sediment transport and by adding more C-14 datings the present level of knowledge presented in the Phase I report will be increased. The importance of the analogue-model as a part of a course-programme has been taken into account in the planning.

On-shore the mapping is planned to be carried out as follows:

- **Logging** of 4-8 profiles at the westcoast of the spit including sedimentological facies to describe the lateral variations of the spit-platform.

- **Sampling** for bio-stratigraphic purposes (palaeo-environmental interpretations from analysis of the foraminiferal and molluscan faunas) and for **C-14 datings**.

- **Georadar mapping**. By applying georadar it will be possible to distinguish between different lithologies. On continuous records throughout the spit it also will be possible to recognise different large-scale sedimentary structures from the spit-platform sequences to a depth of between 10-20 m. Additionally, by a detailed georadar mapping inside a specific area of the spit-platform. Giant scale platform foresets with a maximum thickness of about 5-6 m has been descriped from geo-radar profiles north of Gårdbo Sø (Enclosure 11 and 12). will be attempted to set up a 3-D model for the progradational spit-platform using mapping software. By adding granulometric well-data and a number of C-14 datings the 3-D model will appear as a sequence of the spit development at a certain time.

To support the interpretation of the sediment distribution and the dynamic development of the spit it is suggested to make a few borings after interpreting the georadar profiles.

Off-shore mapping is planned as follows:

High-resolution shallow seismic mapping will be applied in two areas (Fig. 21) for two different purposes.

- **mapping of the offshore continuation of the spit-platform.** Off the Skagen Spit the presumed recent spit-platform progradation can be mapped by use of high-resolution seismic equipment (e.g. watergun, boomer and 3.5 kHz -profiler). The goal is to map the proposed giant-scale cross-bedding until the spit-platform front. A side scan sonar mapping of the seabed in the area of the platform progradation make it is-possible to observe sediment transport mechanisms by studying the bed-form morphol-

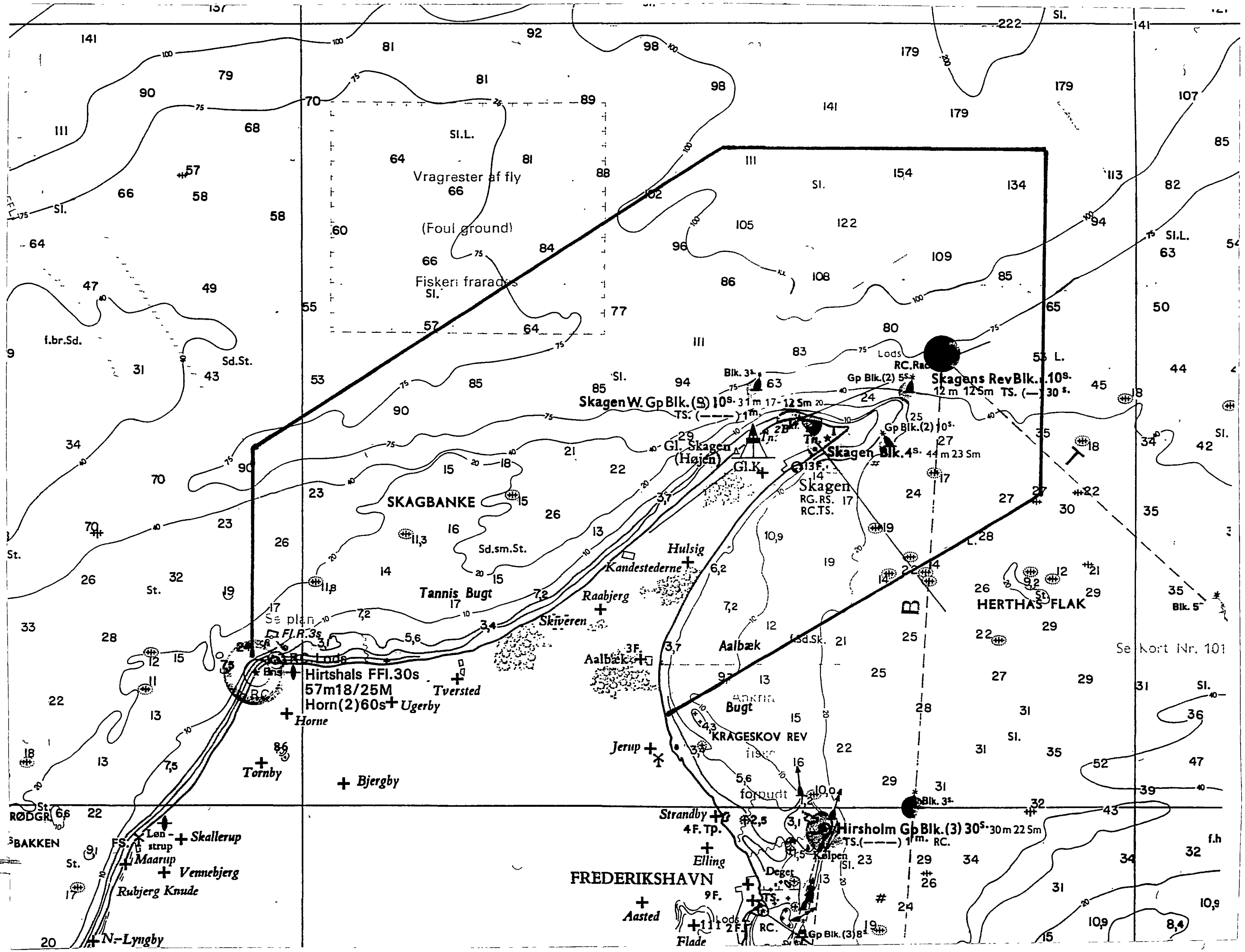


Figure. 2. The limits of the proposed marine seismic survey area.

ogy. Additionally a series of 6 m vibrocores allow interpretations of sedimentological parametres and support the spatial facies distribution.

- **mapping of a proposed submerged spit off Hirtshals.** From the bathymetry at Skagbanke north of Hirtshals a shallow water area can be observed. Emerging glacial grounds at the seabed might have governed the growth of a spit parallel to the Skagen Spit system. Knowing that the Hirtshals area has a similar isostatic rebound as the Skagen Spit area the study of a proposed drowned spit-platform system at Skagbanke might contribute to the understanding of the Skagen Spit development.

A further contribution to the analogue-model is the study of the Skagen Spit development in a regional scale. The Holocene development at the Jutland Bank area (fig. 22) has recently been studied at GEUS. As already discussed in the present report the development of this area during the Holocene might have been one of the agents governing the hydrography in the NE part of the North Sea. An achipelago-like structure of emerging islands of glacial deposits had an obstructive effect to the establishment of longshore currents like the present. Figure 23 shows a palaeo-geographic map of the glacial surface in the Jutland Bank area in a 3-D view.
By coastal processes at the Jutland Bank during the Early Atlantic transgression huge amount of sand have mobilised for a northward longshore coastal and bed load transport.

A comparison of this area to the Skagen area during the Holocene is very essential in the light of isostacy/eustacy. Having the considerable rate of isostatic rebound at Skagen in mind it is useful for the analogue study to compare the development at Skagen with the Jutland Bank representing an area of a much lesser isostatic rebound.

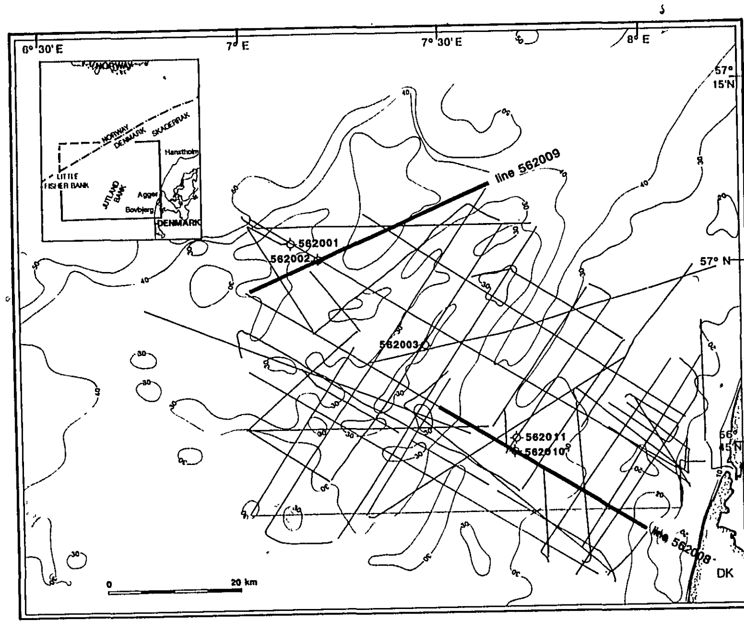


Figure 22. Bathymetry and location map of the Jutland Bank showing the seismic lines of the area. Water depths is in metres. From Leth, 1996.

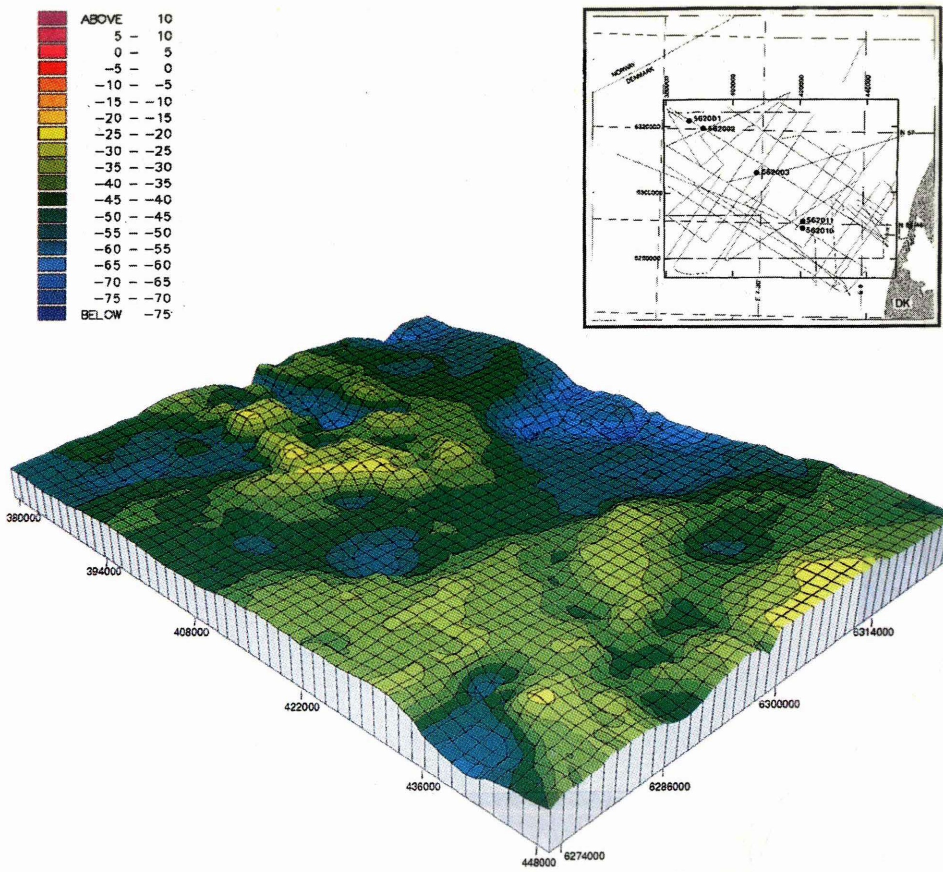


Figure 23. 3-D view glacial contour map showing the modified topography of the glacial surface in the Jutland Bank area. View from the southeast to the Northwest across the study area. Contour interval, 5 metres. The numbers on the sides indicate UTM eastings and northings (UTM-zone 32). From Leth, 1996.

Another important object in the of the analogue-study is the assessment of the sediment mass balance. During the mapping of depositional spit sequences it will be attempted to map ‘time-lines’ (chronostratigraphic surfaces) i.e. sequences related to a well-defined depositional time interval in the Holocene regressive development. From this point an estimation of the sediment volume attached to the time-specific sequence is possible. The total amount of sediment deposited is the sum of the sediment supply due to long-shore processes at the eastcoast and the westcoast and the amount of reworked sediment. That is, the difference between of the preserved sediment volumes from one time to another is related to changes in the depositional processes and sediment magnitude of sediment supply.

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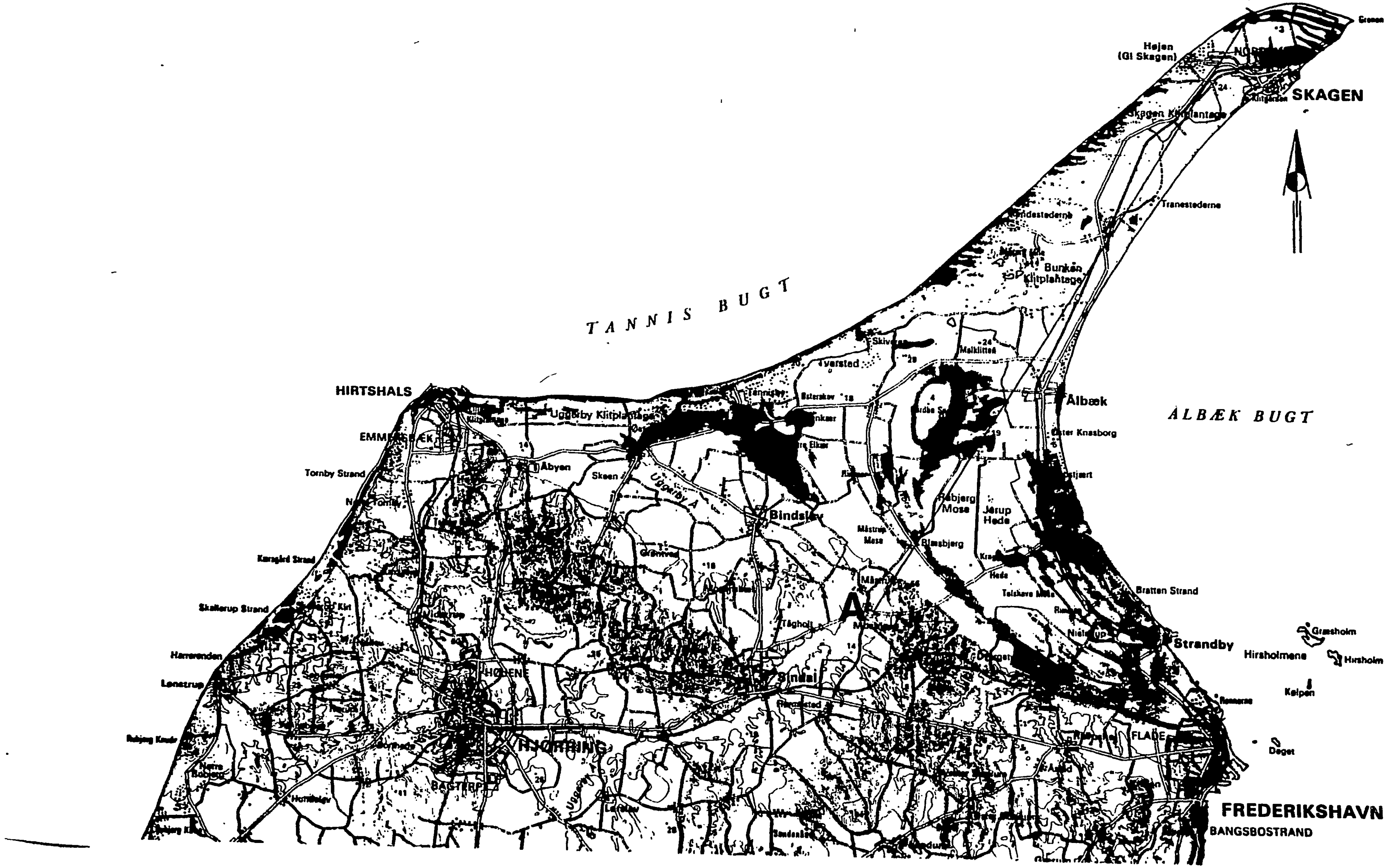
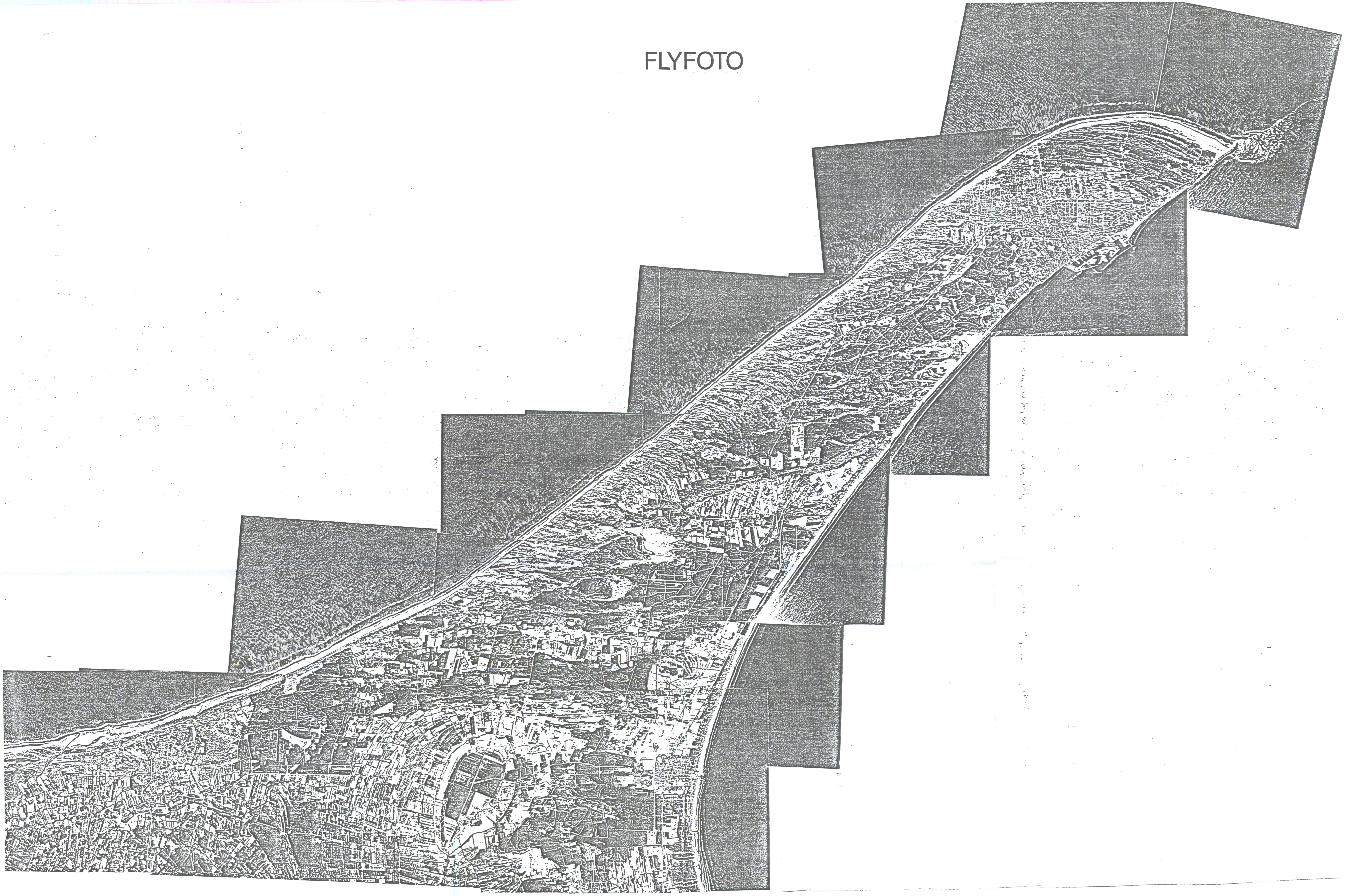
ENCLOSURE 1



SKAGEN
Grenen
Højen
(Gl Skagen)
Skagen Klitplantage
Tranestederne
Bunken
Klitplantage
TANNIS BUGT
ÅLBÆK BUGT
Ålbæk
Øster Knasborg
HIRTSHALS
Uggerby Klitplantage
Tornby Strand
Åbyen
Skeen
Uggerby Å
Bindslev
Råbjerg
Mose
Jerup
Hede
Måstrup
Mose
Bratten Strand
Strandby
Hirsholmene
Græsholm
Hirsholm
Kølpen
Deget
Karrgård Strand
Skallerup Strand
Harerenden
Lønstrup
Rubjerg Knude
HJØRRING
Sindal
FLADE
FREDERIKSHAVN
BANGSBOSTRAND

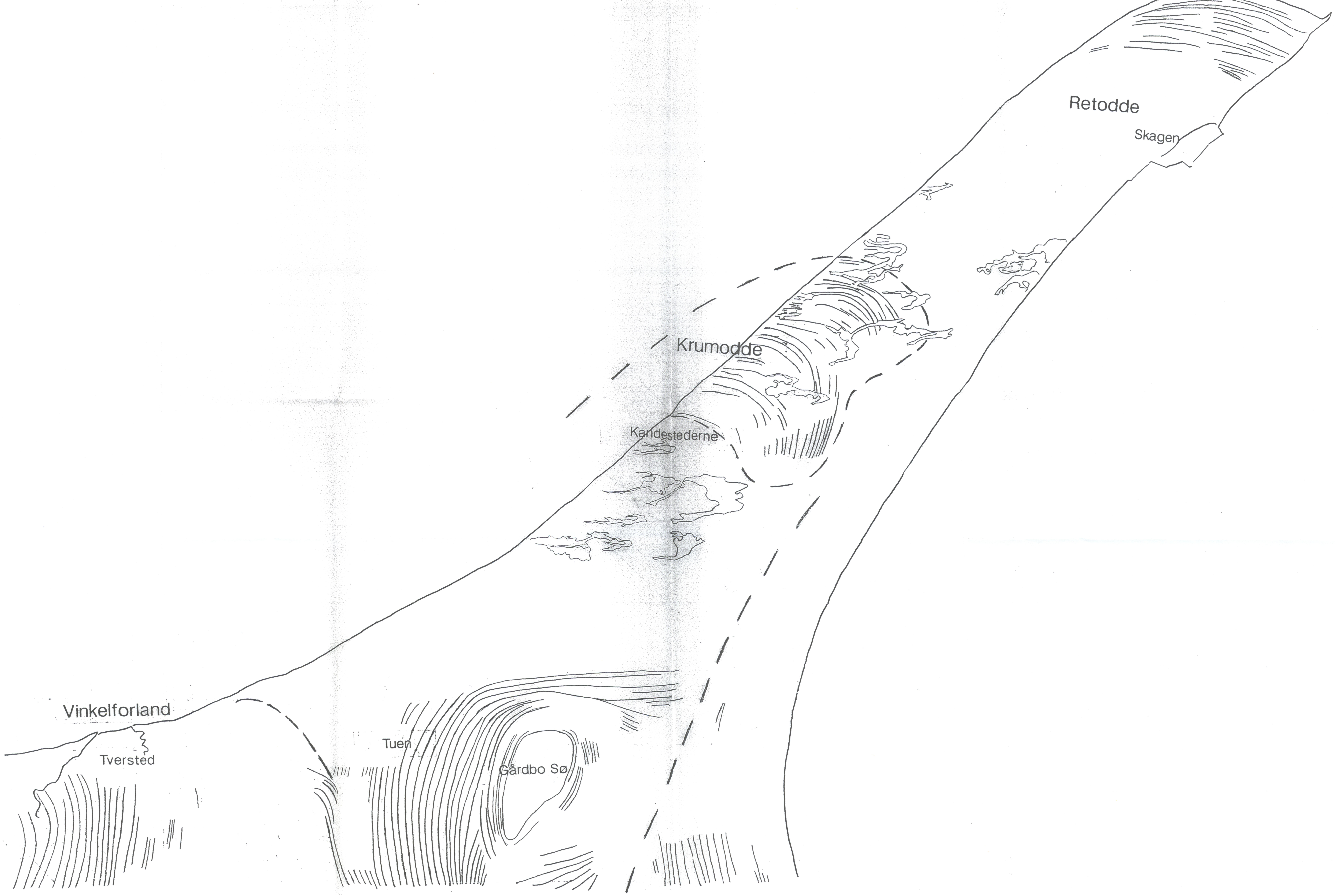
ENCLOSURE 2

FLYFOTO



ENCLOSURE 3

MORFOLOGISKE HOVEDTRÆK

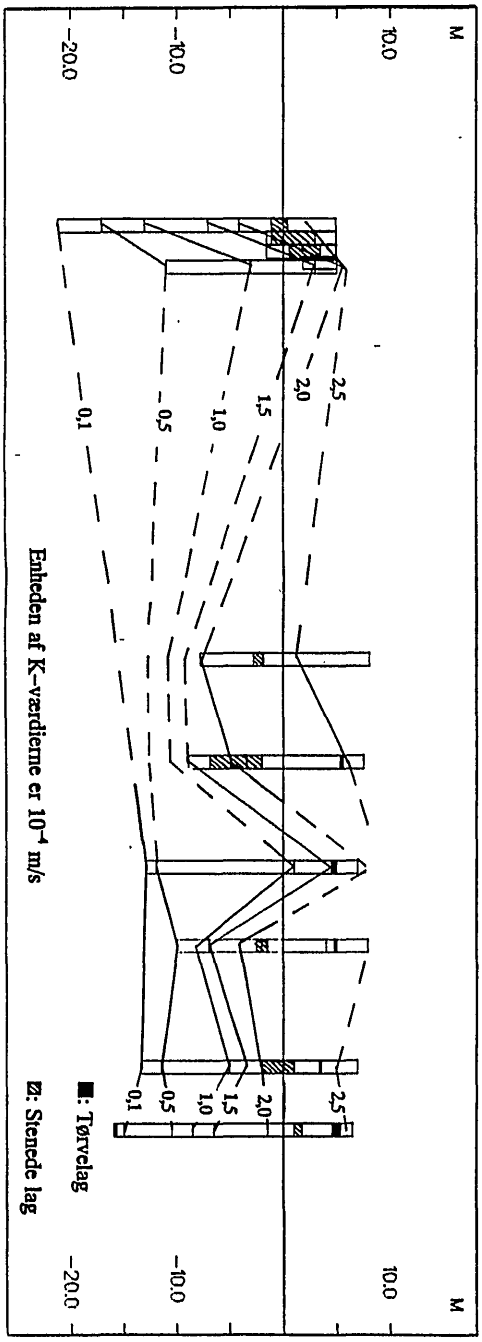


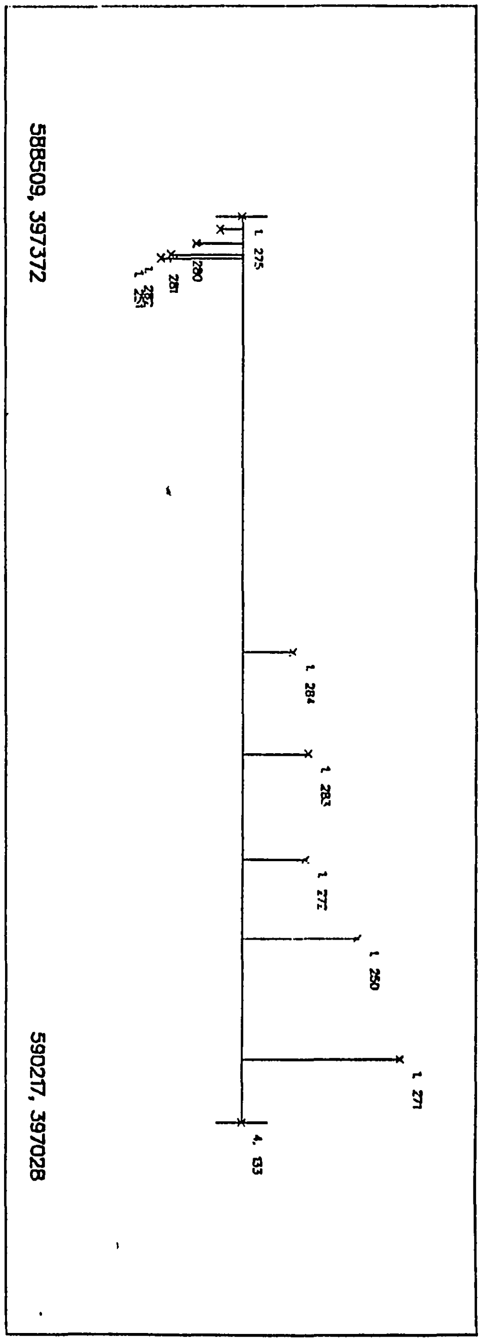
ENCLOSURE 4-8

Profil 1, K (VNV–ØSØ)

Længdemålestok: 1:10000
Højdemålestok: 1:500
Højdelinie: 0 m over DNN
Båndbredde: 700 m

DGU Danmarks Geologiske Undersøgelse 12/ 5 1992

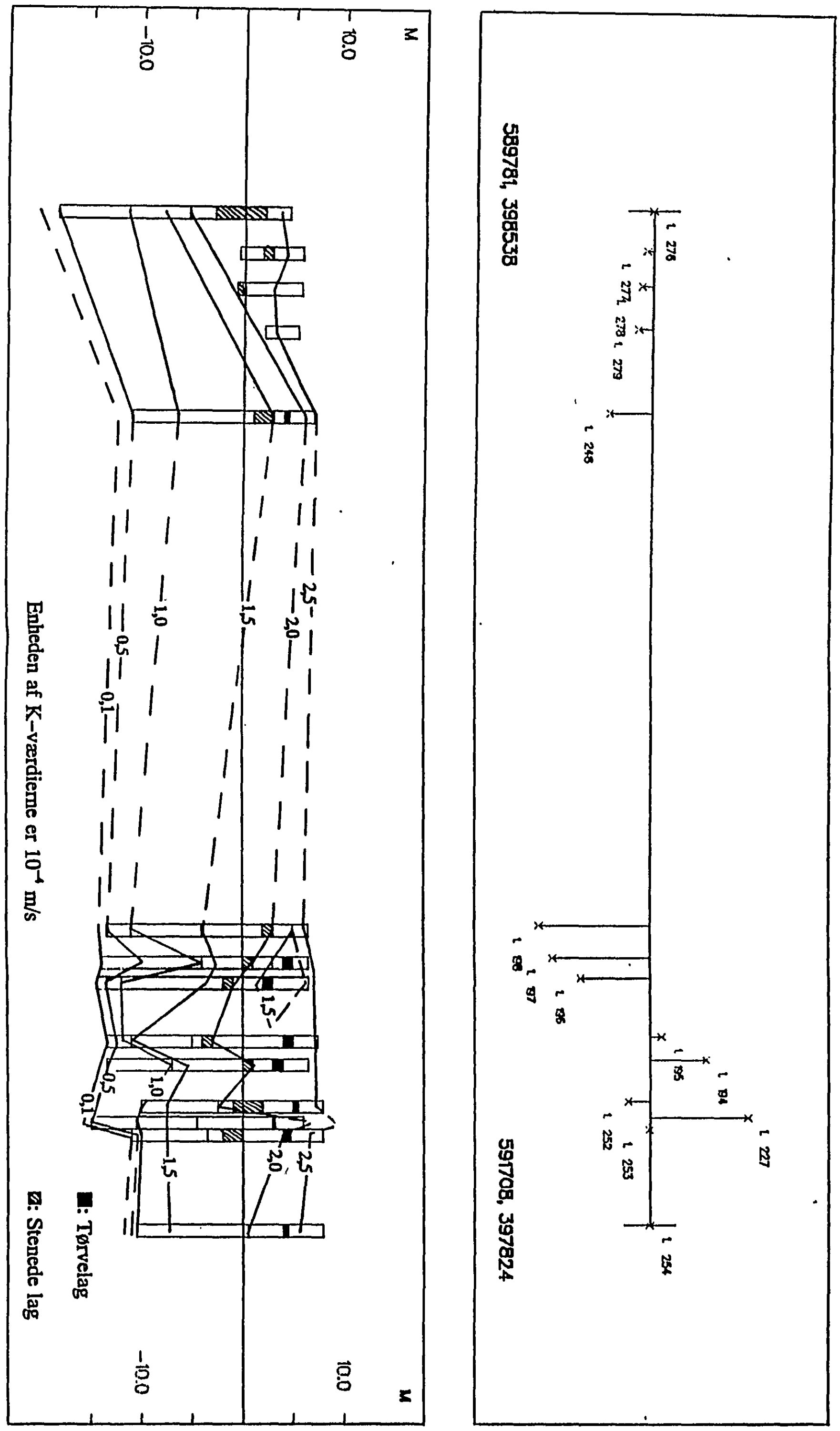




Profil 2. K (VNV–ØSØ).

Længdemålestok: 1:10000
Højdemålestok: 1:500
Højdelinie: 0 m over DNN
Båndbredde: 500 m

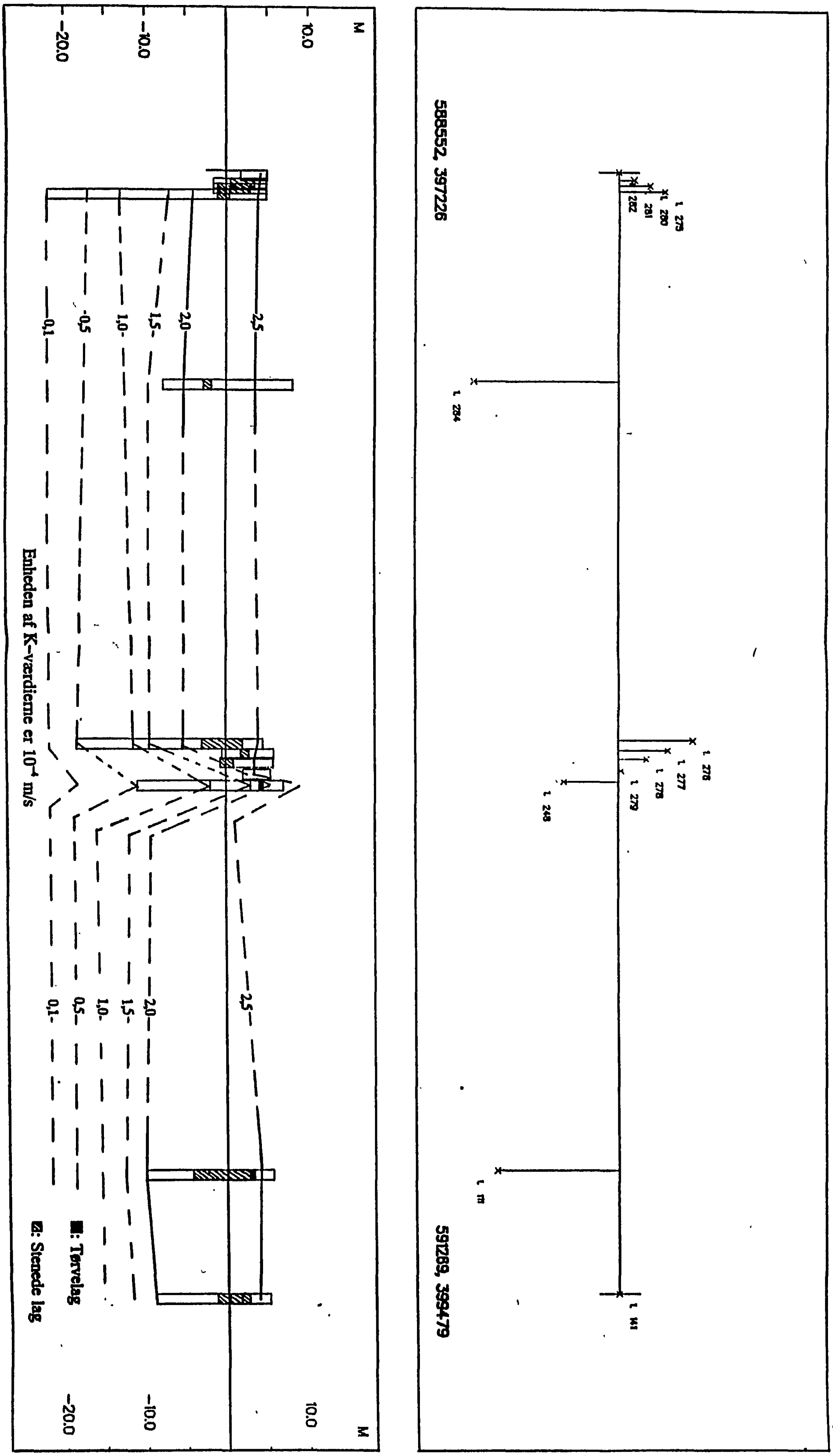
DGU Danmarks Geologiske Undersøgelse 9/ 6 1992



Profil 3, K (SV–NØ).

Længdemålestok: 1:12500
Højdemålestok: 1:500
Højdelinie: 0 m over DNN
Båndbredde: 1000 m

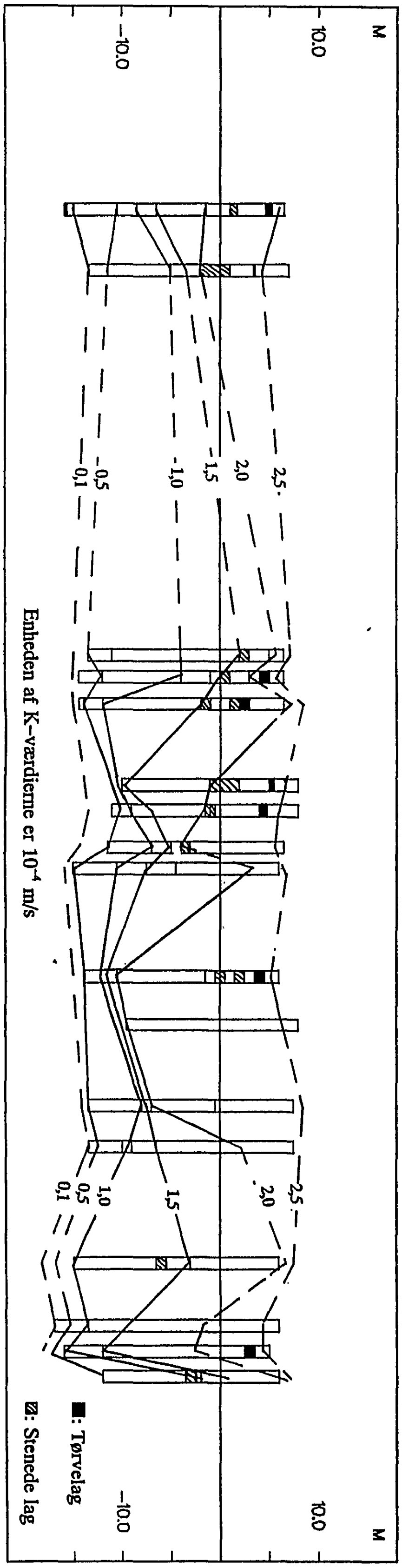
DGU Danmarks Geologiske Undersøgelse 29/ 5 1992

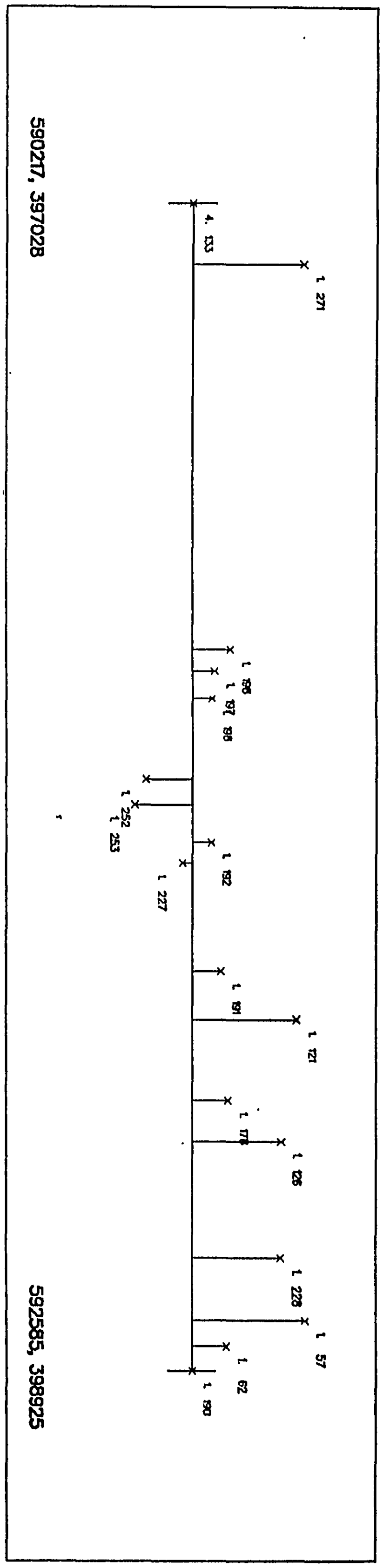


Profil 4. K (SV–NØ).

Længdemålestok: 1:12500
Højdemålestok: 1:500
Højdelinie: 0 m over DNN
Båndbredde: 700 m

DGU Danmarks Geologiske Undersøgelse 29/ 5 1992

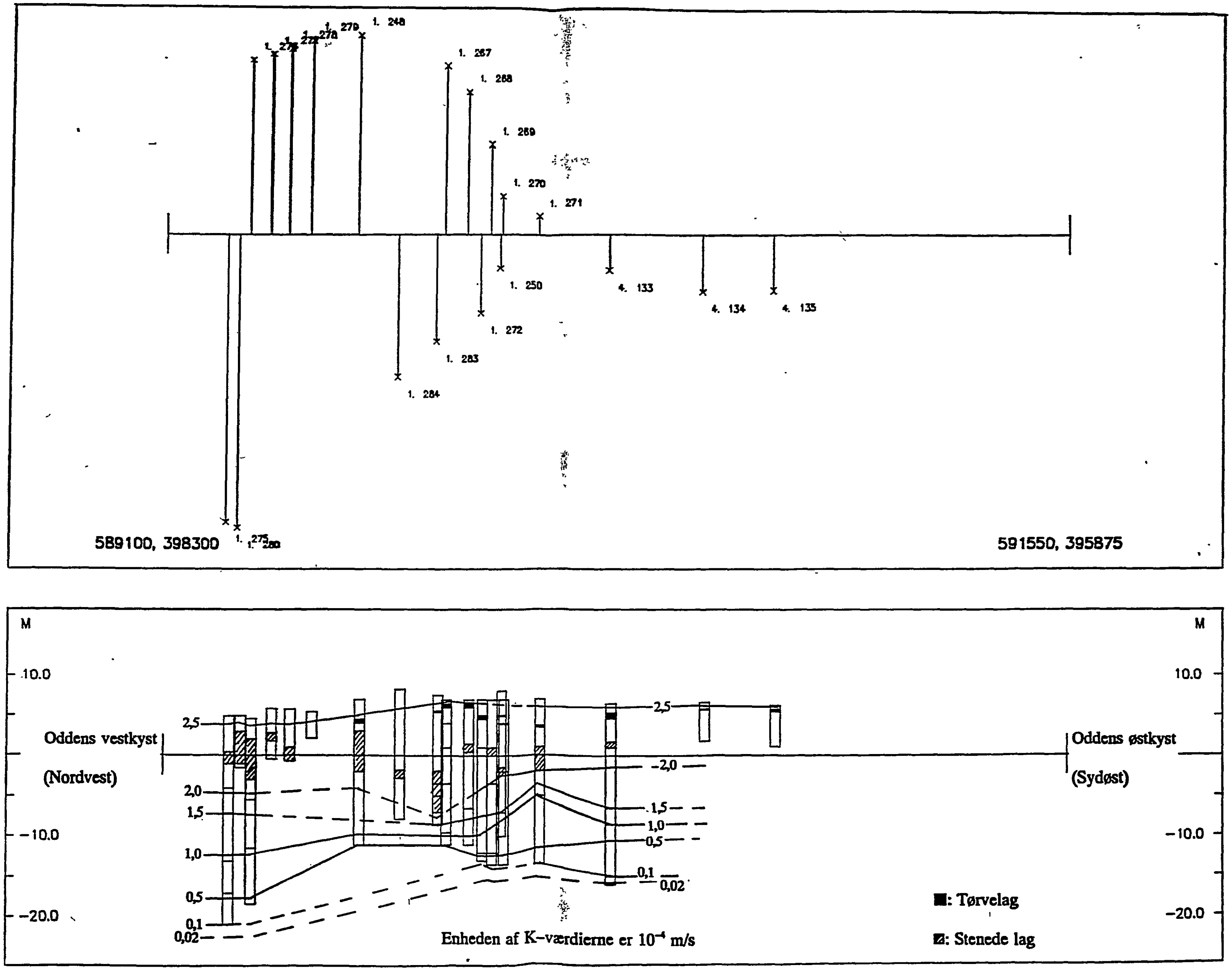




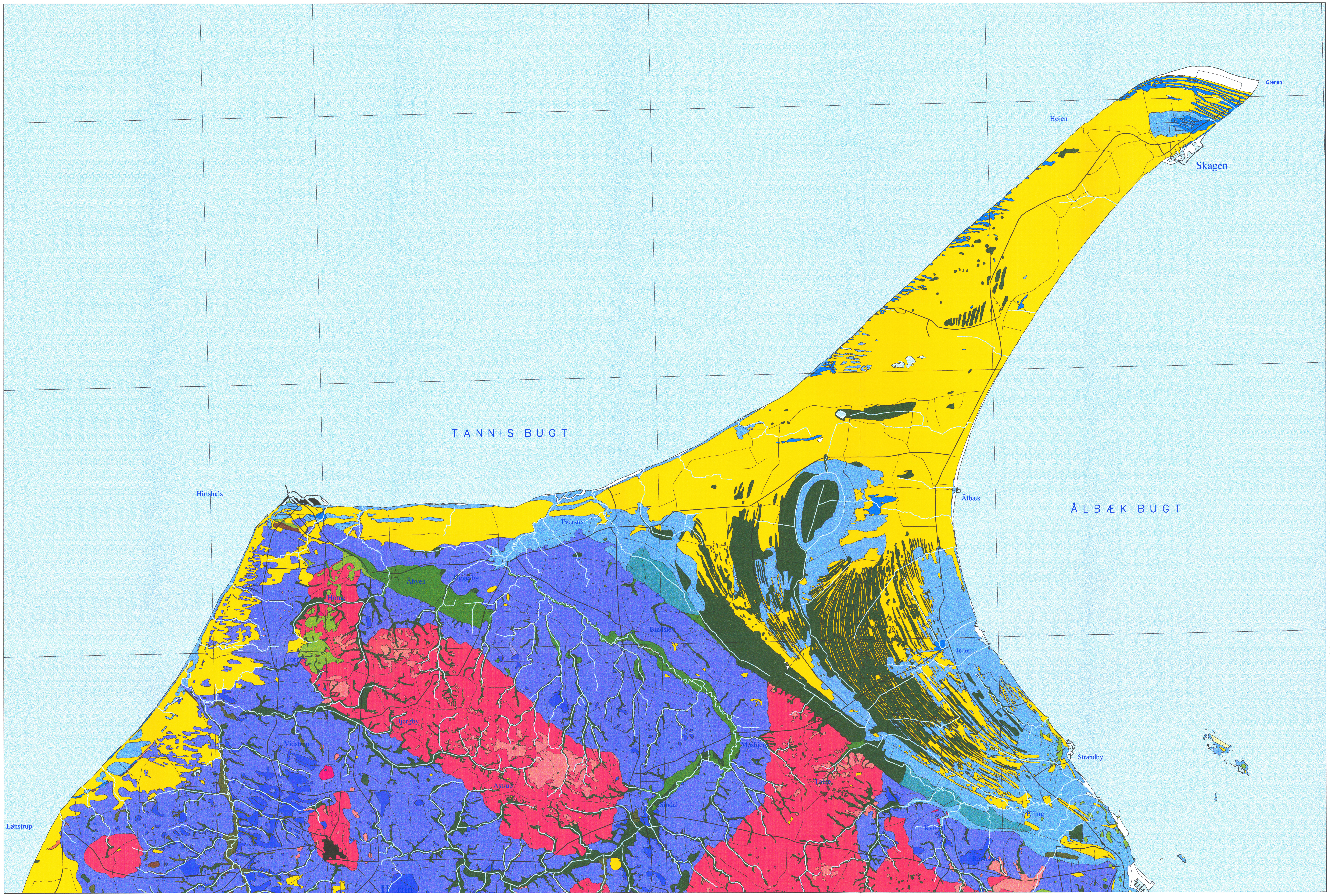
Profil 5, data fra hele kildeplads 2V projiceret ind på profilet.

Længdemålestok: 1:15000
Højdemålestok: 1:500
Højdelinie: 0 m over DNN
Båndbredde: 2200 m

DGU Danmarks Geologiske Undersøgelse 28/10 1992



ENCLOSURE 9



POSTGLACIALE JORDARTER

- FG - ferskvandsgrus
- FS - ferskvandssand
- FI - ferskvandssilt
- FL - ferskvandsler
- FP - ferskvandsgytje
- FT - ferskvandstørv
- FV - vekslende ferskvandslag
- FK - kildekalk, mose- og søkalk
- FJ - okker og myremalm
- HG - saltvandsgrus
- HS - saltvandssand
- HI - saltvandssilt
- HL - saltvandsler
- HP - saltvandsgytje
- HT - saltvandstørv
- HV - veksl. saltvandslag, marsk
- EI - løss
- ES - flyvesand

SENGLACIALE JORDARTER

- TG - ferskvandsgrus
- TS - ferskvandssand
- TI - ferskvandssilt
- TL - ferskvandsler
- TP - ferskvandsgytje
- TT - ferskvandstørv
- TV - vekslende ferskvandslag
- YG - saltvandsgrus
- YS - saltvandssand
- YI - saltvandssilt
- YL - saltvandsler
- YP - saltvandsgytje
- YT - saltvandstørv
- YV - vekslende saltvandslag

GLACIALE JORDARTER

- ZG - issøgrus
- ZS - issøsand
- ZI - issøsilt
- ZL - issøler
- DG - smeltevandsgrus
- DS - smeltevandssand
- DI - smeltevandssilt
- DL - smeltevandsler
- DV - vekslende smeltevandslag
- MG - morænegrus
- MS - morænesand
- MI - morænesilt
- ML - moræneler
- MV - vekslende morænelag

INTERGLACIALE JORDARTER

- IG - ferskvandsgrus
- IS - ferskvandssand
- II - ferskvandssilt
- IL - ferskvandsler
- IP - ferskvandsgytje
- IT - ferskvandstørv
- IV - vekslende ferskvandslag
- ID - ferskvandsgytje, kiselgur
- IJ - okker
- QG - saltvandsgrus
- QS - saltvandssand
- QI - saltvandssilt
- QL - saltvandsler
- QP - saltvandsgytje
- QT - saltvandstørv
- QV - vekslende saltvandslag

G=grus,K=kalk/kridt,L=ler
P=gytje,S=sand,T=tørv,X=ukendt

- mindre vej
- kommunevej
- landevej
- motor/trafikvej
- motorvej
- vandløb

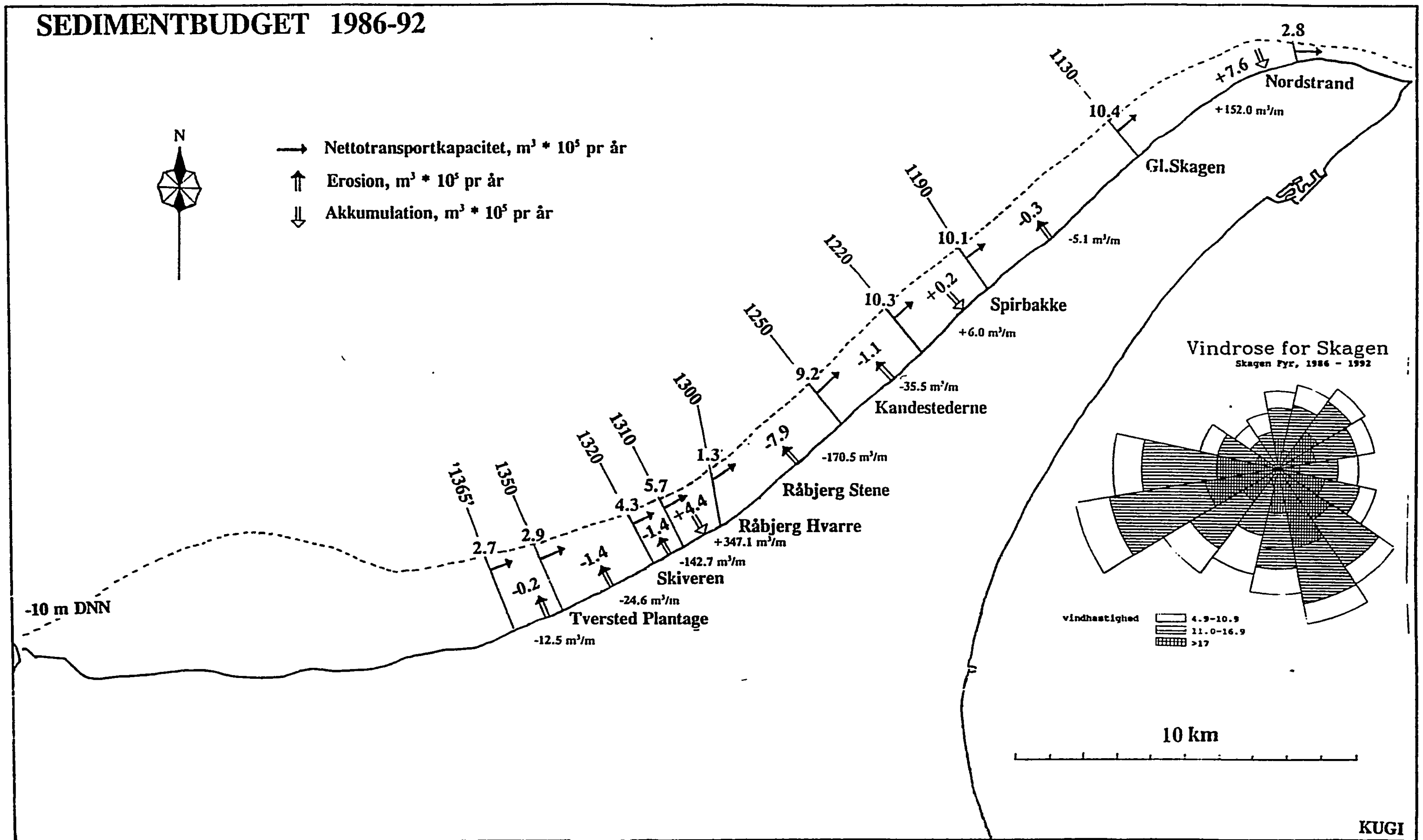
Målestoksforhold 1:50000

ZETA V4.0

DANMARKS OG GRØNLANDS
GEOLOGISKE UNDERSØGELSE
Miljø- og Energiministeriet

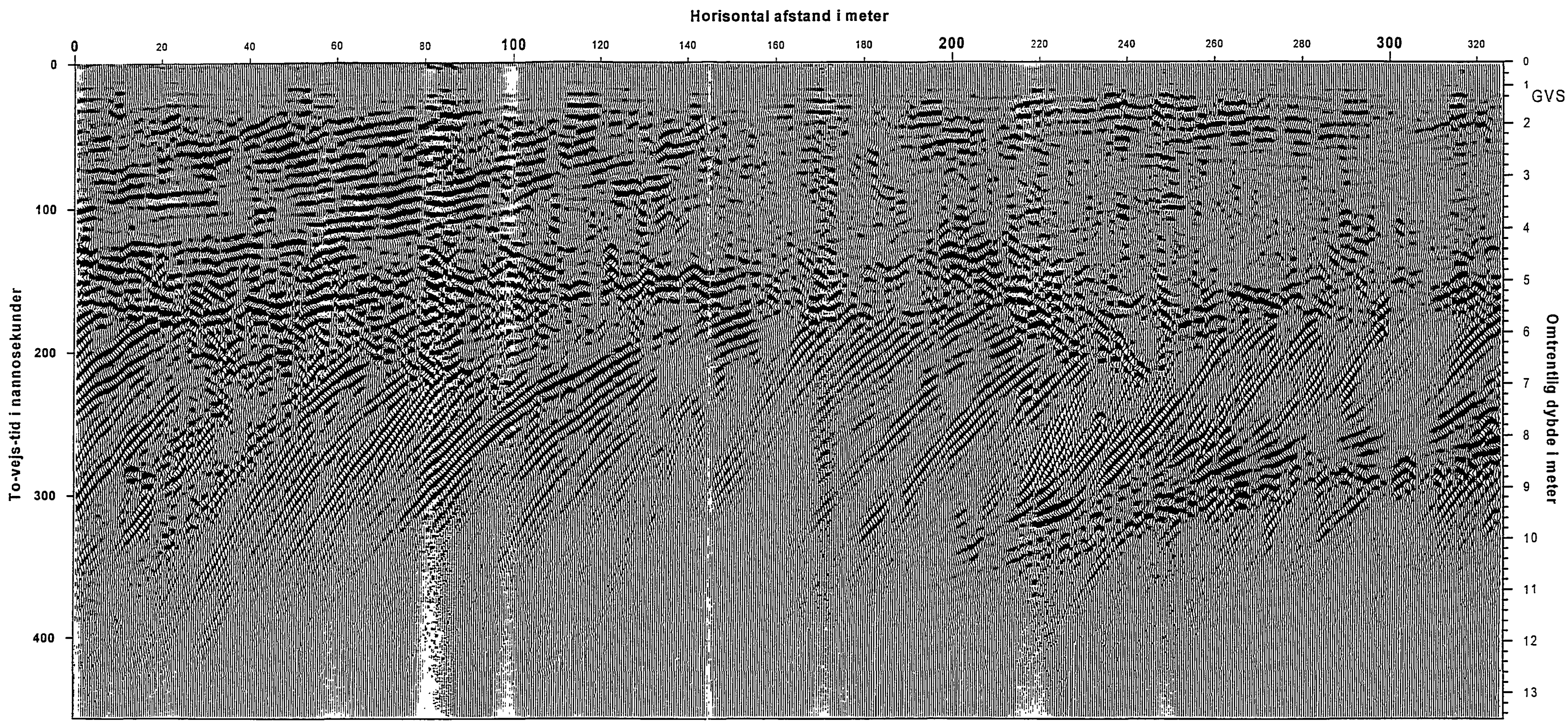
ENCLOSURE 10

Encl. 10



KI-LINJER	1450	1430	1350	1310	1250	1220	1130	
	-14 m	-69 m	+ 8 m	-15 m	-10 m	- 3 m	-13m	Kystlinjebevægelser 1986-92 i følge flyfotoanalyse
	3.8 m	0.5 m	2.3 m	5.8 m	22.8 m	7.8 m	11.5 m	Klit/klinthøjde
	-8.9 m³/år	-5.8 m³/år	+3.1 m³/år	-14.5 m³/år	-38.0 m³/år	-3.9 m³/år	-24 m³/år	Klit/klint ændringer 1986-92

ENCLOSURE 11



SKAGEN ODDE - Opmåling med georadar i område nord for Gårdbo Sø. De marine aflejringer er i dette område dækket af mere end 5 meter flyvesand og derfor ikke tilgængelige for direkte undersøgelser. Radargrammer fra området viser imidlertid tydeligt opbygningen den kystnære del af det store oddekompleks. Dette profil viser et udsnit af oddekomplekset bestående af en sekvens af strandplaner som bygger ud mod nord (til venstre). De øverste 5-6 meter af profilet udgøres af flyvesand adskilt af mindre tørvehorisonter. Under flyvesandet ligger et velbevaret rimme-dobbe landskab bestående af strandvolde, hvis toppunkt på aflejringstidspunktet formodentlig lå i kote 2-3. De markante strandplaner fomodes at repræsentere stormsituationer. Det er almindeligt i dette område at se store reaktiveringsflader, som den der kan ses nederst til højre i profilet. Reaktiveringsfladerne formodes at repræsentere variationer i oddens udbygningsretning.

ENCLOSURE 12

40 MHz

4/60/4/0

F8P Created Jun 17,1994 14:07

1024 samples/scan 22.0132 scans/sec
Position: -121.789 nS range: 900 nS16 Bits
8 scans/meter
20 meters/mark
Range Gain -2 -2 10 26 39 47 50 50

Vert. IIR low pass N=2 F=64

Vert. IIR high pass N=2 F=16

Horiz. low pass TC=5

Horiz. Boxcar low pass N=3

Horizontal Scaling Scans/Marker: 160.0

Mul 0 Mul 0.4

Horiz. Boxcar low pass N=55

Vert. Boxcar high pass N=15

Horiz. high pass TC=64

Auto Gain N=8 G=2 TC=0

Vert. Boxcar high pass N=15

Vert. Boxcar low pass N=7

Horiz. high pass TC=64

RAABJERG, AALBAEK.

Bistatic, very high power transmitter, 8 metres after vehicle on sledge.

Distance between transmitter and receiver: 1.45 meter. Markers: 20 metres.

Mod VNV fra Lodskovvadvej (25) ad Gl Kirkevej mod 24.

23m 0m