Geological Field Trips and Maps

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Sediments and morphodynamics along the Danish West Coast from Skagen to the Wadden Sea

6th International Conference on Tidal Sedimentology, 2-5 August 2004

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Sediments and morphodynamics along the Danish West Coast from Skagen to the Wadden Sea

6th International Conference on Tidal Sedimentology, 2-5 August 2004

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Cover page Figure: Cover picture. Wash-over channel and fan at the root of the Skallingen Peninsular. Photo: Niels Vinther.

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Abstract

The primary objectives of this field trip are to demonstrate relations between process, morphology and sediments on the Danish North Sea coast from the non-tidal Skagen Odde spit with a relative sea level drop of a few tenth of mm y^{-1} to the tidal Danish Wadden Sea with a relative sea level rise of about 2 mm y^{-1} . The tidal conditions along the Danish North Sea coast changes from almost non-tidal in the north to a tidal range of about 2 m in the south. The spit-system is presented by illustrating spit forming processes of today and coastal cliffs revealing preserved sedimentary facies and structures from earlier stages. Further south, coastal erosion releases large quantities of glacial sediments from eroding cliffs. The southern part of the Danish North Sea coast consists of the northernmost part of the Wadden Sea. The exposed coasts are fringed by prominent foredunes dissected by wash-over channels. The back-barriers consist of widespread salt marsh areas. Behind the salt-marsh, tidal flats and tidal channels form the intertidal area separating the Wadden Sea barrier islands from the main land. All typical geomorphological features will be visited using terrain going vehicles, rubber dinghies and a helicopter ride.

Key words

Coastal geomorphology, sedimentary processes, sedimentary facies, non-tidal to tidal morphodynamics, coastal processes, barrier islands, coastal erosion, tidal areas, isostasy.

Program summary

The primary objectives of this four days field trip are to demonstrate relations between process, morphology and sediments on the Danish North Sea coast from the nontidal Skagen Odde spit with a relative sea level drop of a few tenth of mm y^{-1} to the tidal Danish Wadden Sea with a relative sea level rise of about 2 mm y^{-1} (Bartholdy et al., 2004). This well understood and described system illustrates the complexities of interpreting ancient systems. The tidal conditions along the Danish North Sea coast changes from almost non-tidal in the north to a tidal range of about 2 m in the south. It is a high energy coast with a diverging littoral drift system (north in the north and a south in the south). The first day concentrates on the sedimentary processes and depositional features of the Skagen Odde spit system in the northernmost part of Denmark (on the peninsula of Jutland). This part of the coast is still rebounding after the last glaciation and consists of a large prograding spit (Skagen Odde) receiving on the order of 1.5 $\cdot 10^6$ m^3 sand per year. The supply of sand is partly derived from up drift located coastal cliffs and partly from coastal erosion in the proximal part of the ca. 30 km long spit-system. Initially Skagen Odde developed as a cuspate marine foreland in front of a former sea cliff. Shallow lagoons and bays supported by submerged barriers and islands of older sediments gradually amalgamated due to sedimentation and the relative sea level fall. The spit-system possess many advantages for geomorphological and sedimentological interpretations, as the present-day spit-forming processes are well-known from historical records, and as they can be directly contrasted to the preserved sedimentary facies and structures, exposed in 1–13 m high coastal cliffs cut into the proximal to medial part of the spit-system. The second day concentrates on the central part of the west coast, coastal erosion (up to 4-6 m y^{-1}) releases large quantities of glacial sediments from eroding cliffs facing the North Sea. The released sediment forms the basis for a substantial longshore drift, building up elongated narrow bay mouth barriers in front of several micro to non-tidal lagoons. The third- and fourth-day deals with the southern part of the Danish North Sea coast which consists of the northernmost part of the Wadden Sea. This part of the coast is isostatic stable. The exposed ridges and runnel beaches are fringed by prominent foredunes dissected by wash-over channels and fans. The back-barriers consist of wide spread salt marsh areas in which strongly meandering salt marsh creeks exhibit a complete range of channel related morphological features. Behind the salt-marsh, tidal flats and tidal channels form a 5-10 km wide intertidal area separating the Wadden Sea barrier islands from the mainland. On the main land, coastal cliffs exposing old glacial deposits are separated by narrow strips of exposed salt marshes facing dikes in front of low laying former active salt marsh areas. As a rule these are located in old outwash plains from the last glaciation, in which small river estuaries connect the landward drainage system to the Wadden Sea. The drainage area leading to the Danish Wadden Sea covers approx. 5000 km^2. Seaward of the tidal inlets between the barrier islands, large ebb tidal deltas are formed offering protection to the barrier islands exposed to waves from the North Sea. A geomorphological map of Denmark is shown in Fig. 1. This can also serve as a guide to locate the excursion maps shown in greater detail in Fig. 2-5. Location names are given in detail to enable navigation by GPS. Levels are given in Danish Ordnance Level (DNN) close to present mean sea level. All stops are positioned on the detailed maps Fig. 2-5, and are named (day, number).

Pratical information

It is advisable to bring rubber boots. Emergency call is 112 as in the rest of EU. From north to south there are three relevant hospitals: Regionshospital Nørrejylland; Bispensgade 37, Hjørring, 9800, Tlf.: +45 97 64 00 00. Regionshospitalet Holstebro; Lægårdvej 12, Holstebro, 7500 Telf.: +45 78 43 00 00 and Sydvestjysk Sygehus; Finsensgade 35 Esbjerg, 6700, Tlf.: +45 79182000. About accomodation: there are numerous hotels and B&B's along the whole west coast.

Fig. 1 - Geomorphological map of part of Denmark (Schou, 1949). The latitudes are indicated as lines with an increment of 30' starting to the south (beneath) with 54° 30' and the longitude from the west (left) with an increment of 1° starting with 8°. A map of Scandinavia (north of Germany) is found in the lower right in order to indicate the location of the easy recognizeable peninsular Jutland (Jylland).

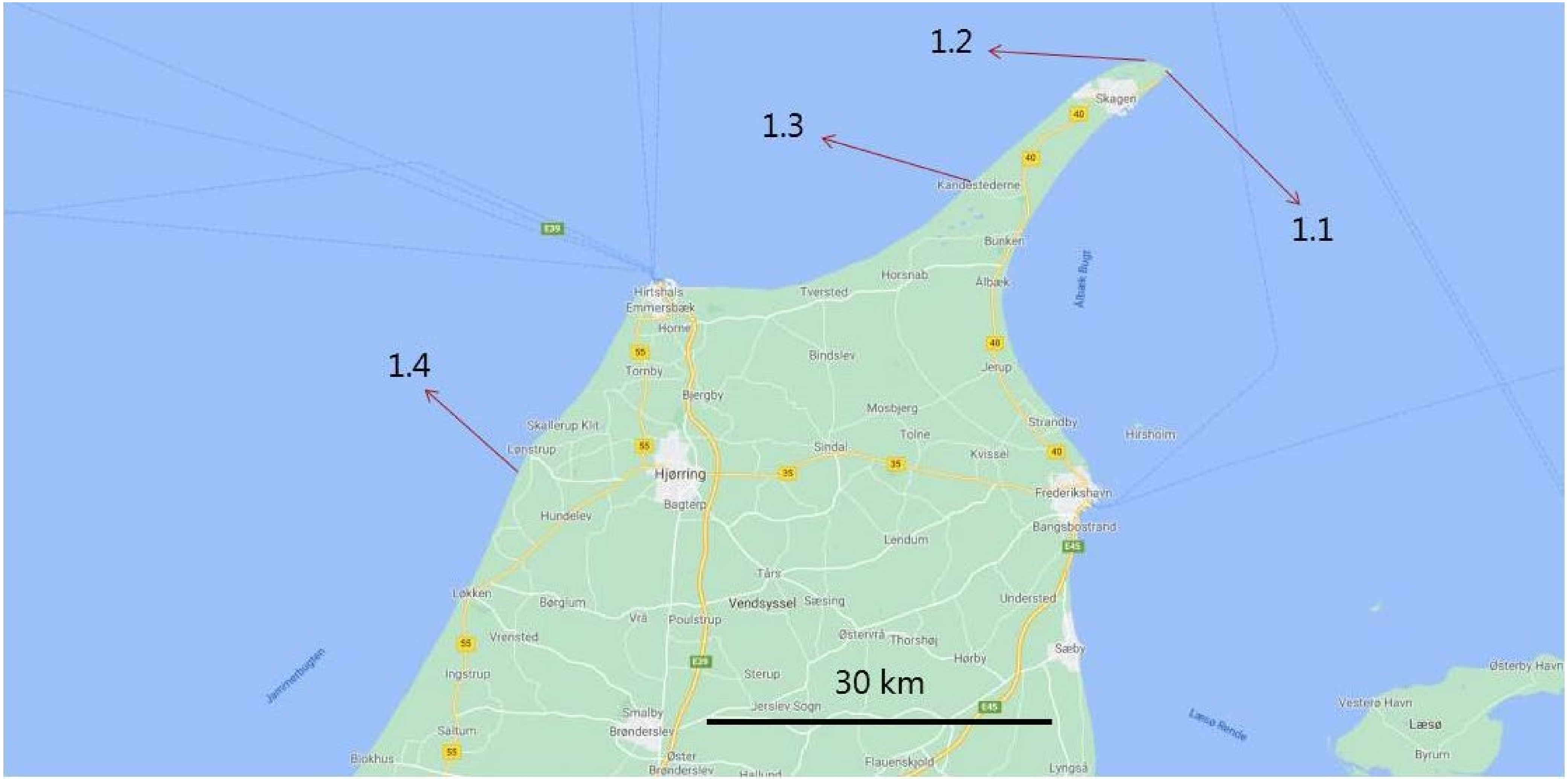

Fig. 2 - Excursion locations of day 1. North is straight up.

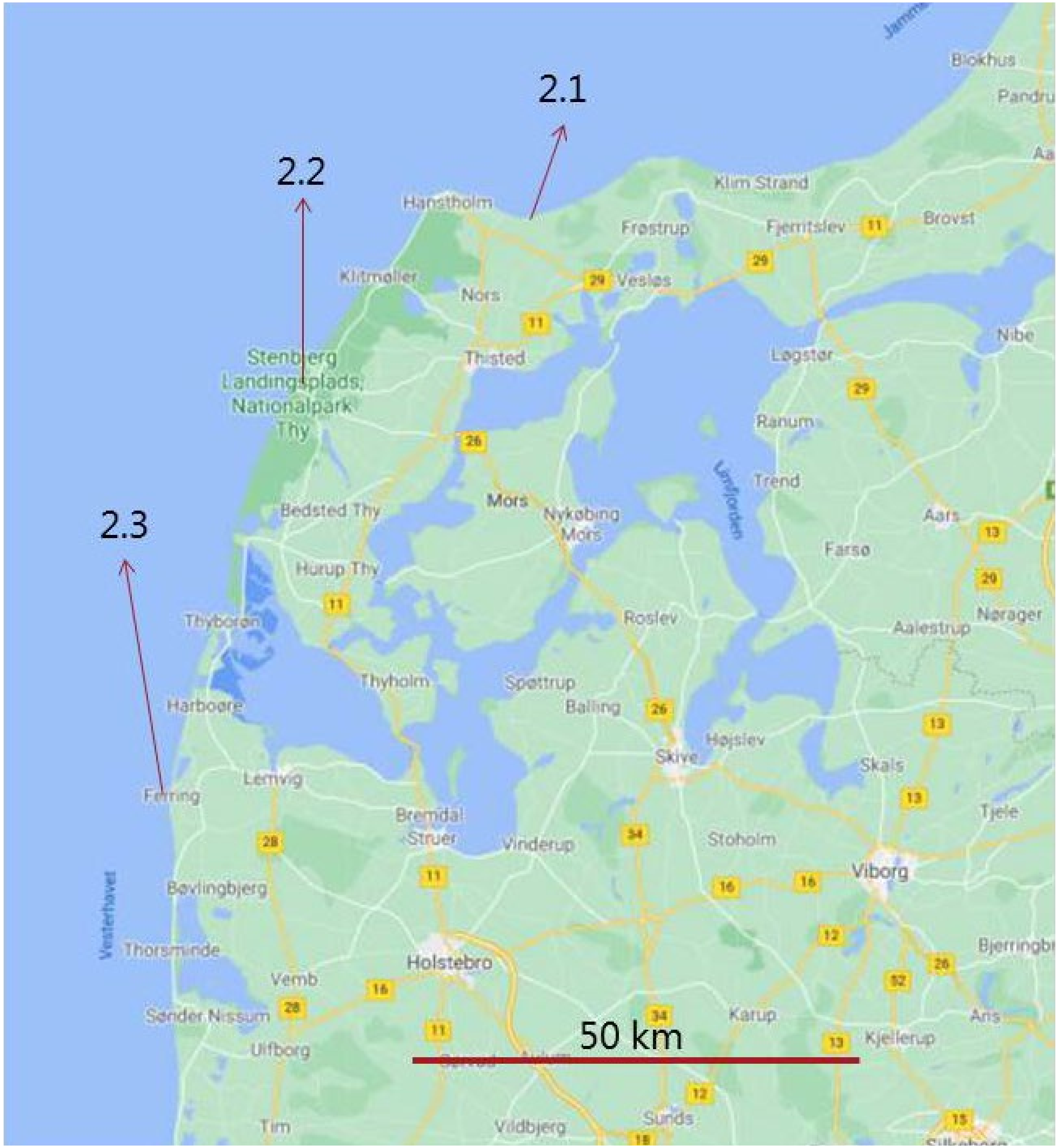

Fig. 3 - Excursion locations start of day 2. North is straight up.

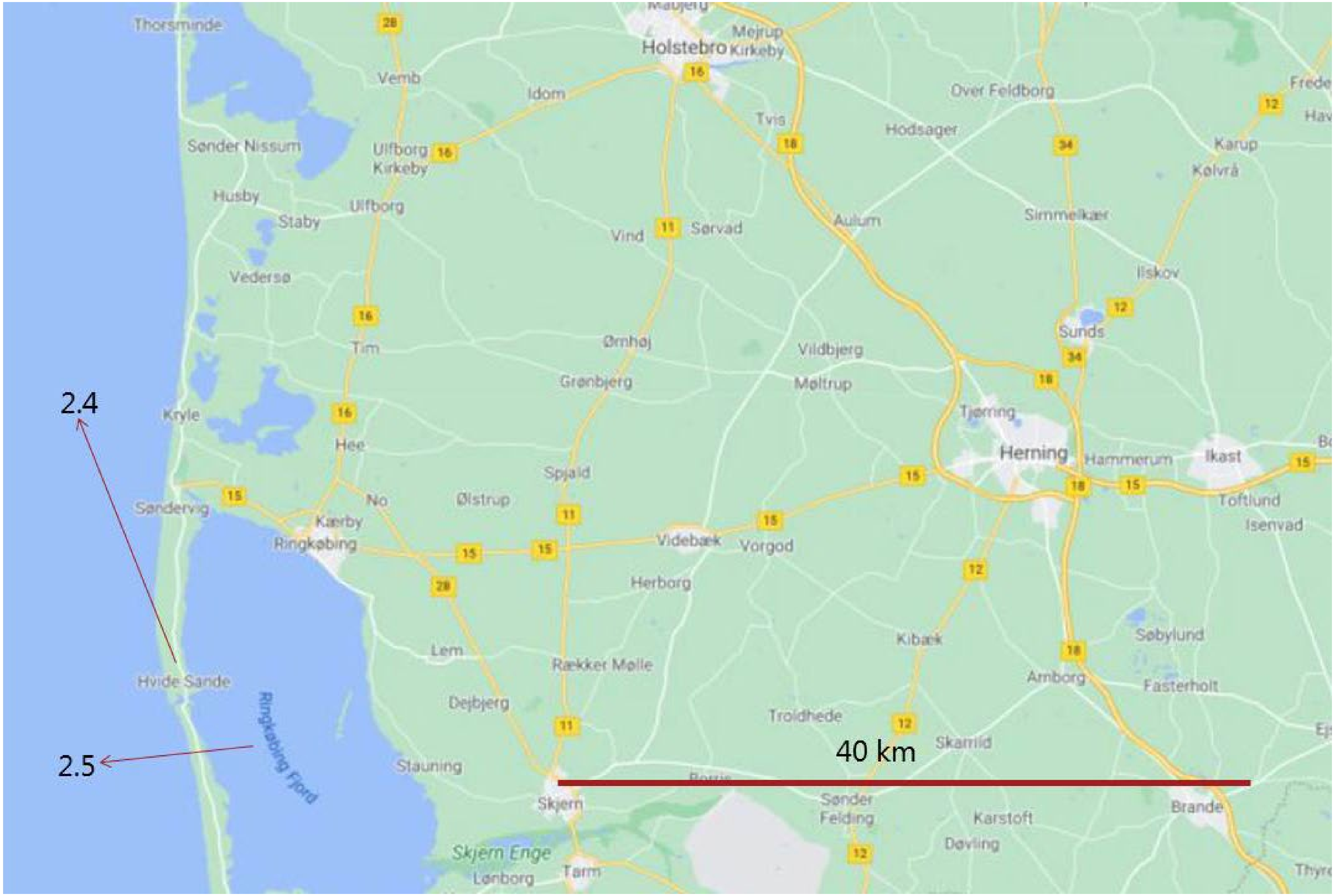

Fig. 4 - Excursion locations at the end of day 2. North is straight up.

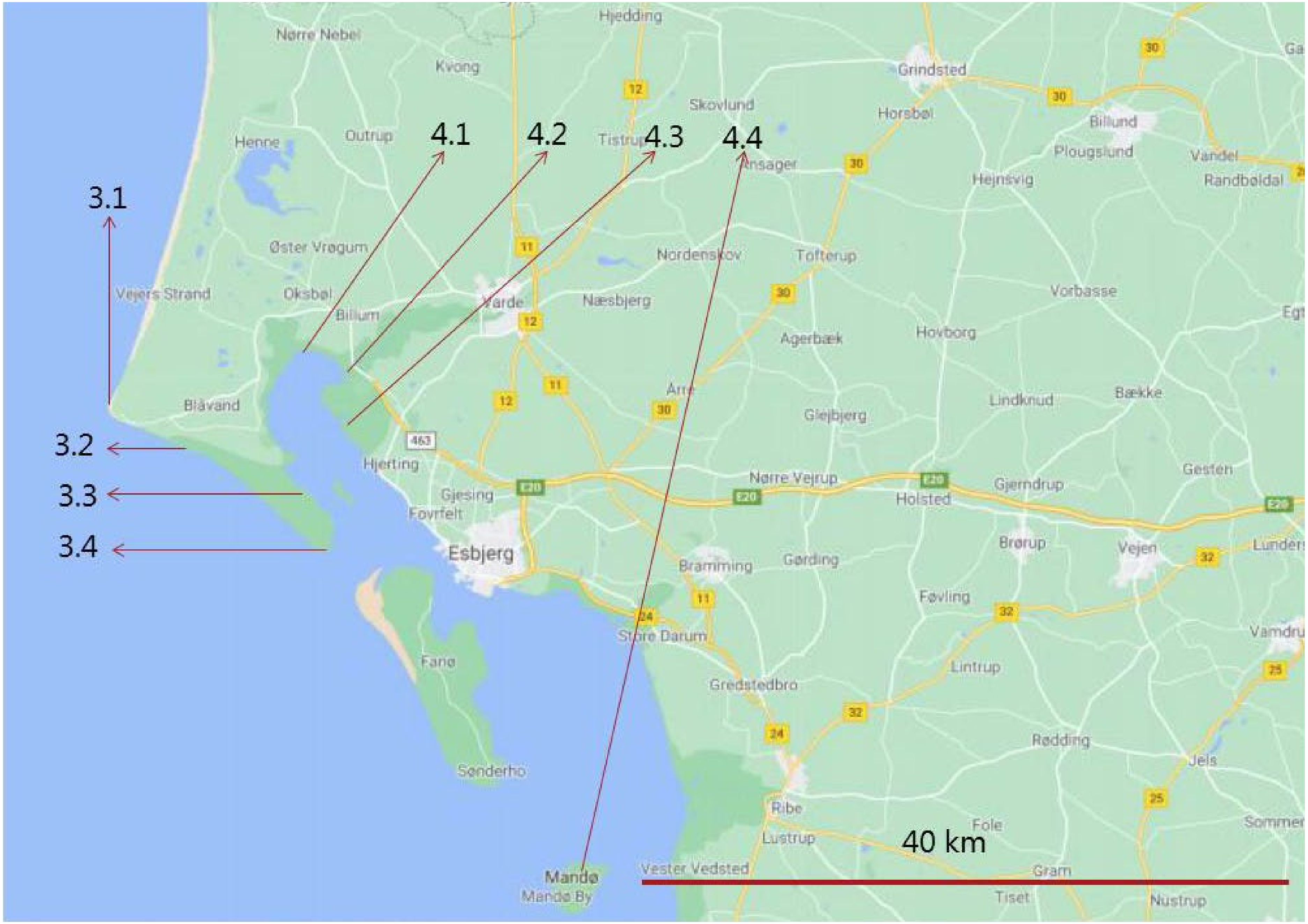

Fig. 5 - Excursion locations of days 3 and 4. North is straight up.

General geological setting of the Danish North Sea Coastal area

Denmark is located west of the prominent elongated fault-zone named the Sorgenfrei-Tornquest zone which separates Denmark from the rest of Scandinavia. The fault zone is about 460 million years old, and still slightly active. During its active periods Denmark has been immersed and in intervals received sedimentary deposits since Permian, while the rest of Scandinavia has increased in level and to day mainly consists of bedrock, the same which can be found up to more than two kilometres under the Danish landscape. Below the glacial deposits in the southern part of the west coast area (south of the area around of the fjord Limefjorden, Fig. 1), the subsurface consists primary of clastic marine and fluvial deposits from Cenozoic while north of here, limestone from Cretaceous constitutes the surface over which the glacial deposits are resting. In some areas the subsurface under the glacial deposits emerges as large slaps pushed up by glacial activity. The area has been covered by ice during at least four ice ages: Menap, Elster, Saale and Weichsel. The last one lasted until about 12,000 years BP, and covered only the northern part with its largest extension located a little south of Limefjorden. The northern part of the west coast area is therefore rebounding after the glacial overburden while the southern part has been affected by a so called forebulge collapse as a result of post glacial level adjustments after the ice left the eastern part of Jutland. See the extent of Weichselain deposits (brown) in Fig. 1.

The glacial deposits in the central part of the west coast area are formed as a simplificated coast, more or less aligned as a result of marine deposits in front of embayments and erosion of glacial deposits protruding from the main land in between. This central part of the west coast area has, to the north delivered sediment to the formation of the Skagen spit, and to the south to the Wadden Sea islands formed in the tidal part of the west coast south of Blåvandshuk. The latter located at a cuspate foreland build up in the lee of a pronounced elongated glacial induced reef, stretching about 40 km out into the North Sea, and separating the tidal southern part of the west coast from the almost non-tidal part of the rest of the coastal area.

There are two typical landscape elements forming the hinterland of the west coast area, the relative high laying glacial deposits from Saale (pink in Fig. 1.) and the melt water valleys formed in between by melting water from the Weichselain glaciation. While at some, relatively few, locations the high laying Saale deposits reach the mainland coast behind the Wadden Sea islands, these are in principal formed by abundant sediments in the relatively gentle sloping melt water valleys covering the entire coast south of Blåvands Huk, and by the littoral drift from north. They are interrupted by tidal inlets, and protect the Wadden Sea behind them, consisting of (from the North Sea to the mainland) tidal beaches, coastal dune areas, salt marshses, tidal flats and tidal channels.

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Day 1

Skagen Odde spit-system – facies architecture and depositional processes

Introduction

This part of the field trip will demonstrate preserved facies of the Skagen spit-system and compare their depositional processes with present day spit-forming processes. The spit-system began to form ca 7,150 years ago and is still prograding (Fig. 6). Its internal structures are visible in up to 13 m high sea-cliffs as the spit-system is undergoing

differential uplift owing to glacial rebound. The present-day spit-forming processes are known from historical records since the 19th century of wind, waves, currents, tidal range, rates of sediment transport and spit growth. The Skagen spit-system may therefore be regarded as a full-scale laboratory where preserved facies in the old part of the spit-system can be compared to active spit-forming processes at the young distal part. This is a clear advantage and unique situation compared to interpretations of ancient depositional systems. The last location of the day is Rubjerg Knude which represents one of the prominent coastal cliffs from where eroded sediment is added to the northerly-directed littoral drift and supplies the Skagen Odde. A comprehensive map of the detailed morphology of the Skagen spit-system is shown in Fig. 7.

Stop 1.1: The eastern part of the WNW–ESE trending accretionary spit-coast (Grenen)
(57° 44’ 62.00’’N, 10° 38’ 56.95’’ E)

This location overviews depositional processes and morphological features at the easternmost part of the accretionary spit-coast. This part of the sub-aerial spit-system is characterised by a broad, flat and very weakly seaward dipping beach of fine-grained sand with relatively few and small pebbles. Small aeolian dunes are formed on the backshore, where they gradually become vegetated, aligned and stabilised. Pebbly beach ridges are mainly formed high on the backshore during storms from north and northeast; wide boggy swales with peat formation occur between the ridges.

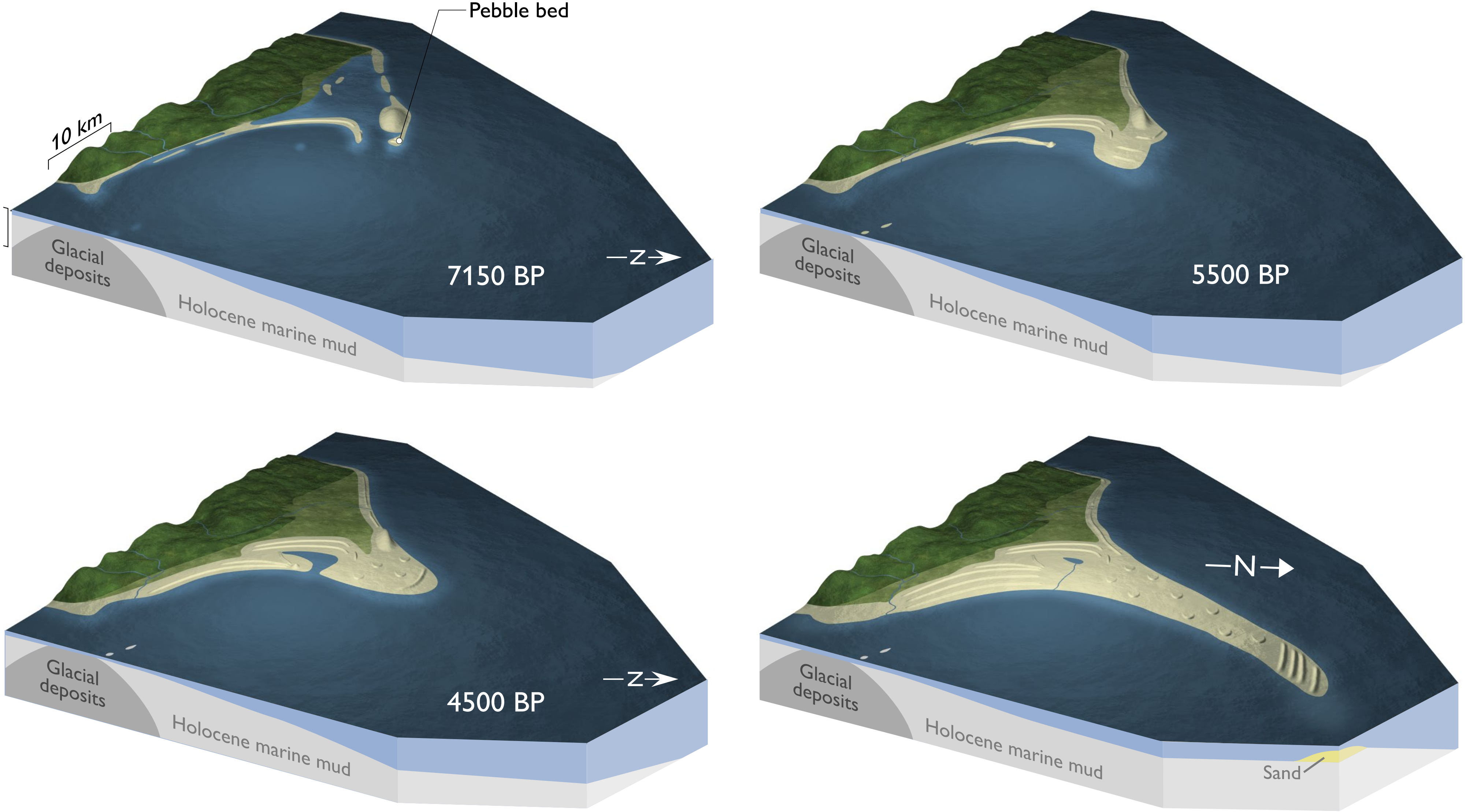

Fig. 6 - Development of the spit, Skagen Odde. After Nielsen and Johannessen (2009).

Legend

Main Land:

⬜ Weichselian glacial till and fluvial sand
Late Pleistocene marine sand and mud (Saxicava San & Yngre Yoldia Clay)

Skagen Odde coastal elements:

🟥 Pleistocene glacial till and fluvial sand

▨ Late Pleistocene coastal sand (Zirphaea sand)

🟨 Glacial till and fluvial sand covered by thin Holocene coastal sand; Tversted Ridge

🟦 Lagoonal sand and mud; Tversted lagoon, Yderhede Lagoon & Gårdbo lagoon/lake

🟪 Spit system sand and gravel; Troldkær spit-system

🟩 Strand plain; Jerup and Damsted strandplains

🟧 Spit system sand and gravel; Skagen spit-system

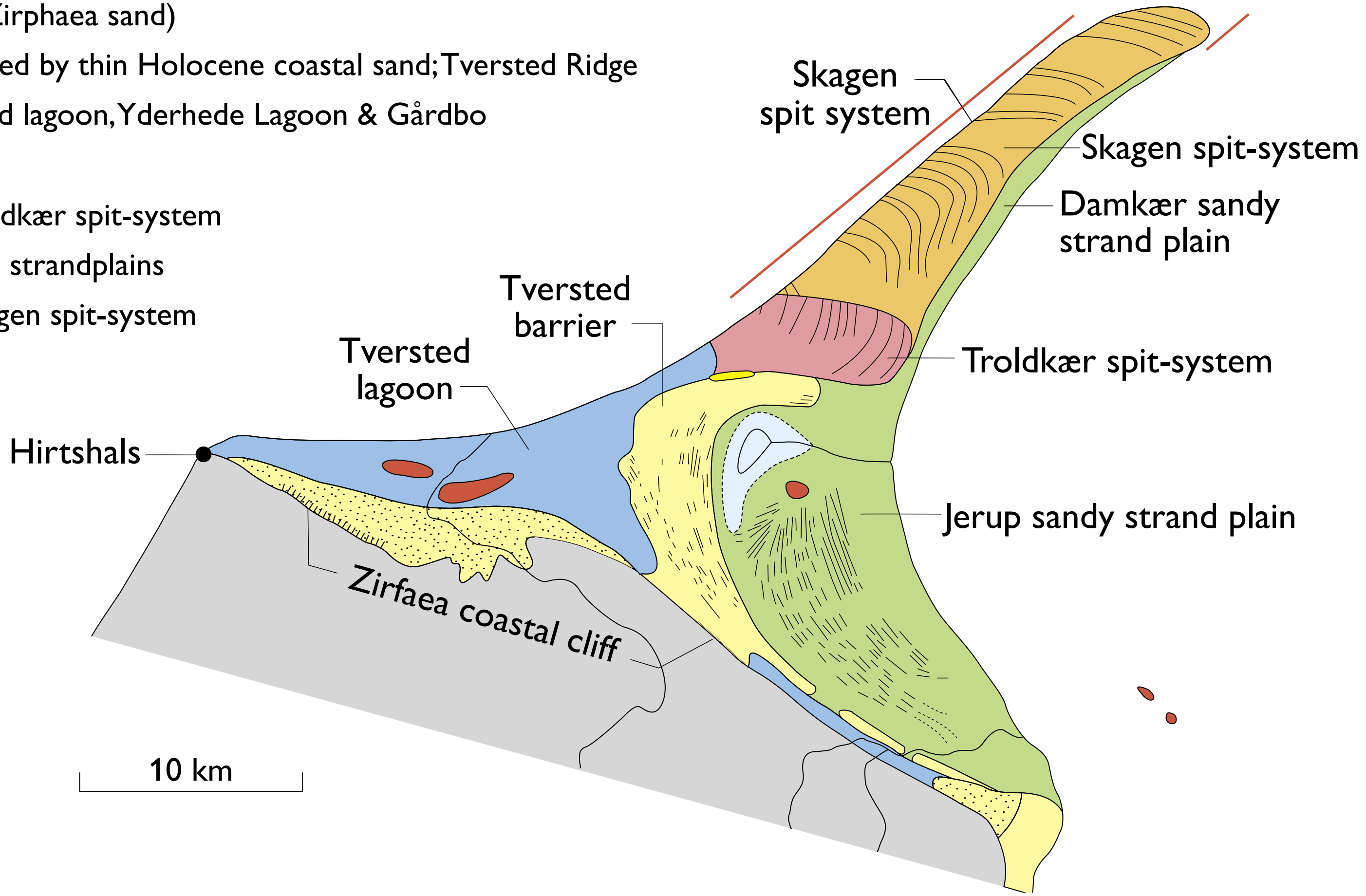

Fig. 7 - The six major morphogenetic elements of Skagen Odde; the excursion focuses on the Skagen spit-system. After Nielsen and Johannessen (2009).

Stop 1.2: The western part of the WNW–ESE trending accretionary spit-coast (Batterivej) (57° 45’ 02.30’’ N, 10° 36’ 22.91’’ E)

The depositional processes and morphological features along the westernmost part of the accretionary spit-coast are demonstrated at this location. This part of the sub-aerial spit-system is characterised by a narrow, steep seaward dipping pebbly beach with large pebbles. High-relief pebble beach ridges characterise the backshore separated by wide vegetated swales with peat formation.

Stop 1.3: Cliff-sections along the retreating, western spit-coast from Højen to Råbjerg Stene (57° 39’ 46.92’’N, 10o 22’ 54.29’’E)

This part of the field trip will include stops along the retreating western spit-coast where exposures allow the study of preserved facies of the Skagen spit-system, i.e. windows into the internal structures of the spit-system. Exposures are very variable over time dependent on wave erosion, and stops will be improvised dependent on actual access. New observations and C^{14} dates indicate that the erosion surface represents a transgressive surface of marine erosion, i.e. a ravinement surface that was formed during the peak of the Early Atlantic transgression. The surface separates the Skagen spit-system from the underlying and slightly older Troldkær spit system that has been recognised in ground penetrating georadar sections. An example of the different facies found in the raised cliffs is shown in Fig. 8 (Nielsen and Johannessen, 2009). Usually this can be seen from the beach at Kannestederne.

Stop 1.4: Rubjerg knude (57° 26’ 55.95’’N, 09° 46’ 27.75’’E)

The coastal cliff at Rubjerg, 30-40 m high dunes on top of a 50-60 m high coastal cliff, was formed during the Weichselian glaciation about 20.000 years ago. An advancing ice from the north pushed glacio-fluvial deposits in the form of alternating sandy and clayey layers to a near vertical position. The Weichselian part of Rubjerg Knude (Fig. 9) is up to 60 m high. The clay layers are rather stable whereas the sandy layers are easily eroded by water, wind and slides. Therefore, the cliff front has furrows (Fig. 10) acting as chimneys facilitating the developments of upward-directed aeolian jets along the steep cliff front during strong onshore winds. During such situations sand can be observed to move up the cliff and cross the cliff top.

Due to coastal erosion and longshore transport of sand to the north, the cliff front has experienced a retreat of about 65 m during the past 100 years. In contrast, sand has accumulated on top of the cliff and has made the cliff about 30 m higher during the same period of time.

Close to the cliff there is a lighthouse (23 m high) which was built in 1899-1900 and was in function from 1900. It was built 200 m away from the cliff front. At that time a small dune 1-2 m high existed between the lighthouse and the cliff front. The lighthouse was in function up to 1968 when the dunes in front of the lighthouse had grown higher than the beam height. In 2019, the lighthouse was relocated a further 70 m inland to avoid it from toppling down into the North Sea.

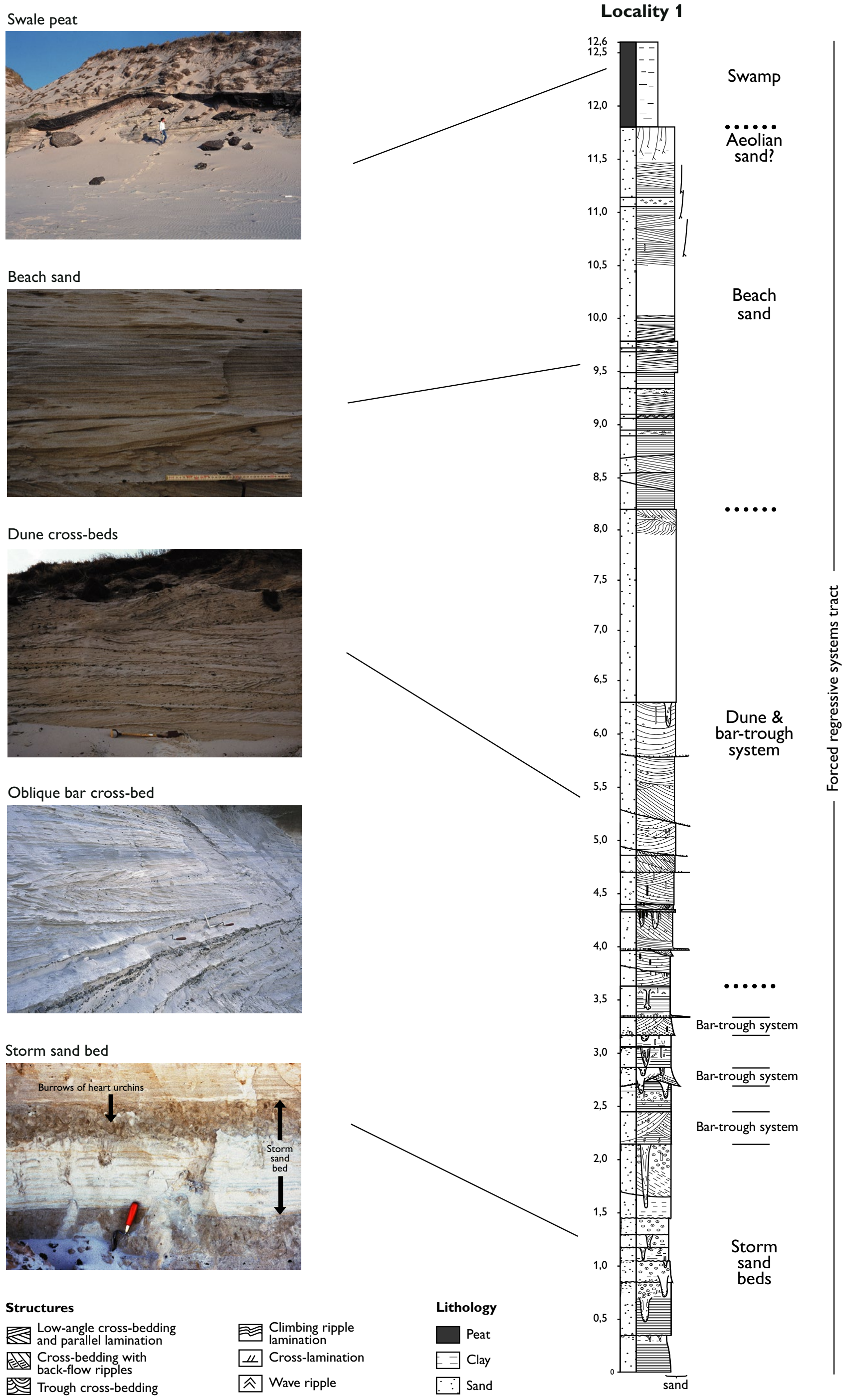

Fig. 8 - Sedimentological log from the raised Skagen spit-system with representative photos of facies types. After Nielsen and Johannessen (2009).

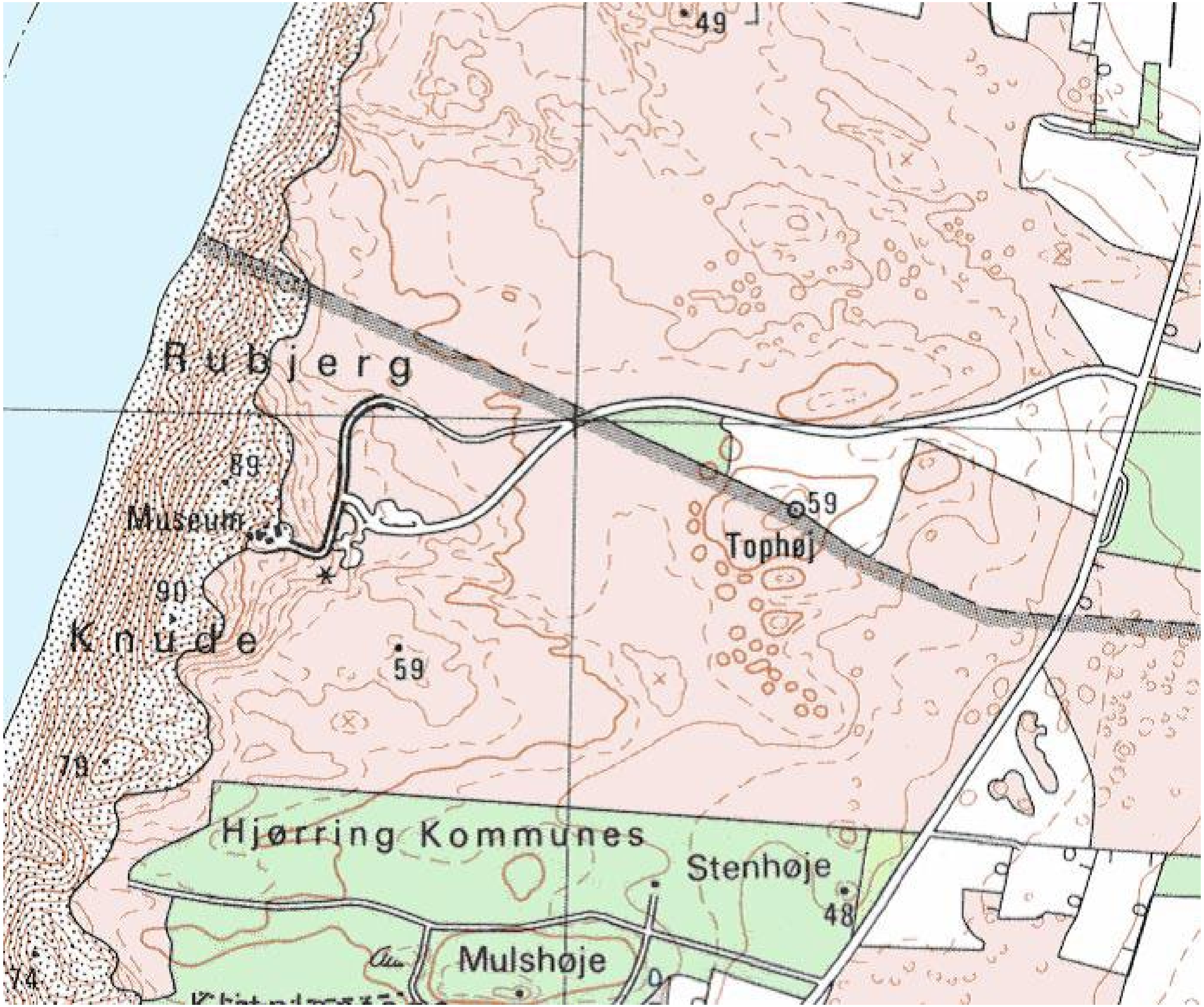

Fig. 9 - Topographic map of the area around Rubjerg Knude, equidistance 2.5 m. North is straight up. For scale, the base of the map is about 1.3 km long.

Fig. 10 - Photos of the cliff at Rugbjerg Knude. The top of the lighthouse is just visible behind the cliff top dunes. Photos from https://www.bing.com/.

Day 2
The Central West Coast of Jutland

Introduction

The Central West Coast of Jutland between Lodbjerg and Blåvand presents some interesting landscape changes and process gradients. In the direction from north to south we proceed from a moraine landscape to areas of outwash plains and from an area with a relatively large uplift since the Holocene transgression to an area which has experienced fore-bulge collapsing and hereafter almost isostatic stability during the Holocene sea level changes. In terms of processes, wave heights decrease in a southward direction while the tidal range increases and the longshore sediment transport becomes increasingly larger in a southward direction. These landscape and process gradients have left noticeable imprints on the coastal geomorphology of the West Coast, being nearly straight with barriers straightening any irregularities in the coastline.

Therefore, the northern part of the West Coast is formed in till and sand is relatively scarce. The Main Stationary Line from the Weichselian for the ice cover is crossed at Fjaltring/Bovbjerg. North of here the hinterland consists of a young moraine landscape and from here to the south it consists of old glacial deposits from Saale separated by Weichselian outwash plains, where sand becomes significantly more abundant.

The largest wave energy levels along this stretch of coastline are found in the northern part, at Lodbjerg and Thyborøn; the wave climate becomes milder towards the south at Vejers/Blåvands Huk and especially off Skallingen/Fanø which are sheltered from north-westerly waves by the shoal Horns Rev. As the tidal range increases from about 0.4 m in the north to a spring tidal range of 1.8 m at Skallingen, the coast is clearly wave-dominated in the north and mixed wave-tide dominated in the south.

The predominant westerly and northwesterly waves have resulted in a more or less continuous littoral drift system from Lodbjerg to Blåvands Huk. Lodbjerg is close to the nodal point separating the northward- and southward-directed littoral drift systems on the west coast and the southward-directed system is characterized by steadily increasing transport rates, except for the local drift reversal at the entrance to Limfjorden at Thyborøn. At Blåvands Huk, the net annual littoral drift amounts to some $2.3 \cdot 10^6$ m^3y^{-1}; south of the break-in shoreline orientation at Blåvands Huk, Skallingen has its own littoral drift system.

Fig. 11 illustrates cross-shore profiles from four locations along the West Coast, starting at
Thyborøn in the north (close to Lodbjerg) and ending at Skallingen in the south. The decreasing wave energy levels and increasing abundance of sand are clearly reflected in the profile configurations. The shoreface profiles

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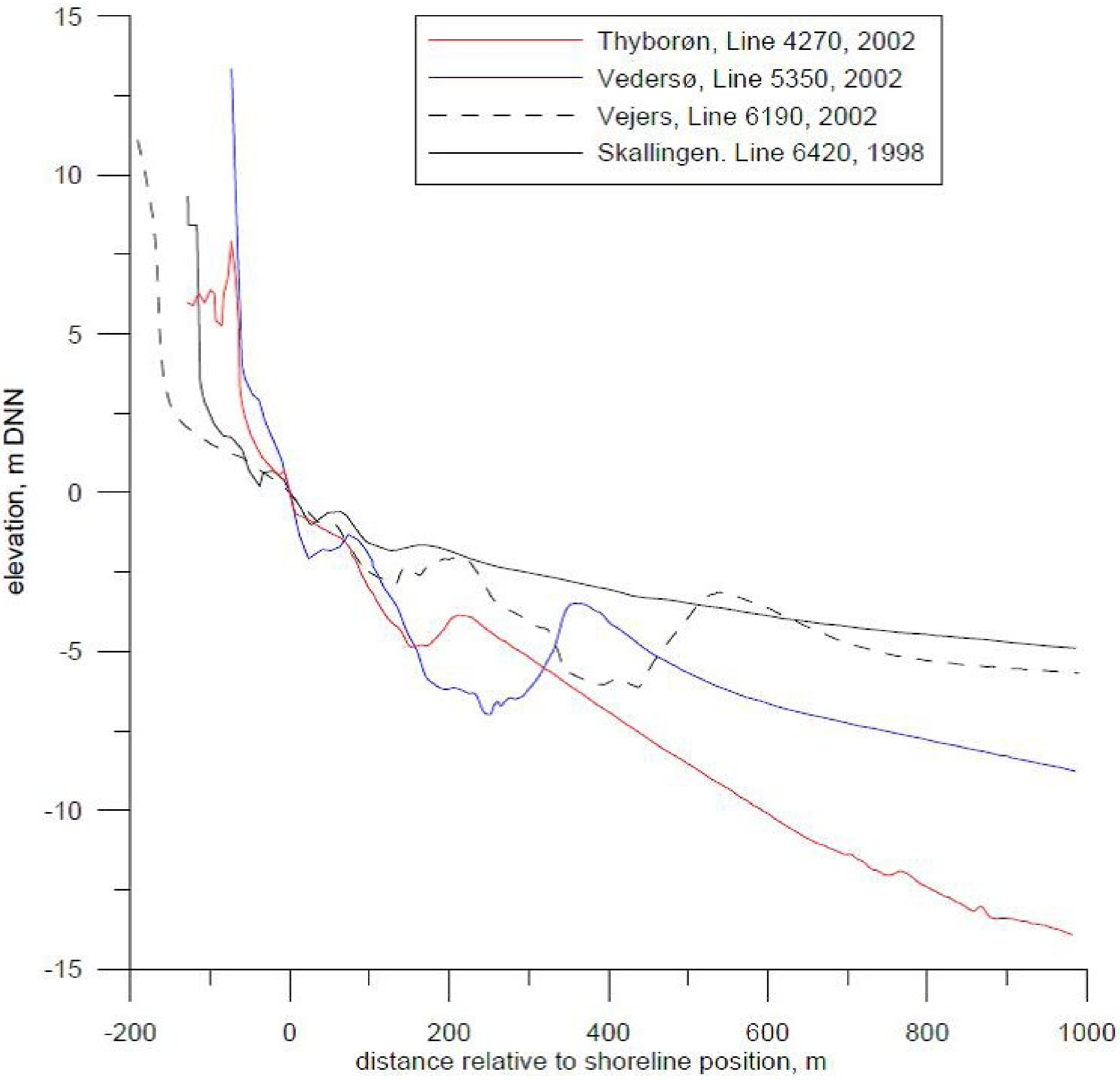

Fig. 11 - Cross-shore profiles from north (Thyborøn) to south (Skallingen) along the Danish North Sea coast. Data source: Danish Coastal Authority.

are steep in the north, with only one longshore bar whereas they are much more gently sloping in the south where the systems are triple-barred. Also note the size of the bars: Large bars exist on the wave-dominated part of the coast and bars are much smaller on the mixed wave-tide dominated shoreface at Skallingen.

Stop 2.1: Vigsø
(57° 06′ 07.22″N, 08° 43′ 48.35″E)

The glacio-isostatic rebound in this area during the last 4-5000 years has raised marine deposits to +5 m msl. It has also closed the former connection between the North Sea and the Limfjorden to the south. The transition between the marine foreland and former islands (in the form of a Danian bryozoan chalkstone) is seen as fossil cliffs. The marine foreland is in many places covered by dunes. Datings of the fossil soils in the dune areas show that dune building activity took place in three major periods (~500 BC, ~500 AD and ~1500 AD). All were characterized by relatively low mean sea levels.

This location illustrates strong erosion evidenced by World War II blockhouses. Westerly winds and very long fetches prevail for 60% of the year. Up to ~1980 the main storm direction was WNW; this direction has hereafter turned more to WSW. Max. wave height 950 m outside the coastline in 18 m depth of water has reached 9 m and storm wave period ranges from 5.9 to 8.8 s (Harbourmaster of Hanstholm, pers. com.). The longshore sediment transport ranges 0.3-0.6·10^6 m^3y^{-1}. The tidal range is up to 0.3 m, which is insignificant compared to the effect of storms which may raise the sea level up to 2.5 m above msl.

Christiansen and Bowman (1990) studied coastal erosion (1944-1986) along 80 km of the NW coast of Jutland (Fig. 12). The study was based on positions of coastline and dune foot relative to World War 2 bunkers evidenced from sequential air-photos. In spite of being situated in a bay, the coastline retreat at Vigsø proved to be as large as 3 m y^{-1} on average.

The strong erosion in the central part of the bay and similar strong erosion in the central bay at Klim may be a response to coastal adjustment to the prevailing WNW winds. Changes in the wind climate since the 1980'ies have made the bay less exposed to storms and evaluated from data in Christiansen et al. (1997) coastal erosion has gone down by 30-40%.

Fig. 12 - A view from land towards the sea at Vigsø in 1970. The location of the World War2 bunkers was used to estimate the coastal retreat to approx 3 m y^{-1}. People on the beach for scale.

Stop 2.2: Lodbjerg
(56° 56′ 17.36″N, 08° 20′ 44.50″E)

Lodbjerg is situated between Hanstholm and Thyborøn. The beach is backed by an approximately 10 m high cliff cut in Weichselian till with an admixture of outwash deposits and an Oligocene clay. The till is overlain by aeolian deposits, so the total cliff height is 15-30 m. The Holocene transgression (≈ 6000 BP) reached elevations of about 2.5 m in the area and at the time, the Lodbjerg area constituted an island. During the ensuing regression, the area has been repeatedly subjected to aeolian activity and the till is now covered by up to 20 m thick aeolian deposits.

The present wind climate at the site is highly energetic with a predominance of westerly and northwesterly winds and gale-force winds occur for 15-20 % of the year. The shoreline is therefore eroding; the present rate of erosion is about 2 m y^{-1} and the coastal retreat has resulted in breaching of the cliff-top dunes and the formation of numerous blowouts (Fig. 13).

With respect to the longshore sediment transport, the site is located close to the nodal point associated with the littoral drift system of the Thyborøn barriers with a small net northward directed net sediment transport, on the order of 50,000-100,000 m^3 y^{-1}. As a result of the high

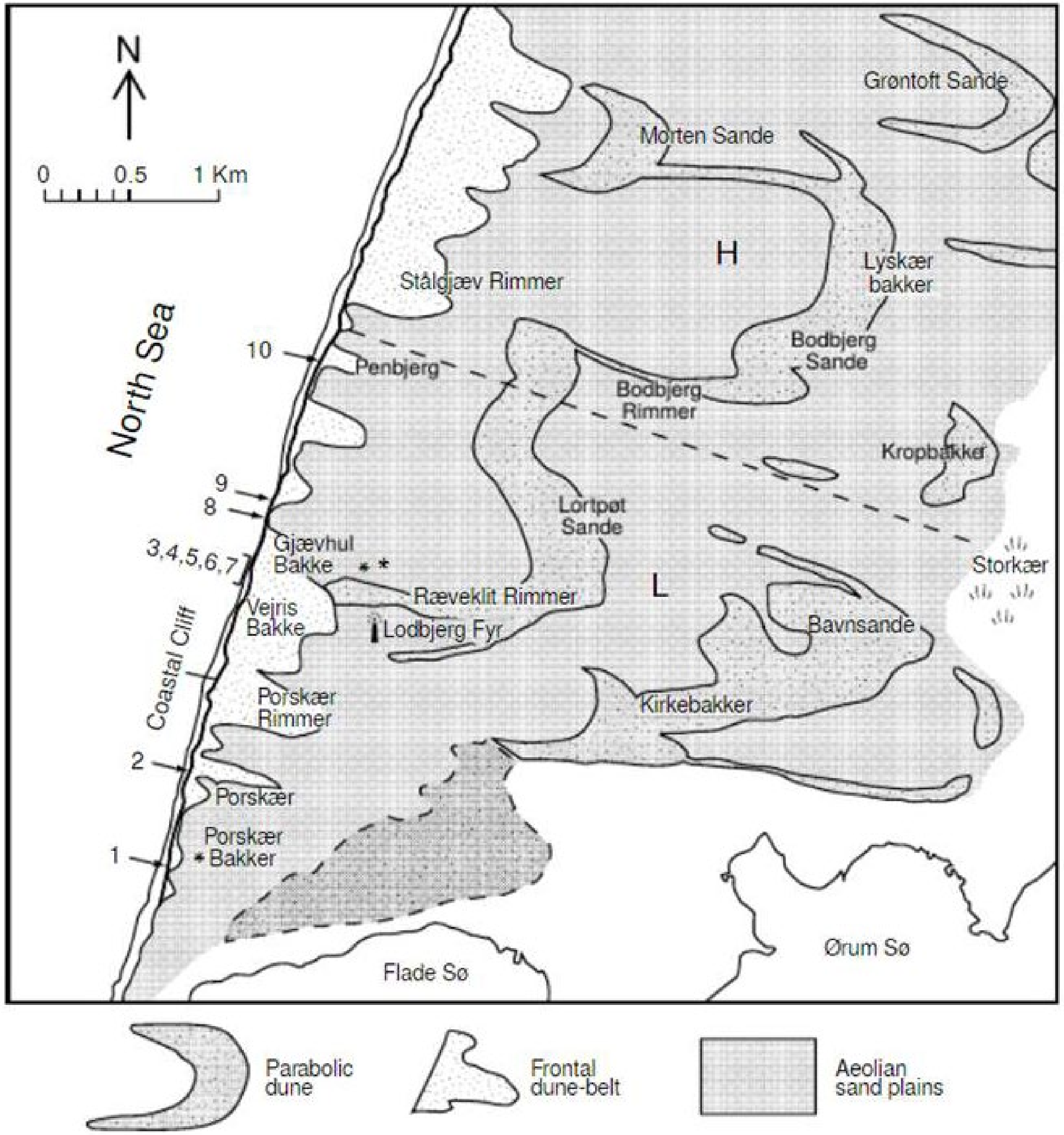

Fig. 13 - Map of the Lodbjerg coastal dune system. The dune outlines were determined from maps 1882/83 and 1989. Source: Clemmensen et al. (2001).

incident wave energy and the net longshore sediment loss in the area, the sand is rather coarse-grained sand with an admixture of gravel and pebbles.

Stop 2.3: Fjaltring
(56° 28’ 30.21’’N, 08° 07’ 32.89’’E)

Fjaltring is situated about 4 km south of the Main Stationary Line from the Weichselian glaciation. This line is marked by a 40 m high coastal cliff at Bovbjerg and the terrain elevation declines gradually towards Fjaltring where clayey and sandy outwash deposits dominate. Bovbjerg is one of the shoreline-anchor points of the Danish West Coast and shoreline erosion has always been a problem here due to the attack of large northwesterly waves which generate a southerly net littoral drift. During the period 1799-1867, the shoreline receded by about 2 m y^{-1} on average and this was the first place in Denmark where coastal protection was put in. In 1875, the first of a series of groynes was constructed at Bovbjerg and later, the groyne field was extended north- and southwards. Today, Groyne Q (constructed 1934) is the southernmost of the series which formerly extended to Mærsk, some 3.5 km south of here (Fig. 14).

The downdrift erosion problems south of the groyne field were considerable and there was a danger that the barrier fronting Nissum Fjord could become breached. The groynes south of Q were therefore demolished. In the 1960’s, the erosion rate immediately south of Q which is now the southernmost groyne had increased to about 10 m y^{-1} and further interventions were required.

Stop 2.4: Holmsland Klit
(56° 22’ 26.37’’N, 08° 07’ 03.32’’E)

Excluding the barriers of the Wadden Sea region, this is the largest barrier system in Denmark. Holmsland Klit is 35 km long, 1-2 km wide and the maximum elevations are about 25 m (Fig. 15). The system is interrupted by artificial locks at Hvide Sande. Geologically, the system is located in a Holocene outwash plain where meltwater drained westward from the glaciers. The amount of Holocene sand on the shoreface is, however, not large and Miocene mica clay outcrops on the shoreface below the 10 m isobath along the northern part of the barrier (Anthony and Møller, 2002). The thickness of the marine sand deposits is generally less than 0.5 m at depths below –10 m. The barrier body consists of several units of wash-over deposits which are capped by large foredunes and parabolics which have now been stabilized by vegetation. The tidal range here is about 0.5 m, and the wave energy level is probably slightly lower than further north. Even so, this is clearly a wave-dominated barrier system.

The tidal range here is about 0.5 m and the wave energy level slightly lower than further north. The mean grain size of the wave-lain deposits is 250-300 microns. The upper shoreface has a gentler slope then further north ($ = 0.007) and it is a double-barred system with the outer bar located some 400 m from the shoreline in 4-5 m depth of water.

The littoral drift is large (about 2.1 million m^3/year) with a positive gradient directed towards the south and this has resulted in significant natural and anthropogenic changes to this barrier system. In a natural state, the lagoon inlet would be located in the southern part of the barrier. The inlet migrated consistently southward

Fig. 14 - Topographic map of the Fjaltring area. North is straight up. There is 1 km between the grid lines, the equidistance is 5 m.

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and in 1897 it was positioned far south of the present position of Nymindegab and Lønne. The evolution of the flood tidal delta complex at Tipperne, in the south-western part of the area is also evident (Fig. 15).

The downdrift movement of the inlet created problems for the inhabitants: the routes to the fishing grounds became larger, the low-lying areas surrounding the lagoon became subject to flooding at times of heavy rain. Therefore, an artificial channel was constructed in 1910 at what is now Hvide Sande but already in 1911, a large storm increased the width of the inlet from 26 to 230 m and this attempt was finally abandoned in 1915. In 1931, a new channel was dug and stabilized by training walls and locks were constructed to regulate the exchange of salt water. The town of Hvide Sande has grown around this artificial channel. The construction of the channel and the piers which shelter the channel has created problems with downdrift erosion and there is a downdrift offset in shoreline position of about 400 m. The erosion rate on the southern part of the barrier was earlier up to 3 m y^{-1} but this has now been reduced to about 1 m y^{-1} mainly through beach and profile nourishment. The southern beaches are nourished with about 0.5 million m^3 of sand per year which is mainly taken from the updrift accumulation area; the nourishments have been augmented by the construction of breakwaters in order to prevent rapid sand losses.

However, the erosion problems are not exclusively due to human interference. The fact that the main body of the barrier consists

Fig. 15 - Topographical map of Holmsland Klit and Ringkøbing Fjord. North is straight up. For scale the base of the map is about 20 km. The equidistance is 5 m.

of wash-over deposits points to that this is essentially a transgressive barrier, and several small villages have been lost to the sea over time.

Stop 2.5: Ringkøbing Fjord
(56° 22′ 15.13″N, 08° 07′ 59.47″E)

The time of transgression of Ringkjøbing Fjord by the Holocene sea can be estimated from C-14 dates in the northern part of the Ringkjøbing Fjord area to be after 4000 BP. The continuing lowering of the glacial forebulge affected the transgression in the Ringkjøbing Fjord area. The occurrences of *Ostrea edulis* point to full marine conditions with regard to the salt content up until 1800's where the inlet got still more narrow, keeping the saltwater out and letting the freshwater from the river Skjern Aa dominate the entire Fjord.

Tidal sediments have been mapped on the Danish Westcoast (Petersen et al., 1992). From studies of coastal sites in southwestern Denmark it is demonstrated that coastal settlements from the Iron Age are still located in their original positions relative to the sea (Petersen, 1985).

From deeper laying marine deposits of Holocene age in the Ringkjøbing Fjord region *Tapes decussatus* has been demonstrated (Johansen and Blegvad 1933-1936). This suggests that at that time the area was a bay facing the North Sea. Furthermore, the occurrence of *Tapes decussatus* tells that we are dealing with the older Tapes Sea deposits. Shells of this species have not been dated here and we have no cored section from Ringkjøbing Fjord at hand. However, from other places in Denmark with marine deposits *Tapes decussatus* is restricted to the Atlantic and not younger.

The occurrences of *Ostrea edulis* also point to full marine conditions with regard to the salt content. The history of the Oyster up into historical time is known to us because of the edible value of this species. And from historical information we know that the Oyster - appreciated as an "edible fish" by the King - was-gathered up to the end of the 18th century (Hofman, 1769). Furthermore, from the time of King Christian the fourth (1577-1648) we have the mapping work of Meyer showing that before 1650 we had the mouth of Nymindegab just south of Argab. Up through the 18th century the "Klitten" starts to grow towards the South making the entrance still more narrow. Consequently, keeping the saltwater out and letting the fresh water from Skjern Aa dominate the entire Fjord, leading to the end of the Oyster-banks (Rambusch, 1900).

The huge area of salt marsh can be seen from the famous bird area Tipperne consulting the newly published map sheet Skjern (Jakobsen et al., 2003).

Day 3
Blåvands Huk and the Skallingen peninsular

Introduction

Blåvands Huk represents the downdrift termination of the littoral drift system which was initiated at Lodbjerg. The cuspate foreland is connected to the system of shallow shoals, called Horns Rev, which extends westward for about 40 km. The Horns Rev is pointing straight into the direction of the dominant waves. Horns Rev serves as a hydrographic barrier in the sense that north of the reef, the tidal range is on the order of 0.6 m while to the south at Skallingen, the mean tidal range is about 1.5 m. Horns Rev also functions as a natural groyne/breakwater as it traps large amounts of the sediment which is carried south by the littoral drift and it separates the regressive barrier system to the north from the transgressive barrier at Skallingen to the south (Fig. 16).

A large breach in the dykes/foredunes occurs on the northern part of Skallingen. It was initiated during a large storm surge on January 26, 1990. The dunes along the margins grew substantially since 1990, especially along the southern part of the fan where the dunes have become massive and now reach altitudes of several meters. The central parts of the fan accreted more slowly but in the course of the past 12-15 years the level has increased to an extent where the fan is rarely inundated. As a whole, the fan has now largely recovered, and dunes also cover the central part.

The Skallingen/Langli barrier complex rests on an over 20 m deep sand package. Since the Middle Age, historical information provides evidence of large variations in the coastal landscape around Skallingen. According to the legend, a fishing village disappeared in a major storm surge in 1634 which also severely damaged other settlements in the area, as well as breaching the root of the former active barrier spit, Langli, leaving this as an island. The salt marsh on the back-barrier of Skallingen is the largest undiked salt marsh area in the Wadden Sea. During the evolution of this barrier spit the fordunes on the west coast have regularly been breached during storms, forming prominent wash-over channels and wash-over fan deposits.

The barrier spit terminus of Skallingen has undergone tremendous changes since the turn of the last century, where erosion has dominated after centuries with accretion of the barrier-spit. Following the erosion of the barrier-spit terminus a large flood tidal delta appeared on the tidal flat east of the barrier-spit terminus.

In contrast to the wash-over site at the updrift end of the barrier spit, the sediment budget has been strongly negative at the parts of the barrier which have not been breached and which are characterized by foredunes and/or dykes. The mean shoreline recession from mid-1990 through 2003 was 52 m, ~ 4 m y^{-1}.

Fig. 16 - Topographic map of the area around Blåvands Huk and Skallingen. North is straight up. For scale the base of the map is 20 km wide. The equidistance is 5 m.

Stop 3.1: Blåvands Huk

(55º 32′ 56.85″N, 08o 11′ 29.82″E)

From the lighthouse, the inner parts of the Horns Rev, the marine foreland of the Vejers spit system to the north, and the Skallingen barrier spit to the south can be seen. The Horns Rev (Fig. 17) is pointing straight into the direction of the dominant waves and is thought to be a remnant of a Saalian terminal moraine system. However, recent investigations (Larsen, 2003) have revealed that large parts of the shoals consist of redeposited marine sand derived from erosion in the Pleistocene sediments. The presence of Horns Rev has led to the construction of the marine foreland north/east of Blåvands Huk. This foreland consists of a system of sandy/gravelly spits which are attached to the Saalian moraine landscape north of the lake Fil Sø (Nielsen et al., 1995; Clemmensen et al., 1996). The spit growth was initiated about 7000 years ago when the rising sea the level started to erode the former

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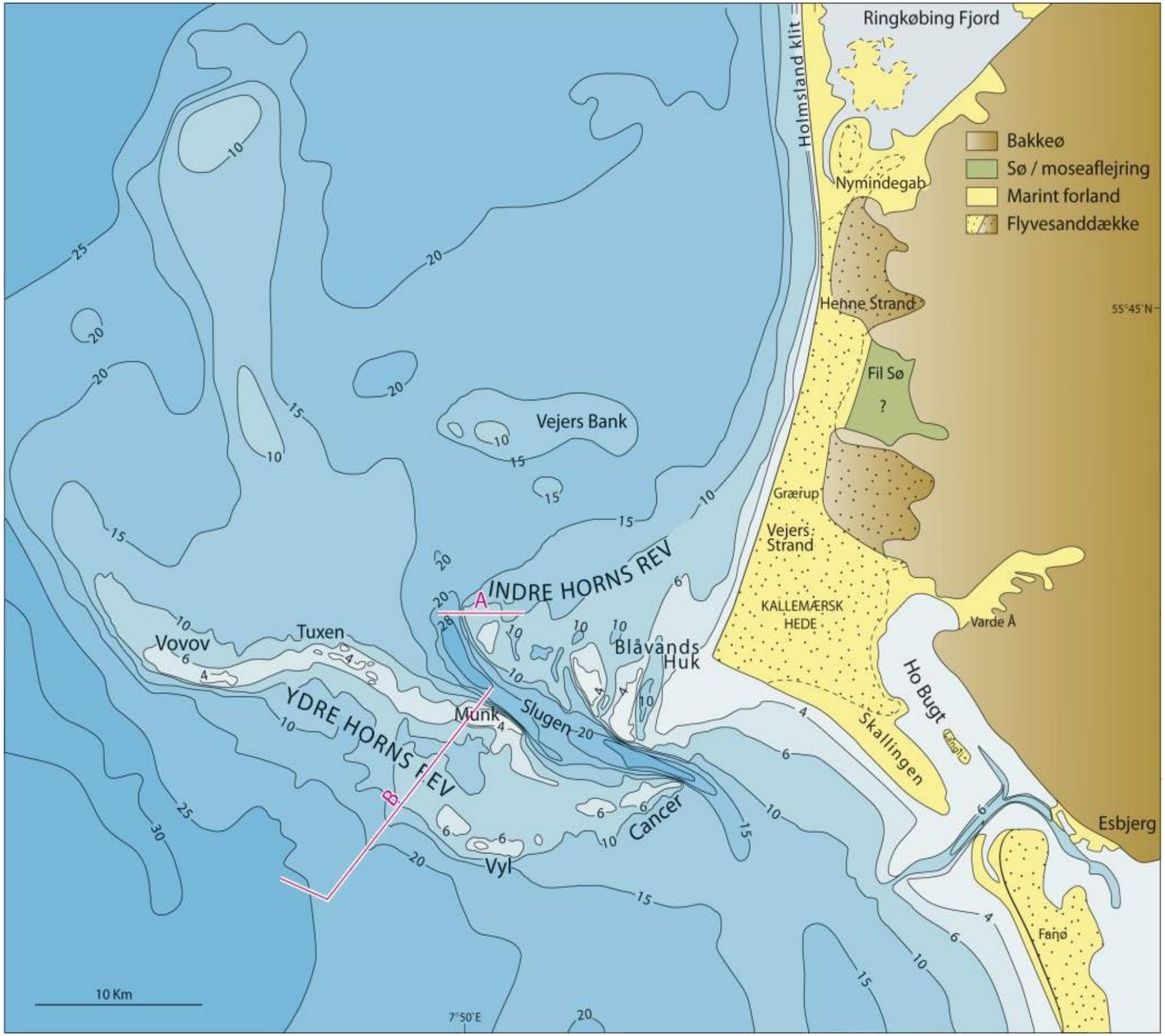

Fig. 17 - Bathymetric map of the Horns Rev area. Brown colors are glacial deposits from Saale, yellow represents marine and aeolian (dotted) deposits; green is lake deposits, and blue is water with depth contours. Source: Larsen (2003).

glacial deposits and the spit system prograded south and west. Today, the spit system is about 22 km long and 1-3 km wide and contains some 700 million m^3 of sand. Fig. 18 illustrates a cross-section of the system. The base consists of sandy shoreface deposits which grade horizontally and vertically into gravelly/sandy beach ridges making up the subaerial spit system which has a top to-level of about +4 m DNN (Danish Reference Level). The sequence is capped by aeolian dunes sand which has the appearance of a sand plain situated at a level of about + 6 m DNN; this plain is superimposed by several dune ridges reaching elevations up to 10-15 m DNN. From the lighthouse, the two outermost foredune ridges are visible, separated by an interdune swale. Further inland, the aeolian plain is characterized by parabolics which have now been stabilized and several phases of transgressive dune activity have been identified (Clemmensen et al., 1996), mainly occurring during the Little Ice Age.

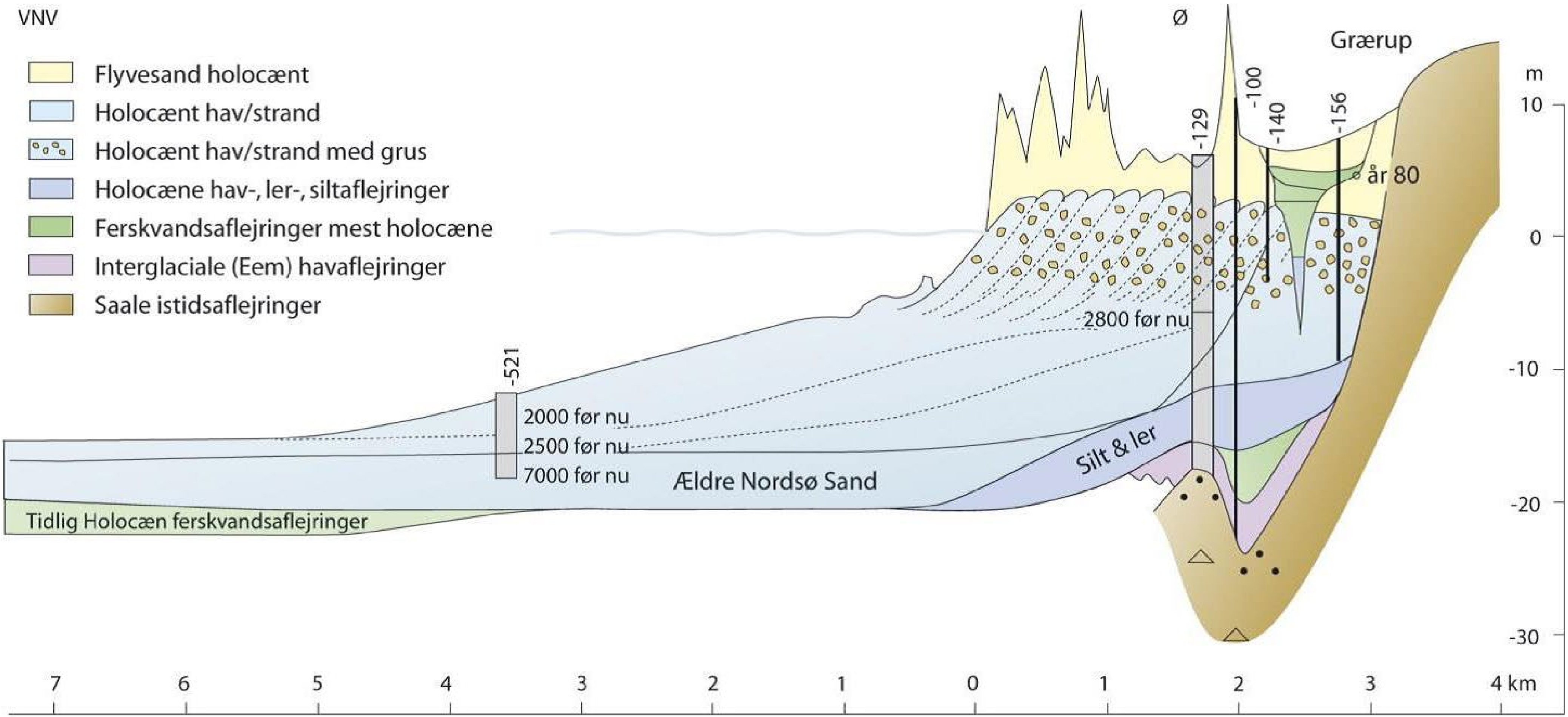

Fig. 18 - Cross-section of the marine deposits west of the Saalian landscape at Grærup (for location see Fig. 17). Brown represents the glacial deposits, yellow the aeolian sediments, light blue is marine sand, or gravelly sand(dots), dark blue is marine silt and clay. At the base of the marine sequence, lower Holocene fresh water deposits are shown in green. C^{14}-datings are indicated (“*før nu*” means BP). Source: Larsen (2003).

Stop 3.2: Wash-over fan at the root of the Skallingen barrier spit *(55° 31′ 15.76″N, 08o 12′ 34.44″E)*

Over the past 200 years, the barrier spit Skallingen has transgressed landward at a mean rate of 3 m y^{-1}. Geomorphological evidence as well as photos from the 1920's and 30's suggest that this was largely due to over-wash activity. This activity was stopped in the 1930's when dykes were constructed. However, as the dykes have not been maintained they have started to breach and the natural behaviour of the barrier has recommenced.

The largest breach in the dykes/foredunes occurs in the northern part of Skallingen. It was initiated during a large storm surge on January 26, 1990 created by a westerly gale and hence the waves hit the coast obliquely, which explain the initial orientation and symmetry of the wash-over fan (Cover picture and Fig. 19). The overall length

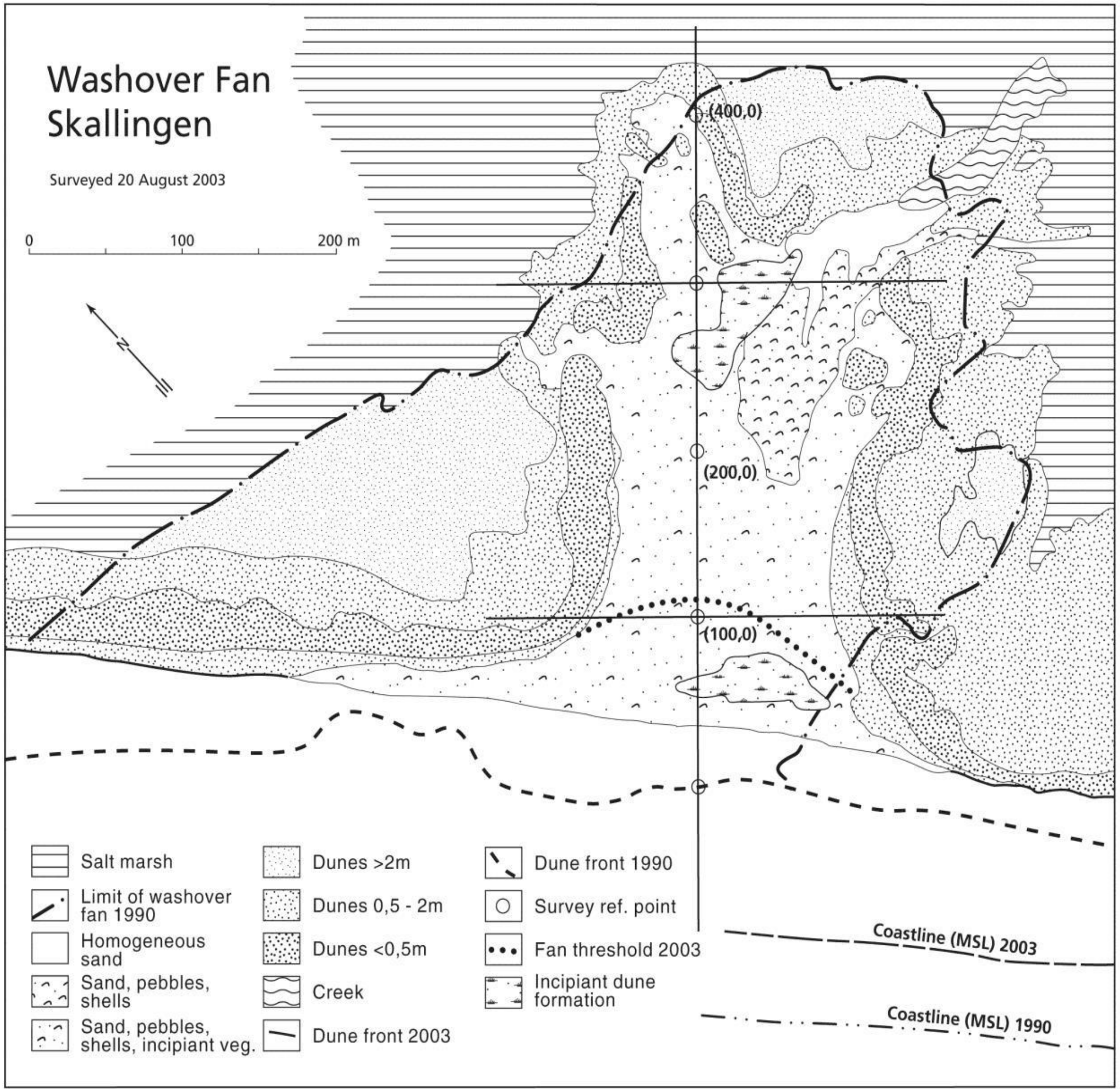

Fig. 19 - Geomorphology of the wash over-fan just south of "Grønningen" see Fig. 17, 2003. The dash-dot line marks the outline of the fan in May 1990. From Nielsen & Nielsen (2004). See also cover picture.

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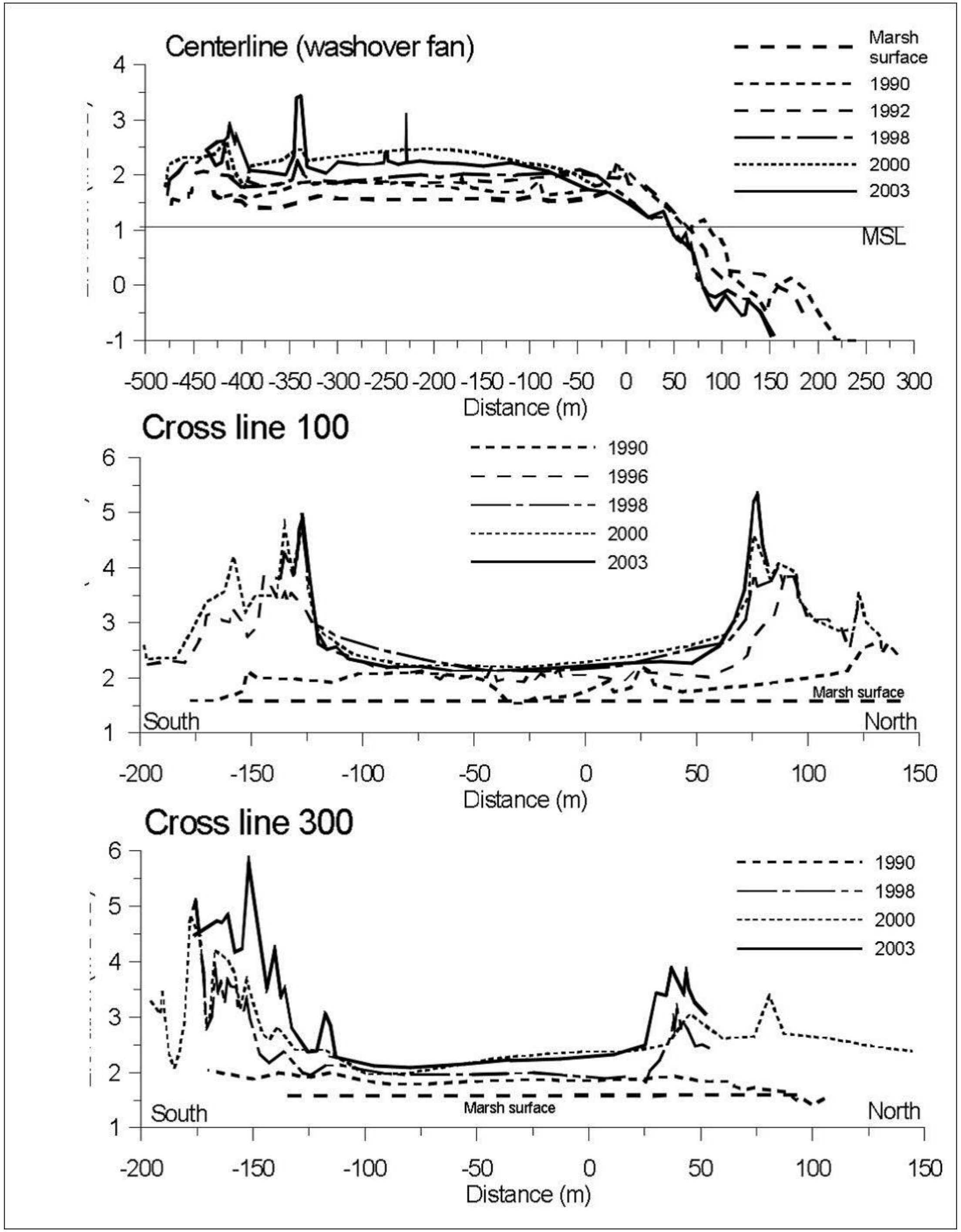

of the fan was c. 500 m and the width about 300 m. The threshold height at the throat was 1.9 m DNN.

The development of the wash-over fan during the last 13 years is shown in Fig. 20. Since the formation of the fan in 1990, there have been several surge events during which the MWL exceeded the fan throat elevation (Nielsen and Nielsen, 2002). The dunes along the margins have grown substantially, especially along the southern part of the fan, where the dunes have become massive and now reach altitudes of 5 to 6 m. Pits dug in transects perpendicular to the coastline after the 1990-surge indicated that a cover of 25 – 45 cm sand had been deposited on top of the marsh surface and the sedimentary structures consisted of parallel lamination or small-scale ripple cross-lamination. Along the fan margin, the stratigraphy displayed cross-bedding units up 30-40 cm in thickness. The texture of the fan sediment is generally homogeneous sand with a mean grain size of about 0.180 mm. Since 1990, the sediment texture of the fan surface has by and large remained constant. No less than 4 storm surge events >3 m DNN, all from W and WSW

Fig. 20 - Profiles demonstrating the development of the wash-over fan 1990-2003. The positions of the profile transects are shown in Fig. 19. From Nielsen and Nielsen (2004).

occurred within one year after the formation of the wash-over fan. This high-energy period was then succeeded by 8 relatively calm years with 25 high water events, but none of them exceeding 3 m DNN. Considering that the threshold level at the fan throat was just below 2 m DNN and that the maximum water level at the barrier normally is 30 – 40 cm below the registered level at Esbjerg Harbour, the morphologic effects of the overwashes have been limited. Only minor sand masses have been transported onto the fan during these overwash situations. The most important effect of the repeated overwashes has presumably been the soaking of the fan with salt water, which has prevented the vegetation to colonize the central part of the fan.

Dune development along the margins of the fan commenced shortly after the fan was created in 1990, because aeolian sand drifting over the fan was captured by the surrounding vegetation, particularly *Phragmites communis*, which came up through the edge of the fan. In the initial phase, the embryonic dunes migrated beyond the fan edges, but when the dune heights became 1 – 1.5 m the migration stopped while the height increased because of the lush growth of *Ammophila arenaria.* During moderate onshore wind speeds, sand accumulates on the stoss side of the fringing dunes so that they expands towards the central part of the fan.

With respect to shoreline position, the annual recession is still about $3my^{-1}$, similar to the rest of the spit. However, the sediment budget has become positive. Calculations of the development of sediment volumes from 1990 until 2003 of the wash-over fan document a positive net sediment budget per metre coastline of + 700 m^3 of which 520 m^3 are deposited in the fringing dunes and only 180 m^3 on the overwash fan itself. To some extent, this is compensated by a sediment loss on the beach and in the intertidal zone, associated with the general shoreline retreat, but still the net sediment budget at the wash-over site is about +570 $m^3 m^{-1}$.

Stop 3.3: The backbarrier of Skallingen
(55° 30’ 53.04’’N, 08° 16’ 04.29’’E)

Since the Middle Age, historical information gives evidence of large variations in the coastal landscape around Skallingen. Up until the 1600$^{'s}$ a fishing village (*Sønderside*) was situated at the old coastline along the small wood *Ho Klitplantage* west of the road leading to Skallingen (Fig 16). It was a well-consolidated village with harbour and a large fishing fleet with access to the North Sea through Hobo Dyb. Thus, in those days Hobo Dyb – as navigation channel - cut across what is now several km of fertile salt marsh. Only the name of the small creek, now crossing the salt marsh *“havnegrøften”* (the harbour ditch), give away memories of former “glory”. According to the legend, Sønderside disappeared in a major storm surge in 1634 which also severely damaged

other settlements in the area, as well as it cut through the root of the former active barrier spit, leaving Langli as an island.

The salt marsh on the back-barrier of Skallingen is the largest undiked salt marsh area in the Wadden Sea (Fig. 21). During the evolution of this barrier spit, as documented by the mapping sequence in Fig. 22, the foredunes on the west coast have regularly been breached during storms, forming prominent wash-over channels and wash-over fan deposits, like the one at Location 3.2, across the barrier (Davis et al., 2001).

The mean tidal range is about 1.5 m but the wind induced sea-level variations add to this and the active intertidal zone is enlarged by frequently occurring wind tide. The highest measured highwater at Esbjerg (4.40 m DNN) was measured during the storm surge of November 24, 1981. Because of the setup, high water levels at Skallingen are somewhat lower, up to 0.7 m (Bartholdy and Aagaard, 2001) than at Esbjerg.

The salt marsh started to develop in the beginning of the 20th century synchronously with the formation of salt marsh creeks (Nielsen, 1935).

Fig. 21 - Aerial photo of the Skallingen back-barrier 1995. The two ends of the surveyed salt-marsh profile are marked with “P”. The most prominent salt-marsh creek is named Storelo. Profile 9 in Storelo is surveyed since 1979 (see Fig 23b).

The fine-grained deposition took place directly on top of the old whashover platform, consisting of fine sand with a mean grain-size of 2.5-2.25 phi (0.177-0.210 mm). The salt marsh deposition depends on vegetation and the salt marsh continues to spread eastward on the adjacent tidal flat. The first two plants to colonize the tidal flats are *Spartina townsendii* and *Salicornia maritima*. The salt marsh starts to grow when the level reaches the approximate level of the mean high tide (0.7-0.8 m DNN). At this level, the tidal flat vegetation is replaced by the first salt marsh plants: *Puccinellia maritima* and *Suaéda maritima* followed by *Halimione portulacoides*, *Limonium vulgare*, *Aster tripolium*, *Plantago maritima* and *Artemisia maritima* at the highest levels. At levels higher than about 1.5 m DNN these typical salt marsh plants are gradually being replaced by other coastal zone plants. The typical salt marsh sediment consists of 40-45 % clay (<2 µ), 40-55 % silt (2 - 63 µ) and 5-15 % sand (>63 µ) with an ignition loss of 10-20% (Bartholdy, 1997). According to Deyu (1987), the clay minerals in the salt marsh consist of 57 % illite, 20 % kaolinite, 16 % chlorite and 7 % smectite.At the turn of the 19th century the salt marsh started to grow in two elongated sections parallel to the long axis of the barrier spit (Fig. 22, 1910). The inner zone formed along the eastern sheltered part of the foredune area where concentric ridges, related to the washover channels, raised the surface high enough for the plants to invade. The outer zone formed in relation to beach ridges about one km further to the east-facing the tidal flats. Between these two salt marsh zones, a poorly drained algae covered tidal flat developed, and transformed the former sandy surface into a barren salt suffering shallow pond. Concurrent with the salt marsh formation, salt marsh creeks developed and initiated a backward erosion which slowly drained the algae flat and allowed

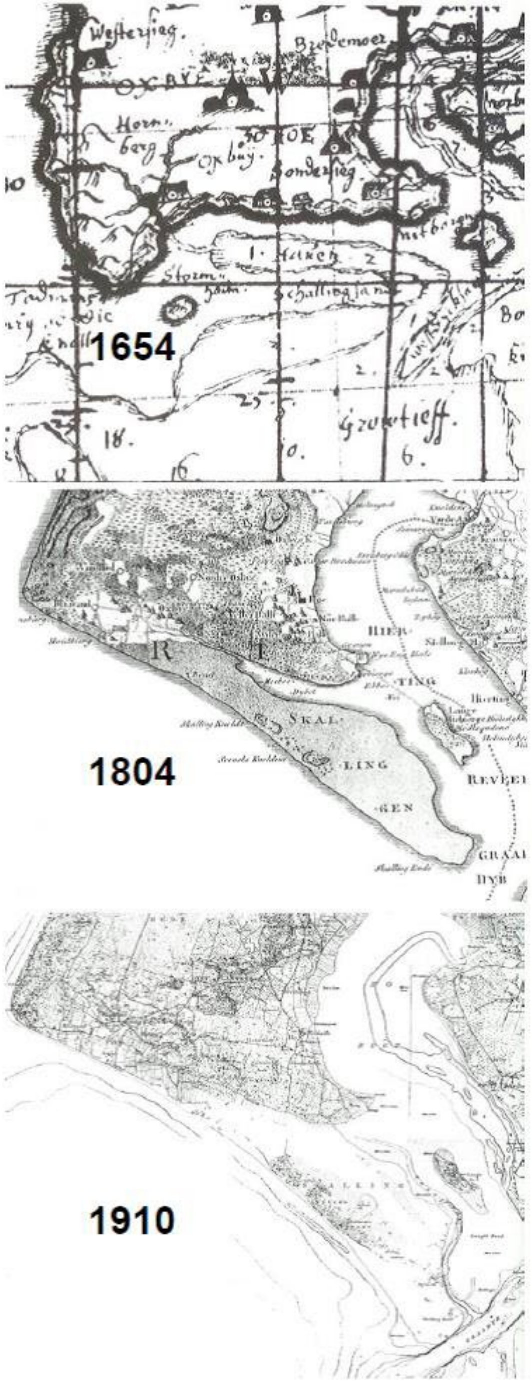

Fig. 22 - Old maps showing the development of Skallingen since the 1600's. The oldest map is published by the geodesist Johannes Meyer in 1654. The 1804 map is part of the first correctly triangulated survey of Denmark carried out by the Danish Society of Natural Sciences. The 1910 map is part of the regular mapping of Denmark.

vegetation to get a foothold along with the formation of a salt marsh creek drainage system (Fig. 23a). The salt marsh creeks are meandering and still adjusting towards wider and more shallow cross-sections. A Profile of the most promenent salt marsh creek (for location see Fig. 16) has been surveyed since 1979 (Fig 23b).

The salt marsh deposition was early (1931) followed carefully by means of measuring its thickness above a red-coloured sand layer spread out on the surface (Nielsen, 1935; Fig. 24). These measurements were continued up until 1958 and have been used to calibrate a model relating salt marsh deposition to inundation (frequency and level) and position relative to the tidal flat (Bartholdy et al., 2004). Originally Nielsen started these measurements in order to understand and quantify salt marsh deposition in general, today the resulting model is used to, among other things, to study the vulnerability of salt marshes in relation to an expected sea level rise.

The model results were compared with measured deposition covering a fifty-year period along a cross profile from the tidal flat to the central part of the peninsula (Fig. 25). From here it is evident that distance to the tidal flat and elevation of the salt marsh are the primary controlling factors. The deposition varies from c. 4 mm y^{-1} in the part closest to the tidal flat over a minimum of a little over 1 mm y^{-1} on one of the above-mentioned ridges to about 2.5 mm y^{-1} in the central part.

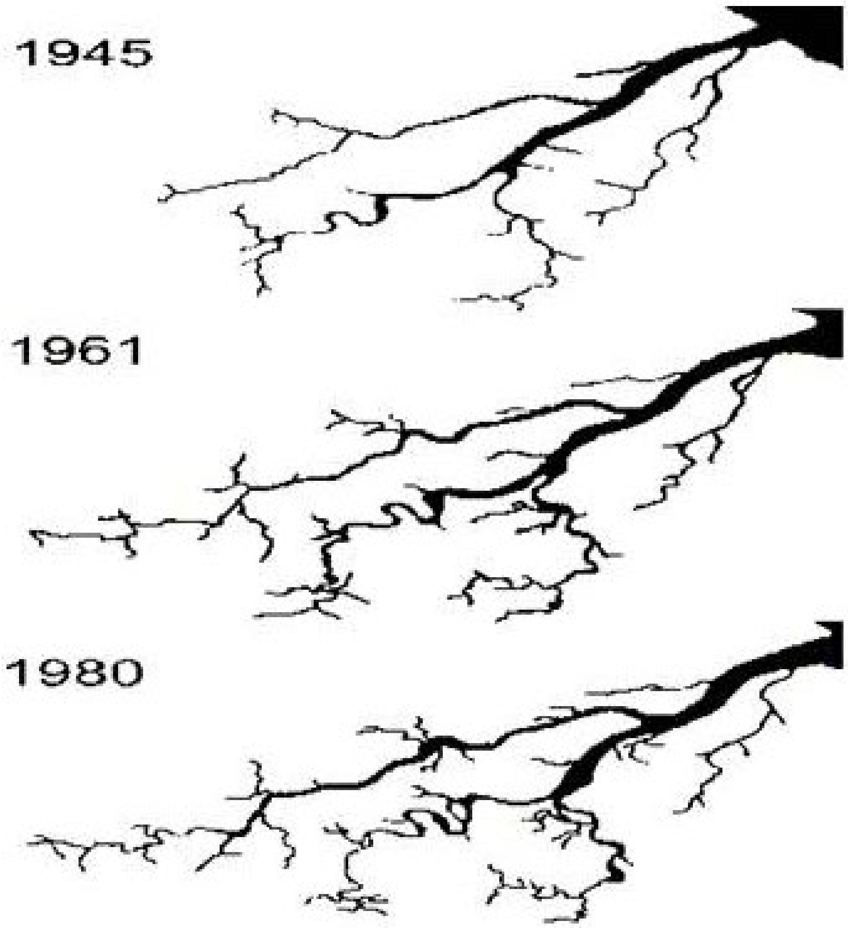

Fig. 23a - Development of the drainage system of the creek just south east of the line PP (for location see Fig. 21) on Skallingen from 1945 to 1980. For scale, the base of the figure is about 1 km wide. North is straight up.

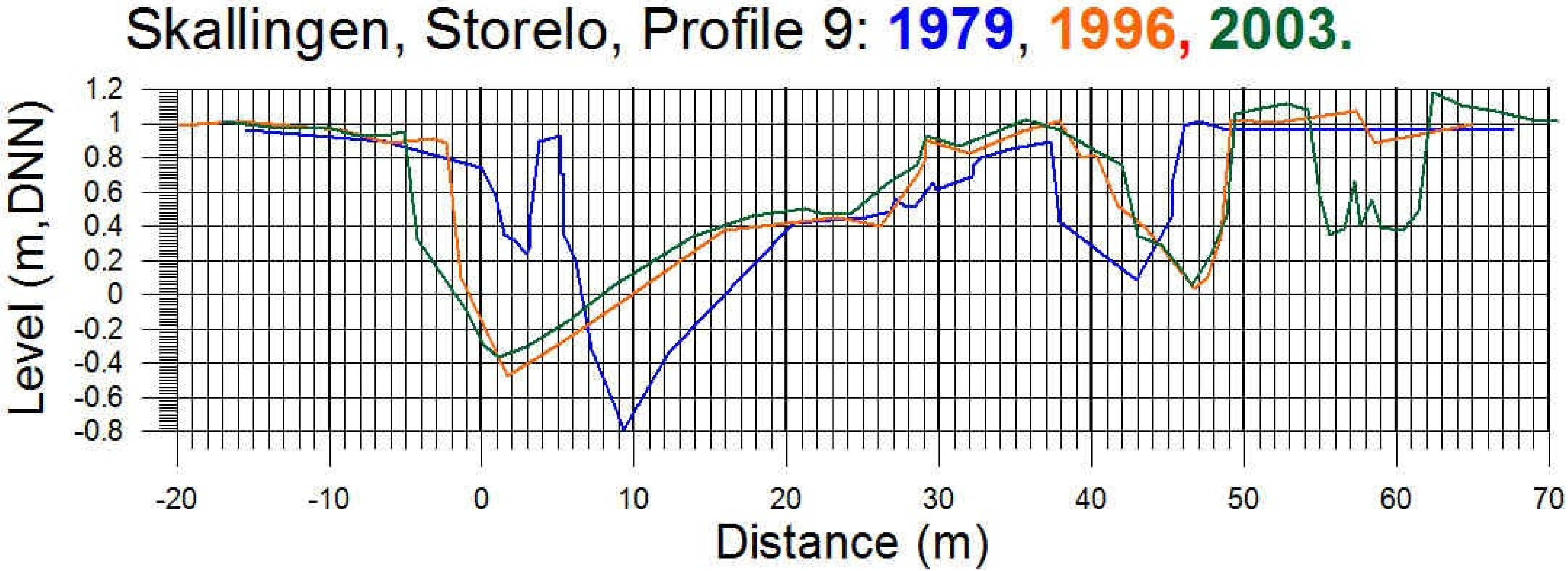

Fig. 23b - Development of a cross profile (Profile 9) in the salt Marsh creek Storelo (for location see Fig. 21) between 1979 and 2003. The ebb direction is into the paper.

Stop 3.4: Skallingende and the Skallingen west coast
(55º 28’ 45.28’’N, 08º 18’ 01.69’’E)

The barrier spit terminus of Skallingen (Skallingende) has undergone tremendous changes since the turn of the last century, where erosion has dominated after centuries with build-up of the barrier-spit.
The barrier spit grew, and extensive aeolian dune ridges developed between 1807 and 1905 (Aagaard *et al.*, 1995). In 1905 the terminus of Skallingen extended to Grådyb. Based on digitized aerial photographs the more recent development of the barrier-spit terminus is presented in Fig. 3.26. From 1905 to 1945 the barrier-spit terminus had only eroded slightly up-drift, but became narrower. The construction of two wooden groins on the western side of the barrier-spit terminus hindered erosion. However, in the winter of 1973–74 the southern

groin collapsed during a storm and the southern tip eroded about 380 m back. After the destruction of the northern groin the area was no longer protected and a storm in 1976 resulted in erosion of additional 750 m. Between 1977 and 1982 the barrier-spit terminus did not erode significantly even though the greatest storm surge ever measured in the area, hit it in 1981. After decades of erosion a state of equilibrium seemed to have been established. In defiance of this equilibrium two boulder groins were established between August and November 1982. The response came rapidly and the groins resulted in heavy lee side erosion. Between August 1982 and February 1983, the recession of the spit-terminus amounted to 300 m. The erosion has continued ever since although in a reduced rate. Between 1983 and 2000 the barrier spit terminus eroded ~260 m and the total retreat of the barrier-spit terminus since 1945 is 1950 m.

After the erosion of the barrier-spit terminus in the 1970's a large flood tidal delta appeared on the tidal flat east of the barrier-spit terminus. It was formed after the tidal flats behind the barrier-spit terminus got exposed to waves and tidal currents.

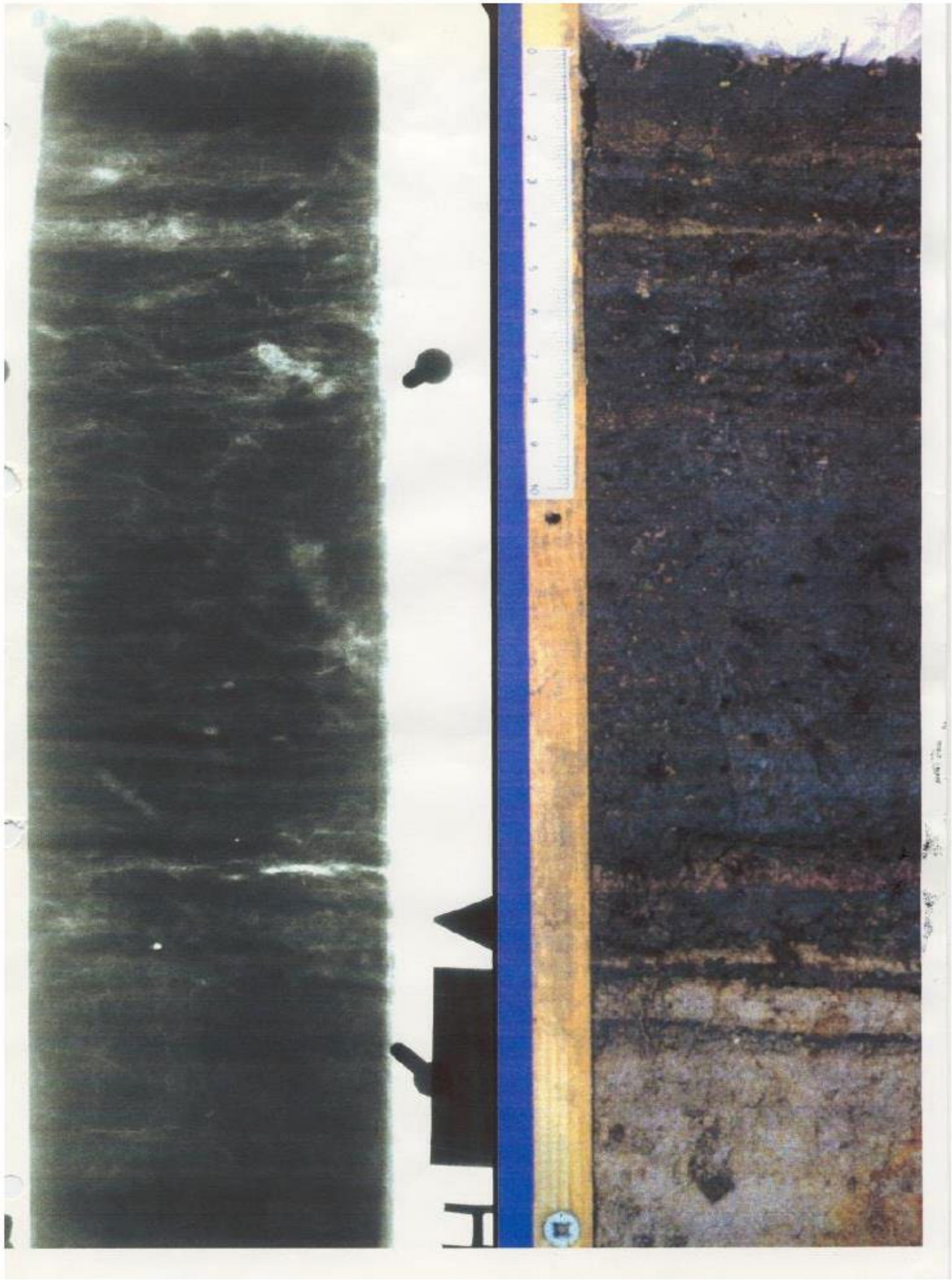

Fig. 24 - A salt-marsh core from one of the first sites where collared sand was spread on the surface in 1931. The core was collected in 1998. Left and right X-ray radiograph and colour photograph, respectively. The red sand is visible 19 cm under the surface on the colour photo and as a crack in the core (white line) on the X-ray radiogram. The rider is 10 cm long.

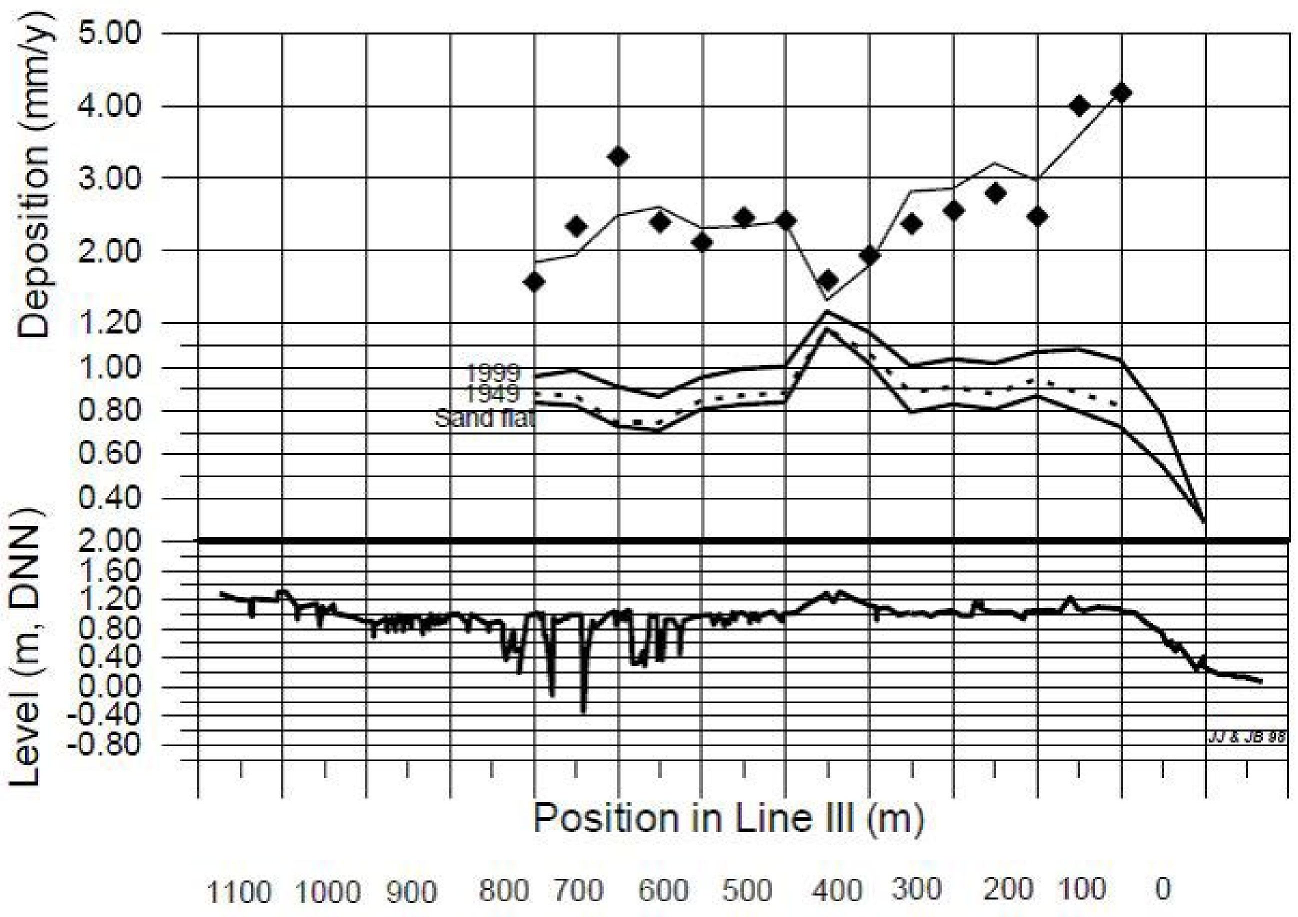

Fig. 25 - Profile across the Skallingen back-barrier from the tidal flat to the central part of the peninsula shoving the topography beneath and levels of the sand flat, salt-marsh surface, 1949 and salt-marsh surface, 1999 in the middle. Above are the measured (diamonds) and modeled (line) deposition rates. The profile ends are marked with "P" on the aerial photo Fig. 21.

The erosion of the barrier spit terminus has exposed an extensive intertidal spit-platform between the barrier-spit terminus and the tidal channel resulting in a cyclic variation in shoals and channels of which a synthesized version presented in Fig. 27.

In contrast to the wash-over site at the root of the barrier spit (Locality 3.2), the sediment budget has been strongly negative at the parts of the barrier which have not been breached and which are characterized by foredunes and/or dykes. Fig. 28 illustrates a representative profile for this major section of the coast. Note that the storm surges in early 1990 caused a shoreline recession of about 35 m (Aagaard et al., 1995), while the following relatively calm period of nine years until 1999 only resulted in an additional recession of 31 m. Subsequently, the shoreline retreated by more than 15 m during a single storm event in December 1999. The mean shoreline recession from mid-1990 through 2003 was 52 m, ~ 4 m y^{-1}. It is significant that deposition of aeolian sand transported from the beach and dune front to the lee side of the dune has been limited, and the net sediment budget at this site therefore has been negative.

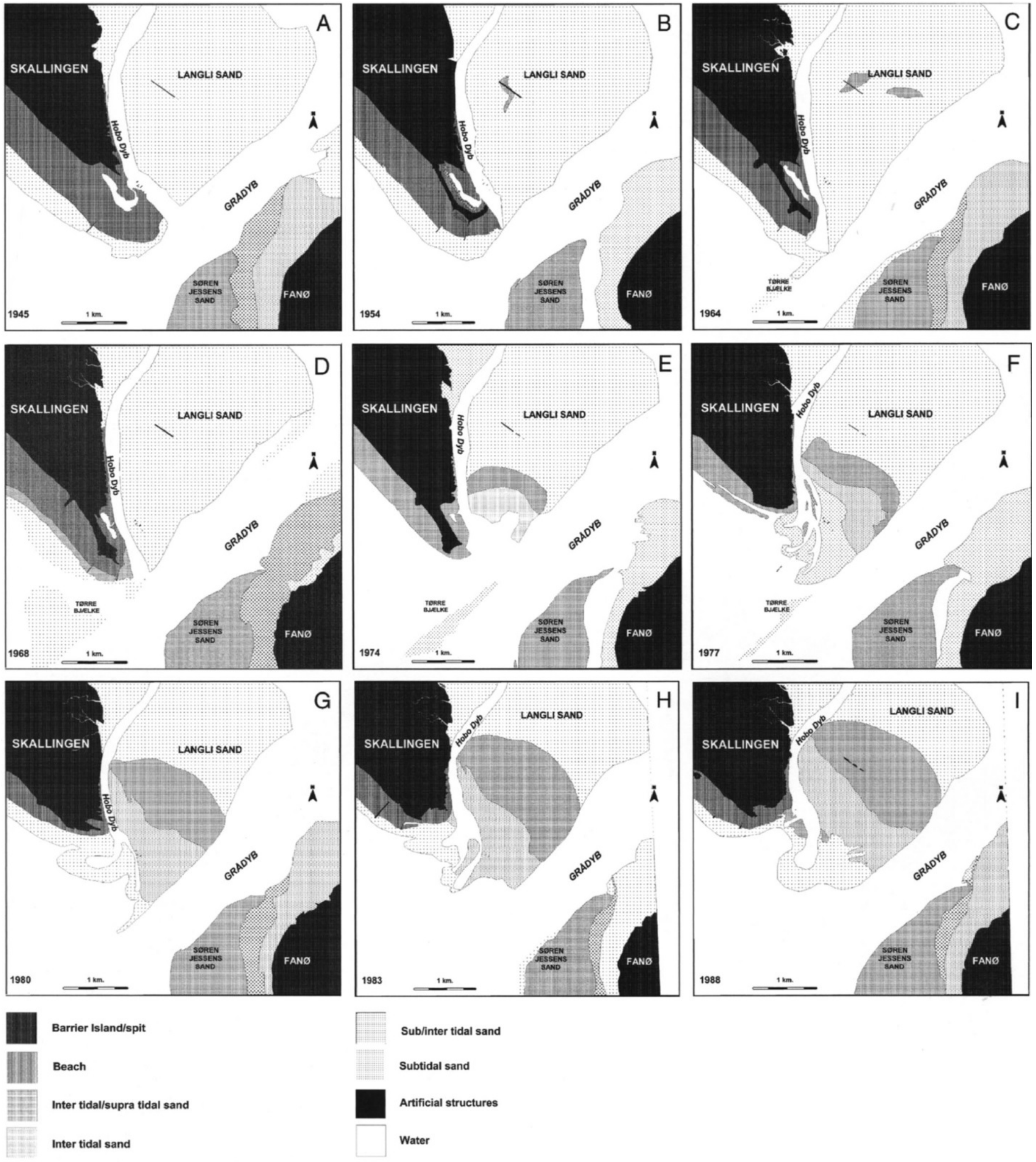

Fig. 26 - Digitized aerial photographs from 1945 to 2000 showing the recent development of the barrier spit terminus. Dramatic erosion took place between 1945 and 1977, where the barrier-spit terminus eroded more than 1100 m in the updrift direction of the littoral transport. The flood tidal delta on the tidal flat, Langli Sand, migrated 1740 m towards the east and has increased in height and width. From Vinther (2006).

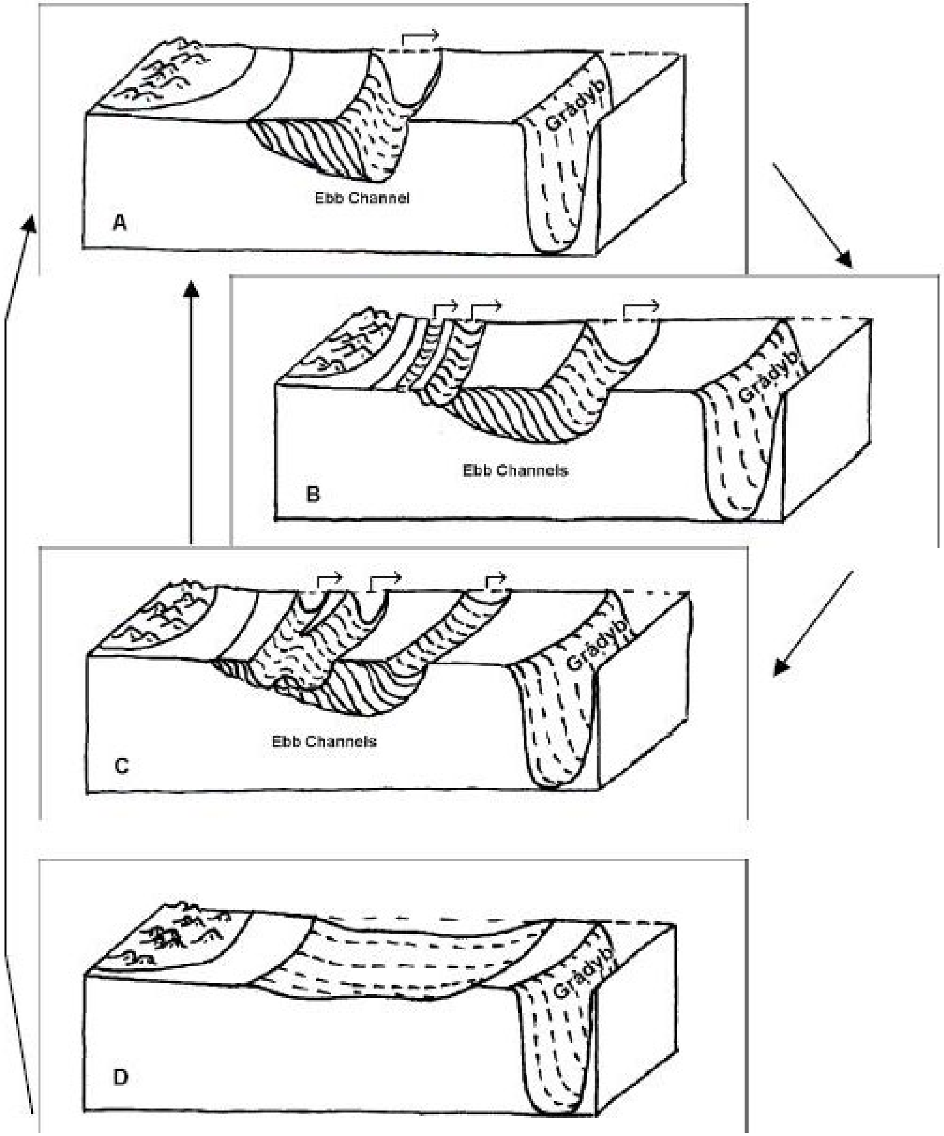

Fig. 27 - Cyclic stages of the spit-platform south of Skallingen after periods with low and moderate wind set ups (A, B and C). The deep channel to the right is the artificially dredged inlet tidal channel, Grådyb. Build-up of the sand bar takes place after periods with low energy input (A). Periods with increased energy input and water levels result in the formation of one or more channels, which dissect the sand bar and grow at the expense of the channel downstream, which in turn gets infilled (B and C) (modified after Oost, 1995). In the last sketch (D) the spit-platform has been even out during a storm, and acts as a wide and shallow channel which again will be dissected by migrating channels during succeeding low energy periods. From Vinther et al. (2004).

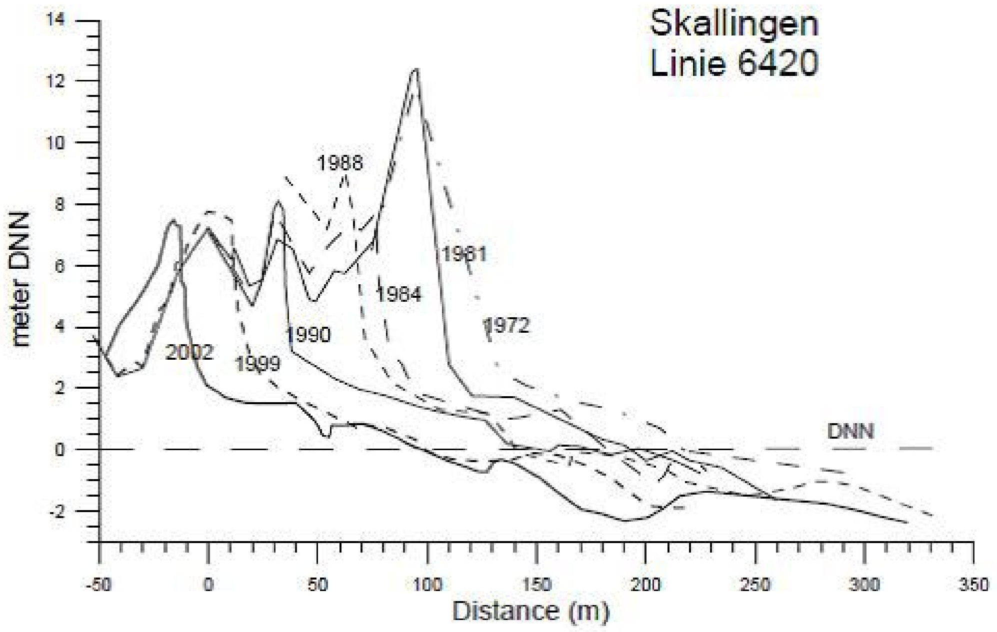

Fig. 28 - Profile representing the morphological development 1972-2002 on the mid-distal part of the Skallingen barrier spit. The mean shoreline recession from mid-1990 through 2003 was 52 m, ~ 4 m y^{-1}.

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Day 4

The mainland coast of the Danish Wadden Sea and a large exposed sand flat

Introduction

The Danish has as the rest of the European Wadden Sea suffered from land reclamation and the construction of dikes which separate large saltmarsh areas from their natural connection to the sea. However, in the northernmost part (Ho Bugt) there are still natural mainland saltmarsh areas as well as a natural river estuary with no dikes and sluice gates (Fig. 16 and Fig. 29). Further to the south Ho Bugt's mainland coast consists of Quaternary and Tertiary deposits pressed up as frozen slaps by glaciers during former glaciations, now exposed in eroding coastal cliffs. Along the mainland coast south of the town Esbjerg the salt marsh areas are diked and the foreland regulated by land reclamation. South of the town Ribe a so-called ebb road (useable at low water) enables a "dry" drive to the island Mandø. This island is located in a more easterly position than its neighbouring islands. West of Mandø a huge exposed sand body faces the North Sea.

Fig. 29 - Topographic map of the northern part of the Danish Wadden Sea. For scale the base of the map is 32 km. The equidistance is 5 m. North is straight up.

Stop 4.1: Holocene deposits in the northern part of Ho Bugt
(55° 34′ 03.42″N, 08° 14′ 06.57″E)

A series of corings were undertaken in the vicinity of Ho Bugt in order to investigate the salt-marsh stratigraphy. These corings were part of a wider investigation to establish a middle and late Holocene sea-level history of the region. The cores were collected from transects across the salt marshes along the northern and western side of Ho Bugt, and is here represented by the Bredmose transect (Fig. 30); it shows basal peat up to 2m thick. It occurs to a level of 0 m DNN and has been dated at this level to 2200 – 2700 BP. Two very interesting layers occur in this transect. The first, a sand layer, is found between 2.46 and 0.95m DNN. This sand layer thickens towards the landward part of the transect. The date of this sand layer is estimated to be ca. 1600 AD, and is associated with a period of heavy aeolian activity during the Little Ice Age. A second interesting layer is a black humified layer. This is found between 1.38 and 0.63 m DNN, and varies in thickness but in most cores, it is found to be ca. 10 cm thick. Through extrapolation of existing radiocarbon dates, it is estimated to be 800AD.

Stop 4.2: The Varde Å Estuary
(55° 34′ 39.11″N, 08° 19′ 26.09″E)

In the north/eastern part of Ho Bugt a large turbidity maximum is situated close to where the river Varde Å has its outlet. This estuary runs across a natural estuarine salt marsh environment without dikes, and it is in fact the only estuary left in the Wadden Sea without sluice gates. The drainage area of the river is 1055 km^2 and the mean freshwater discharge 16.6 $m^3 s^{-1}$ (maximum is close to 100 $m^3 s^{-1}$). Normal tides reverse the flow as far as 7 km inland from the estuary mouth whereas during storm surges seawater can inundate the whole lower part of the valley, and flooded areas can be found as far inland as the town Varde (Fig. 29).
When water enters the estuary at the beginning flood, turbid water enters from the turbidity maximum in the inner part of Ho Bugt (Fig. 31). The concentration continues to increase until the current loses its power around high water slack, and the suspended sediment settles out. This produces a local minimum on the concentration curve. After the turn of the tide the ebb current resuspends the settled material and a somewhat smaller but more elongated ebb peek is produced on the concentration curve. During the ebb peek, the estuary floor is swept clean and the concentration drops to a minimum in the last part of the tidal period. Here the estuary is filled with fresh water from the drainage area in which the concentration of suspended sediment only seldom

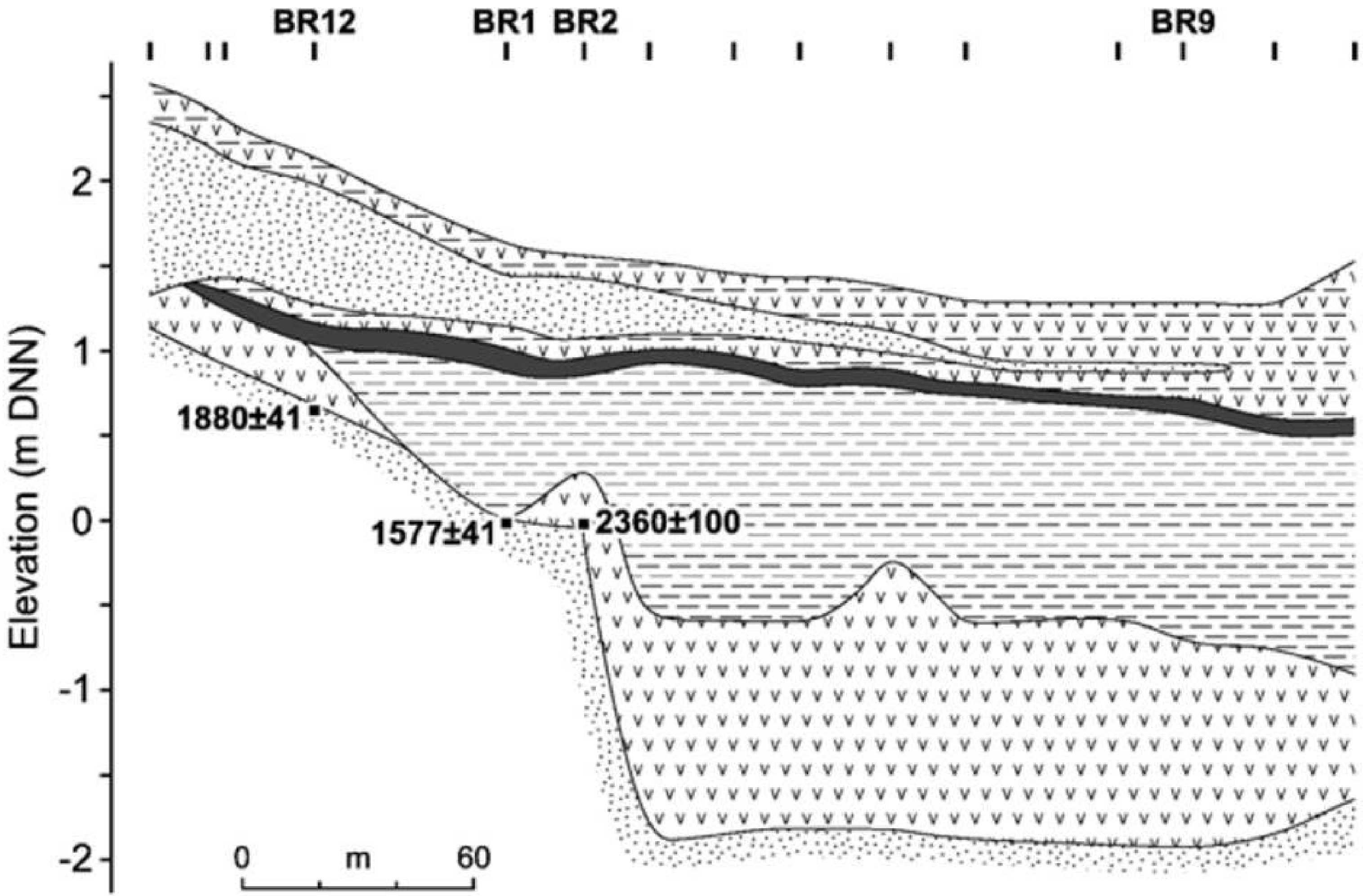

Fig. 30 - Stratigraphy of the Bredmose transect in the northern part of Ho Bugt. The transect shows the typical sucession of the transgrated salt-marsh areas with basal peet overlain by marine clay. Furthermore, there are two very interesting layers in this transect. The first, a sand layer, is found between 2.46 and 0.95m DNN. This sand layer thickens towards the landward part of the transect. The date of this sand layer is estimated to be c. 1600AD, and is associated with a period of heavy aeolian activity during The Little Ice Age. A second interesting layer is a black humified layer. This is found between 1.38 and 0.63 m DNN, and varies in thickness but in most cores, it is found to be ca. 10 cm thick. Following extrapolation of existing radiocarbon dates, it is estimated to be 800 AD.

exceeds 50 mg l^{-1}. The described dynamic controlled variation in the concentration of suspended sediment in the estuary, is remained although the concentration level is three folded from a maximum concentration of about 100 mg l^{-1} to about 300 mg l^{-1} during the succeeding high energy situation.

Stop 4.3: The cliffs along the mainland coast of Ho Bugt
(55° 32′ 12.54″N, 08° 20′ 02.57″E)

During the second last glaciation (Saale) frozen slaps of Quaternary and older primary Neogene deposits were pressed up in the area located north of the town Esbjerg. The cliffs resulting from coastal erosion in these deposits, activated by the post-glacial transgression, are amongst the favourite spots for local landscape painters, expressing the beauty of the native countryside (Fig. 32). Often the punctuality of these artists reveals details of importance for research. In the painting (Fig. 32) from the cliff at Marbæk formed in fluvioglacial material, it is clear that a pronounced *podsol* has developed in the upper part of the cliff, as well as several of the large boulders on the beach are so precisely described that relocating them today, will make an evaluation of the cliff retreat in the intervening period possible. In general, the coastal erosion in these cliffs amounts to about 0.5 m y^{-1}. The locality is famous for wind grinded stones (ventifacts).
South of Marbæk, another slab consisting of older

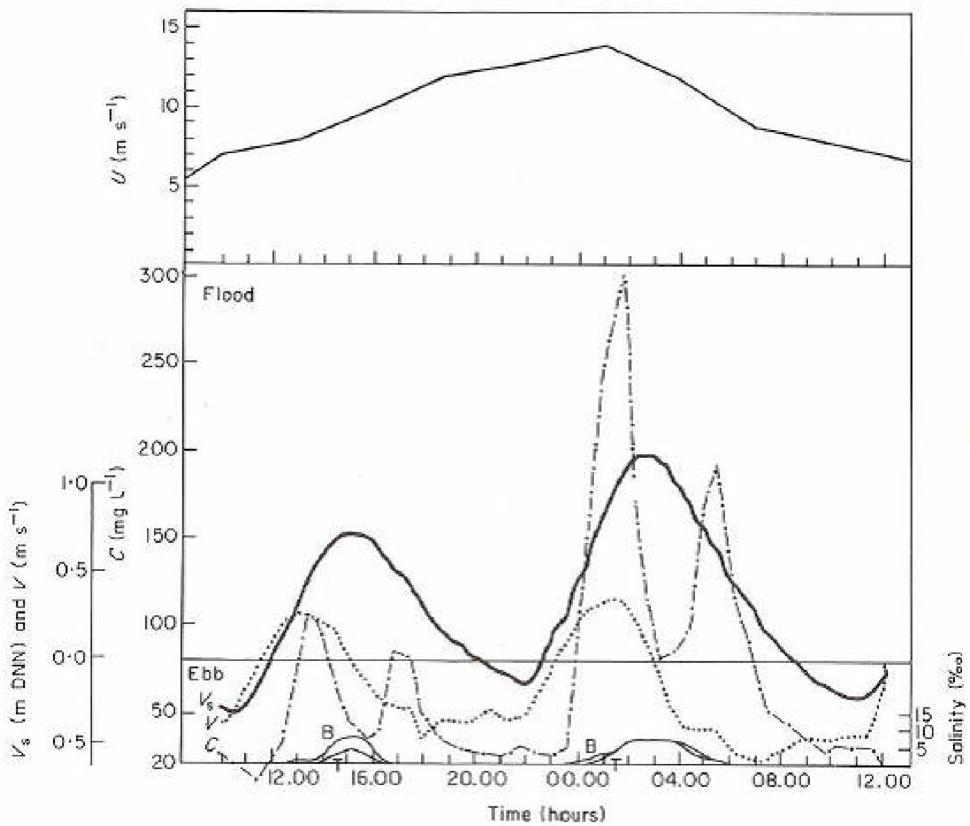

Fig. 31 - The dynamic conditions just inside the mouth of the Varde Å Estuary during a calm "normal" tidal period (the first) and a tidal period characterized by a westerly gale (the last). U: wind speed, Vs: water level, V: Current velocity, C: Concentration of suspended material, and B and T: salinity at bottom and top respectively. Note the typical variation in concentration of suspended matter: a peak formed by turbid water from the turbidity maximum during flood, followed by deposition during high water slag and resuspension in the following ebb period. This pattern is repeated but accentuated in the second tidal period marked by a gale from south west. From: Bartholdy (1984).

Cenozoic red sandstone – forms the cliff. The deposits are here of fluvial origin, and their exact age has been a matter of discussion. It is either Miocene, which in other places constitute the pre-glacial basis of the area in form of mica clay, or Pliocene which is the age of a similar formation forming the core of the Wadden Sea island Sylt. The occurrence of silicified material containing fossils from Silurian favours the latter suggestion. This material is regarded as fluvial transported material from the Baltic deposited on top of former Pleiocene marine sediments.

Fig. 32 - The cliff at Marbæk as it was seen by the painter "Riber" early in the 20th Century. Note the pronounced podsol developed in the upper part of the cliff, formed in glaciofluvial deposits from Saale.

Stop 4.4: Mandø and Koresand
(55º 15′ 55.86″N, 08º 32′ 49.98″E)

Mandø is the smallest of the Danish Wadden Sea islands. Situated east of the line connecting the chain of isles in the rest of the Danish Wadden Sea, Mandø is believed to be a remnant of a former island chain consisting of Langli, the eastern bulges on Fanø (Fig. 29), and similar features further south.

Mandø was cut into two halves during a storm surge in 1560. The actual dike protecting Mandø today was constructed in the 1930's, and was damaged in a large storm surge in 1981, flooding the lower parts of the island. The connection from the island to the mainland takes place through an elevated kind of ebb road (låningsvej) which, with a level close to the mean high-water level (Figs. 33 and 34), effectively divides the two tidal areas *Juvre dyb* to the south and *Knudedyb* to the north.

Mandø is situated close to the merging point of southward littoral driven sand from the north and northward littoral drift from the south (Fig. 35). As such it is situated in a prograding part of the exposed Wadden Sea coast but even so, no barrier has been formed in front of Mandø. Former beginnings of initial barrier formations (Bartholdy and Pejrup, 1994) have not had the necessary impact in order to form a barrier. The reason for

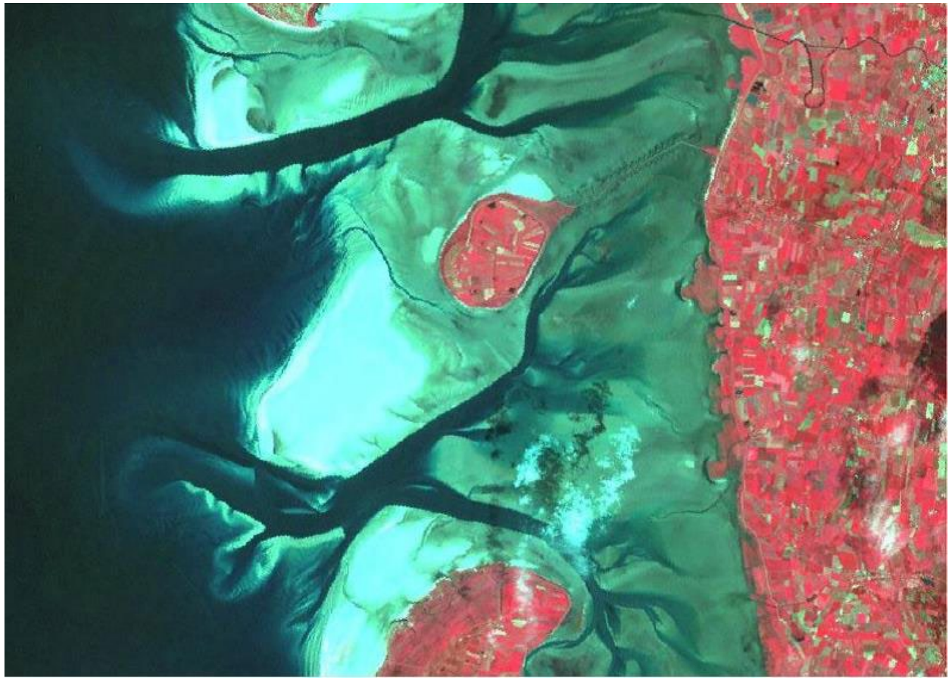

Fig. 33 - Landsat scene in "false colour" from the spring of 2002 at a "low" low water. The ebb road to Mandø, with land reclamation "squares" on both sides, is clearly visible in the centre of the image. North is straight up. For scale the base of the image is about 20 km in length. Notice how Juvre Dyb (the inlet to the south) has a tendency of taking a southerly direction at the end of its course and how Knudedyb to the north give the impression of an inlet with an almost straight alignment perpendicular to the coast line but at the end is bending to the north.

this is still a puzzle. Factors like frequently shifting littoral drift directions close to the zero point and the fact that the area is situated in a narrow strip of coastline between two prominent ebb tidal deltas have been among the suggested reasons.

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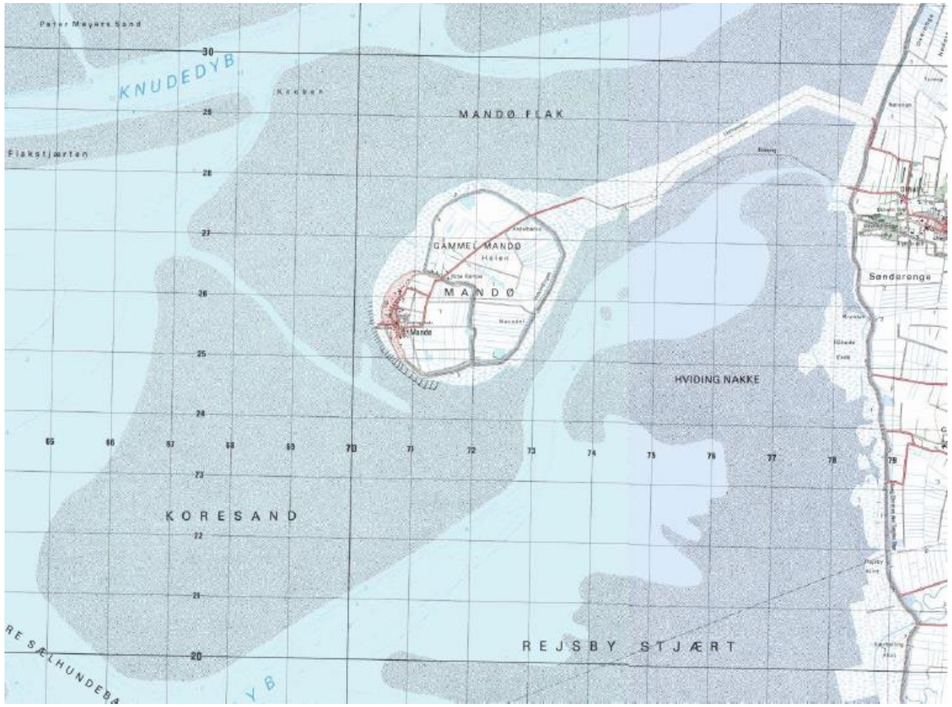

Fig. 34 - Map of Mandø and Koresand. North is straight up. For scale the grid is 1 km.

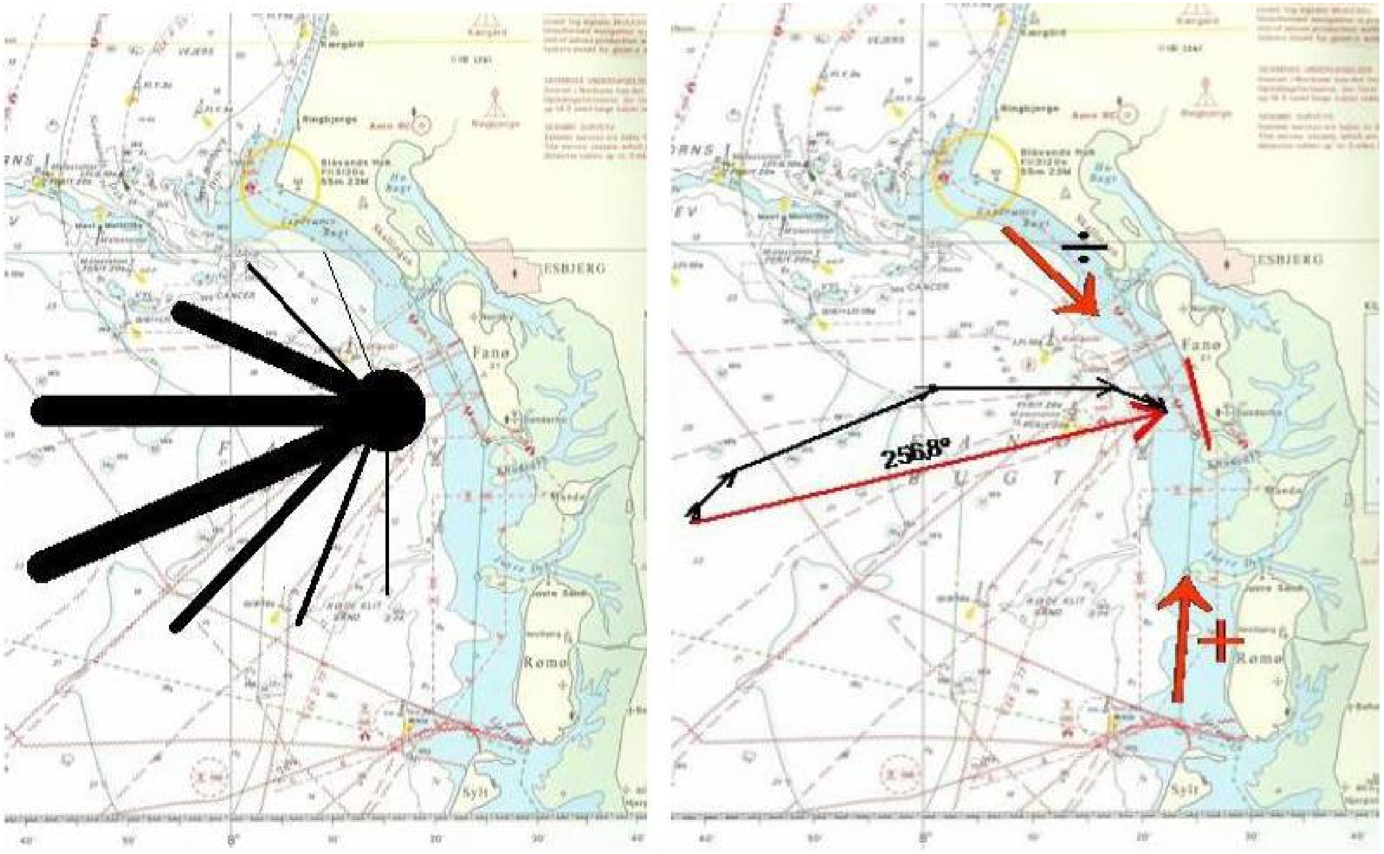

Fig. 35 - Left: Significant wave height (length) and frequency (thickness) of waves recorded by the Danish Coastal Directory in the period 1998-2002 off the coast of Fanø. Right: The resulting wave impact on the coast (vector in red) calculated as $(H_{sd}^2 \cdot T \cdot F / \Sigma_{(d)} H_{sd}^2 \cdot T \cdot F) \cdot 100$ where H_s is significant wave height, T is wave period, F is frequency and d is direction. Minus indicates sediment deficit and plus sediment surplus in the coastal budget. The red line at the southern tip of the Wadden Sea island Fanø, is perpendicular to the resulting wave impact at 256.8°N.

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