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Geotechnical and geological aspects of differential subsidence in the Skaw Spit, Denmark

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SYNOPSIS: Local differential subsidence has been observed by means of repeated precise levellings in the township of Skagen at the northernmost tip of the Skaw Spit in Jutland. We have studied the possible causes of the subsidence. Oedometer tests have been carried out on undisturbed clayey samples from the Holocene in a boring at the depth interval 30-114 m. Seismic profiles were acquired in Kattegat along the coast and on land. The geotechnical investigations indicate that the consolidation process in the Holocene sediments is completed. Other possible causes: lowering of the groundwater table in water supply wells, and filling in the harbour area seem to be insufficient to account for the subsidence. In the Quaternary the seismic profiles indicate dislocations that may be related to faults in the pre-Quaternary substratum. A relationship between the subsidence and active faulting is considered a possibility.

1. INTRODUCTION

The Skaw Spit forms the northernmost part of Jutland (Fig. 1 and 2). The spit protrudes about 40 km NNE-ward from the mainland of Jutland (Vendsyssel). A comprehensive study of the geomorphology and recent geology of the spit was given by Hauerbach (1992). The Quaternary sequence of the spit has been studied geologically and geotechnically in two borings (Knudsen 1994, Thorsen 1995 a,b). Skagen 3 is a deep boring with cores and undisturbed samples recovered from 30 to 220 m depth, and Skagen 4 is a cable percussion boring with continuous Split Spoon sampling covering depths to 30 m. The borings are located between the town of Skagen and the tip of the spit (Fig. 2).

In 1995 a boring, Skagen 5, was taken to 40 m's depth and continued as a CPT to 80 m's depth. The boring was carried out in the town of Skagen (Thorsen & Mortensen, 1995).

The foundation of the spit was established in the period after the disappearance of the Weichselian Ice from Kattegat and Skagerrak. Since that time approximately 15,000 years ago an about 130 m thick sequence of marine sediments has accumulated. The sequence is tripartite (Fig. 3) with a lower clay layer followed by a clayey silt layer covered by a sandy top layer called "Oddesand" (= Spit sand).

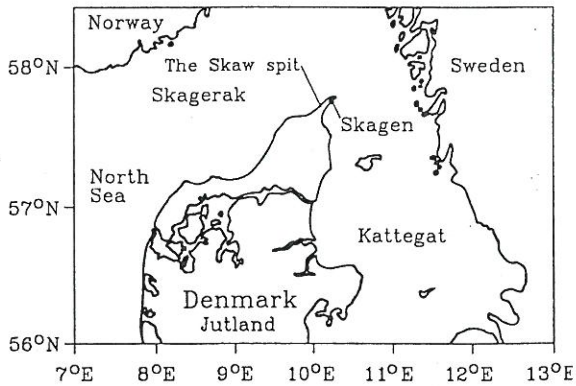

Fig. 1. Location of the Skaw Spit.

Detailed ^{14}C-datings show that the sedimentation rate has been increasing throughout the period. The uppermost 30 m Oddesand were deposited within 1000 years (Nielsen et al. 1995). A sample from level -35 m in boring Skagen 5 was radiocarbon dated to about 400 BP, corresponding to level -60 m in boring Skagen 3. (Conradsen & Nielsen, 1995). The main volume of the spit sediments - 115 m of 130 m (Skagen 3) - are of Holocene age. The Skaw Spit constitutes the western, highest part of a huge Holocene sediment body deposited in the northern Kattegat as described by Flodén (1973) and Fält (1982).

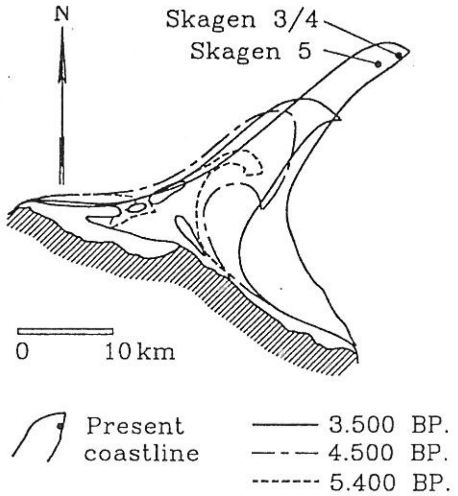

Fig. 2. The Skaw Spit and its development through the last 5400 years (Hauerbach, 1992). Location of borings Skagen 3, 4 and 5.

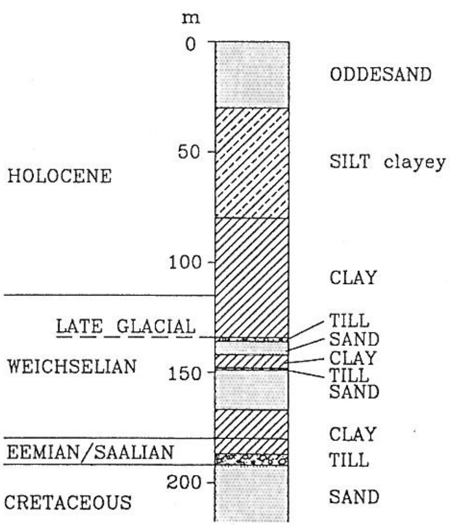

Fig. 3. The Skagen 3 boring. Lithologic and stratigraphic logs from Knudsen (1994).

2. LEVELLINGS

Repeated levellings have been carried out on the Skaw Spit in the years 1942, 1953, 1983, 1991 and 1994. The levellings were carried out partly by the National Survey and Cadastre and partly by Poul Hauerbach. The National Survey and Cadastre kindly placed their results at our disposal.

According to the regional picture of the isostatic uplift of Scandinavia it was predicted that the Skaw Spit was to be uplifted with a gentle northward increase in uplift velocity. However, contrary to expectations, the levellings showed, that the northernmost part of the spit is subject to relative subsidence (Fig. 4). The time series in Fig. 4 show a steady subsidence for all points except between the latest two measurements, where all points are uplifted. At present we do not have any sensible explanation of that observation.

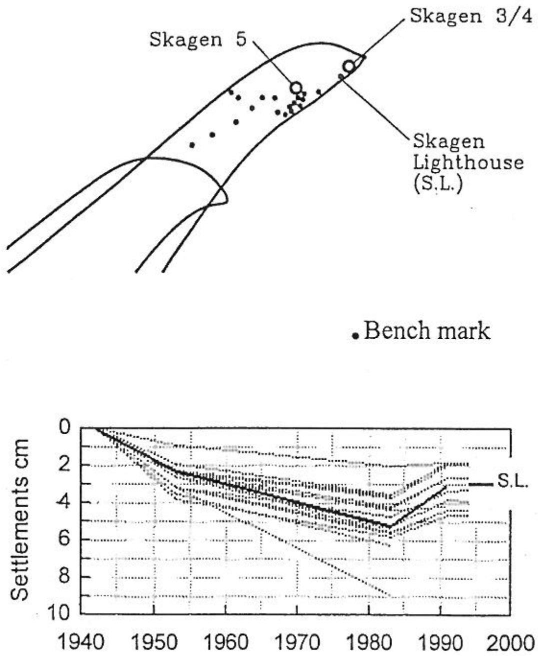

Fig. 4. Relative vertical movements 1942-1994 of the Skaw Spit (Hauerbach 1992 and results from the levelling in 1994).

The geographical distribution of the levelling points is not optimal for appraisal of the area variations in the vertical movements, but two features clearly appear from the data (Fig.5), namely a SE-gradient along the Kattegat coast in the town of Skagen, and a subsidence maximum located centrally on the spit about 3 km SW of the town. As suggested by the iso-lines in Fig. 5, a zig-zag zone with excess subsidence may cross the spit with an overall ESE-WNW direction.

The rather steep gradients in the subsidence values indicate that the cause/causes of the subsidence are local and possibly relatively shallow. We have considered a variety of possible soil mechanical and geological explanations of the observed anomalous movements.

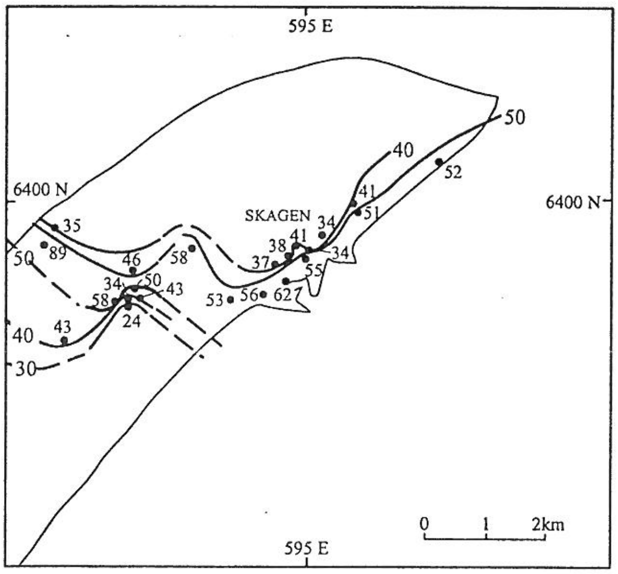

Fig. 5. Relative subsidence (mm) 1942-1983.

The possible soil mechanical explanations encompass two different types of causes, namely natural causes, such as differential subsidence created by consolidation of the Holocene sediments, and man-made causes such as settlements due to lowering of the groundwater table in water supply wells located southwest of the town, or settlements caused by local excess load on the sediments from dumping of earth material during construction work in the harbour of Skagen.

The ground water exploitation from the shallow Holocene sands may contribute to the subsidence, but it is anticipated that the contribution is far less and far more localized than is observed in the area southwest of the town.

The effect from dumping of sediments in the harbour area during construction work related to the expansion of the harbour may possibly have a local effect, but it could hardly create the seaward gradient that is observed over a distance of more than two kilometres in the town.

The two remaining possibilities that seem reasonable to us, i.e. consolidation effects and geological causes, have been investigated in some detail.

3. GEOTECHNICAL INVESTIGATIONS

One of the main objectives of the geotechnical investigations performed on undisturbed samples from the Skagen 3 boring has been to estimate the state of consolidation and the creep rate of the Holocene sediments. Results of Oedometer tests have indicated that the consolidation process in the Holocene sediments caused by sedimentation of the "Oddesand" is completed (Thorsen 1995a).

Based on the maps depicting the development of the spit (Hauerbach 1992) it is possible to estimate that the sedimentation of the Oddesand was terminated about 200 years ago at the site of Skagen 3. From that it is concluded that last time the creep age could have been reduced to zero by loading was 200-300 years ago. Based on this the present creep rate of the sediments was estimated to be less than 0.5 mm/year (Thorsen 1995b). It is noted that this value is of the same magnitude as the observed excess subsidence rates. Thus it cannot be excluded that creep processes may play a significant role, but this will not explain the observed uplift from 1983 to 1991/94.

4. SEISMIC INVESTIGATIONS

With the objective to provide images of the structure of the Quaternary layers and the underlying succession of pre-Quaternary sequences, reflection seismic investigations have been undertaken at sea in Kattegat and on land along the coast southwest of the town of Skagen (Fig. 6).

Both groups of profiles were acquired with a 24-channel system. The marine source was two simultaneously fired 10 cubic inch sleeveguns. On land 50 g dynamite charges were used. At sea the station distance was 6.25 m and data coverage 1200%. On land the corresponding figures are 5 m and 600%.

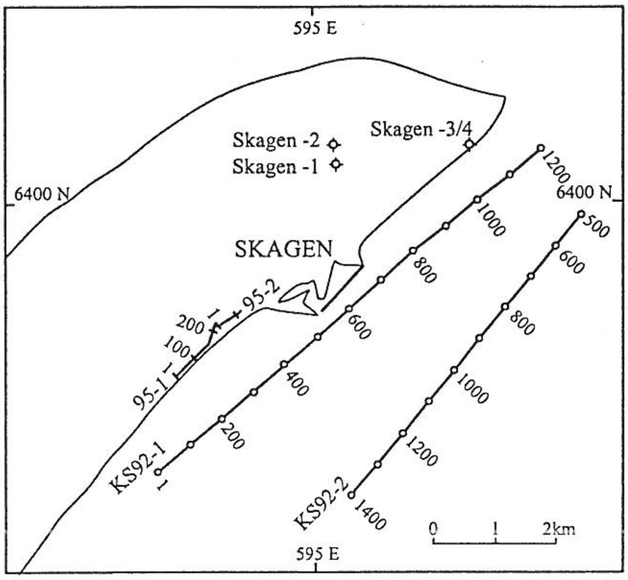

Fig. 6. Reflection seismic profiles acquired at sea in 1992 (KS92-1,2) and on land in 1995 (95-1,2).

The marine profile adjacent to the coastline was extended as close as possible to the site of Skagen 3, in order to estimate the stratigraphic position of the observed reflections. To obtain a correlation between the depths in the boring with the two-way reflection times of the seismic profiles, a well-velocity survey was undertaken in the Skagen 3 boring. A hydrophone was lowered into the hole, and at depth intervals of 1 or 2 m a small charge was fired in a water filled groove at the surface, and the travel time from the surface to the hydrophone was recorded. The result is shown in Fig. 7.

It is noted that the seismic velocity, measured as twice the gradient of the curve, is systematically increasing with depth. This is what should be expected in a normally consolidating sequence of sediments. The local deviations in the depth intervals 130-150 m and 170-190 m are probably due to caving related to the composite lithologies in these intervals (cf. Fig. 3).

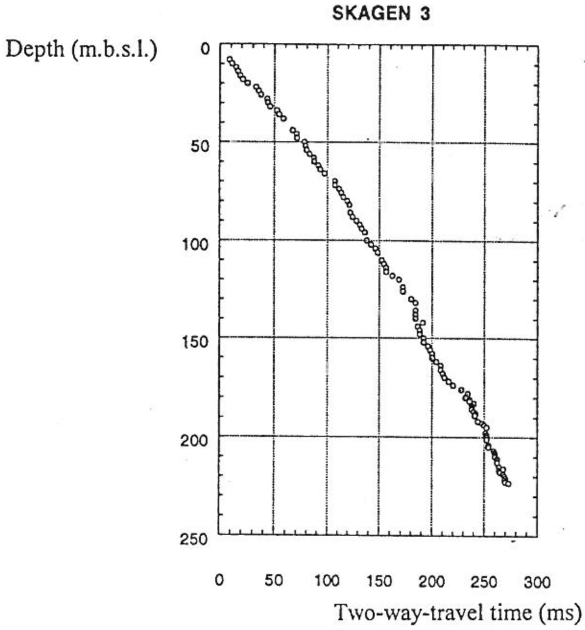

Fig. 7. Relation between depth and two-way reflection times, as measured in Skagen 3.

The seismic profiles and their interpretations are shown in Fig. 8 and 9. It is noted that the stratigraphic levels in the pre-Quaternary part of the profiles have been obtained by correlation with the deep borings, Skagen 1 and 2 (cf. Fig. 5).

The marine profile KS92-1 penetrates down to the crystalline basement. The vertical resolution allows identification of relatively small features. The reflections with the wavy appearance in the uppermost part of the profile, seem to correspond with the Oddesand. The pre-Quaternary sequence is cut by a fault at station 300-400. The displacement is estimated at maximum 30 m. The fault displaces the reflection that is correlated with the base of the Quaternary deposits and possibly also the reflection correlated with the base of Lateglacial-Holocene sequence. At the base of the Oddesand no fault displacement is observed. But the base of the Oddesand on the north side of the fault is lowered 10-15 m relative to the level on the south side of the fault. This feature is taken to indicate sub-recent movements along the fault.

On the marine profile KS92-2, about 2 km seawards of profile KS92-1, a similar fault is observed at station 1250 (cf. Fig. 5). If the two faults are correlated, they fall on a SE-NW line. This happens to be the most prominent structural direction in this area (Berthelsen 1992), and for that reason the correlation seems to be valid.

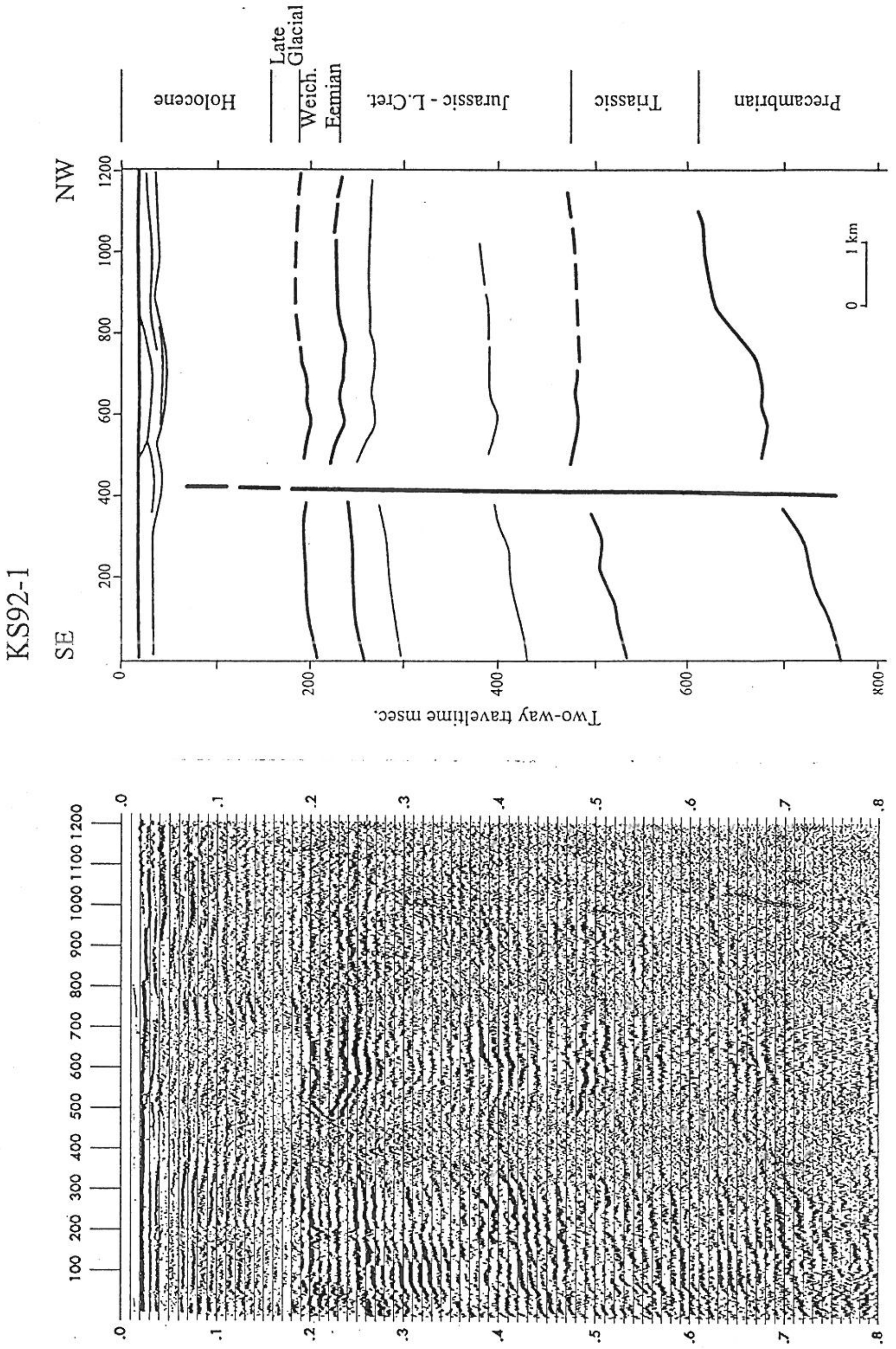

Fig. 8. Reflection seismic profile KS92-1 (left) and interpretation (right). For location see Fig. 5.

The land profiles are shown as a composite profile in Fig. 9. The quality of this profile is inferior to the marine counterpart. By experience we know that it is very difficult to obtain decent reflection seismic profiles with good penetration and resolution in the Skagen area. The reason seems to be minor contents of methane gas in the superficial sediments.

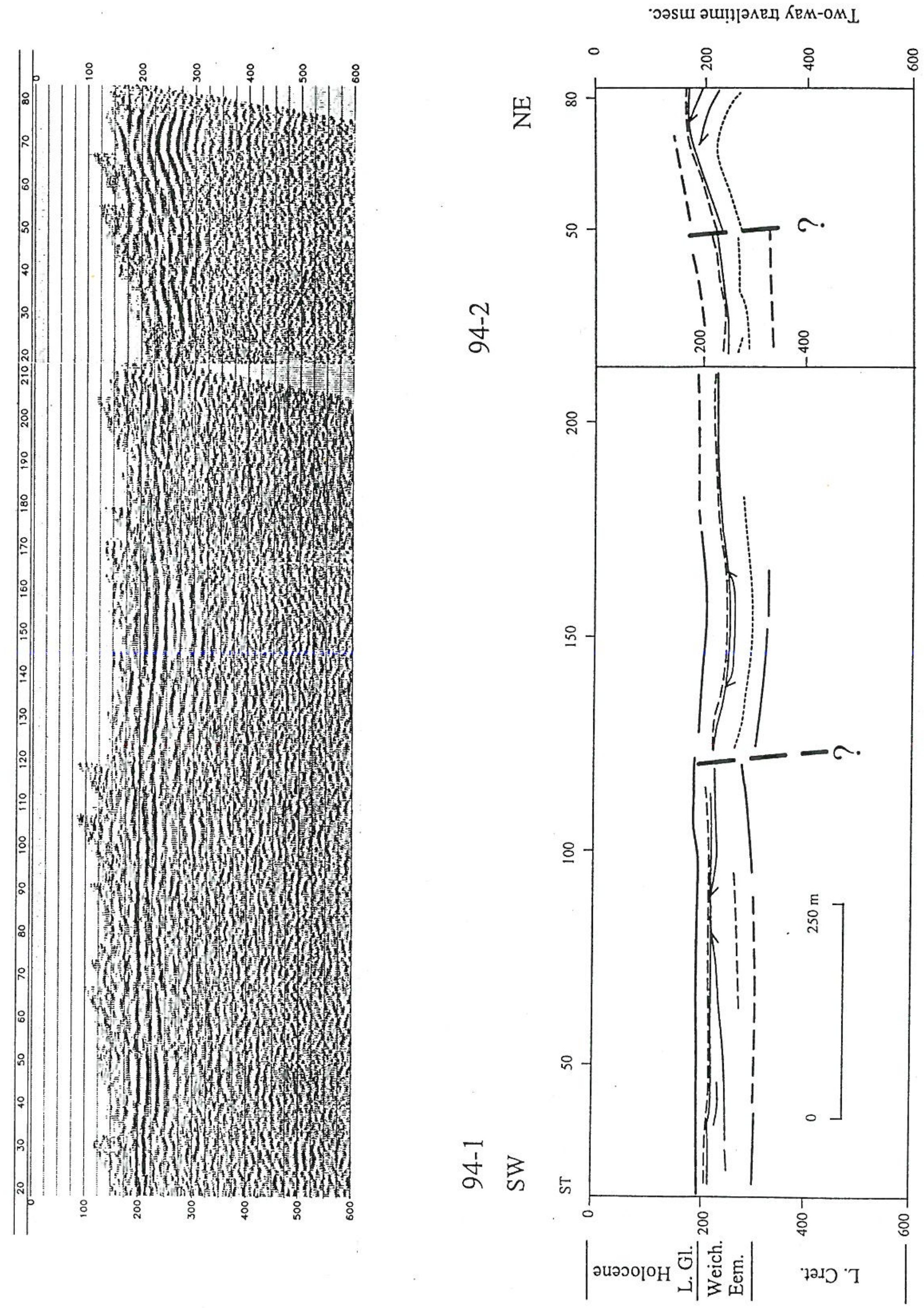

Fig. 9. Reflection seismic profile 94-1 and 2 (left) and interpretation (right) For location see Fig. 5.

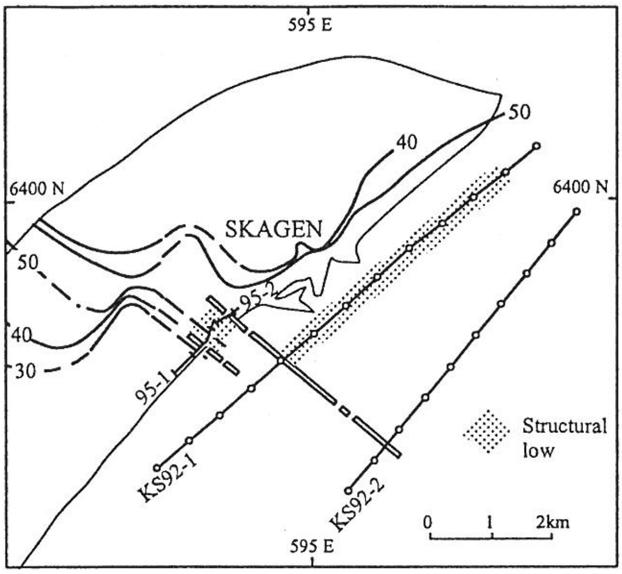

Fig. 10. Map showing the structural features derived from the seismic profiles in relation to the contours indicating the recent subsidence.

The base of the Quaternary can be identified in approximately the same depths as in the marine profile. Also the base of the Lateglacial and Holocene sequence can be traced with confidence. Two faults are indicated with big questionmarks. With no information on the pre-Quaternary reflections it is virtually impossible to identify true i.e. basement related faults. The most interesting feature in the profile is the sag in the reflections north of station 125.

The base of the Lateglacial-Holocene is lowered 20-25 m relative to the level further south. This sag may be of the same origin as was anticipated for the sag observed in the marine profile. In the northern end of the profile an anticlinal structure rises about 50 m above the surrounding levels. The interpretation of this feature is unclear, but it is noted that the structure is located on the extrapolated fault tracé as shown in Fig. 10.

5. CONCLUSIONS

The repeated precise levellings at the Skaw Spit indicate a local subsidence pattern along the coastline in the town of Skagen and across the spit immediately southwest of Skagen. Geotechnical investigations show that the consolidation process of the Holocene clays most probably has ceased. The creep rate has been estimated, but due to uncertainties concerning the interpretation of the calculated rate, the significance cannot be evaluated at the present stage. At this stage it is concluded that consolidation is not responsible for the observed subsidence. The possible importance of creep processes still remains to be quantitatively evaluated, but the uplift registrated in the latest levellings seems to indicate other causes. It is argued that effects from lowering of the groundwater table and from dumping of fill material in the harbour, are probably too local to be considered significant. The seismic profiles carry indications of active faulting in the area. The observed subsidence may possibly be the surficial layers response to movements on basement-rooted faults. The only independent indication of active tectonic movements in the area is the recording of two earthquakes in the vicinity of Skagen in the period 1929-1992 (Gregersen et al. 1995). In 1993 a long-term project was initiated by Poul Hauerbach and Kaj Borre, Aalborg University, with the objective to measure directly possible movements in the Skagen area. The project utilizes the GPS technique for repeated, precise determinations of x, y and z coordinates on a number of stations located on either side of the suspected fault zone.

6. REFERENCES

Berthelsen, A. (1992). From Precambrian to Variscan Europe. In: Blundell, D., Freeman, R. & Mueller, S. Acontinent revealed - *The European Geotraverse, Cambridge University Press*, pp. 153-180.

Conradsen, K & Nielsen, S.H.(1995). Holocene paleoceanography and paleoenvironments of the Skagerak - Kattegat, Scandinavia. *Paleoceanography.* Vol. 10, no 4, pp. 801-813.

Flodén, T. (1973). Notes on the bedrock of the eastern Skagerrak with remarks on the Pleistocene deposits. *Stockholm Contribution to Geology,* Vol. XXIV, pp. 79-102.

Fält, L.-M. (1982). Late Quaternary sea-floor deposits off the Swedish west coast. *Chalmers University of Technology and University of Gothenburg*, Vol. A37, 259 p.

Gregersen, S., Leth, J., Lind, G. & Lykke-Andersen, H. (1996). Earthquake activity and its relation to geologically recent motion in Denmark. *Tectonophysics,* (in press).

Hauerbach, P.(1992). Skagen Odde - The Skaw Spit - an area of land created between two seas. *Folia Geographica Danica.* Tom XX. Copenhagen: Reitzel.

Knudsen, K.L. (1994). The marine Quaternary in Denmark: a review of new evidence from glacial-interglacial studies. *Bulletin of the Geological Society of Denmark,* 41, pp.203-218.

Nielsen, S. H., Conradsen, K., Heinemeier, J., Knudsen, K. L., Nielsen, H. L., Rud, N. & Sveinbjörnsdóttir, A.E.(1995).Radiocarbon dating of shells and foraminifera from the Skagen core, Denmark: Evidence of reworking. *Radiocarbon.*37, pp. 119-130

Thorsen, G. (1995a). Preconsolidation pressure and creep settlements. Estimations based on results of oedometer tests. *Balkema. Proc. IS-HIROSHIMA'95.* Vol. 1. pp. 287-292.

Thorsen, G. (1995b). The Skaw Spit - a question of settlements. *Proc. XI ECSMFE, DGF-BULLETIN 11*, Vol. 3. pp. 263 - 268.

Thorsen, G. & P.K. Mortensen (1995). CPT-investigation in young sediments in the northern part of Jutland. *Proc.CPT'95. SGF Report 3:95.* Vol. 2 pp.317 - 322.