GEOLOGIE EN MIJNBOUW VOLUME 54 (3-4), p. 130-145 1975

LATE QUATERNARY HISTORY OF THE SKAGERRAK; AN INTERPRETATION OF ACOUSTICAL PROFILES

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SUMMARY

In the Skagerrak several sedimentary units are present that were found previously in the Norwegian Channel. The thickness and distribution of late-postglacial sediments is measured and mapped. The origin of the sediments are discussed and a model for the late-Quaternary sedimentary history of the area is suggested. The occurrence of shadow zones is related to gasbubbles or coarse materials in the subsoil.

Sedimentary structures such as large scale foresets and giant sand waves are found along the southern border of the Skagerrak.

The sand waves are considered as relict structures.

The bottom relief in the Skagerrak is closely related to the sedimentary history; along the southern border ice grounding has probably played an important role.

INTRODUCTION

In August 1971 and March 1972 an acoustic reflection survey was carried out in a great part of the Norwegian Channel and the western part of the Skagerrak by a team of the N.I.O.Z., Texel. In order to obtain information concerning the eastern part of the Skagerrak, a cruise was made with the R.V. "Aurelia" from 7 – 17 May 1973 (fig. 1). The main purpose of the research was to investigate the distribution of late-Quaternary sediments in the Norwegian Channel and the Skagerrak, so that conclusions might be drawn concerning the late-Quaternary sedimentary history of the eastern North Sea area.

The Skagerrak is situated along the northeastern borderzone of the North Sea Basin, and borders on the Precambrian rocks of southern Norway and southwestern Sweden that belong to the Fennoscandian (Baltic) shield.

In the Skagerrak continuous seismic profiles indicated the existence of thick (locally up to 380 metres), presumably Quaternary sediments, wedging out towards the Norwegian coast and overlying uncomformably the eroded Mesozoic strata that form the bottom of the trough (Sellevoll & Aalstad, 1971).

In Denmark the Quaternary deposits reach a maximum thickness of about 300 metres in Frederikshavn, but great differences occur due to tectonic movements in the underground and the uprising of salt domes which brought Permian and Triassic rocks in contact with Pleistocene sediments (Hansen, 1965).

The origin of the Skagerrak has been ascribed to tectonic subsidence (O. Holtedahl, 1960, 1964; Pratje, 1952) while Shepard (1931) and Kuenen (1950) favoured a glacial mode of formation. Recently also Sellevoll and Aalstad (1971) supported the "glacier activity" hypothesis. As is evident from the presence of glacial deposits in Denmark, Germany and the southern North Sea, glaciers of the Saale and Weichsel glaciations partly covered the North Sea area. Presumably, the Skagerrak was covered with ice as well, at least during the Saale and possibly also in the Weichselian (Valentin, 1957).

APPARATUS

During the cruise no samples were taken. Navigation was done with the aid of the Decca Navigation System, using a Mark-21 receiver. The Raytheon penetrating echosounding equipment used, consisted of a 3,5 kHz transducer (built in the ship's hull, at 3,5 m depth) in combination with a 2000 W transceiver and a signal-correlator or CESP. Returning signals were recorded on a precision electrographic recorder. Only when the velocity of sound in the penetrated bottom sediments is known, the recorded time differences can be converted into thickness or depth. Since such information is not available the velocity of sound in sediment is taken to be the same as the velocity in water.

BATHYMETRY AND BOTTOM RELIEF

Bathymetry

From the data obtained a bathymetrical map was compiled (fig. 2). Though some uncertainties exist due to the rather wide spacing of the ship's tracks, its general picture is not different from the map of O. Holtedahl (1940) and

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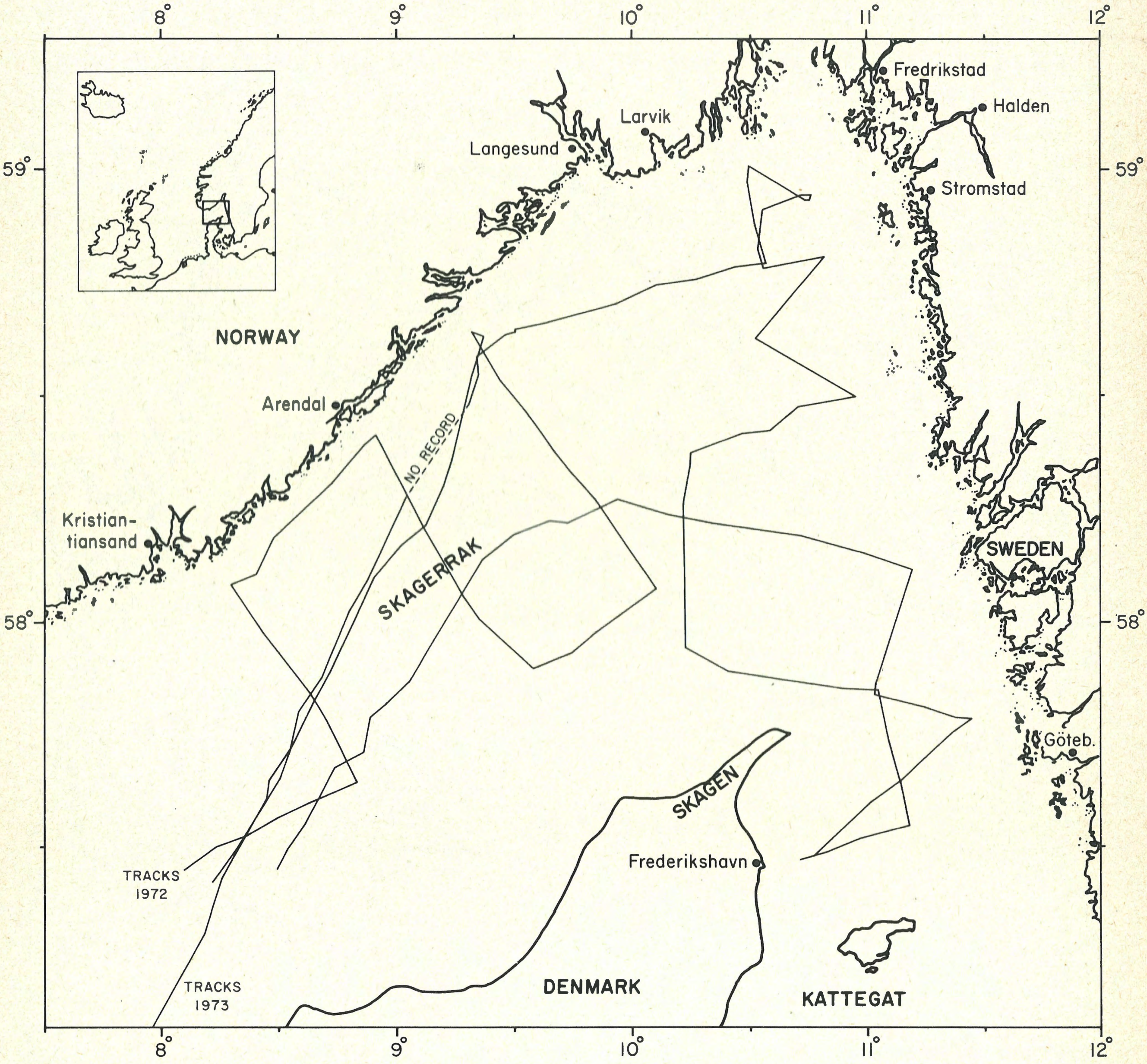


Fig. 1
Location of reflection profiling traverses.

recent fisheries charts. The pattern of the depth contours south of Langesund shows the possible extension of the Langesund Channel into the Skagerrak, while the deep trough west of Stromstad represents the submarine continuation of the Oslofjord.

The over-all N-S direction of the depth contours in the eastern part of the Skagerrak is believed to reflect the deeper geologic structure of the Fennoscandian border zone.

In the Skagerrak the floor of the central deep basin generally is flat, with a northern slope that is relatively irregular and steep, leading to the Norwegian continent. The eastern slope has an almost flat surface with only minor relief and a gradual inclination, whereas the southern slope of the Skagerrak has a convex form, a very gradual inclination and some marked incisions (O. Holtedahl, 1964; Pratje, 1952).

Bottomrelief

The profiles show the presence of relief on the seabottom on a scale that is generally not reflected in bathymetrical

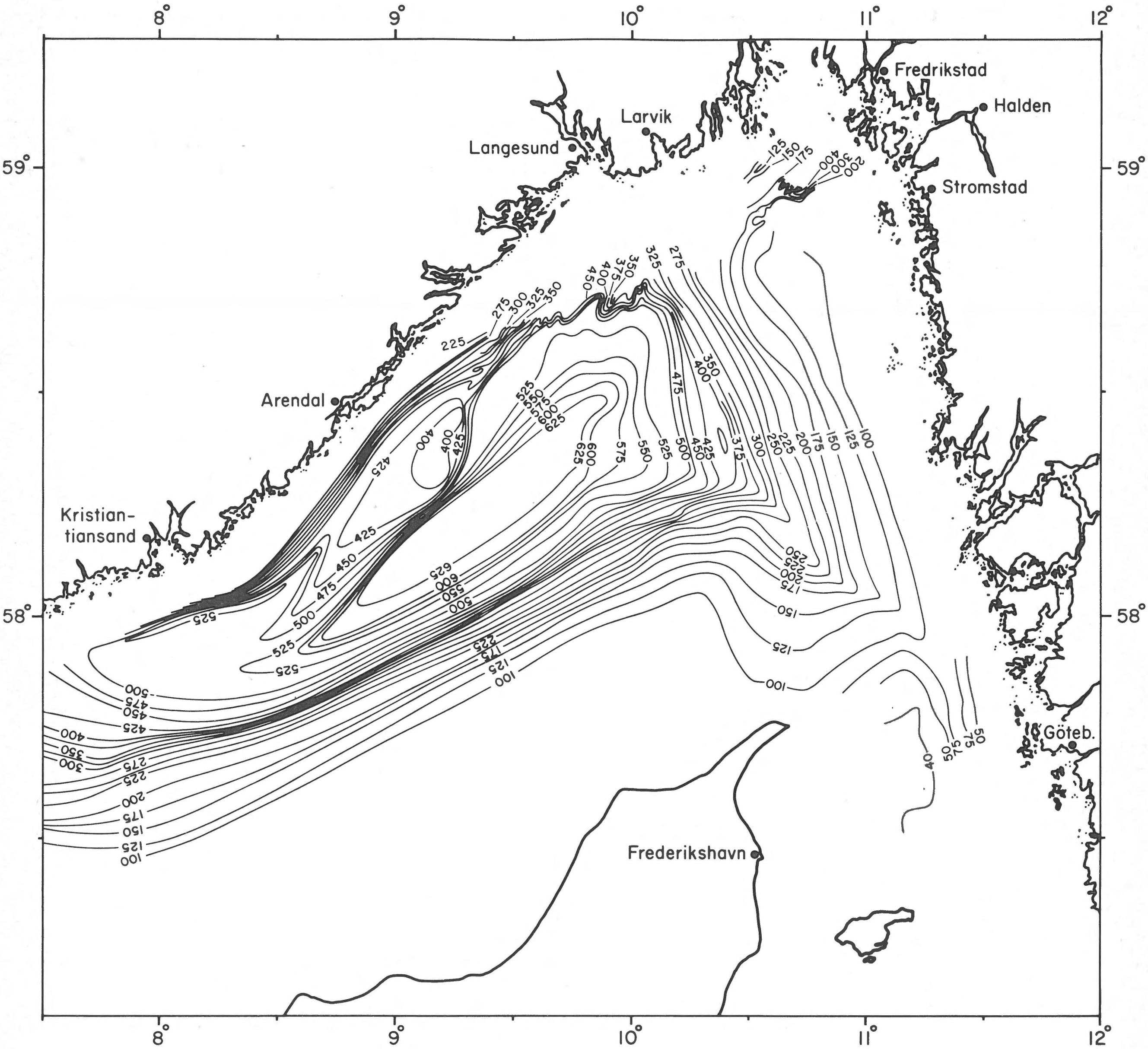


Fig. 2
Bathymetric map (depth in m. below sea level).

maps. Five relief types can be distinguished (fig. 3) and are described shortly. Type a (fig. 4) shows large scale irregularities, partly reflected in bathymetrical maps. This relief is found mainly in a zone along the Norwegian continent and is caused by the hard, relatively steep peaks of Pre-Cambrian and locally Permian rocks that form the continent. The younger, loose sedimentary cover follows pre-existing topography. In contrast, relief type b (fig. 5) is very even and has a smooth sediment-water interface. Locally an irregular, hard reflector is visible under a thick sedimentary cover, but the sediments have smoothened out the pre-existing irregularities. Only near the Swedish coast hard rocks occasionally rise out of the sedimentary cover and are then called monadnocks (Mörner, 1969). For agreat part this zone coincides with the occurrence of shadows (see section on shadow zones).

Bottom relief c (fig. 6) is only present in a minor part of the area. It is characterised by the occurrence of irregular relief with differences of 20-15 metres.

Relief type d (fig. 7) is the relief found along the deeper part of the southern slope of the Skagerrak. Here a zone occurs which shows the presence of grooves and ridges in the

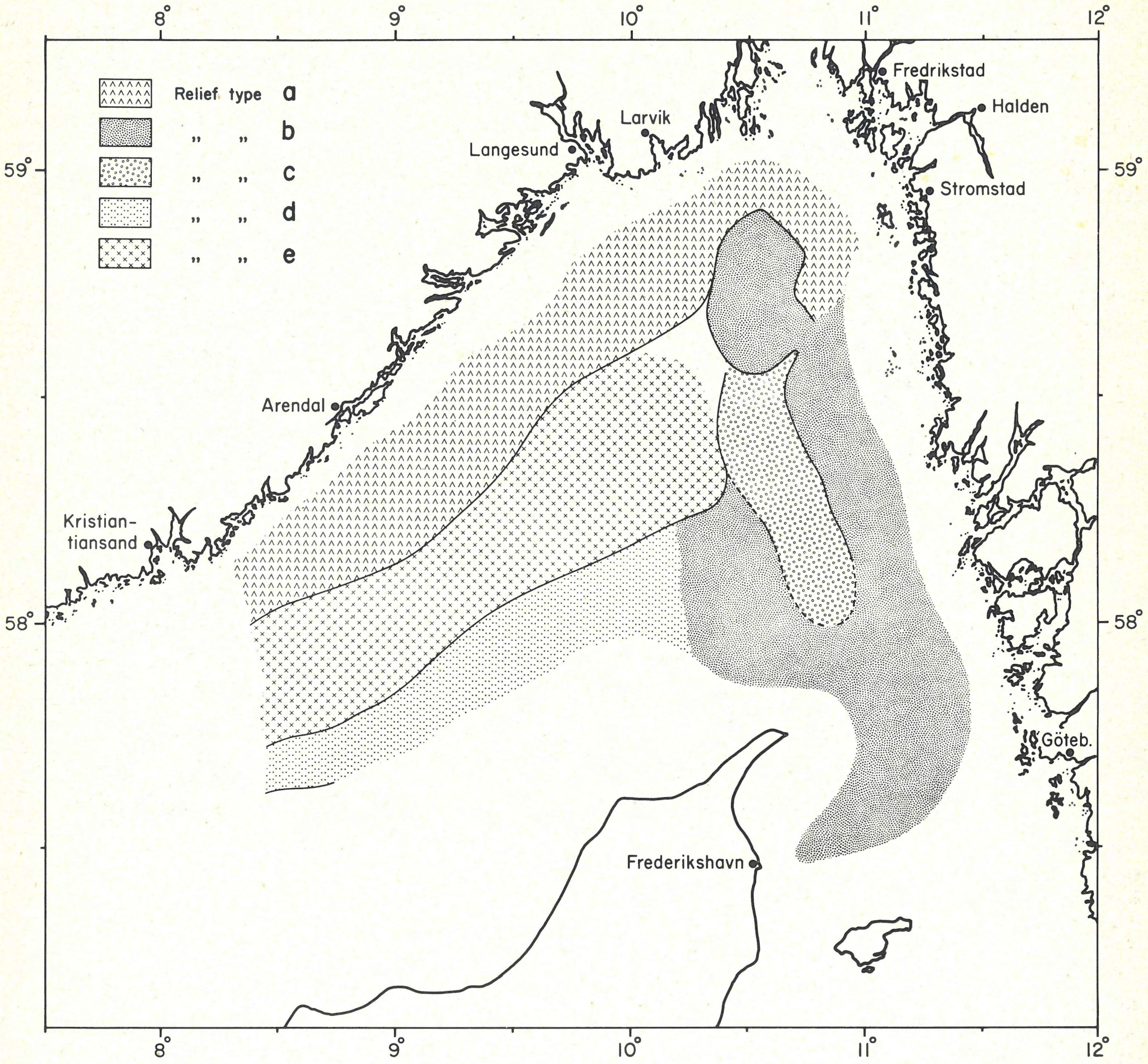


Fig. 3
Map showing distribution of relief types.

order of 6-10 m, with locally 10-20 m difference between top and bottom. This relief is found only at depths exceeding 150 m and coincides with the occurrence of shadow zones along the southern border of the Skagerrak. It was mentioned also by Holtedahl (1964) and Pratje (1952), but not explained. Relief type e (fig. 8) is characterised by an almost completely flat and smooth sediment-water interface and is found in the central, deepest parts of the Skagerrak.

RESULTS OF INTERPRETATION

Sediments

Acoustical character and distribution. – Previous investigations in the Norwegian Channel and the Skagerrak (van Weering et al., 1973) revealed that thick accumulations of late- and postglacial sediments are present, which can be

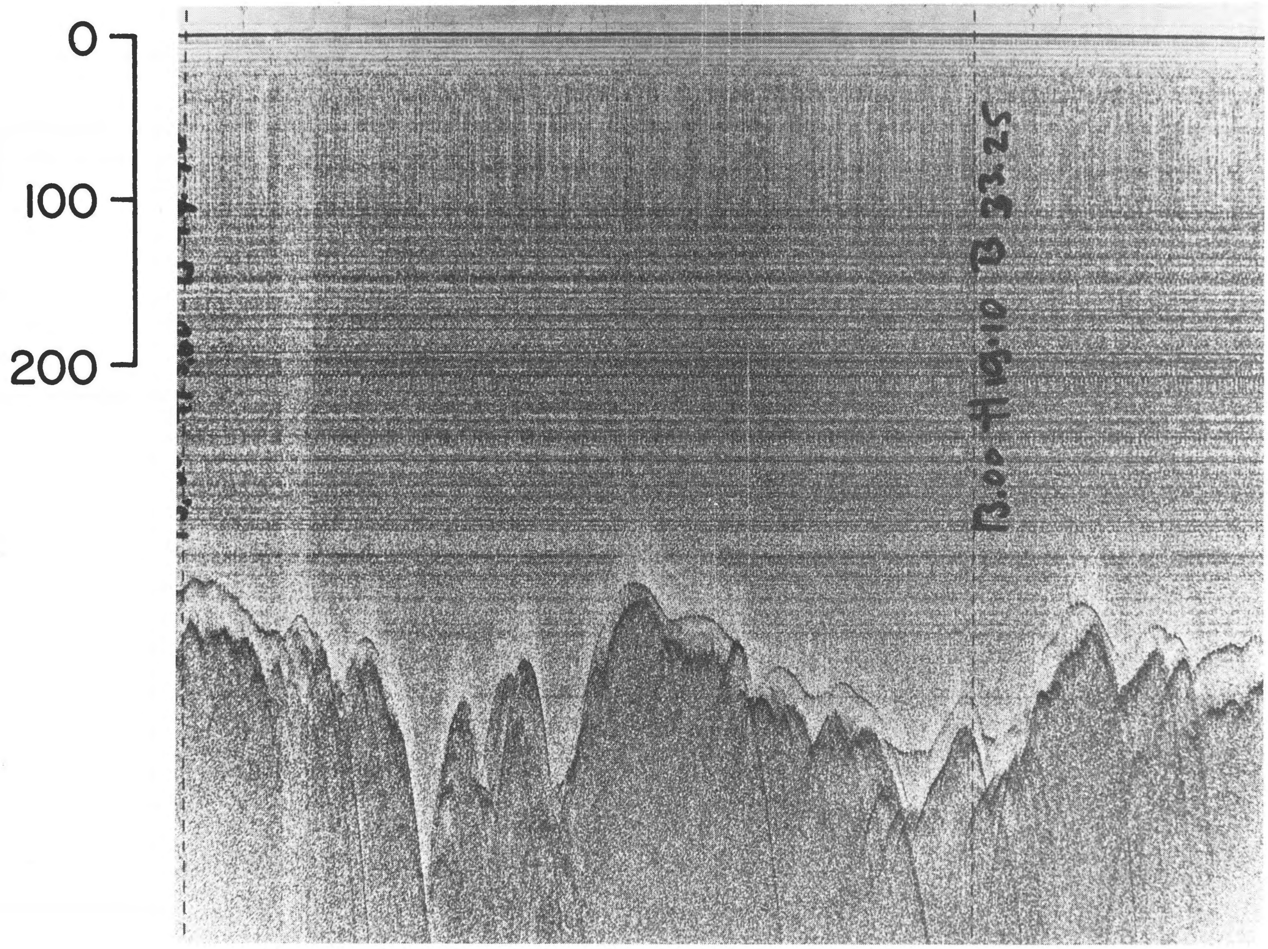


Fig. 4
Relief type a, showing strong relief along the Norwegian coast (depth in m. below sea level. Vertical exaggeration x20).

divided into several sedimentary units. In the eastern Skagerrak and the Kattegat also thick deposits have been found (Mörner, 1969; Flodén, 1973).

The sedimentary units distinguished previously, are separated by relatively strong reflectors and have different internal characteristics (summarised in fig. 9).

Unit 3 and unit 4 deposits have an irregular, undulating surface and are characterised by the absence of internal stratification, while internal reflections in the form of hyperbolic Λ's are present which may indicate the occurrence of stones and boulders.

Unit 4 is overlain by unit 3 and has a less pronounced, somewhat flattened topography, suggesting that it has been partly eroded. Both units have been interpreted as representing glacial drift deposits.

Unit 4 deposits have been found at a few localities along the southern margin of the Skagerrak, while unit 3 deposits cover large areas in the Norwegian Channel and the Skagerrak.

In the present survey unit 3 deposits were recognized all along the southern border of the Skagerrak, and are possibly also present along the slope leading towards the Norwegian continent. Only in the deepest parts of the Skagerrak this unit has not been detected. North of Egersund a unit 2A has been found, with a few weak, irregular internal reflections that follow the topographic irregularities of the underlying unit 3 deposits. This unit is partly covered by unit 2 deposits and has been interpreted as having a possible mixed glacial-marine origin.

Though during this cruise a deposit could be distinguished underlying unit 2 deposits in the deeper parts of the Skagerrak, this deposit has a rather different appearance and hence may not be comparable with unit 2A. The origin of this unit is not yet clear.

Unit 2 deposits are well stratified and have many internal reflections of varying intensity, which can be traced over large distances, though lateral variations occur as well.

Thick acoustically transparent layers, separated by strong

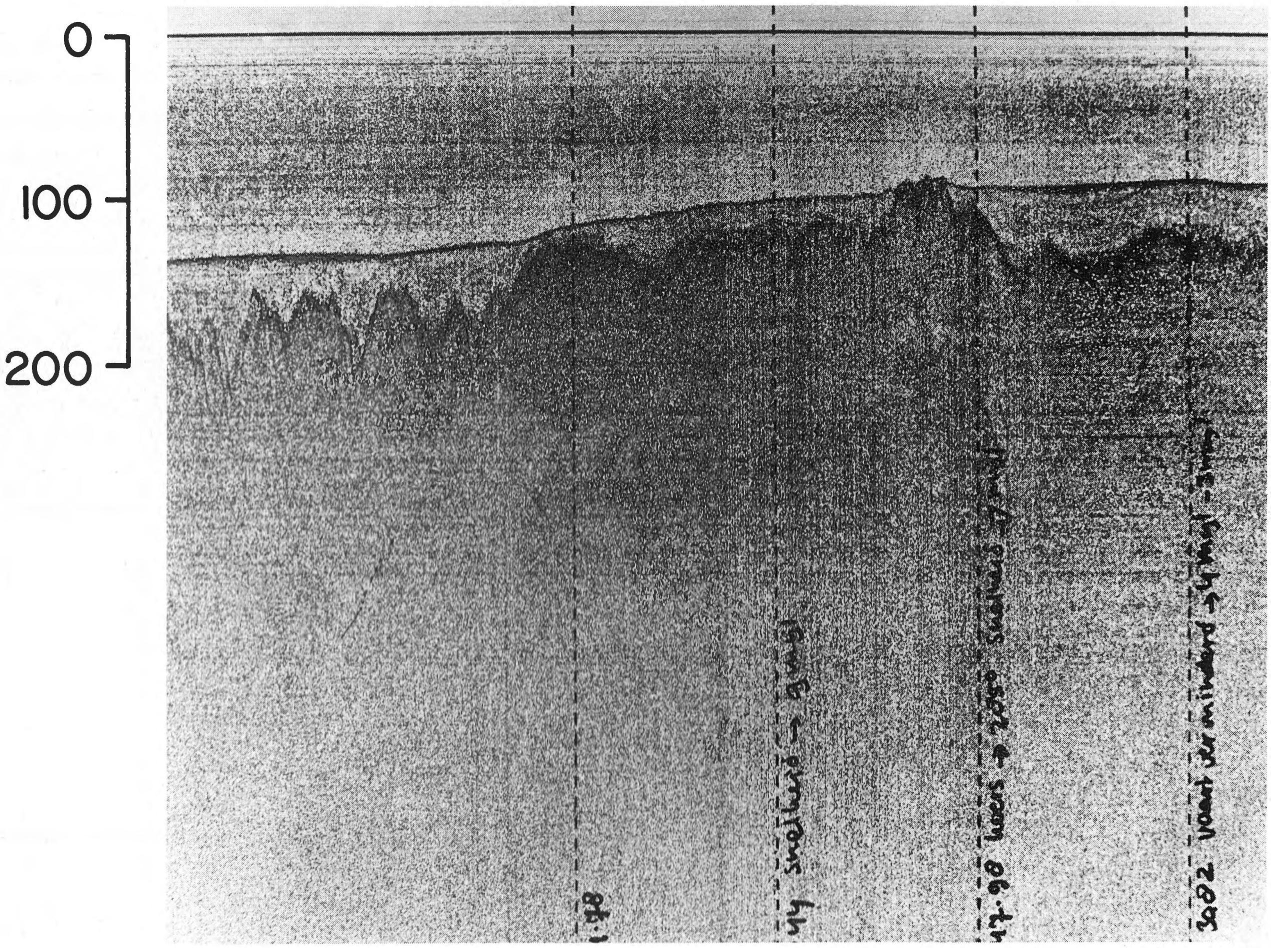


Fig. 5
Relief type b, with monadnocks rising out of the flat sedimentary cover (depth in m. below sea level. Vertical exag. variable).

reflectors are present in the lower part of this unit, resembling unit 1.

Unit 2 deposits were interpreted as being of mixed glacial-marine, partly proglacial origin, the strong reflectors representing possibly layers of pebbles, gravel or consolidated clays, whereas the transparent layers represent thick deposits of fine materials.

Along the southern margin of the Skagerrak a hard reflector can be distinghuished, underlying unit 2, which occasionally crops out. Presumably this reflector represents the top of (eroded?) Mesozoic strata.

During this cruise unit 2 deposits were recognised in the whole area of survey, partly covering unit 3 deposits; along the Norwegian coast unit 2 deposits locally cover the hard rock formations of the Norwegian continent.

Unit 1 is the most recent deposit; generally it is acoustically transparent but locally weak internal reflections are found. This is especially the case in the eastern part of the Skagerrak, where the transition from unit 2 into unit 1 deposits can hardly be distinguished. Therefore these units are mapped together (Fig. 10). This unit represents the youngest marine infill and, where sampled, consists mainly of mud (Lange, 1956); it is found over the whole area of survey, except along the southern margin of the Skagerrak where (reworked) unit 3 sediments are present.

The thickness of the late- and postglacial sediment infill (units 1 and 2 together) reaches a maximum on the sides and slopes towards the central deep. Locally along the slope leading towards the Norwegian continent, thicknesses exceeding 80 m were measured, while along the southern slope of the Skagerrak a thickness of more than 50 m was found. The eastern slope shows the same features with thick deposits that diminish towards the central deep where a continuous cover of 10 – 20 m thickness is present, but the frequent occurrence of shadow zones on the eastern slope made determination of thickness in this part impossible.

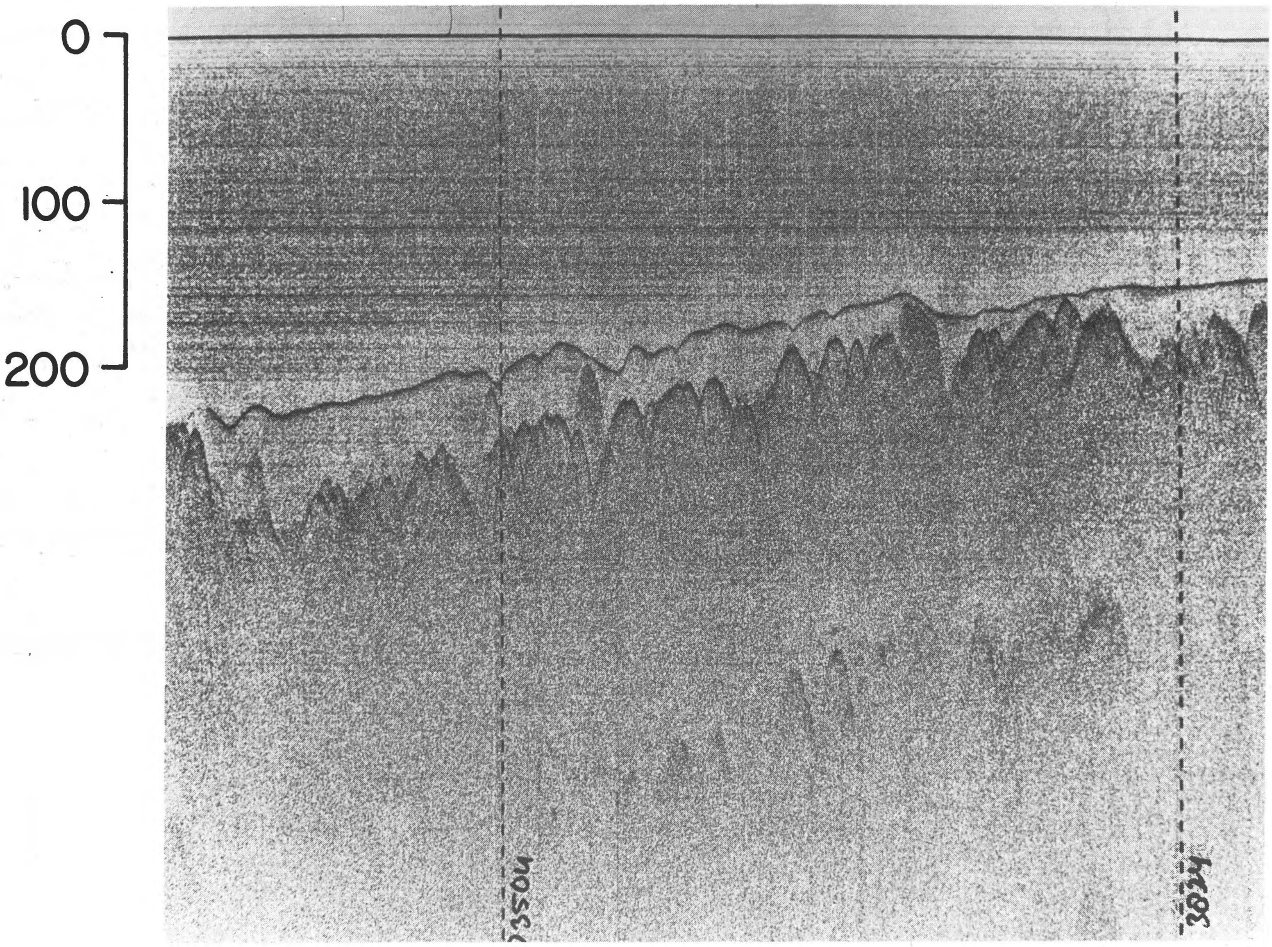


Fig. 6
Relief type c, with irregular sea bottom surface and irregular reflectors underneath. Locally shadows are present (depth in m. below sea level. Vertical exag. x20).

Sedimentary structures. – 1. Large scale foresets. The unit 2 deposits along the southern slope of the Skagerrak trough overlying unit 3 deposits are very regularly stratified. The strata have a slight inclination towards the NE with a dip varying between 0,15° and 0,25°, giving the impression of deltaic low angle, large scale foresets.

2. Sand waves. Directly south of the large scale foresets mentioned before, a zone is present where sand waves occur (see fig. 11). The term sand wave is used here in the same sense as applied by McCave (1971), describing a ripple form with a wavelength exceeding 30 m, and with a height of more than 1½ m.

The observed sand waves are asymmetric and have their leesides orientated towards the N or NE. The sand waves are varying strongly in length and steepness, but as only a limited number of traverses cross the zone where sand waves are found, different types cannot be characterized yet Anyhow, heights were measured varying from 6-10 m, and the wavelengths are at least several hundreds of metres. Locally, the sand waves have secondary sand waves superimposed on their flanks, so that a composite sand wave is formed.

The sand waves are found at depths not exceeding 60 m, and are likely to consist of reworked unit 3 sediments.

Shadow zones

1. Occurrence and distribution. – Shadow zones, i.e. zones where the penetration of sound in sediment is prevented (for the frequency used), are present on the southern slope of the Skagerrak (van Weering et al., 1973). The recordings show that shadow zones in this area have a much greater extension than previously thought (see fig. 12). Also in the central and northeastern part of the Skagerrak large areas are impenetrable whereas towards the entrance of the Kattegat penetration is almost completely prevented. The character of

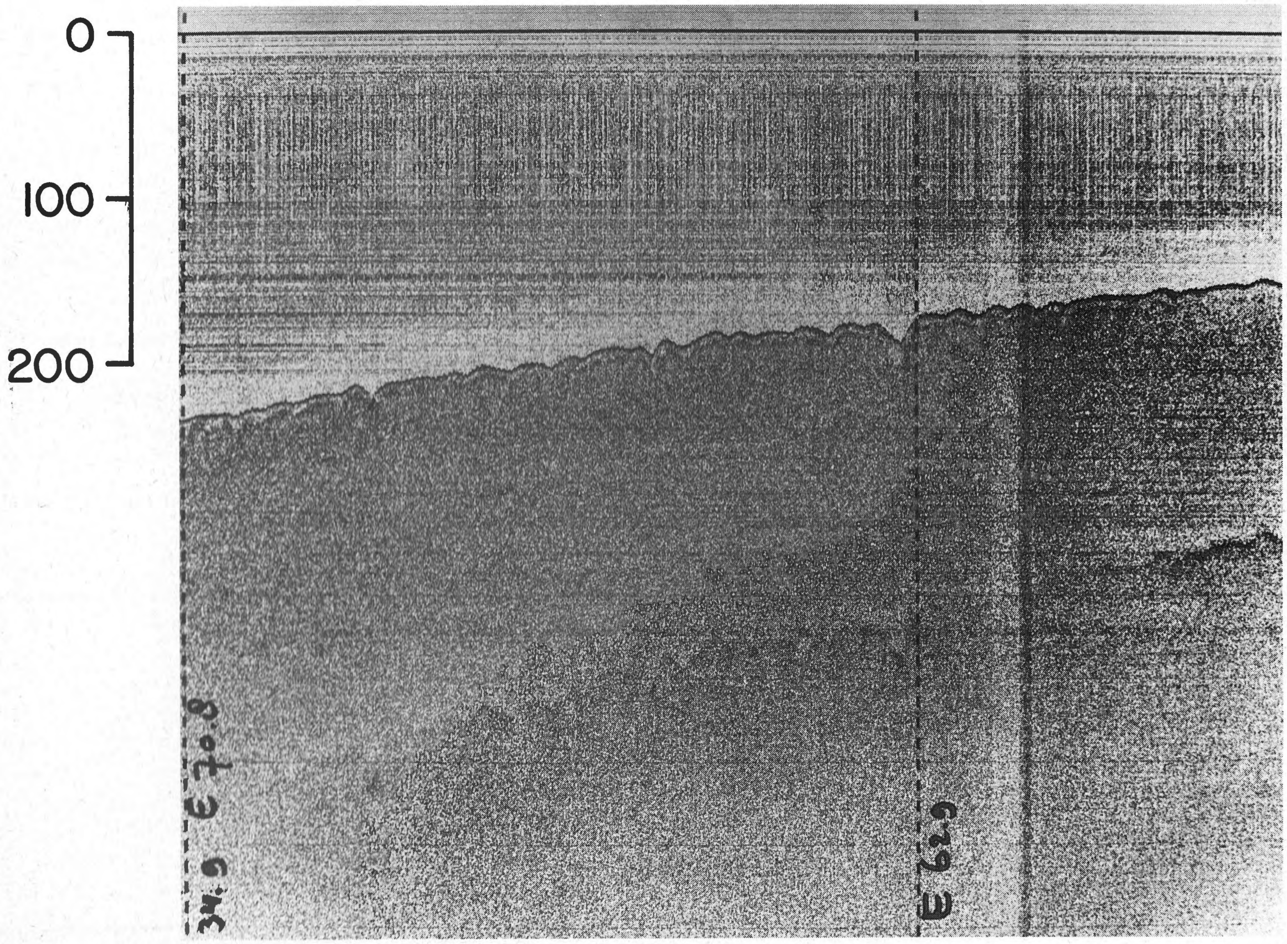


Fig. 7
Relief type d, with ice plough marks and shadow zones (depth in m. below sea level. Vertical exag. x20).

the shadow zones in the central and northeastern Skagerrak is the same as along the southern rim of the Skagerrak. The shadow begins where a more or less strong reflector is present near the surface and deeper reflectors suddenly are cut off (fig. 13). Near and in the entrance of the Kattegat shadows almost completely mask the underlying structures, but here no distinct reflectors are found on top of the shadows. The depth of the shadow zones varies from 5 – 1½ m under the sediment-water interface. The depth below sea level at which the shadow zones occur varies between 75 and 300 m, being even less in the entrance towards the Kattegat (up to 30 m).

2. Origin. – Shadow zones have been reported from a number of other places in the world under various names, o.a. "acoustic turbid zones" and "acoustically impenetrable sediments". Harbison (1969) ascribed the occurrence of acoustic turbid zones in the Gulf of Maine to the effect of small size glacial debris, surrounded by a matrix of acoustical transparent material.

Grim et al. (1970) in a subbottom study of Long Island Sound mention the presence of areas where reflections are obscured. These areas are of two types characterised by either soft or by hard bottom materials. Hinz et al. (1971) conclude that their "Beckeneffect" (a diffuse blackening on the recorded profiles caused by an irregular and diffuse dispersion of energy) is produced by the presence of gasbubbles. (Schubel & Schiemer (1972) reported acoustic turbid zones in Chesapeake Bay which were partly caused by the presence of gasbubbles, while also buried shell beds had the same effect. Recently, in a paper on a high resolution seismic survey near Nome, Alaska (Tagg and Greene, 1973) the occurrence of acoustical sinks has been reported, which are interpreted as the result of scattering seismic energy by gravels associated with buried stream channels and beach ridges.

Thus, either the acoustic turbid zones are the effect of the presence of gasbubbles in the subsoil – methane being the most important gas in marine sediments (Claypool et al.,

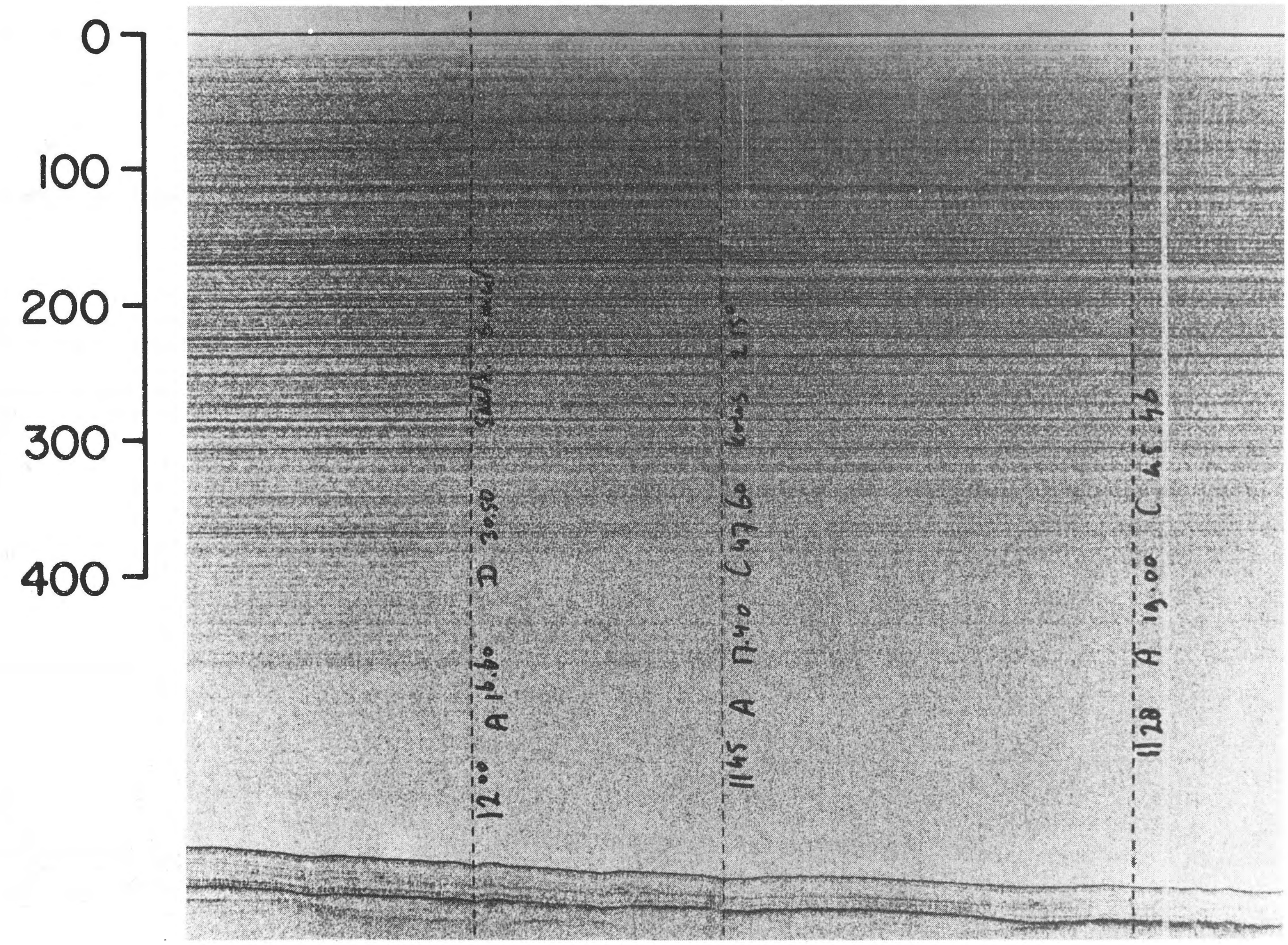


Fig. 8
Relief type e, with smooth sediment-water interface and regular stratification in underlying units (depth in m. below sea level. Vertical exag. x20).

1971) – and in that case they are associated with relatively fine sediments and high sedimentation rates (Vilks et al., 1974), or they are caused by shells, gravel or glacial debris that scatter the reflected energy.

The shadow zones found in the eastern Skagerrak and the entrance of the Kattegat occur in the uppermost part of the sedimentary cover. Possibly gasbubbles which are trapped in the thick layer of fine sediments that form the most recent deposit in the Skagerrak (Lange, 1956) and the Kattegat (Mörner, 1969; Flodén, 1973) cause a dispersion of energy, resulting in the occurrence of the shadow zones. Along the southern border of the Skagerrak the shadow zones are probably mainly due to the presence of coarse material, presumably reworked from unit 3 deposits. Though methane is known from interglacial deposits from Denmark (Sorgenfrei and Buch, 1964) it forms only a minor constituent and hence may not be responsible for the widespread occurrence of shadow zones here.

SEDIMENTARY HISTORY

Sedimentary succession

The crystalline rocks along the coast of southern Norway and southwest Sweden belong to the basement rocks of the Fennoscandian shield and are mainly of Precambrian age. Along the Swedish coast a peneplain exists with a gradual slope towards the west. Mesozoic strata in the eastern Skagerrak tend to wedge out to the N and to the E.

The Lower Cretaceous, in northern Denmark locally underlying Pleistocene glacial drift, is extending in the Skagerrak towards the N and Upper Cretaceous is occasionally cropping out on the sea floor towards the W (Sellevoll and Aalstad, 1971).

Tertiary sediments are well known from land in Denmark but their occurrence and distribution in the Skagerrak has not yet been established.

The late Quaternary history of the area of survey is greatly influenced by the repeated advance and retreat of glaciers that spread out from Scandinavia and the Baltic and occupied great parts of western Europe.

According to Mörner (1969) the readvance of the ice in the last glacial started with a strong outflow of ice from Norway. In southern Sweden this ice stream met the Baltic

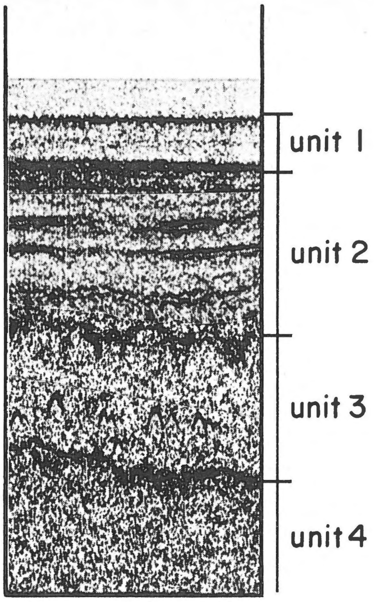
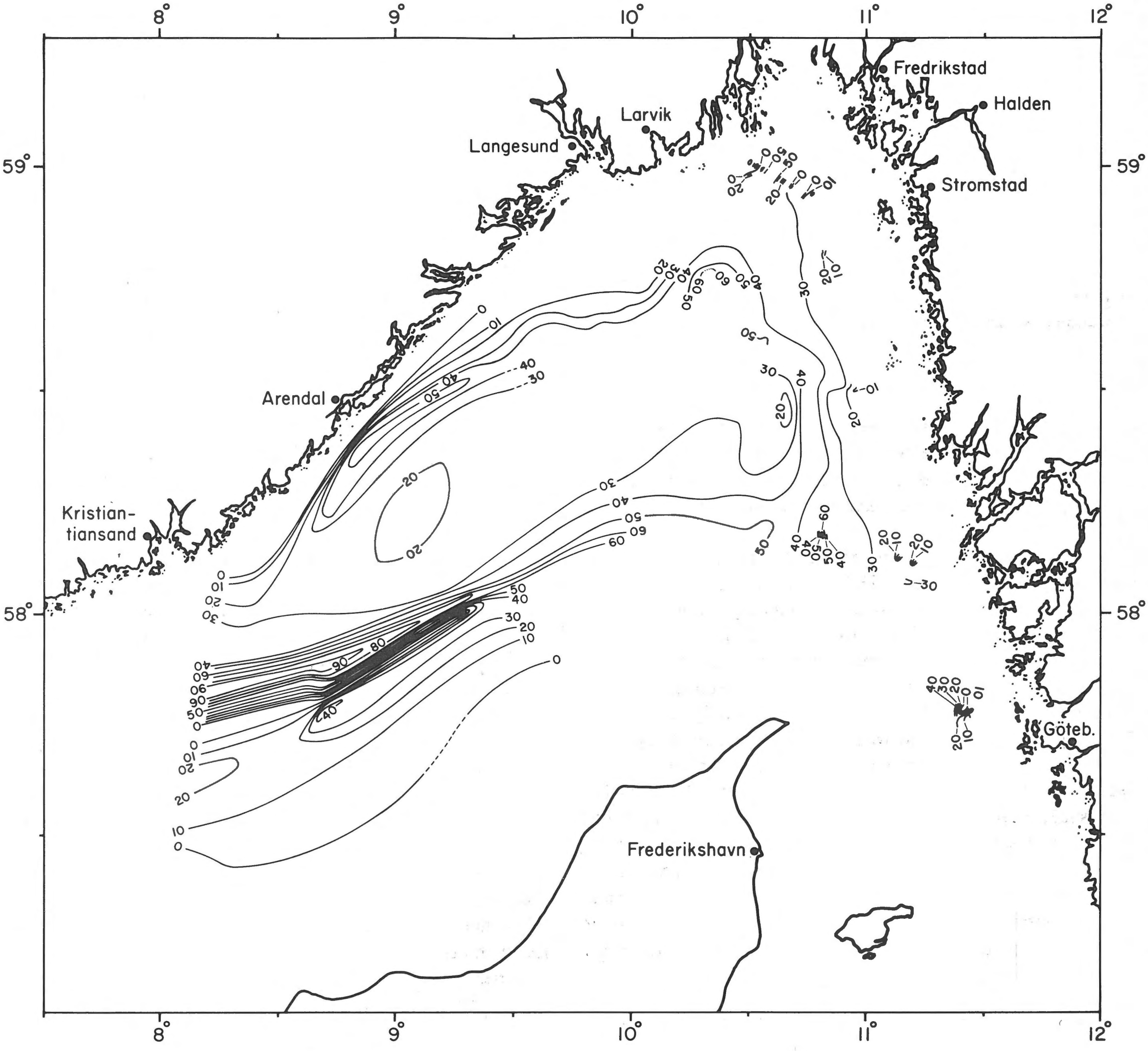


Fig. 9
Schematised column summarising acoustical character of sedimentary units.

Fig. 10
Thickness (in m.) of late-postglacial sediment infill (units 1 and 2 together).



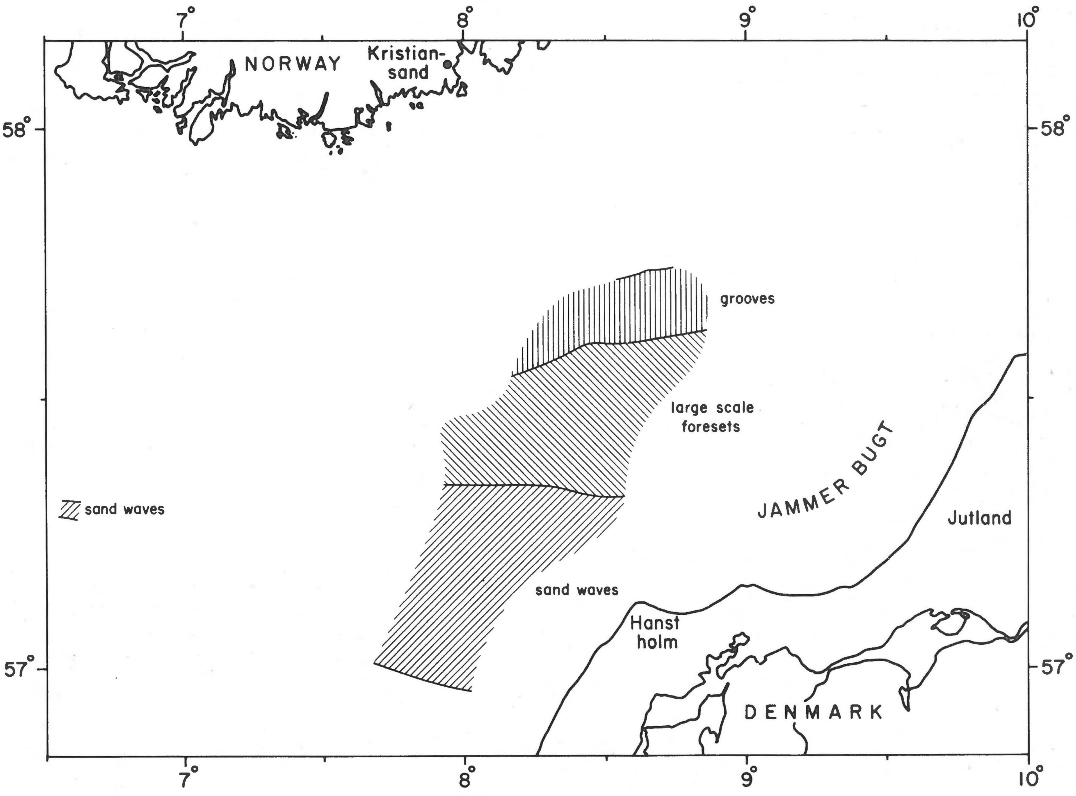


Fig. 11
Location of areas with sand waves, large scale foresets and ice grooves.

ice stream and was forced westwards. This means that in the Kattegat the ice movement was mainly from the NE. Great parts of the Skagerrak and southwestern Norway got occupied by the so-called Skagerrak glacier (Andersen, 1965).

The maximum extension of the Weichselian ice sheet is well known in Denmark. The ice sheet did not cover the whole of Denmark, but reached a boundary, known as Main stationary line or C-line (Madsen, 1928). In the North Sea the boundary of the maximum extension of the Weichselian ice sheet is not well known. Pratje (1951) concluded that the ice margin of the Weichselian glaciation only reached the western border of the Norwegian Channel and the Skagerrak. Valentin (1957) situated the ice margin far more to the south, as far as Doggerbank, west of which the Scandinavian ice sheet met the English ice sheet. Veenstra (1965, 1970) suggests an even more southern boundary on basis of the origin of gravels found on the southern North Sea floor.

From our own observations it was evident that glacial drift deposits stretch out from the Norwegian Channel as far as the Fladen grounds (Jansen, in prep.) and also far south of the Skagerrak.

All evidence points to a Weichselian age of these deposits (van Weering et al., 1973), which means that units 2 and 1 formed after the ice had retreated and are of late Weichselian and Holocene age. In southern Norway several submarine morainic ridges have been found, a.o. the Lista moraine, dated at about 13.000 years B.P. (Andersen, 1965). The Lista moraine has probably a submarine extension towards Egersund and the thick morainic deposits found in front of the western coast of Norway may have the same age as well, suggesting that at that time glaciers covered rather great parts of the Norwegian Channel and the Skagerrak.

This would mean that both the Skagerrak and the Kattegat were ice covered from the time, when the readvance of the ice started, (after 27.000 B.P.) until about 13.000 years B.P. when the Lista moraine was deposited. South of Lista the maximum depth at present is approximately 350 m. When the thickness of late- and postglacial deposits together is considered (about 30 m) and the relative sea level is assumed to be about 80 m below present (Holmes, 1965), then the Skagerrak during a great part of the last glaciation might have been an ice covered basin, possibly with floating ice in the centre and grounding ice along the borders. An ice thickness of about 300 m would be sufficient to block the outlet of this basin towards the Norwegian Channel. In fact

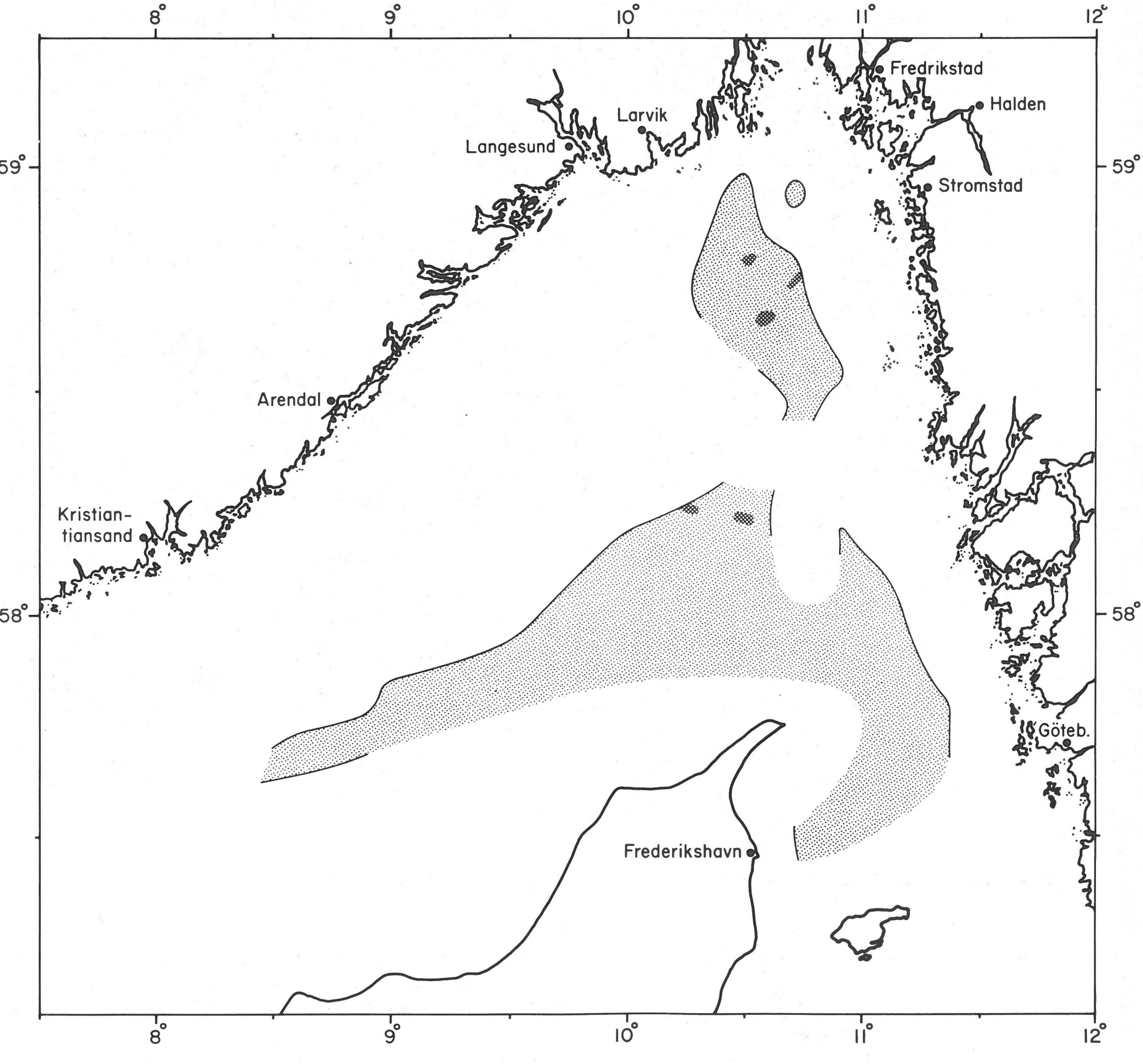


Fig. 12
Distribution of shadow zones. Heavily accented areas indicate irregular occurrence of shadows.

there are indications (van Weering et al., 1973) that such a thickness was reached. No moraines were found in the eastern Skagerrak during the present survey. Although the occurrence of shadow zones may obscure them, they actually may be entirely absent. Flodén (1973), using an airgun, observed no morainic deposits in the eastern Skagerrak. Mörner (1969) who studied in detail the recessional ice margins in the Kattegat distinguished several recessional lines, of which the most marked are D line, dated at 13.000 – 12.800 and the very distinct E line marking a stagnation at about 12.600. This line is seen in Skagen and is directed north towards the Skagerrak. Other recessional lines in the Kattegat are situated more towards the east and make a southward bend, after the Norwegian ice in the southern Kattegat separated from the Baltic ice stream at about 11.800 (Mörner, 1969).

When it is taken into account that the marginal moraines in southern Norway, which are found along parts of the

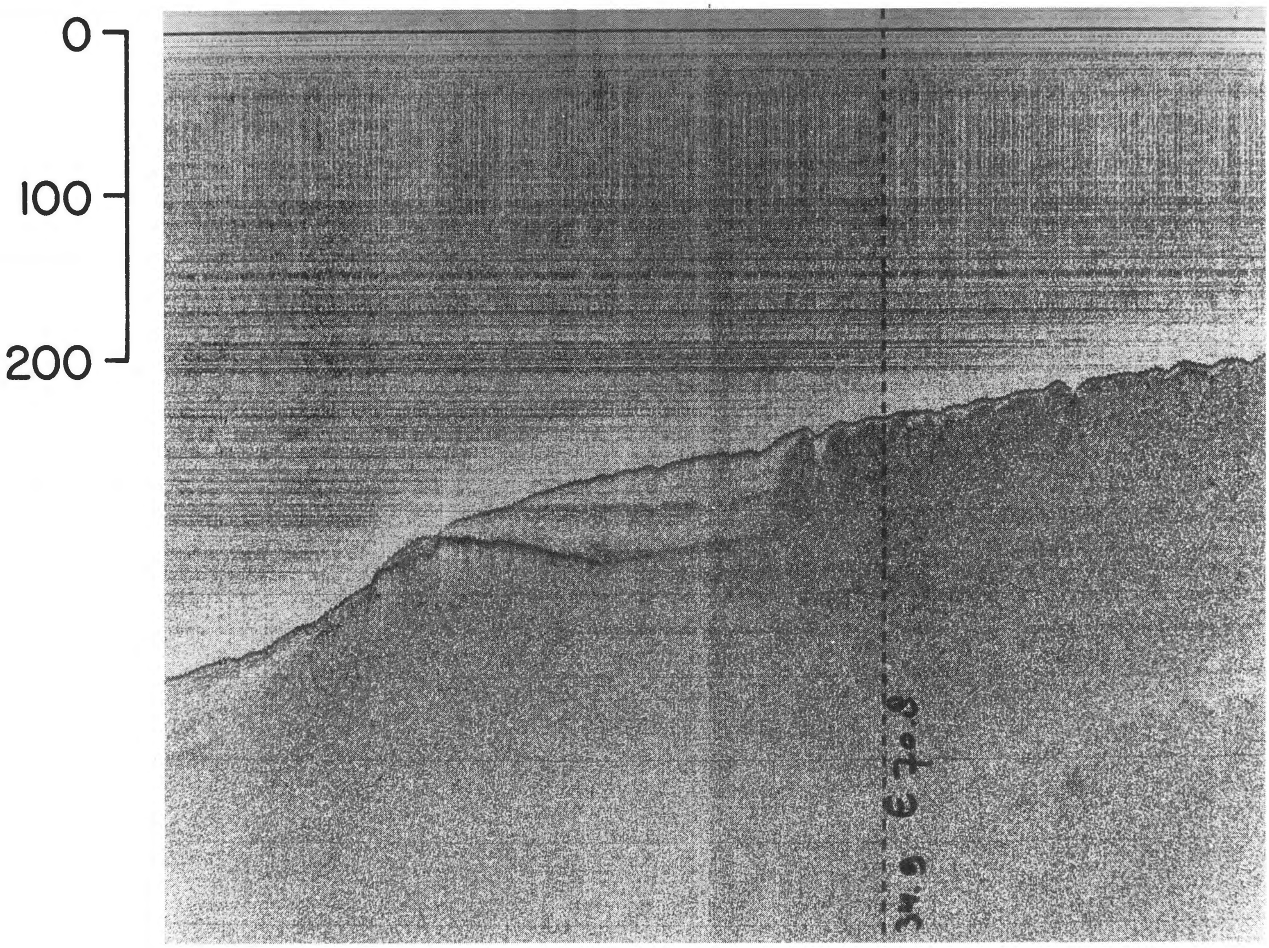


Fig. 13
Deeper lying reflector, suddenly cut off by shadow (depth in m. below sea level. Vertical exag. x20).

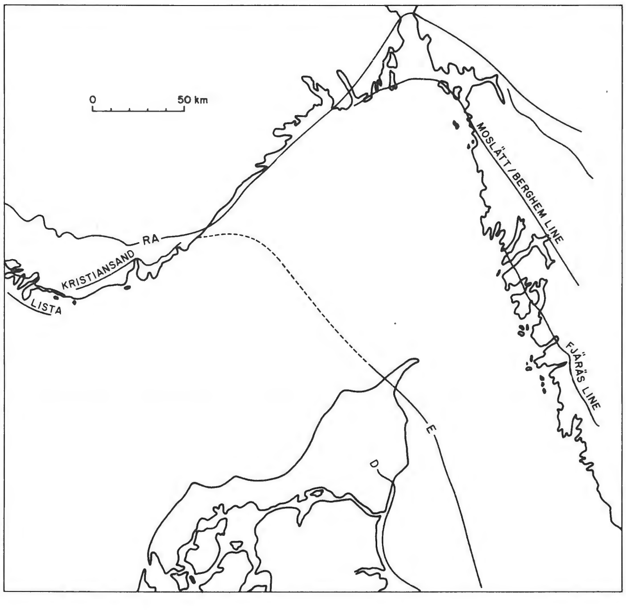


Fig. 14
Ice-recessional margins in the Skagerrak (modified after Mörner, 1969). Dotted line indicates possible ice margin at ± 12500 yB.P.

coast, i.e. the Kristiansand moraine and the Ra moraines are dated respectively 12.500 (Andersen, 1960), and about 10.000 years (Andersen, 1965), it seems reasonable to connect the Kristiansand moraine with the E line in Skagen (see Fig. 14). At that time the eastern part of the Skagerrak was probably still covered with ice, until about 10.000 years B.P., when the ice had receded almost completely in this region, occurring only as glacier tongues along parts of the coast.

During the melting of the glacier that covered the Skagerrak and the Kattegat, the ice front receded, sea level rose and it is likely that the previously deposited unit 3 sediments along the southern border of the Skagerrak were washed out and were transported by wave action and bottom currents.

Thus the well-stratified unit 2 deposits, with their lateral variations and sometimes strongly reflecting beds would be proglacial deposits, that have been formed beyond the limits of the glacier (Flint, 1957).

That the unit 2 sediments in the central deep part of the Skagerrak are much thinner may be explained by assuming, at least for the deeper parts of unit 2, a deposition from ice rafting because of melting at the base of the glacier that covered the Skagerrak. According to Carey and Ahmad (1961) a wet base glacier under receding conditions may result in deposition of mud as the dominant sediment. This can possibly also account for the presence of transparent layers observed in the undermost part of unit 2 deposits in the deepest part and along the borders of the Skagerrak, though the alternation of strongly reflecting beds and transparent layers may indicate a repetition of processes, and as a consequence possibly an older age for the undermost part of unit 2 in the deeper parts. Later, when the area was not longer covered by a continuous ice sheet, also coarser fragments were deposited, yielding the observed irregularities in strongness of the reflectors. The character of unit 2 sediments along the Norwegian continental border can be explained by assuming an ice rafted origin for the undermost part, and an outwash origin for the uppermost part.

When, about 10.000 years B.P., the ice had receded almost completely and the sea level had become so high as to allow a tidal circulation pattern similar to the present one, glacial deposits on the floor of the North Sea were washed out and transported (Veenstra, 1965, 1969). Due to transport by a tidal current, combined with stronger wave action because of a small water depth, relatively coarse fractions were transported and formed the regular stratified deposits of the upper part of unit 2. The sorting effect of the tidal current will have caused that of these coarser components the relative finer particles weren transported more to the deeper parts of the Skagerrak and towards Skagen, where also thick deposits were found (Mörner, 1969; Flodén, 1973).

When the sea level reached about its present height, only fine material was transported forming the gradual transition from unit 2 into unit 1. This is confirmed by an age of about 7000 years of the uppermost 10 metres of clay deposited in the Skagerrak (Lange, 1956).

Deposition of mud in the Skagerrak and the Kattegat probably still goes on since mud derived from the large rivers in the southern North Sea is moved anti-clockwise northwards along the Danish coast (Eisma, 1973).

Origin of sandwaves

When our hypothesis of a stronger transport of material along the bottom in the beginning of the Holocene is correct, this can also explain the presence of the sand waves observed along the southern border of the Skagerrak. Sand waves have been reported from various other places in the North Sea (a.o. Stride and Tucker, 1960; Stride, 1963; Dingle, 1965; Langeraar, 1966; Houbolt, 1968; McCave, 1971; Terwindt, 1971 and many others).

Stride has proposed tidal currents as the agent forming the sand waves (Stride, 1963, 1965). McCave (1971) coupled important conditions concerning tidal velocity, wave action and current velocity to a tidal origin for sand waves and related the form of the sand waves to the net tidal sand transport. He pointed out that where a sufficient range of grain sizes is present, mega-ripples superimposed on sand waves occur.

The superimposed sand waves found, are broadly of the same dimensions at those reported by Bruun and Vollen (1972) from an area off Flamborough Head, Yorkshire, England. The same authors explain the sand waves off the Danish coast as caused by internal waves or lee waves behind a barrier on the sea bottom. In my opinion the occurrence of the superimposed sand waves may be related to a gradual diminishing of net sand transport because of increasing water depth and decreasing bottom current velocities since the beginning of the Holocene. Terwindt (1971) doubts whether the asymmetry of the sand waves observed in the Southern Bight of the North Sea has been created by present day hydraulic conditions, and Kirby and Kelland (1972) describe sand ridges from the southern part of the North Sea that are covered with a clay cap of approximately 4000 years. It thus seems possible that sand ridges can be preserved, even in a region with stronger tidal currents and smaller waterdepths than in the area of survey, and therefore the sand waves in front of the Danish coast may be considered as relict forms; only further research may reveal their exact age and mode of formation.

Relation to relief

The different relief types observed are closely related to sub-bottom conditions. Relief type a, showing large scale irregularities is found along the Norwegian continent. The underground here consists probably of Precambrian and Permian rocks, with markedly topographic differences. More to the east and northeast along part of the Norwegian and Swedish coast, where relief type b is found the Precambrian rocks forming the continent dip to the west and are covered by extensive glacial and postglacial deposits. The transition from type b to type c can be explained by greater differences in the sub-bottom, possibly related to the occurrence of the so-called Koster fracture zone here. Descending the slope type c relief passes into a smooth flat relief as found on the floor of the deeper parts of the Skagerrak, representing relief type e.

The transition may mark the boundary of Mesozoic and Precambrian rocks, underlying glacial deposits there. Relief type d is found along the southern slope of the Skagerrak at depths between 150 and 275 m. The notches present there are 10 to 15 m deep, while horizontally they measure up to 300 m though this figure may be due to oblique crossing the notches.

The incisions seem to erode into unit 2 deposits and some of them are partly filled up on the northern side. They do not resemble the pockmarks (King & McLean, 1970) that occur in large quantities along the western side of the Norwegian Channel (van Weering et al., 1973). The notches observed have greater relief at greater depth.

This is also mentioned by Belderson et al. (1973a), who described similar features with a maximum width of 100 m and maximum depth of 10 m, from an area north and west of the Shetlands and in the vicinity of the Faroër Islands. They are also known from Lake Superior (Berkson and Clay, 1973), Alaska (Reimnitz et al., 1972) and Canada (Weber, 1958). All these areas have been or are partly covered by ice, and the grooves and ridges observed in these regions are ascribed to the ploughing action of icebergs in (fine) sediment.

These similarities point to an ice grounding origin for the notches along the southern rim of the Skagerrak*, at a stage in the glacial recession, when occasionally large icebergs may have occurred, the largest of which have formed the deepest notches. Only one incision is much deeper and may have another origin.

Towards the north relief type d shades off into the smooth relief as found in the deeper parts of the eastern Skagerrak, representing relief type e.

CONCLUSIONS

The late-Quaternary sedimentary history of the Skagerrak area is greatly influenced by the late Weichselian glaciation. This is illustrated by the occurrence and distribution of sedimentary units as found previously in the Norwegian Channel.

The differences in acoustical character of the deposits can be explained by assuming a different origin.

Along the southern margin of the Skagerrak glacial drift deposits are present, partly covered by glacial-marine or proglacial deposits, and fully marine deposits. The proglacial deposits have low-angle large scale foresets and occur directly north of a zone with giant sand waves.

These features are possibly caused by a gradual increase of water depth since melting of the glacier that covered the Skagerrak had started. The bottom relief along the southern slope of the Skagerrak is probably the result of ploughing icebergs in a relatively late stage of the glacial recession.

Rising water level and subsequently decreasing bottom current velocities and wave action may have led to a gradual diminishing of net sand transport, so that at present mainly mud is deposited.

The occurrence of shadow zones in the eastern Skagerrak may be related to the presence of either gas bubbles or coarse components in the sub bottom.

ACKNOWLEDGEMENTS

I thank Dr. Eisma and Dr. Collette for critically reading the manuscript and also Dr. Bodenhausen for his comments. Thanks are also due to Captain and crew of the R.V. "Aurelia" for their help. Mr. B. Verschuur made the drawings, I thank him as well.

REFERENCES

Andersen, B.G. (1960) – Sørlandet i sen-og postglacialtid.– Norg. geol. Unders. 210: 1-142.

(1965) – The Quaternary of Norway. In: K. Rankama. The Quaternary. Intersc. Publ., New York: 91-138.

Belderson, R.H., N. Kenyon and J.B. Wilson, (1973a) – Iceberg plough marks in the North East Atlantic. Paleog. Paleoclim. Paleoecol. 13: 215-224.

Belderson, R.H. and J.B. Wilson, (1973b) – Iceberg ploughmarks in the vicinity of the Norwegian trough. Norsk. Geol. Tidssk. vol. 53, p. 323-328.

Berkson, J.M. and C.S. Clay (1973) – Microphysiography and possible iceberg grooves on the floor of western Lake Superior. Bull. geol. Soc. Am., 84: 1315-1328.

Bruun, P. and O. Vollen, (1972) – Sandwaves on the bottom of the sea. Schiff und Hafen 24: 139-142.

Carey, S.W. and N. Ahmad, (1961) – Glacial marine sedimentation. In: Geology of the Arctic. Proc. 1st Int. Symp. on Arctic Geology, 11-13 Jan. 1960. Calgary. Vol. 2. Univ. Toronto Press: 865-894.

Claypool, G.E., B.J. Presley and I.R. Kaplan, (1971) – Gas analyses in sediment samples from legs 10, 11, 13, 14, 15, 18 and 19. Intial Reports of the Deep Sea Drilling Project vol. XIX, p. 879-884.

Dingle, R.V. (1965) – Sand waves in the North Sea, mapped by continuous reflection profiling. Mar. Geol. 3: 391-400.

Eisma, D. (1973) – The sediment distribution in the North Sea in relation to marine pollution. In: North Sea Science. E.D. Goldberg (ed.) M.I.T. press, Cambridge, Mass.

Flint, R.F. (1957) – Glacial and pleistocene Geology. Wiley and Sons, New York: 1-553.

Flodén, T. (1973) – Notes on the bedrock of the eastern Skagerrak with remarks on the pleistocene deposits. Stockholm Contr. Geol., 24: 80-102.

Grim, M.S., C.L. Drake, and J.R. Heirtzler, (1970) – Subbottom Study of Long Island Sound. Bull. geol. Soc. Am. 81: 649-666.

Hansen, S. (1965) – The quaternary of Denmark. In: K. Rankama. The Quaternary. Intersc. Publ. New York: 1-91.

Harbison, R.N. (1969) – Possible morainal deposits in the Gulf of Maine. Maritime Sediments 5: 19-21.

Hinz, K., F.C. Kögler, D. Richter and E. Seibold, (1971) – Reflexionsseismische Untersuchungen mit einer pneumatischen Schallquelle und einem Sedimentecholot in der westliche Ostsee. Teil 2. Untersuchungsergebnisse und geologische Deutung. Meyniana 21: 17-24.

Holmes, A. (1965) – Principles of physical geology. Nelson, London: 1-1288.

Holtedahl, O. (1940) – The submarine relief off the Norwegian coast. Norske Videnskaps-Akademi, Oslo: 1-49.

—— (1960) – On supposed marginal faults and the oblique uplift of the landmass in Cenozoic time. Norg. geol. Unders. 208: 351-357.

—— (1964) – Echo soundings in the Skagerrak. Norg. geol. Unders. 223: 139-160.

Houbolt, J.J.H.C. (1968) – Recent sediments in the southern bight of the North Sea. Geol. en Mijnb., 47: 245-273.

Jansen, J.H.F. (in prep.) – Acoustic reflection profiling in the central North Sea.

King, L.H. and B. MacLean (1970) – Pockmarks on the Scotian Shelf. – Bull. geol. Soc. Am. 80: 83-96.

Kirby, R. and N.C. Kelland, (1972) – Adjacent stable and apparently mobile linear sediment ridges in the southern North Sea. Nature Phys. Science, 238: 111-112.

Kuenen, P.H. (1950) – Marine geology. Wiley, New York, 1-458.

Lange, W. (1956) – Grundproben aus Skagerrak und Kattegat, microfaunistisch und sedimentpetrographisch untersucht. Meyniana, 5: 51-86.

Langeraar, W. (1966) – Sandwaves in the North Sea. Hydrographic Newsletter 1: 243-246.

McCave, I.N. (1971) – Sandwaves in the North Sea off the coast of Holland. Mar. Geol. 10: 199-225.

—— (1973) – Mud in the North Sea. In: North Sea Science. E.D. Goldberg (ed.) M.I.T. press, Cambridge, Mass.

Madsen, V. (1928) – Summary of the geology of Denmark. Danm. geol. Unders. Raekke 5, Nr. 4: 14-47.

Mörner, N.A. (1965) – The late Quaternary history of the Kattegat Sea. Sver. geol. Unders. Serie C 640: 1-486.

Pratje, O. (1951) – die Deutung der Steingrunde in der Nordsee als Endmoränen. Dt. hydrogr. Z. 4: 106-114.

—— (1952) – Zur Geologie der Norwegischen Rinne. Abh. naturw. Ver. Bremen, 33: 79-88.

Reimnitz, E., P.W. Barnes, T. Forgatsch and C. Rodeick, (1972) – Influence of grounding ice on the Arctic shelf of Alaska. Mar. Geol., 13: 323-334.

Schubel, J.R. and E.W. Schiemer, (1972) – The origin of acoustically turbid sediments in Chesapeake Bay. Chesapeake Bay Institute Report 72-5. (Unpublished report).

Sellevoll, M.A. and I. Aalstad, (1971) – Magnetic measurements and seismic profiling in the Skagerrak. Mar. geoph. Res. 1: 284-302.

Shepard, F.P. (1931) – Glacial troughs of the continental shelves. J. Geol. 39: 346-360.

Sorgenfrei, T.H. and A. Buch, (1964) – Deep tests in Denmark 1935-1959. Geol. Survey Denmark III Series, 36.

Stride, A.H. (1963) – Current swept sea floors near the southern half of Great Britain. Q.J. Geol. Soc. London, 119: 175-199.

—— (1965) – Periodic and occasional sandtransport in the North Sea. In: La Revue Petrolière, 1 – Proc. Intern. Congr., 1st Monaco, "La Pétrole et la Mer" 111, 4 pp.

Stride, A.H. and M.J. Tucker, (1960) – Internal waves and waves of sand. Nature 188: 933.

Tagg, A.R. and H.G. Greene, (1973) – High resolution survey of an offshore area near Nome, Alaska. Geol. Survey Prof. Paper 759-A.

Terwindt, J.J.H. (1971) – Sandwaves in the southern bight of the North Sea. Mar. Geol. 10: 51-67.

Valentin, H. (1957) – Die Grenzen der letzten Vereisung im Nordseeraum. Abh. dt. Geogr. tg. Hamburg 30: 359-372.

Veenstra, H.J. (1965) – Geology of Dogger Bank area, North Sea. Mar. Geol. 3: 245-262.

—— (1969) – Gravels of the southern North Sea. Mar. Geol. 7: 449-465.

—— (1970) – Quaternary North Sea coasts. Quaternaria 12: 169-184.

Vilks, G., M.A. Rashid and W.G. van der Linden, (1974) – Methane in Recent Sediments of the Labrador Shelf. Can. J. Earth. Sci 11: 1427-1434.

Weber, J.N. (1958) – Recent grooving in lake-bottom sediments at Great Slave Lake, Northwest Territories. J. Sed. Petr. 28: 333-341.

Weering, T. van, J.H.F. Jansen and D. Eisma (1973) – Acoustic reflection profiling of the Norwegian Channél between Oslo and Bergen. Neth. J. Sea Res., 6: 241-263.