Pleistocene and Recent Sediments of the Norwegian Continental Shelf (62°N-71°N), and the Norwegian Channel Area

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The surface sediments covering the area under consideration can be divided into 4 groups: 1. Till, mainly composed of material derived from the adjacent mainland. 2. Till, mainly containing material derived from Mesozoic–Tertiary bedrock on the continental shelf. 3. Lag deposits from 1 and 2, mainly in shallow areas. 4. Secondarily transported sand and finer material winnowed out from 1 and 2, probably partly mixed with meltwater deposits, and deposited at intermediate and greater depths.

There is a clear relationship between depth and sediment texture. The thickness of post-Tertiary sediments varies between zero and about 400 m. In areas with thin cover, the glacial sediments have a lithology greatly influenced by the subsurface rocks.

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Introduction

Looking at the bathymetrical features of the Norwegian continental shelf, as well as the post-Tertiary sediments covering it, one has to consider the very special events which took place during the Pleistocene and Holocene epochs. We know that ice sheets developed in northern Europe several times during the Pleistocene, and that the mountainous areas of Norway and Sweden were glacial growth-centres for these ice sheets.

While the outer limits of the ice-covered areas during the various glaciations in the continental parts of northern Europe are fairly well established, they are far less clear in the areas now covered by the sea. Considering the Würm glaciation, the extension of the ice sheet in the present sea areas has been much disputed. Later papers and cartographical compilations often show separate ice sheets over Scandinavia, the British Isles and the Shetlands during the Würm, while these areas are assumed to have been covered by one continuous ice sheet during previous gleaciations. Some authors, however, have held the view that coalescence between the Scandinavian and British ice sheets did occur during the Last Glaciation.

From field studies in the Shetland islands, Hoppe (1970, 1972) and co-workers have given strong support to the view that this area was overridden by the Scandinavian ice during the Würm. From field work in the Svalbard area, especially from studies on isobases of uplift, they have also assumed the existence of an ice-centre situated in the central parts of the Barents Sea during the same period, and suggested the possibility that this ice-sheet was connected with the ice-sheet of northern Norway.

With regard to the western limit of the Scandinavian ice, various authors have expressed divergent opinions, and strong views, especially from biologists, have been put forward in favour of ice-free areas along the Norwegian west coast during the Würm glaciation, and possibly also during previous glaciations.

Most geologists, however, have had difficulties in accepting these views, and one of the main arguments has been the special bathymetrical features of the Norwegian continental shelf, which has a clear relation to glacial erosion and accumulation, a fact which was stressed by F. Nansen seventy years ago (Nansen 1904; also O. Holtedahl 1929, 1940; Shepard 1931, 1973; H. Holtedahl 1955; H. Holtedahl & Sellevoll 1971, 1972).

Some information on the types of sediments which are present on the Norwegian continental margin was obtained around the turn of the century by various oceanographic expeditions, which, however, spent most of their time exploring the deep sea (see H. Holtedahl 1955, p. 139). The information was extremely sparse, and one may say that our knowledge of the sediments on the Norwegian continental shelf before 1940 mainly came from the notations on the nautical charts obtained by the sounding work with plumb-lines by the Norwegian Hydrographic Office, as well as from information from fishermen.

In 1950, the first systematic investigations of the sediments on the Norwegian continental shelf, as well as geomorphological studies, were started at the University of Bergen, but it was not until 1968 that one was able to continue these studies as a result of growing interest in the Norwegian continental shelf, primarily due to oil and gas prospects in the North Sea area. In this work financial backing has mainly come from the Continental Shelf Division under the NTNF (Norwegian Research Council for Science and Technology). It may be mentioned that, recently, Soviet researchers have published some information on the sediment distribution on the Norwegian continental shelf (Litvin 1970).

Even though more systematic investigation of the surficial deposits on the Norwegian continental shelf has been carried out in later years, with the collection of a great number of sediment samples especially in the shelf-area off the coast of Møre–Trøndelag and off the coast of Troms, and to some extent in the Skagerrak area, there are still large areas which lack detailed information. This is especially true of the relatively deep parts of the continental shelf off the coast of Nordland, the shelf off Lofoten, and the Norwegian part of the North Sea.

An attempt to draw a sediment-distribution map of the Norwegian continental shelf from latitude 62°N up to latitude 71°N, and of the parts of the Norwegian continental shelf which include the Norwegian Channel, must therefore, to a great extent, still be carried out using, old chart notations and geological assumptions. Plate 1 shows a map which has been drawn from all the available information.

The inner continental shelf ('skjærgård') region

Along the entire Norwegian coast, with a few exceptions, is a submarine continuation of the coastal platform – the '*strandflat*' with the '*skjærgård*' region. This submarine area is extremely irregular, mainly rocky, and with a topography caused by glacial erosion in crystalline rocks with marked fracture patterns (O. Holtedahl 1940; H. Holtedahl 1960a, 1960b). Sediments are generally found in depressions, and in certain areas ice marginal accumulations are present, such as the Younger Dryas terminal moraine on the Skagerrak coast and a somewhat older terminal moraine along the south-west coast in the Lista–Jæren area, which can be traced as ridges or longitudinal accumulations over great distances (Andersen 1954, 1960; Klemsdal 1969). This latter coastal area is also one of the few where thick glacial deposits have been formed on land, covering large regions and reaching thicknesses of more than 100 m.

Some detailed work has been done in the submarine terminal moraine areas off the south coast by the senior author, and the distribution of sediments is shown in Fig. 1. The Younger Dryas moraine, which occurs as a very marked submarine ridge and which also appears above sea level as an island (Jomfruland), can be traced for very long distances. It is assumed to consist of boulder clay (as can be seen from subsurface excavations on the island Jomfruland), and has a covering lag-deposit of course material, mainly boulders, stones and gravel, down to a water depth of 50 m. Sand, washed out from the moraine, covers the bottom further out in a zone of varying width and depth. Further out, boulder clay appears in certain areas, and below a depth of about 100 m sandy and silty clay occurs.

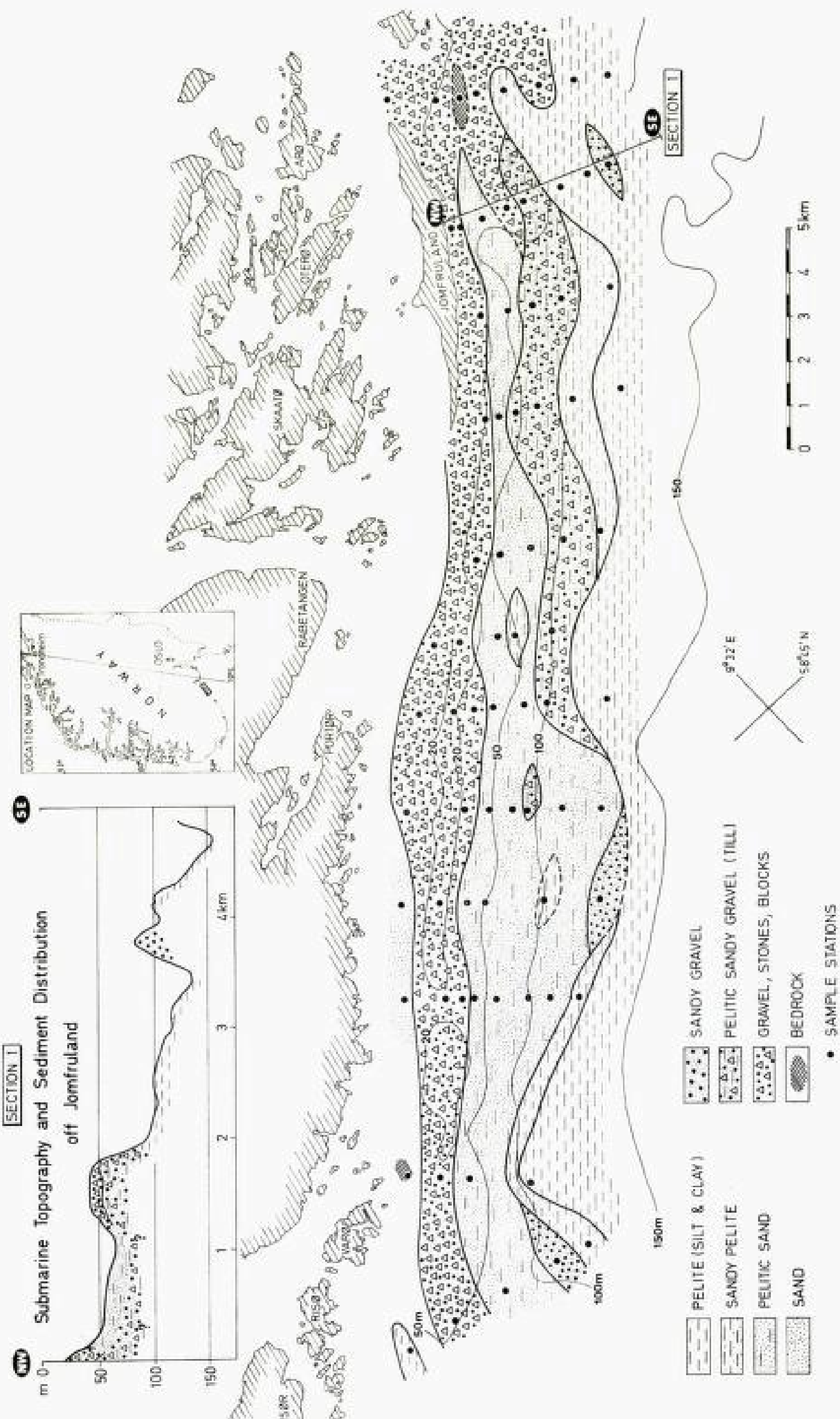
The Norwegian Channel area

With regard to the Norwegian Channel area, Quaternary deposits in the northern part of the Skagerrak have been shown by Sellevoll & Aalstad (1971) to attain a maximum thickness of about 380 m. As will be seen from the line-drawing from a seismic profile (Fig. 2a) the deepest part of the channel is covered by relatively thin deposits, while the thickest accumulations are present on the southern side towards Jutland. A maximum value of 380 m is not unreasonable, bearing in mind the thickness of some 220 m at Skagen in northern Jutland.

A recent acoustic reflection study by van Weering et al. (1973) in the Skagerrak and Norwegian Channel area further north, reveals several sedimentary units in the Quaternary accumulations (Fig. 2b).

The upper, most recent unit, which is acoustically transparent, is present in the deeper parts of the Channel, and has a maximum thickness of about 30 m in the Skagerrak, and 15–20 m off Egersund further west. Towards the sides it wedges out.

The upper unit rests on a well-stratified deposit which has about the same


Submarine Topography and Sediment Distribution off Jomfruland
SECTION 1
NW
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m 0
50
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1
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LOCATION MAP
NORWAY
OSLO
JOMFRULAND
RABBETANGEN
RISØR
50m
100m
150m
9°32'E
58°45'N
0
1
2
3
4
5km
PELITE (SILT & CLAY)
SANDY PELITE
PELITIC SAND
SAND
SANDY GRAVEL
PELITIC SANDY GRAVEL (TILL)
GRAVEL, STONES, BLOCKS
BEDROCK
SAMPLE STATIONS

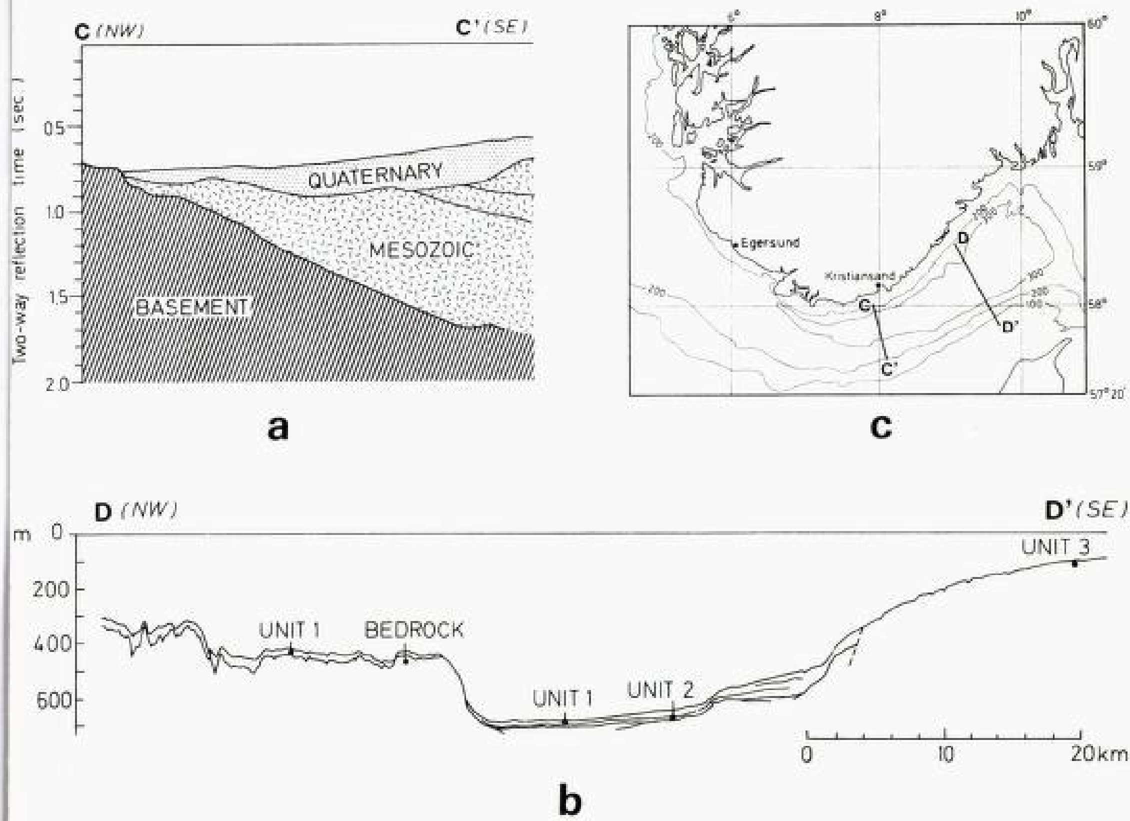

Fig. 2a. Line-drawing of seismic profile in Skagerrak south of Kristiansand. From Sellevoll & Aalstad (1971).
b. Line-drawing of acoustic profile in Skagerrak, south of Arendal. From van Weering et al. (1973).
c. Location map.

areal distribution, but which extends more to the east from Egersund and southwards. This lower unit has a greater thickness than the upper, with a maximum thickness of 90 m in the Skagerrak and more than 60 m off Egersund.

These two sedimentary units rest, with a few exceptions, on a thick deposit which has an irregular undulating surface giving a strong reflection and limited acoustic penetration. The thickness of this deposit, which is interpreted as glacial drift, could only be determined locally where a fourth sedimentary unit, or bedrock, could be traced underneath.

The most likely conclusion, according to van Weering et al. (1973), is that the supposed glacial drift found below the two upper units is of Würmian age, and deposited by a 'Skagerrak glacier' moving along the deepest part of the

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Fig. 1. Sediment map and profile of the submarine Younger Dryas terminal moraine and distal slope on the Skagerrak coast. Sediment classification based mainly on field studies of samples.

Channel, and that the two upper units represent deposition during the Holocene.

The view of the present authors, however, is that the glacial drift was not deposited by a 'Skagerrak glacier' moving *along* the Channel, but by glaciers moving *across* the Channel. This is in agreement with the views of Andersen (1964), Feyling-Hanssen (1964) and Sellevoll & Sundvor (1974). According to Andersen and Feyling-Hanssen, the deposits at Jæren, present up to 200 m above sea level, which were previously believed to have accumulated by a glacier moving along the south-west coast, are probably marine deposits containing coarse material dropped from icebergs.

A series of bottom samples was collected in the Skagerrak by the senior author in 1965 from the Naval Research vessel *H. U. Sverdrup*. The sediment map of Plate 1 is partly based on analysed surface samples from this cruise. A study of the foraminifera fauna in some of the cores was carried out by Kihle (1971). Lange (1956) found in the Skagerrak that at least the upper 10 m of the clays were deposited after 7,000 B.P., i.e. during the Holocene.

A recent seismic survey by Sellevoll & Sundvor (1974) in the Norwegian Channel west of Bergen and northwards (see also Flodén & Sellevoll 1972), shows Quaternary deposits with a thickness varying between 245 m and 45 m (1.85 m/sec.). A seismic profile along the central part of the northern part of the Channel shows a thickness of 220–240 m increasing to about 500 m approaching the shelf edge. It is interesting to note that the morphology of this part of the Norwegian Channel is due to varying thicknesses of Quaternary sediments, and not to erosional features of the underlying pre-Quaternary basement. The profiles show a number of continuous reflectors in the Quaternary deposits, but it is yet too early to interpret these features. Interesting is the observation by Sellevoll & Sundvor (1974) that the stratification in the northern part of the Channel indicates two main directions of transport, one a glacial transport across the trench, and a later mass transport of material towards the north, possibly by fluvial or glacifluvial action. If the stratified deposits, resting on the supposed foreset beds, are fluvial or glacifluvial, it requires a relative sea level depression of 500–600 m, an amount which is far greater than that concluded from the known facts about sea-level oscillations due to eustatic and isostatic movements during the Quaternary. This point obviously needs clarification, and it is hoped that drilling projects in connection with oil and gas exploration in this part of the North Sea may be able to give us some information.

Data concerning the surface sediments in the Norwegian Channel off the west coast of Norway are very sparse. A few core-samples off the Sognefjord at the bottom of the trench have been described by the senior author (H. Holtedahl 1955). The typical sediments were silty clays.

The sediments between 62°N and 71°N

The special morphological features which characterize the Norwegian continental shelf north of latitude 62°N are great variations of depth, irregularity of surface, submarine continuations of fjords, large trough-like depressions cutting across the shelf, and more or less narrow channels running almost parallel to the coast. The most shallow areas are also the narrowest ones; one is the bank-area off the coast of Møre, with depths mainly less than 200 m and a few banks even less than 100 m; and the other is the area off the Lofoten islands and the coast of Troms with similar depth conditions.

The submarine regions between these two relatively shallow areas have depths mainly greater than 200 m, and depressions down to depths of 500 m are known. It is obvious that depth variations of this order will have an effect on the sediments which have been deposited, and which are being deposited.

In the areas between latitude 62°N and 71°N (Plate 1) where information has been collected from echo-soundings, continuous seismic profiles, and from analysed sediment samples (grab, dredge, corer) from about 600 sampling stations, the surface sediments may be divided into several categories:

1. Till, mainly composed of material derived from the adjacent mainland.
2. Till, mainly containing material derived from Mesozoic–Tertiary bedrock on the continental shelf.
3. Lag deposits from 1 and 2, mainly in shallow areas.
4. Secondarily transported sand and finer material winnowed out from 1 and 2, and deposited at intermediate and greater depths. This material is probably partly mixed with meltwater deposits.

The distribution of the various categories of sediments reveals a clear relationship to depth. In the comparatively shallow areas off the coast of Møre–Romsdal and Lofoten–Troms, with depths mainly less than 200 m, the surface consists to a large extent of coarse lag deposits, mostly boulders, stones and gravel, but also sand which is secondarily transported by the action of waves and currents. Sand is also found at greater depths, and is also here supposedly secondarily transported.

On the deeper parts of the shelf, as well as on the continental slope, boulder clay occurs, showing little or no winnowing at the surface. This type of deposit is found to cover large areas of the bottom. In other deep parts silty clays are present, which to a great extent have been deposited during the later part of Würm and during the Holocene. Probably large proportions of this clay have been washed out from tills in more shallow water, but during the withdrawal of the ice-front from the continental shelf area, a large amount of fine material from meltwater must have settled. It is believed, however, that very little of the fine particles brought to the sea from land during the major part of the Holocene actually settled on the continental shelf. Most of this material presumably settled in the fjords, and the very fine fraction bypassed the shelf (H. Holtedahl 1965).

The thickness of the Quaternary deposits of the continental shelf north of latitude 62°N outside the '*strandflat*' shows great variation, according to the seismic investigations carried out by the Seismological Observatory at the University of Bergen (Eldholm & Nysæther 1969; Nysæther et al. 1969; H. Holtedahl & Sellevoll 1971, 1972). Off the coast of Trøndelag and Nordland the sediment cover varies in thickness from zero to about 400 m. The greatest thicknesses are found in the peripheral areas close to the continental slope, while areas with sparse accumulations are especially noticeable between Haltenbanken and Frøyabanken.

The present submarine topography, with great variations in depth, can be ascribed partly to an unevenly eroded sub-Quaternary surface, and partly to the varying thickness of the Quaternary sediments.

Glacier movement along the entire coastline has been more or less normal to the coast and the main ice-movement on the continental shelf between latitudes 62°N and 71°N during the maximum extent of the glaciation was directed towards the west and north-west.

LITHOLOGY

The lithological composition of the Quaternary surface sediments which have been sampled on the continental shelf between 62°N and 71°N is clearly related to the total thickness of the Quaternary deposits. In areas of great thickness, the material is primarily derived from the crystalline rocks on the mainland and consists of rocks and mineral grains, including clay minerals, typical of glacial deposits on land. An admixture of types, obviously dropped from icebergs, and with a long transport to a large extent from the Oslo area, has been shown to occur (H. Holtedahl 1955).

In areas of thin Quaternary cover, the deposits contain a large percentage of sedimentary rocks of Tertiary and Jurassic–Cretaceous age (H. Holtedahl & Sellevoll 1971), to a large extent unmetamorphosed sandstones, claystones and limestones. Of macro-fossils belemnite rostra were commonly found in the dredge samples. This material has presumably been picked up by the glaciers from the underlying bedrocks, and transported in the direction of ice-flow over a distance which may in certain cases have been very short.

A sediment core 4.5 m long, sampled on the northwest slope of a submarine ridge between Haltenbanken and Frøyabanken at a depth of 310 m, consisted of an upper, mainly postglacial clay, 150 cm thick, and a clayey deposit with more or less disintegrated sedimentary rock fragments and a high organic content, supposedly representing a glacial till (Fig. 3). The fossil assemblage of the rock fragments, as well as of the matrix, was of Middle and Upper Jurassic, Cretaceous and Lower Tertiary age. Furthermore, the clay mineral assemblage differed markedly from the assemblage in the upper part, in having a high content of kaolinite (30–40%) and montmorillonite (30–40%). This assemblage was clearly related to clay minerals in the nearby pre-Quaternary rocks. The major part of the material of till was considered to have had a fairly short transport, thus giving an indication of the bedrock lithology to the east of the sampling station (H. Holtedahl et al. 1974).

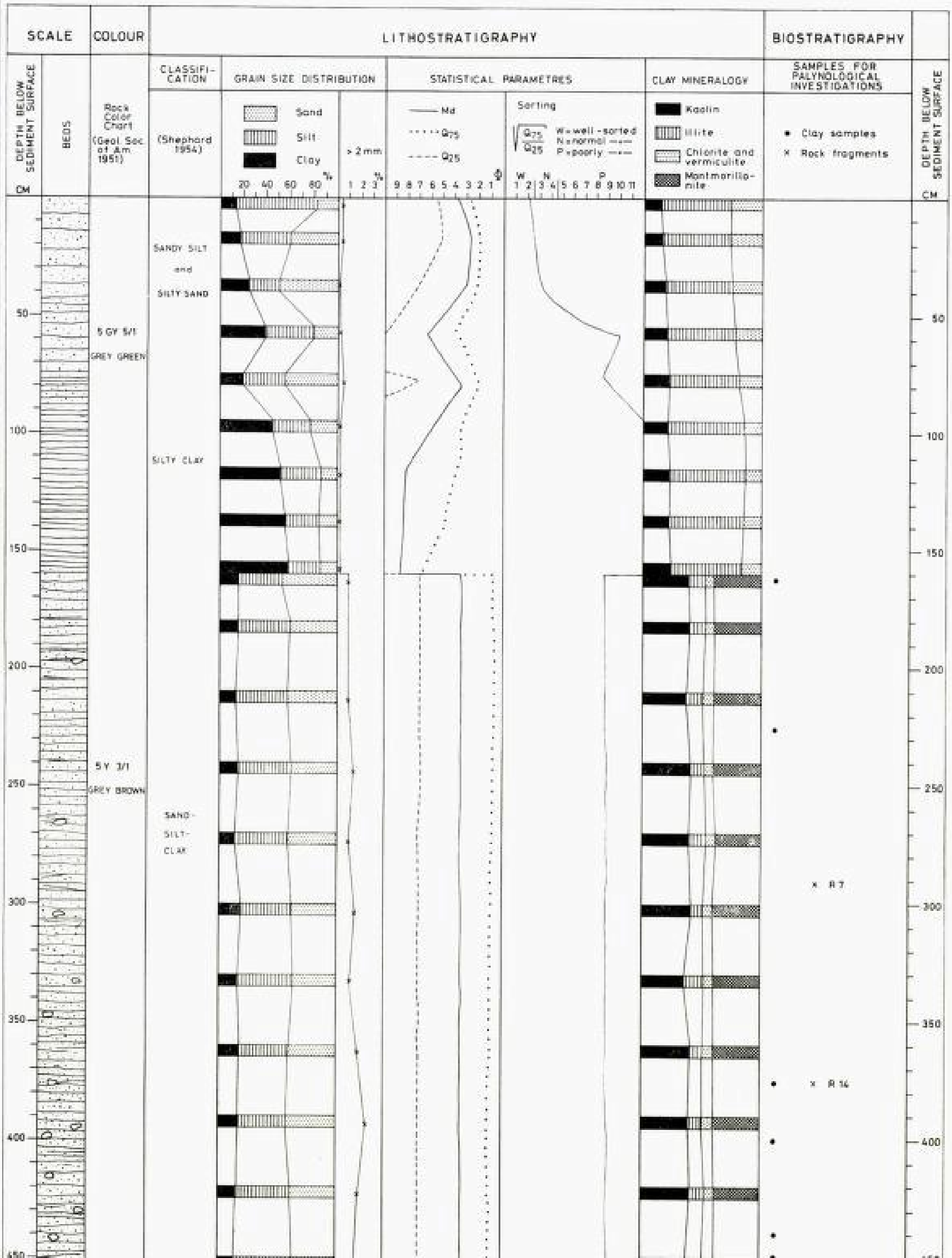

Fig. 3. Lithostratigraphy of sediment core between Haltenbanken and Frøyabanken. From Holtedahl et al. 1974).

Another relationship between components of Quaternary deposits and the underlying sedimentary rocks in thinly covered areas has been demonstrated by the junior author (Bjerkli 1972) in the distribution of certain minerals of the sand fraction. Bjerkli has found a concentration of glauconite in an area between Haltenbanken and Frøyabanken, which points to a source in the underlying Mesozoic and Tertiary rocks.

A lithological analysis of the components of the Quaternary sediment cover is, according to these investigations, a good indicator of the thickness of this cover, as well as of the composition of the underlying pre-Quaternary bedrock surface.

Special textural investigations on quartz grains from Quaternary sediments off the coast of Møre have been carried out by Strass (1973). By using scanning electron microscopy, she was able to distinguish grains with a different origin and transport history. According to Strass, the very well-rounded and frosted quartz grains, which occur as a minor part of the glacial sediments on the continental shelf off Møre, have not acquired their eolian texture on dry bank areas during the Pleistocene, as has been suggested by the senior author (H. Holtedahl 1955), but are probably derived from eolian sandstones of the underlying pre-Quaternary bedrock surface.

General consideration of Quaternary history

The Norwegian continental shelf, including the Channel area in the North Sea and the Skagerrak, has been greatly influenced by glacial activities during the Pleistocene. It is believed that the inland ice, which during its maximum had its culmination in the central parts of the Fennoscandian area, covered the entire continental shelf. During other stages, the high mountains of especially the western parts of Norway were ice accumulation centres, producing glaciers which extended more locally over the continental shelf to varying distances from the coast. The great depths, present especially near the coast in the Norwegian Channel area as well as off the west coast, are probably due to heavy glacial erosion in rocks with limited resistance. The increased thickness of Quaternary sediments towards the peripheral areas is natural when these regions are considered as the peripheral parts of the continental ice sheet.

Sea level oscillations on the continental shelf have no doubt been extensive during various phases of the Pleistocene, and have greatly effected sedimentation. At the outer coast, especially the west coast, caves formed by sea abrasion, and other sea-abrasional features, at levels high above the maximum sea level during the final disappearance of the ice in Late Würm times, are commonly found. Along the coast of Møre, signs of sea abrasion are distinct up to levels of 80 m above present sea level, while the Late Würm marine limit is about 20 m (H. Holtedahl 1960a, 1960b). This indicates a considerable isostatic depression of the crust in these coastal areas during the maximum of glaciation, which again indicates a considerable ice thickness. A great isostatic depression of large parts of the continental shelf must therefore be assumed, interfering with the general eustatic lowering of sea level.

High former sea levels, far above the Late Würm marine limit, are also known from the Jæren–Sandnes area on the south-west coast, where supposed glacial-marine clays are found up to a level of 200 m. In this area Late Würm marine limits are only 10–20 m, and as mentioned above the clays have previously been reckoned as deposits from a 'Skagerrak glacier'.

As to indications of lower sea levels on the continental shelf, the senior author has proviously pointed to a very marked increase in rounded stones and gravel at a depth of about 100 m, suggesting that banks less than this depth have been dry during the later parts of the Würm glaciation (H. Holtedahl 1955). The study of textures on quartz grains by scanning electron microscopy, carried out by Strass (1973), has supported this assumption.

A lowering of sea level to the extent which was thought necessary to explain the assumed foreset–topset structures in the northern part of the Norwegian Channel has not been verified by studies on the continental shelf north of the Channel. In any case, the relative sea level has shown great oscillations and the crustal movements have been extensive, due primarily to the glacial isostatic effect. To what extent, if any, these verical movements of the crust have influenced the migration of oil, has yet to be seen.

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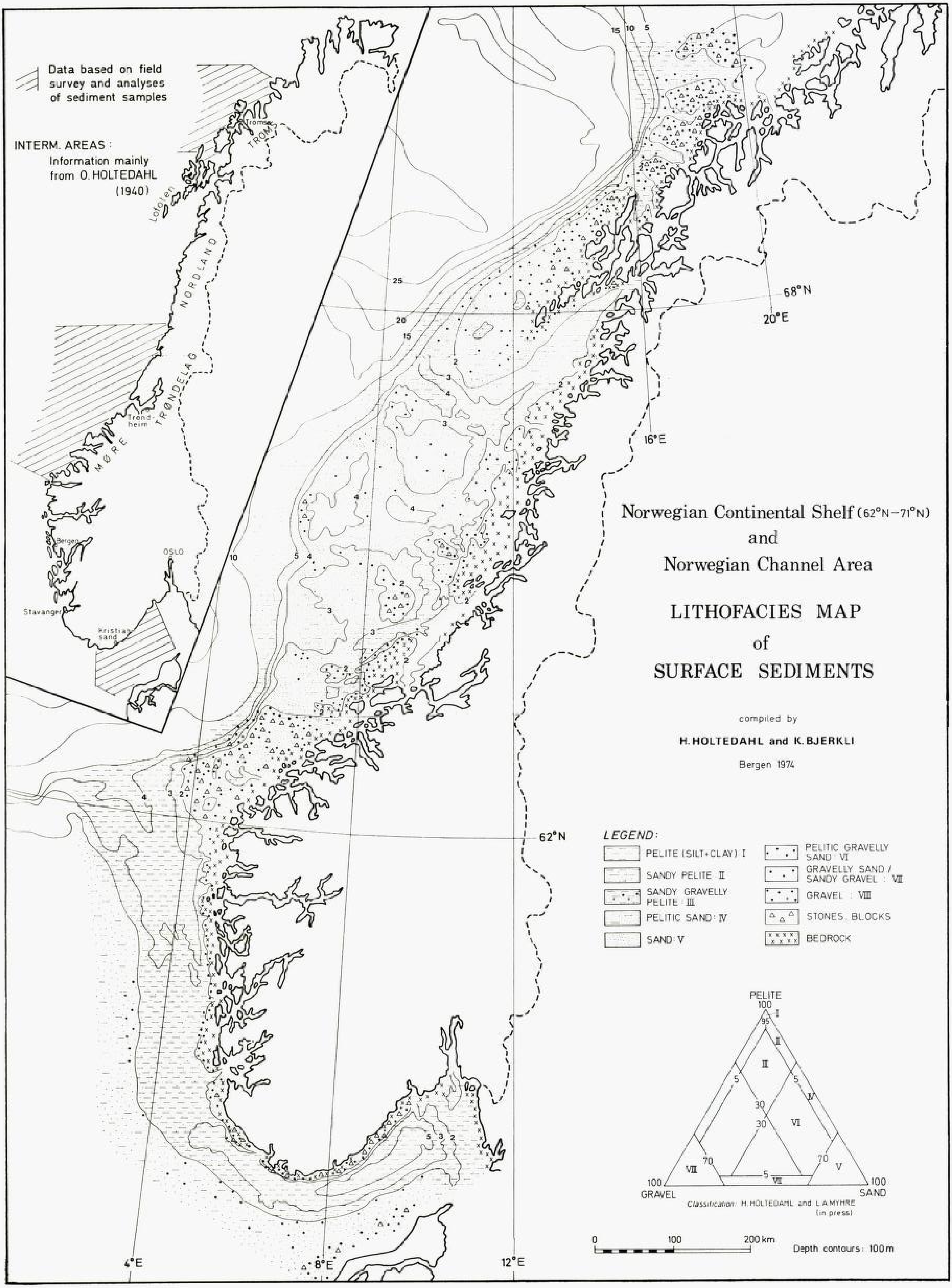

Plate 1. Sediment map showing lithofacies of surface sediments. Areas where information is based on field surveys and detailed analyses of collected sediment samples (grab, dredge, core) are marked on the inset map. Information from other areas mainly from O. Holtedahl (1940).