Sedimentological and mineralogical investigations of Quaternary bottom sediments off the Norwegian west coast

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Mineralogical composition of what is probably till of Weichselian age in the North Sea off Nordfjord indicates provenance from the Norwegian mainland and from Tertiary and Mesozoic rocks (the Skagerak-Denmark region?). A very similar mineralogical composition in the overlaying ca. 1 m thick unconsolidated Late Glacial mud and poorly sorted Post Glacial cover sand suggests that these two units originate from reworking of the till. The Late and Post Glacial sedimentary processes are thus restricted to local erosion and deposition; where the increased energy with deposition of sand is related to the influx of Atlantic water as the oceanic polar front moved into the Arctic basin early in Holocene time.

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The present paper describes the textural and mineralogical composition of superficial Quaternary bottom sediments on the continental shelf off Nordfjord, west Norway (Fig. 1).

Quaternary sediments, 100–400 metres thick, rest with angular unconformity upon westward-dipping Tertiary and Mesozoic sedimentary rocks (Fig. 1).

Near the Norwegian coast the Quaternary sediment cover is generally thin and overlies crystalline basement. The Quarternary deposits include tills, interglacial marine sediments, and glaciomarine/glaciofluvial sediments (Jansen 1976, Löken 1976), which in shallower parts of the North Sea have been reworked, leaving lag deposits. The winnowed finer grades have been deposited in deeper water as a coarsening upwards unit (Haldorsen 1974, Holtedahl et al. 1974).

The source rocks of the Quarternary sediments fall into three groups (cf. Holtedahl 1955, Holtedahl & Bjerkli 1975):

Underlying Tertiary and Mesozoic strata, chiefly fine-grained clastic rocks – often with high kalolinite contents – and carbonate rocks.

Precambrian gneisses and metamorphosed Palaezoic rocks from the adjacent mainland.

Palaeozoic (meta)sediments and Permian intrusives from the Oslo Region and Tertiary and Mesozoic rocks from the Skagerak – Denmark region.

Samples

In the autumn of 1974, Oljedirektoratet organised a programme of shallow core sampling for the geochemical prospecting of hydrocarbons in the two blocks (35/3 and 36/1). These blocks were later drilled.

Gravity cores 0.4 – 2.5 metres long were collected approximately 100 metres apart and this paper deals with 14 such cores from three profiles. 12 cores were analysed in detail while the other two were only examined for stratigraphical purposes (Fig. 2).

Bathymetry and hydrological conditions

The studied area is a gentle westward dipping slope (maximum 1°), continuing down the northwestern part of Norskerenna, with a plateau between 200 and 250 metres in the central parts. Maximum and minimum depths are 350 metres (in west) and 160 metres (in east) respectively.

The present surface current pattern is controlled by the north-flowing Norwegian Coastal Current (Sætre 1976). However, the directions at the bottom currents in the area are occasionally random, and measured maximum bottom current velocities south of the study area are 40–50 cm/s (Statoil unpbl. report 1976).

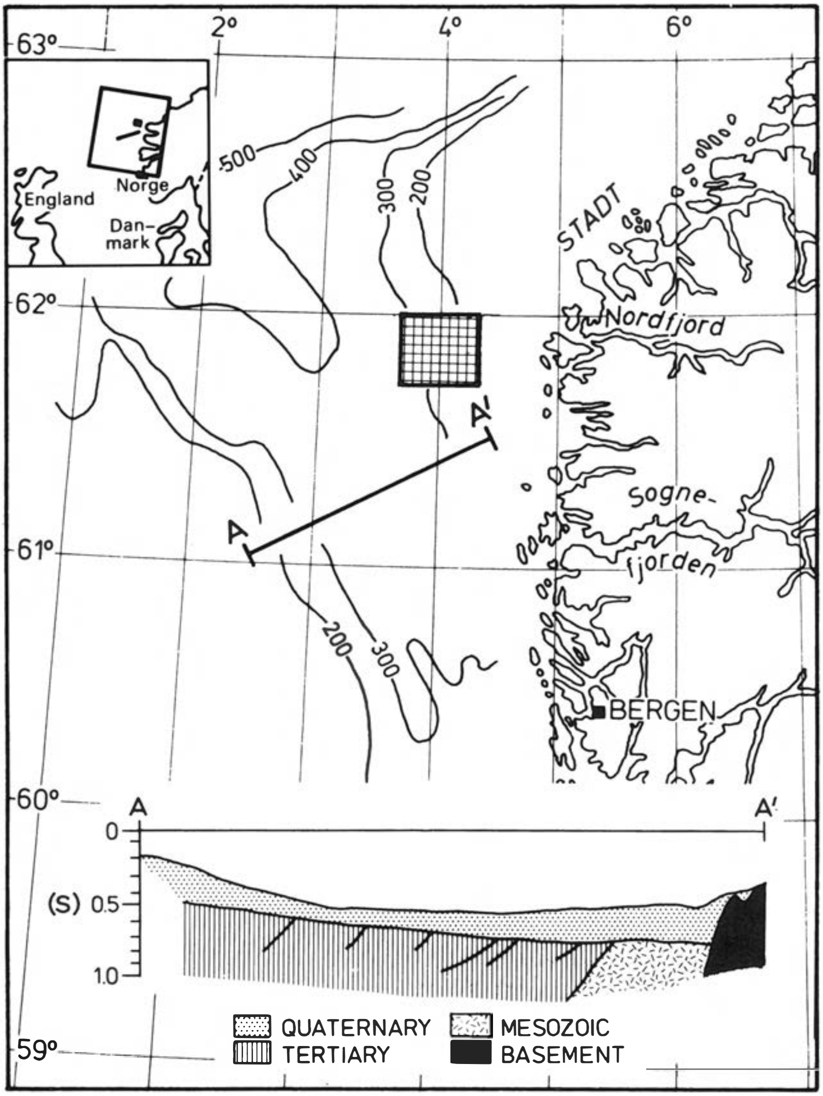


Fig. 1. Location map. The seismic profile (A–A') in two-way reflection time is interpreted as representative for the continental shelf outside west Norway. (A–A'-from Sellevoll & Sundvor 1974).

Analytical procedures

The cores were split with an osmotic knife for better preservation of the sedimentary structures, and some were analysed radiographically for detailed study of the structures. The grain-size analyses were carried out after splitting the samples at 63 μm. The coarser fractions were dry sieved, while the silt and clay fractions were analysed by pipette (Folk 1968), employing whole phi intervals. The grain-size distribution is expressed in weight per cent, plotted on probability paper.

Geotechnical analyses, such as water content and undrained shear strength by cone measurement, were done, but since the cores had been stored for 1 1/2 years, the results are tentative. The colour description of the samples follows Munsell Soil Color charts (1954).

Mineral analyses by X-ray diffraction analysis (XRD) were carried out on the clay, silt, and sand fractions, and the latter were sup-

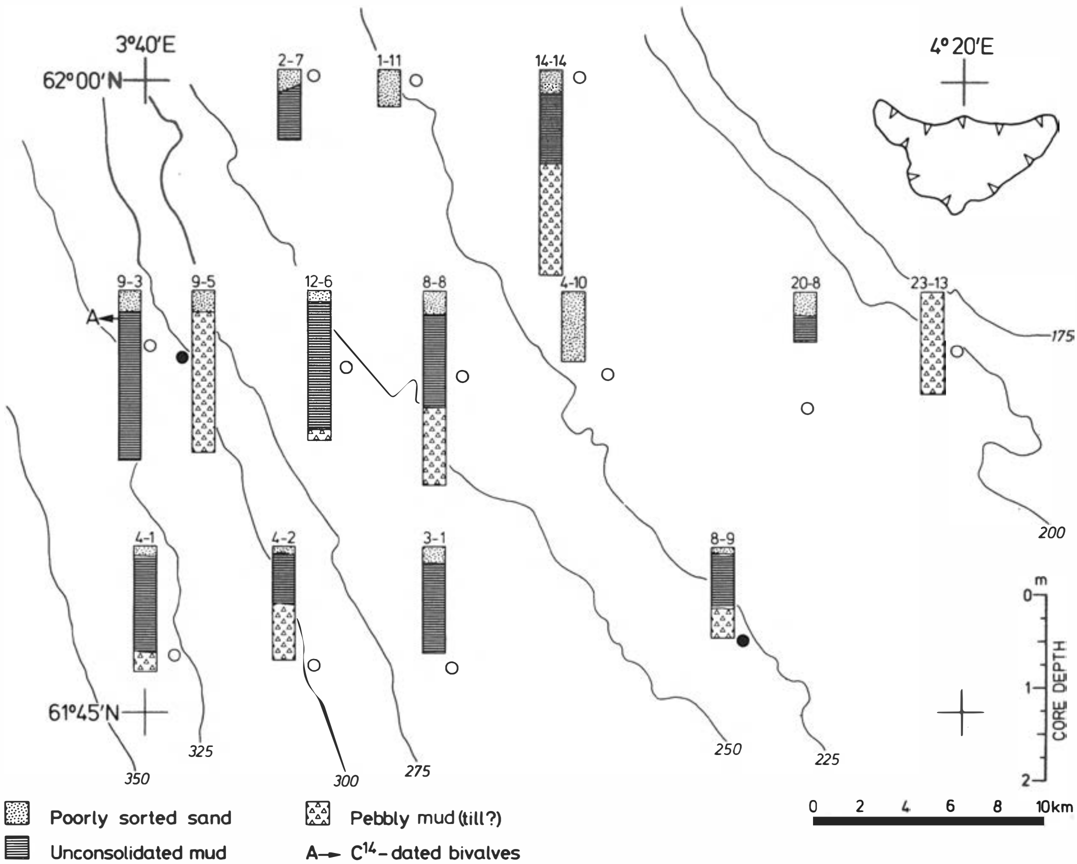


Fig. 2. Bathymetric map showing sample locations and the stratigraphy in the cores. Contour interval: 25 metres. Map is reproduced with permission from Institutt for Kontinentalundersøkelser.
Open circle: Samples for detailed sedimentological and mineralogical analysis.
Black circle: Samples for stratigraphical analysis.

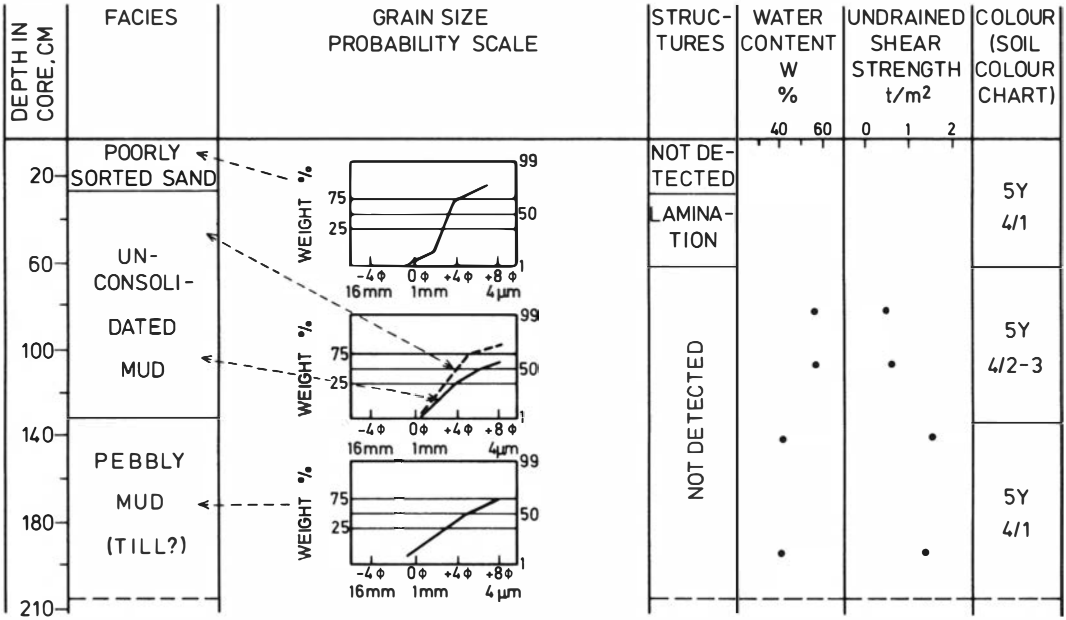
plimented by thin section and microscope analyses. The clay and silt fractions were prepared by sedimentation technique, sediments coarser than 20 μm being ground in a McCrome water mill for 10 minutes, producing homogenous samples of fine-silt sizes. X-ray slides were prepared by vacuum filtering from suspension onto Millipore filters, a method which causes little mineral separation on the X-ray slides (Stokke & Carson 1973).

The bulk mineralogy in the silt and sand grades was calculated semi-quantitatively from X-ray records as peak intensity (peak height multiplied by width at half-peak height). Since the mineral assemblages are relatively simple in these fractions, the mineral composition is illustrated by the concentrations of some important major elements such as Si, Al, K, and Ca. The geochemical analyses were carried out by X-ray fluorescence (XRF).

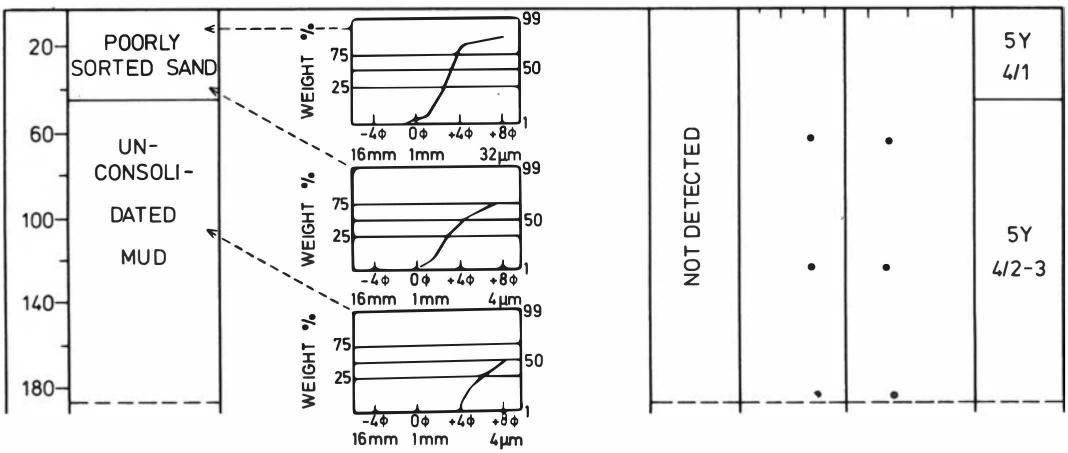
The identification of the clay minerals on XRD curves followed procedures outlined by Graff-Petersen (1961), Biscaye (1964), and Caroll (1970), and the phyllo-sheet silicate mineralogy was calculated semi-quantitatively, based on peak intensity measured by planimeter.

Sediment stratigraphy and sedimentary environment

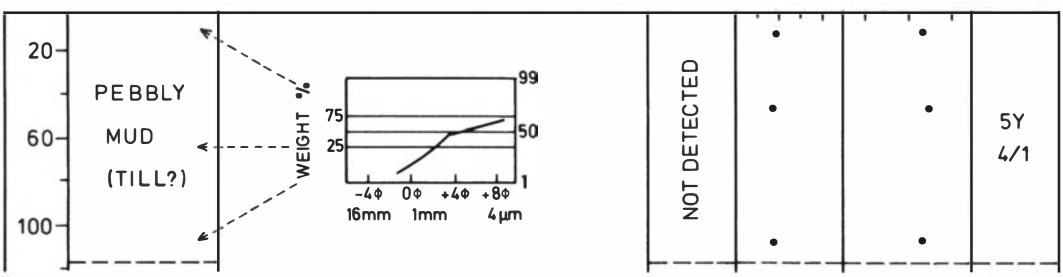
There are three principally different sediment facies represented in the cores (Figs. 2 and 3); Poorly-sorted cover sand; unconsolidated mud; and underlying stiff mud with angular clasts (pebbly mud).



SAMPLE NR: 9-3 WATER DEPTH:310M



SAMPLE NR: 8-8 WATER DEPTH:240M



SAMPLE NR: 24-13 WATER DEPTH:183M

The pebbly mud

The pebbly mud has a blue-grey colour (5Y 4/1) and is primarily present in the lower parts of the cores. However, in the easternmost core it is exposed at the top (Fig. 2), and local exposures of this mud in other parts of the area were indicated by the difficulty in obtaining samples (field report, Oljedirektoratet 1974).

The grain-size distribution of the pebbly mud shows maxima in the clay/fine silt and the sand sizes (Fig. 3), while the pebbles make up 0–10% of the sample.

The clasts are mainly crystalline, derived from Norway, augmented by minor quantities of Tertiary and Mesozoic material (p. 279). Tests of *Elphidum* sp. indicating a cold foraminifera fauna were also detected in some samples.

At present no acceptable criteria have been identified for distinguishing sediments deposted below a shelf ice from those deposited in front of the shelf ice (Curey & Ahmend 1961, Sugden & John 1976). Thus the origin of the pebbly clay is interpretated as follows.

Thick Quaternary sediments underlie the area, with the Tertiary and Mesozoic strata below (Fig. 1), and it seems unlikely that pebbles could have been derived directly from these underlying strata. Ice rafting of materials from the Oslo Region and Skagerak-Denmark regions has been reported for Late Glacial time (Holtedahl 1955), and the Tertiary and Mesozoic components in the pebbly clay may have been introduced in this way. The presence of a cold foraminifera fauna is also consistent with a glaciomarine environment.

No laminations have been observed, and compared with the overlying mud, the pebbly mud shows greater compaction (0.6 t/m^2 to 1.2 t/m^2 respectively, Fig. 3).

Water depth in Norskerenna outside Måløy varies between 160 and 350 metres, probably giving marine shelf ice condition for the retreating Late Weichselian ice sheet at a position just east of the study area (a position reached at least 12–13,000 years BP.

Glaciomarine sediments containing foraminifera and ice-rafted Tertiary and Mesozoic sediments may have been eroded during minor advances of the shelf ice. The pebbly mud is slightly overconsolidated compared to the overlying mud and this compaction may be explained as due to deposition below a wet shelf ice (Curey & Ahmed 1960). The present author interprets the pebbly mud as a till formation from an ice shelf.

The unconsolidated mud

On the lower parts of the shelf there is a structureless, unconsolidated, brown mud (5Y 4 2/3) (Figs. 2 and 3). It is very fine grained (50% less than 4 μm) but contains scattered sand and gravel grains. ^{14}C dating of *Astarte crenata* from this mud (Fig. 2) gave a Late Glacial age (12,570 $\pm$ 550 BP). Based on the texture and age, it seems likely that these sediments were deposited rapidly from suspension in a proglacial environment, with the coarser clasts being deposited by ice rafting.

The mud is generally massive and becomes coarser upwards and towards land. However, lamination can be recognized in radiographs in cores taken in less than 250 metres water depth.

The poorly sorted cover sand

The sand is fine-grained and poorly sorted (Fig. 3) and has a high content of *Uvegerina* sp., a Boreal foraminifera. Commonly the sand is overlying the mud, but in one core it lies directly upon the till, while elsewhere gravelly deposits have been locally observed (field report, Oljedirektoratet 1974), suggesting Post Glacial winnowing from the till. However, winnowing has probably not occurred on a large scale; the distribution of the surface sediment and the textural composition of the cover sands rather indicate that both erosion and depositional processes were active in the area. A probable explanation is that periods of erosion producing small lags have alternated with more quiet periods with deposition of locally derived clay, silt, and sand, which are supplied by bed-load transport and fall out from suspension. Similar environments are reported from the southwestern part of the English Shelf at water depths between 100–150 metres (Channon & Hamilton 1976).

Fig. 3. Sedimentological description of three cores in the western, central and eastern part of the area.

Coarsening upwards in the Late and Post Glacial sediments

Along the Norwegian coast and in the northwestern part of the Barents Sea, the Late and Post Glacial sediments are locally derived and characterized by coarsening upwards (Holtedahl et al. 1974, Bjørlykke et al. 1978).

The cover sand probably indicates active erosion by the present Norwegian Coastal Current down to 300–350 metres water depth, while the muddy sediments below reflect a calm environment in the northeastern part of Norskerenna during Late Glacial time. Outside Måløy only minor sea-level changes occurred in Late and Post Glacial time (Fareth 1970), and it seems likely that the velocity of the watermasses themselves has increased.

The triggering mechanism of the Norwegian Coastal Current is not fully understood, but the warm Atlantic water seems to influence greatly the present current pattern (M. Mork, pers. comm. 1977). In Late Glacial time the polar front was lying in the central parts of the North Atlantic Ocean, and as the deglaciation was completed, the polar front moved north and west into the Arctic Ocean (Ruddiman & McIntyre 1973, Mangerud 1977). A possible explanation for the increasing velocities is that the Norwegian Coastal Current first developed with flow pattern roughly similar to the present, early in the Holocene, In Late Glacial time (with the polar front in the southern areas and an ice sheet still covering Scandinavia), coastal water circulation was still either less marked or followed quite different routes.

In this way the coarsening upwards in the sediments outside Måløy is due to a changing current pattern, which also may have influenced the situation along the coast of Møre and Trøndelag (southeastern Norwegian Sea). Here attention has previously only been given to eustatic/isostatic changes (Haldorsen 1974, Holtedahl et al. 1974).

The development of the coarsening-upwards unit indicated by changing current patterns also probably took place in the Barents Sea, in Sub Atlantic time (Bjørlykke et al. 1978), when the oceanic polar front retreated from north of Spitsbergen to its present position just south and east of Bjørnøya (Mangerud 1977).

Rock fragments (> 1mm) and provenances

The rock fragments can be divided into two main groups: gneisses and metamorphic rocks of probably Precambrian and Palaeozoic age; sedimentary rocks of Tertiary and Mesozoic age.

MINERALOGY

FRACTIONS	KAOLINITE	ILLITE DIOCTAHEDRAL	MUSCOVITE	ILLITE TRIOCTAHEDRAL	BIOTITE	CHLORITE	VERMICULITE	RANDOM MIXED-LAYER 10-14Å MINERALS	RANDOM MIXED-LAYER 14-14Å MINERALS	GLAUCONITE
0.5 - 2.0 mm	○		●		●	⊕	○	○		○
20 - 500 µm	○		⊕		⊕	○	○	○		●
8 - 20 µm	⊕	●		●		●	◑	○	◑	○
2 - 8 µm	◑	●		●		●	◑	○	◑	
<2 µm	●	●		⊕		●	○	●	●	

LEGEND:
○ NOT DETECTED ⊕ TRACE
◑ MINOR COMPONENT ● MAJOR COMPONENT

Fig. 4. Semi-quantitative clay mineralogy based on peak intensity, common for the three different facies.

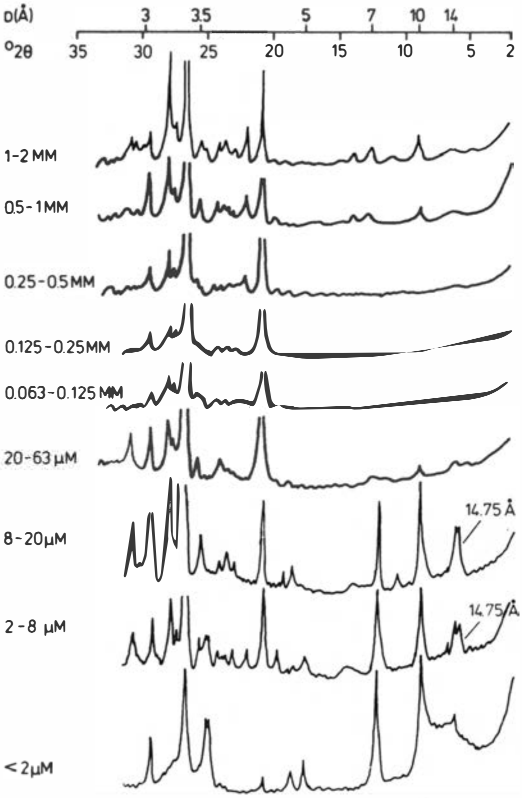


Fig. 5. X-ray diffraction pattern for the sand-silt-clay fractions of Quaternary superficial sediments; North Sea, northeastern part. The samples were saturated with Sr^{++}.

The first group is responsible for up to about 80% of the gravel fraction.

The gneisses and metamorphic rocks

Among the crystalline fragments the following two types may be related to rocks in the Nordfjord area, west Norway (Bryhni 1966, I. Bryhni pers. comm. 1977): light green quartzite with sutured grains; rock fragments with light grey perthitic and antiperthitic feldspar. Other common fragments are mica-gneisses with both muscovite and biotite. These fragments are interpreted as representing westward glacial transport into the studied area.

The sedimentary rocks

Limestones and chalk are common, sometimes with a high glauconite content. The clastic rock fragments include shale, mud-, and sand-stones, and occasional siderite concretions. These are lithologies that can be recognised in Tertiary and Mesozoic strata from the North Sea, and thin section analyses of the chalk and limestone clasts show lithologies very similar to Maastrichtian and Danian rocks. (Comparison with unpublished data from R. Nylend, Universitetet i Oslo 1976.)

Provenances of the sheet silicates

In the sediments investigated the clay minerals are smaller than 20 μm, while mica and minor amounts of chlorite occur in gneiss fragments and as single clastic minerals in the coarser sand sizes (Figs. 4, 5 and 11). Glauconite is only found in the fine-sand sizes (Fig. 4).

In the fine-silt sizes and the coarser-sand sizes, well-crystallized illite can be identified (Fig. 6), and a significant shift in the 10 Å peak to 14 Å was observed after extraction of K^+-ion by natriumtetraphenylborat (NaTPB) (Fig. 6), suggesting the presence of trioctahedral mica (Robert 1973). Biotite and muscovite were

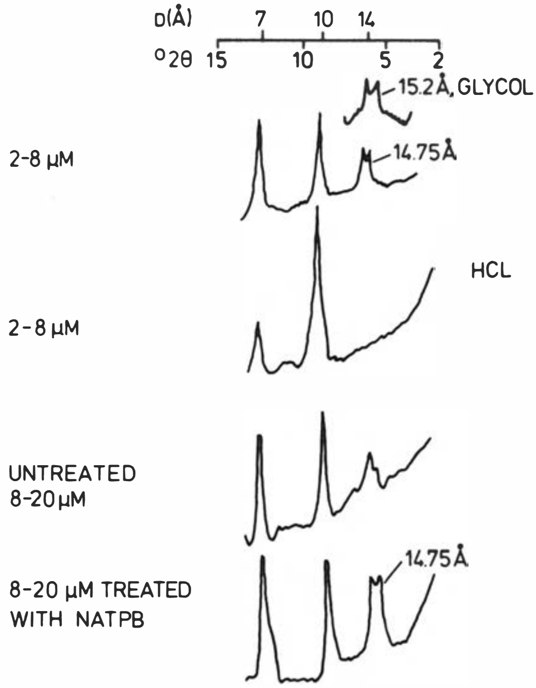


Fig. 6. X-ray diffraction diagram of fine-grained silty sediments after different types of chemical treatments. The samples were saturated with Sr^{++}. The natriumtetraphenylborat (NaTPB) treatment extracts potassium from trioctahedral illite, transforming it to a vermiculite mineral at 14.75 Å.

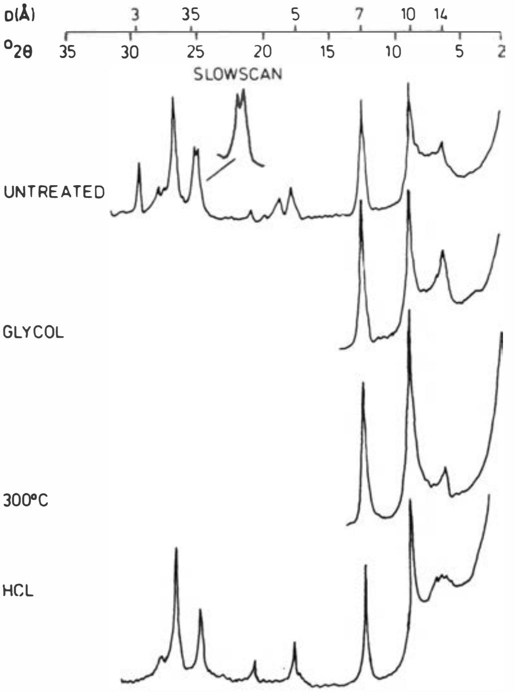


Fig. 7. X-ray diffraction diagrams for the < 2 μm fraction of Quaternary superficial sediments; North Sea, northeastern part. The samples were saturated with Sr^{++}.

further detected by thin section analyses in the coarser-sand sizes.

In the fine silt, sand sizes (2–20 μm) and expansion of the 14 Å peak to 15.2 Å after ethylene-glycol treatment revealed the presence of vermiculite (Fig. 6).

Kaolinite is enriched in the < 2 μm fraction, which also contains dioctahedral illite, chlorite, and mixed-layer minerals including random illite-smectite (10–14 Å) and probably smectite-vermiculite-chlorite (14–14 Å) (Figs. 4 and 7).

These mineral assemblages observed in the sediment fall into two main groups with respect to provenance.

Sheet silicates derived from rocks in Norway, with a mineralogy which mainly reflects the source rock, and clay minerals produced by intensive weathering derived from Tertiary and Mesozoic rocks. These minerals (kaolinite, dioctahedral illite and random mixed-layer minerals of illite and smectite) are essentially confined to the clay fraction.

Trioctahedral illite is easily weathered during leaching, forming vermiculite, and it seems likely that the vermiculite identified in the fine-silt sizes represents altered trioctahedral mica from the gneissic rocks in the provenance area and their fragments in the sediments. Biotite and vermiculite in the fine-silt sizes are also commonly found in Norwegian Quaternary deposits (Berry & Jørgensen 1971), and their presence indicates the immature nature of the sediments derived from the Norwegian crystalline basement.

Kaolinite is a common mineral in Mesozoic and Tertiary rocks below the North Sea, and an abundance of kaolinite in the Quaternary sediments is a clear indication of the degree of reworking of pre-Quaternary stratigraphical units. Random mixed-layer minerals of illite and smectite are also rare in Norwegian Quaternary deposits (Roaldset 1972), and those in the present sediments are presumably derived from Tertiary and Mesozoic rocks.

The glauconite in the Quaternary sediments is also probably reworked from Tertiary and Mesozoic rocks (p. 279). Reports by Bjerkli & Østmo-Sæther (1973) of glauconite formation in Boreal foraminifera tests, suggest, however, that

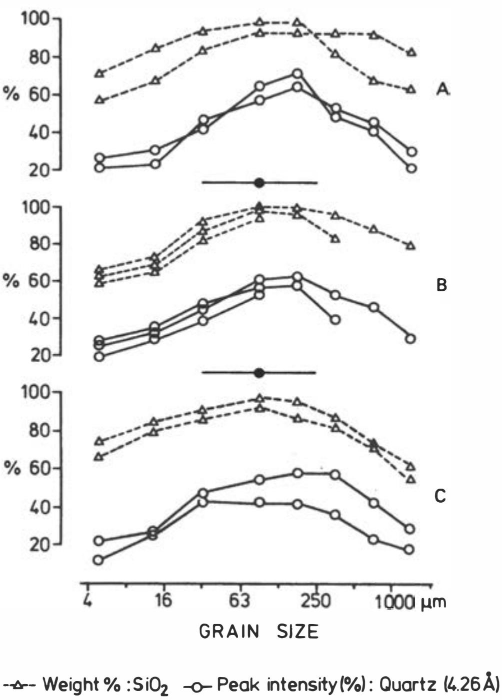


Fig. 8. Plot of the X-ray intensity percentage for quartz and weight % for SiO_2 for the silt and sand fractions for the different facies. (A: Poorly sorted sand, B: Unconsolidated mud, C: Pebbly mud (till ?).

glauconite could also have been formed during the Pleistocene.

As shown, the sheet silicate composition varies greatly with grain size, and if analyses are restricted to the < 2 μm fraction, a misleading picture of the sheet silicate composition of the samples will result. The analytical procedures have to be selected with respect to the actual provenances.

The distribution of quartz, feldspar, and calcite

The fine and medium sand grain sizes of the cover sand and the pebbly clay consist of nearly pure quartz (90 – 100% SiO_2) (Fig. 8). Quartz optima in the fine-sand fraction are also reported in tills derived from Precambrian rocks, reflecting the primary grain size in the source rock (Sørensen 1970, Korböl & Jørgensen 1973).

In the coarser sand and silt sizes, a higher total feldspar content is observed (Fig. 9). The dominant feldspar in the silt sizes is plagioclase, while in the sand sizes there is a more scattered pattern (Fig. 12). The high plagioclase content may be attributable to anorthositic rock provinces in west Norway (I. Bryhni pers. comm. 1977), and the higher microcline/plagioclase ratio in the sand fractions may be due to selective breakdown of the less resistant plagioclase minerals during glacial transport. However, in the finer (i. e. silt) fractions this process is less efficient, and some of the silt-sized feldspar may also have been reworked from the Tertiary and Mesozoic rocks.

Carbonate minerals – particularly calcite – occur in the coarser sand and gravel fractions as poorly consolidated clasts (Tertiary and Mesozoic provenance), which during glacial transport seem to disintegrate directly into fine silt and clay sizes, thus encouraging a bimodal grain-size distribution (Fig. 10). Similar bimodality for calcite is also reported from tills derived from carbonate rocks (Dreimanis & Reavely 1953).

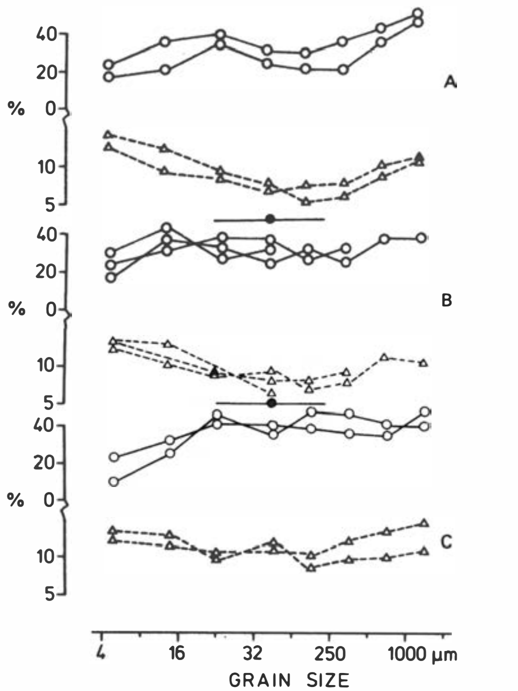


Fig. 9. Plot of the X-ray intensity percentage for plagioclase and potashfeldspar and weight % for Al_2O_3 in the silt and sand fractions for the different facies. (A: Poorly sorted sand, B: Unconsolidated mud, C: Pebbly mud (till ?).

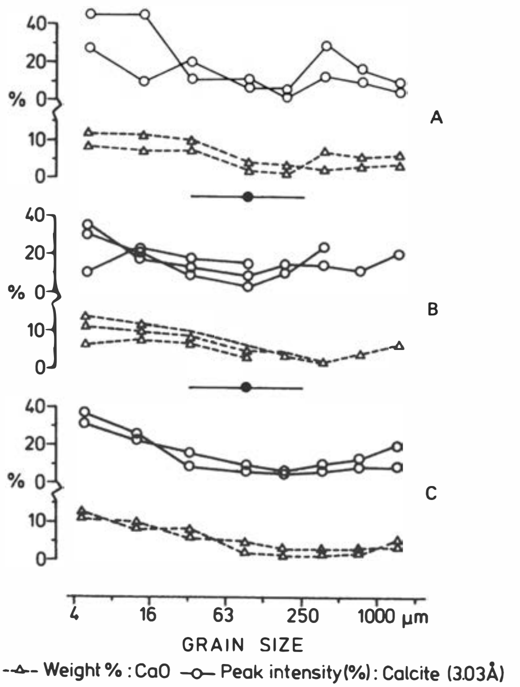


Fig. 10. Plot of the X-ray intensity percentage for calcite and weight % for CaO in the silt and sand fractions for the different facies.
(A: Poorly sorted sand, B: Unconsolidated mud. C: Pebbly mud (till?).

Table 1. Semi-quantitative bulk mineralogy based on peak intensity of the different facies. Mean value ($\bar{X}$) and standard deviation (S) are listed.

Facies	Quartz (4.26 Å)	Plagio-clase 3.19 Å	K-feld-spar (3.25 Å)	Calcite (3.03 Å)	Clay Minerals (7 Å + 10 Å)
Pebbly mud (till ?)	$\bar{x}$:36.86	$\bar{x}$:24.33	$\bar{x}$: 8.33	$\bar{x}$:26.67	$\bar{x}$: 5.34
(6 samples)	s: 7.01	s: 7.97	s: 7.40	s: 4.89	s: 3.78
Unconsolidated mud	$\bar{x}$:35.86	$\bar{x}$:21.02	$\bar{x}$: 9.13	$\bar{x}$:25.76	$\bar{x}$: 8.17
(16 samples)	s: 9.93	s: 5.14	s: 5.70	s: 6.19	s: 5.76
Poorly sorted sand	$\bar{x}$:59.63	$\bar{x}$:17.44	$\bar{x}$: 9.00	$\bar{x}$:13.31	
(16 samples)	s:18.58	s: 9.24	s: 5.59	s: 7.98	Trace

The mud and the cover sand show essentially the same mineralogy as the till, with a similar ratio of Tertiary/Mesozoic to Norwegian-derived minerals (Table 1, Figs. 4, 9, 10 and 11). Derivation from the underlying till seems likely, as sediment augmentation from outside would probably have altered this ratio.

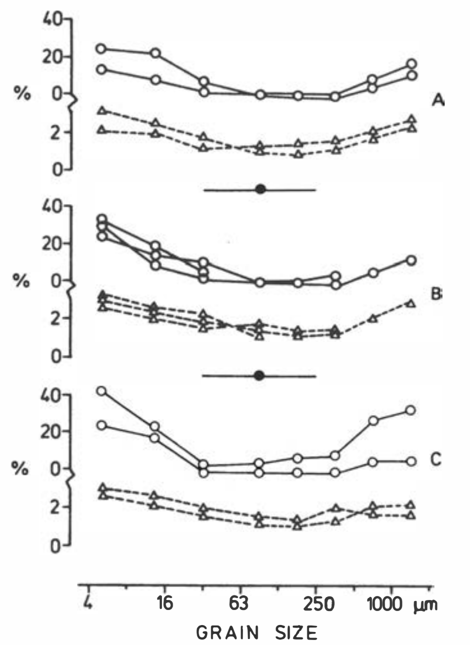


Fig. 11. Plot of the X-ray intensity percentage for mica and weight % for K_2O in the silt and sand fractions for the different facies.
(A: Poorly sorted sand, B: Unconsolidated mud. C: Pebbly mud (till?)).

Conclusion

The Quaternary sediments in the northwestern part of the North Sea consist of:

Till of probably Weichselian age. Its cold foraminifera fauna suggests incorporation of glaciomarine sediments.

Late Glacial unconsolidated mud characterized by an upward and landward coarsening.

Post Glacial poorly sorted sand, high content of Boreal foraminifera.

The cover sand probably indicates active erosion by the present Norwegian Coastal Current down to 300–350 metres water depth, and the increased energy in the water masses from Late to Post Glacial time is related to development of the present current pattern as the oceanic polar front moved into the Arctic Ocean and the deglaciation was completed early in Holocene time.

Based on sediment petrography investigations it has been possible to distinguish between two main provenances: Tertiary and Mesozoic rocks; and the Norwegian mainland.

The Tertiary and Mesozoic contribution is characterised by low metamorphic fine-grained clastic rocks and chalk and limestones, in addition to kaolinite and mixed-layer minerals of dioctahedral illite and smectite, confined to the $< 2\ \mu m$ fraction.

High metamorphic rocks and minerals of the Nordfjord province of west Norway, including quartzite and characteristic perthitic/antiperthitic feldspar, can be recognised in the offshore Quaternary sediments. Also immature clay minerals such as trioctahedral illite and vermiculite are derived from these sources.

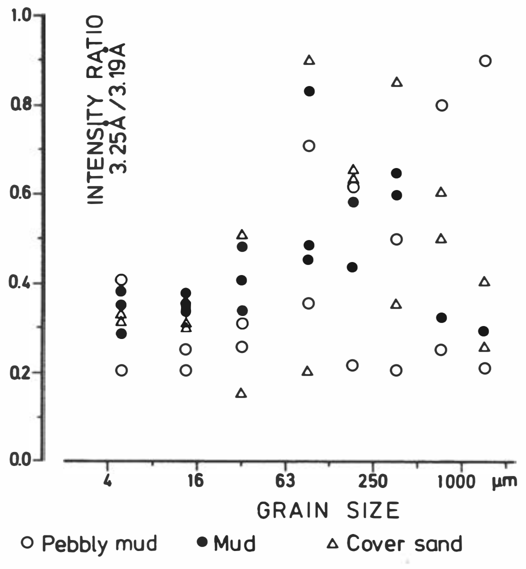


Fig. 12. Plot of the intensity ratio of potashfeldspar and plagioclase in the silt and sand fractions for the different facies.

The fact that the Late Glacial mud and the Post Glacial sand overlying the Pleistocene till contain a high content of kaolinite and have a similar composition to the underlying till show that very little sediment has been supplied from the land in Late and Post Glacial time. The sediments overlying the till are probably partly Late Glacial and partly reworked till material.

The till is relatively enriched in quartz in the fine-sand fraction, in the clay and fine-silt fractions calcite is enriched, while feldspars are more evenly distributed. This distribution of minerals reflects the grain-size distribution in the source rocks, which have mostly been disintegrated into single mineral grains during glacial transport.

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