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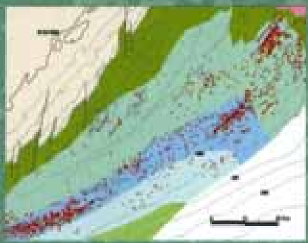
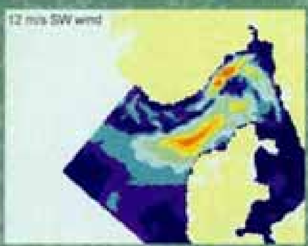
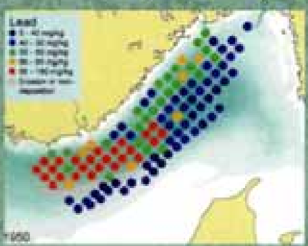
SPECIAL PUBLICATION 8

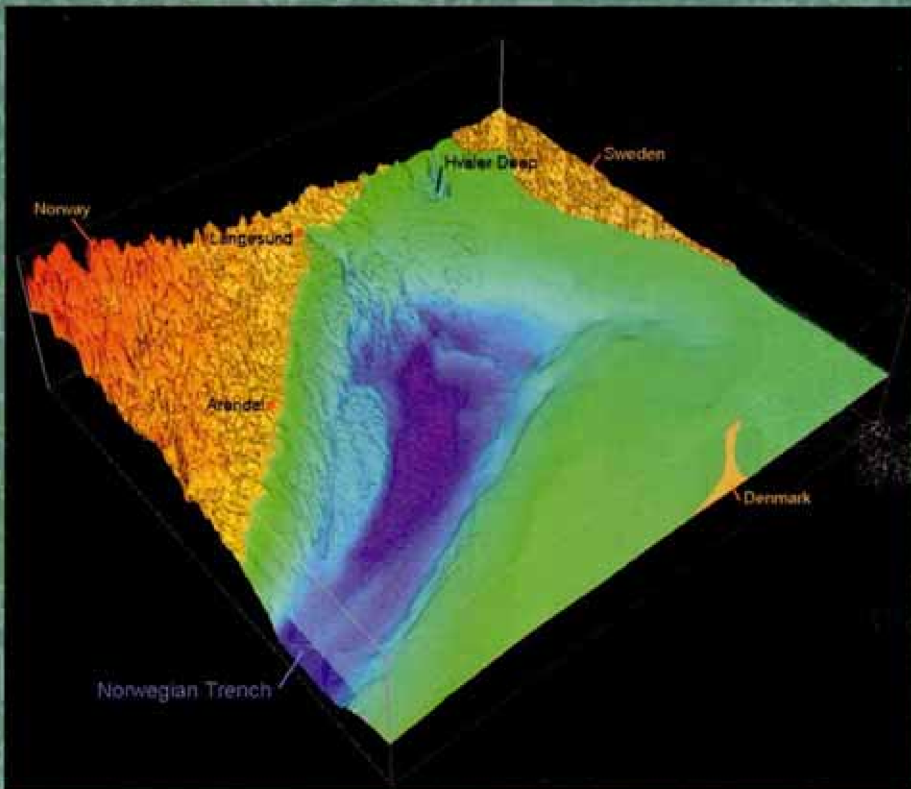
Skagerrak in the past and at the present

An integrated study of geology, chemistry, hydrography and microfossil ecology









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Main figure: 3D-model of the northern part of the Skagerrak and surrounding land areas. The model is based on multibeam bathymetry data from the Norwegian Hydrographic Service. The 3D-model was produced by Smedvig Technologies, using GeoSea software.

Upper figure, left column: Bedrock geology in the northern part of the Skagerrak. Red triangles show the distribution of pockmarks caused by gas seeping to the seabottom from the underlying sedimentary rocks and sediments.

Second figure, left column: Reconstruction of the ice flow and palaeogeography 18 000 years before present.

Third figure, left column: Ocean current velocity after a few days of gales from the southwest. The colour-coding reflects high (red and yellow) and low (blue) current velocities. Based on model data from the Institute of Marine Research, collected during the SKAGEX Project.

Fourth figure, left column: Time-slice map, showing the lead concentrations in sediments deposited in c. 1950. The time-slice is based on short cores, where the ages of sediments at various depths in the cores have been calculated using measured and interpolated sedimentation rates.

Fifth figure, left column: One of the microfossils (benthic foraminifera) which are common in the Skagerrak.

Skagerrak in the past and at the present - an integrated study of geology, chemistry, hydrography and microfossil ecology

**NORGES GEOLOGISKE UNDERSØKELSE
SPECIAL PUBLICATION NO. 8**

Skagerrak in the past and at the present - an integrated study of geology, chemistry, hydrography and microfossil ecology

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Preface

The Skagerrak Project is the first major task of the MGK-programme (MGK is the Norwegian acronym for Marine geological mapping of Norwegian sea-floor areas), which is a joint effort of six governmental institutions involved in various aspects of marine work. The primary aims of the MGK-programme are to:

- produce and supply marine geological information from the upper part of the sea-floor in Norwegian sea areas for the use of public services, industry, planning and science.
- give premises for national involvement in international co-operation with regard to issues relevant to the environment and resources.

The MGK-activities are governed by a steering committee, with representatives from the Norwegian Petroleum Directorate (OD), the Norwegian Polar Institute, the Norwegian Hydrographic Service, the Norwegian Pollution Control Authority, the Institute of Marine Research and the Geological Survey of Norway (NGU). OD has the chairman of the committee, while NGU has the responsibility for the co-ordination of the MGK-tasks, as decided by the MGK-committee. Future projects will focus on other areas of special interest to the society, such as the North Sea, the continental margin of Norway and the Barents Sea.

The basic idea is to utilise the scientific and methodological competence of several national institutions, in order to achieve the primary aims. We have focused on a multi-disciplinary approach, integrating geological, chemical, hydrographic and micropalaeontological data. In this way, we can provide an understanding of both large-scale, long-term (millions of years) and short-term (decades) processes relevant for the utilisation and environmental management of the Skagerrak.

The Skagerrak Project has demonstrated how governmental institutions can cooperate successfully with a considerable synergetic effect, achieving results beneficial to society in a cost-effective manner.

Co-operation on a scientific and partly also logistic level with national and international scientific institutions (primarily the University of Bergen, and the Universities of Oslo and Gothenburg, and the Laboratories in Risö) has been crucial for the project. The huge database collected during the project has formed the basis for two doctoral theses and a number of scientific publications in national and international journals. Large parts of the database are available in digital format for future public research. A number of scientific publications are in preparation or planned by the involved institutions.

This report gives state-of-the-art knowledge of the sea-bed environment at the present and in the past 200 years for use by broad public. It should provide basic knowledge needed in planning further utilisation (fisheries, underwater engineering, hydrocarbon exploration etc.), in management by governmental bodies such as the Ministries of Environment, Industry, and Oil and Energy, and in science. The huge database of bathymetric, chemical and geological data cannot be fully documented in a report like this. However, it is our hope that those interested in a general overview may find the report fulfilling and interesting, while specialists looking for more detailed data may use the report as a guide to the huge data material on which the report is based. Finally, we hope that the report will be used as an aid when future scientific and applied projects in the Skagerrak are designed.

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Institute of Marine Research (organic chemistry, oceanography, cruise time, scientific board)
Norwegian Hydrographic Service (detailed bathymetry, cruise time)
University of Bergen (trace metal chemistry, sedimentology, cruise time, scientific board)
Norwegian Pollution Control Authority (environmental data, scientific board)
Norwegian Petroleum Directorate (reference data, scientific board)
Norwegian Polar Institute (scientific board)

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University of Bergen
Norwegian Pollution Control Authority

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1 Executive summary

The growing concern for the environment, and for sustainable development of marine environments in particular, has put focus on the Skagerrak. The Skagerrak is an important part of the North Sea ecosystem, with a high biological production. It is an important breeding and living area for some of the fish stocks populating the North Sea. Annual landings of fish caught in the Skagerrak amount to approximately 300 000 tons. Severe contamination in the Skagerrak may have a major impact on the Skagerrak ecosystem. The Skagerrak is the main shipping route for traffic to and from the Scandinavian and Baltic countries. The potential for hydrocarbon resources in the Skagerrak has attracted the attention of the oil industry, and the future may see hydrocarbon prospecting.

Geological processes, acting on a timescale from millions of years to years or even less, have an important bearing on these issues. Deep crustal processes which occurred several hundred million years ago and also later, have influenced the sedimentary environment and thus the potential for formation of oil and gas source rocks (Chapter 2). Large parts of the Skagerrak are covered by sedimentary rocks, generally of the same type as found in the hydrocarbon provinces in the North Sea. Seepages of shallow gas to the sea bottom from these sedimentary rocks are important, both in terms of hydrocarbon prospecting, and in terms of potential hazards to offshore drilling (blow-outs). Uplift of southern Norway of the order of 2000 m during several phases in the last 50-60 million years, but particularly during the last 2 millions years in the Skagerrak (c. 1000 m) is the main factor influencing the present distribution of sedimentary rocks. This uplift has affected the possibility for preservation of potentially economic hydrocarbon resources.

A serious change towards a colder climate occurred c. 2.5 million years ago (Chapter 3), and initiated several ice ages affecting Northwest Europe. This led to the growth of glaciers in the high Norwegian mountains, formed partly as a result of the uplift during the last 50-60 million years. At their maximum, these glaciers covered the North Sea and extended to the British Isles. The glaciers flowed from the Scandinavian mountains, and probably started to excavate the Skagerrak and the Norwegian Trench. The excavation was at least partly controlled by large-scale bedrock structures. Repeated glaciations continued the excavation process, reaching a climax c. 18 000 years ago, during the peak of the last ice age to affect Norway. During this final phase of glacial moulding, bedrock and previously deposited sediments were removed down to depths in excess of 700 m, relative to the present sea-level, leaving the Skagerrak, at present the deepest part of the North Sea. Retreat of the glaciers onto the Norwegian mainland c. 15 000 years ago, combined with a considerably lower sea-level (c. 100 m), created a landscape in which most of the present North Sea were tidal flats or dry land dissected by large rivers derived from the melting glaciers of Northwest Europe. The Skagerrak and parts of the Norwegian Trench were a fjord at this time, with floating icebergs, perhaps rather similar to the situation in e.g. the Greenland fjords today. Rising sea-levels eventually caused flooding of the North Sea, and the present ocean circulation and sediment deposition pattern were established 7 000-4 000 years ago.

Since then, the Skagerrak and the Norwegian Trench have been the major deposition areas for fine-grained material entering the North Sea (Chapter 4). The bulk of the particles deposited in the Skagerrak derives from the Atlantic Ocean and the North Sea, with minor contributions from the Scandinavian mainland and the Baltic Sea. The sediment dynamics in the Skagerrak, i.e. processes of sediment deposition and sea-bed erosion, are largely controlled by water depth, the shape of the basin and the oceanic circulation. Modelling of current velocities and directions in response to varying wind situations has demonstrated the significance of climatic conditions. Increased sediment transport from the North Sea is a possible consequence of stronger winds during the last decades. Complex interactions between sedimentation and erosion are indicated in certain areas, probably related to short-term shifting climatic conditions influencing the oceanic circulation. This is important for environmental monitoring (see below), because sea-bed sediment samples from the erosional areas may yield sediments deposited 10 000 years ago, and tell nothing about the present environmental situation. Potential hazards to seabed installations such as erosion, large-scale instability, deep erosional scours (up to 45 m deep) and gas-laden sediments and sedimentary rocks have been demonstrated, and should be considered in future planning of e.g. sub-sea cables.

The large-scale transport of fine-grained particles, including organic matter, from the North Sea (and the Atlantic Ocean) has an important bearing on the environmental analysis of the Skagerrak (Chapter 5). Many contaminants, both organic compounds like polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), and trace metals like lead or mercury, are extensively attached to fine particles. The fate of the contaminants is therefore largely controlled by the sediment transport and deposition processes. Once deposited, these contaminants are, to a large degree, removed from the Skagerrak ecosystem, because the majority of the contaminants remain in the sediments. Integration of geological and chemical data demonstrates significant temporal and spatial trends in the contaminant load to the Skagerrak. Estimates of contaminant fluxes indicate that a substantial part of e.g. lead deposited in the Skagerrak is derived from man-made inputs to the North Sea, while for elements like copper and zinc, the anthropogenic contribution is insignificant in comparison to the amounts derived from natural sources (e.g. erosion of bedrock).

Assessment of the contamination situation demonstrates clearly elevated levels for the polycyclic aromatic hydrocarbons (PAHs), and the trace metals lead and mercury. While lead and the PAHs are probably derived to a large extent from the North Sea, the dominant mercury input appears to be from the Scandinavian coasts. A certain input from the offshore industry is indicated by elevated levels of barium, deriving from drilling muds. Even though the discharges for some contaminants such as trace metals have been reduced in the last decades, it is considered likely that the sediments in the deepest parts of the Skagerrak will probably still receive high, or even increasing contaminant loads in the next decades. Changes in the micro-fauna (foraminiferas) in the bottom-sediments of this area suggest that the input of organic matter (dominantly from the North Sea) has increased during the last decades (Chapter 6), which may be a consequence of the euthrophication of the North Sea. Consequently, this area should be given special attention in future environmental monitoring. Other parts of the Skagerrak, however, indicate a decreased contaminant load during the last few decades, shown by decreasing contaminant content in the seabed sediments. This environmental improvement is probably mainly the result of reduced contaminant discharges to the Skagerrak and the North Sea in this period.

In general, the Skagerrak acts as a final sink for large parts of the anthropogenic contaminants released to the marine environment of the North Sea; popularly it can be said that the Skagerrak and the Norwegian Trench are the «dustbin» of the North Sea. The regional understanding of the sediment dynamics and contaminant distribution in the Skagerrak provides a sound basis for future environmental monitoring, and the sediment dynamics are important in future planning of sea-bed installations. The presence of gas probably derived from sedimentary rocks, seeping to the sea bottom, should be of both interest and concern for hydrocarbon-related activities. The geochemical mapping of the sea-bed sediments constitute a large part of the baseline studies needed, in the event of future hydrocarbon prospecting in the Skagerrak.

2 Bedrock in the Skagerrak - from 540 to 65 million years ago

The Skagerrak is the deepest part of the North Sea, and the result of a long geological history. Shaping of the Skagerrak basin has occurred during repeated glaciations over the last million years, but cycles of deep crustal processes, faulting, uplift, erosion and deposition have occurred since Cambrian times, c. 540 million years ago, and have defined the geological framework for the basin. The oldest rocks in the Skagerrak are Precambrian gneisses (Sigmond 1992), which occur in the coastal areas (Fig. 2.1) and beneath the sedimentary rocks in the deeper parts of the Skagerrak. The Precambrian rocks are originally sedimentary and crystalline rocks which have been altered to gneisses (metamorphism) at deep levels of the earth's crust (several tens of kilometres). By the beginning of the Palaeozoic era (Fig. 2.2), these rocks had been uplifted and eroded down to an even surface.

The Skagerrak and Hardangervidda - once covered by the same sea

Sediments were deposited on these old gneisses from Cambrian time (on an almost horizontal surface commonly termed the sub-Cambrian peneplain), and the Lower Palaeozoic rocks are made up of conglomerates, shales, sandstones and limestones. Locally, for instance in the Skien-Oslo area, these rocks are rich in fossils such as trilobites. Similar rocks are found on Hardangervidda and in Sweden, showing that Scandinavia at that time was covered by a shallow sea. The sub-Cambrian peneplain is presently found at widely different elevations; from 1300 m above sea-level on Hardangervidda, to >300 m below sea-level in the coastal areas of the Skagerrak, and considerably deeper in the central parts. This demonstrates that the originally almost horizontal Cambrian sea bottom has today a large-scale «wavy» form, which is the result of disturbances caused by crustal processes such as faulting, folding and tilting (see also below). The Palaeozoic rocks in the Skagerrak (Fig. 2.1) occur as a continuation of the Cambro-Silurian rocks (Fig. 2.2) found in the Oslo region, where subsidence of the crust caused thick accumulations of sediment. Towards the end of Silurian times, these rocks were slightly deformed and faulted, uplifted and partly eroded during the Caledonian Orogeny, an event during which European and American continents (Baltica and Laurentia, respectively) collided and mountain chains were built in Norway.

In Late Palaeozoic times, the crust beneath the Skagerrak and the Oslo region was stretched (rifted), and large masses of melted rocks intruded into the sedimentary rocks. In the Oslo region, both sedimentary and volcanic rocks were formed, and some faulting in the Skagerrak was associated with this rifting phase (Fanavoll & Lippard 1994). In the Skagerrak, sedimentary and probably volcanic rocks were deposited along the fault margin of the developing Skagerrak Graben (Ro et al. 1990).

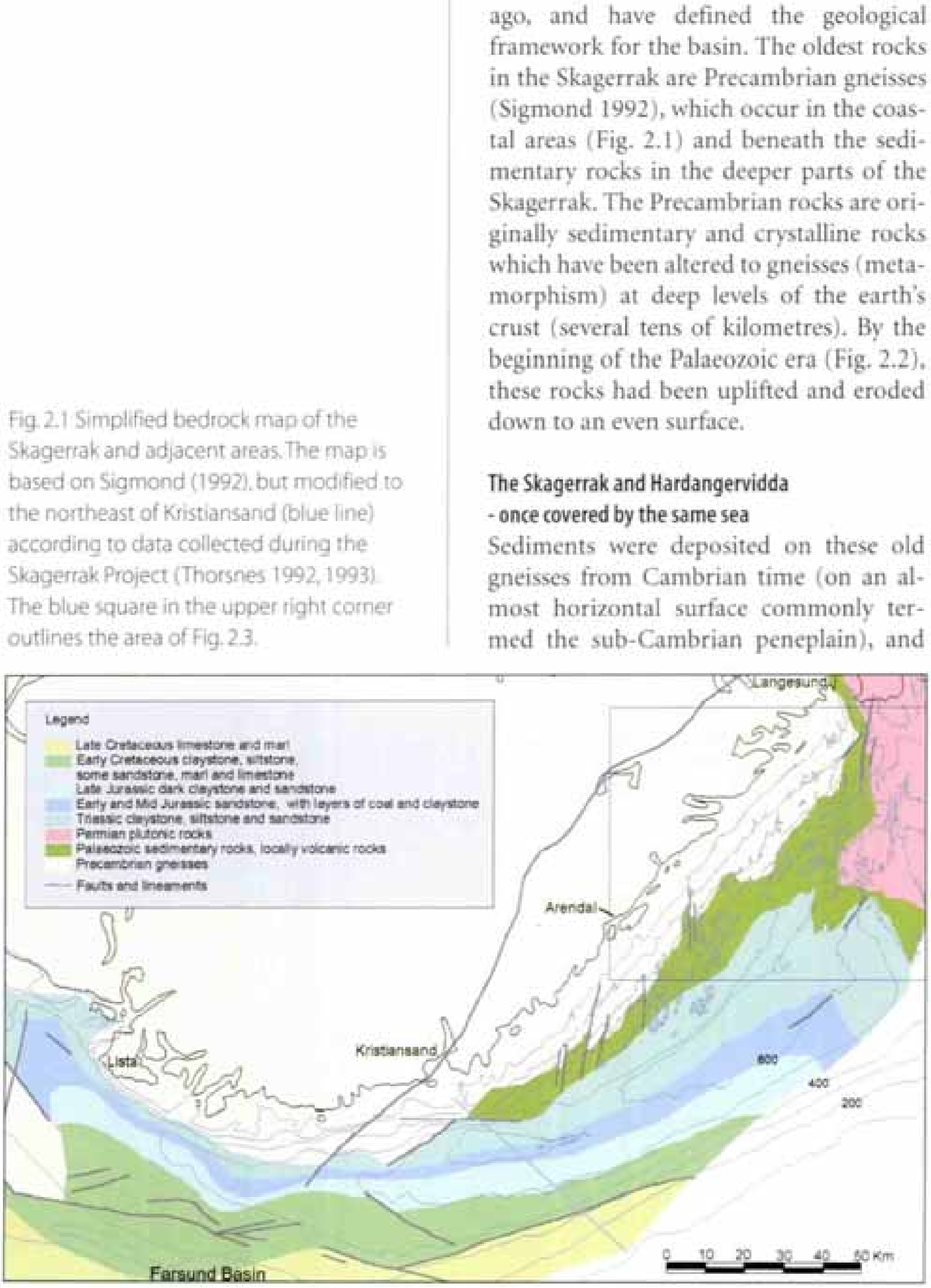

Fig. 2.1 Simplified bedrock map of the Skagerrak and adjacent areas. The map is based on Sigmond (1992), but modified to the northeast of Kristiansand (blue line) according to data collected during the Skagerrak Project (Thorsnes 1992, 1993). The blue square in the upper right corner outlines the area of Fig. 2.3.

Uplift and subsidence

A major geological boundary, seen in the seismic records as a truncation of inclined Palaeozoic layers overlain by nearly flat-lying, younger sedimentary rocks (see geoseismic sections in Fig. 3.11, Chapter 3), demonstrates that the Palaeozoic rocks were subjected to uplift and erosion during a considerable time period. Subsequently, the area was submerged and sediments of Triassic age were deposited. The Mesozoic (i.e. Triassic, Jurassic and Cretaceous - Fig. 2.2) sedimentary rocks are claystones, siltstones and sandstones, reflecting changing relative sea-levels and variable depositional environments. Since early Mesozoic times, only minor faulting has taken place in the Skagerrak. The boundary between Precambrian and Palaeozoic/Mesozoic rocks is sub-parallel to the coast. One exception is found southwest of Lista where Precambrian rocks extend southwards into the Norwegian Trench (Fig. 2.1). The Precambrian rocks crop out as sea-mounts, called the Hidra Mountains by local fishermen, at the bottom of the Norwegian Trench. The alignment between the coastline and the Palaeozoic/Mesozoic boundary is basically due to large-scale uplift of southern Norway relative to the offshore areas (Riis 1996). The uplift of southern Norway appears to have started in the Late Cretaceous, with particularly strong uplift during the last two million years of the Quaternary (in excess of 1000 m) also affecting the Skagerrak. This uplift was followed by severe erosion, and 500-1000 m of sedimentary rocks covering the Skagerrak and adjacent land areas have been eroded (Riis 1996). Due to deep burial of the sedimentary rocks prior to the uplift, the Jurassic sedimentary rocks may have been buried sufficiently deep to generate oil from organic matter, and the Farsund Basin (Fig. 2.1) could become a future hydrocarbon province in the North Sea (Jensen & Michelsen 1992).

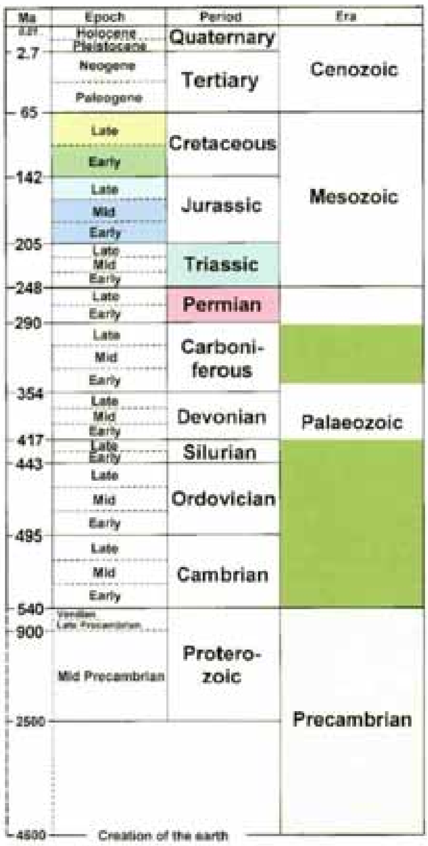

Fig. 2.2 Simplified stratigraphic column, with the major time divisions. The coloured fields correspond to rock units present in the Skagerrak and adjacent areas in Fig. 2.1. Ma - million years. Modified from Gradstein & Ogg 1996.

Submarine landscapes - related to different rock types

The shape of the Skagerrak basin is strongly influenced by the different rock types, ranging from hard (and resistant) Precambrian gneisses to soft Mesozoic sedimentary rocks. During repeated glaciations in the Quaternary, the Mesozoic rocks were easily eroded, while the tougher Precambrian gneisses resisted the glacial erosion better. Variable resistance to

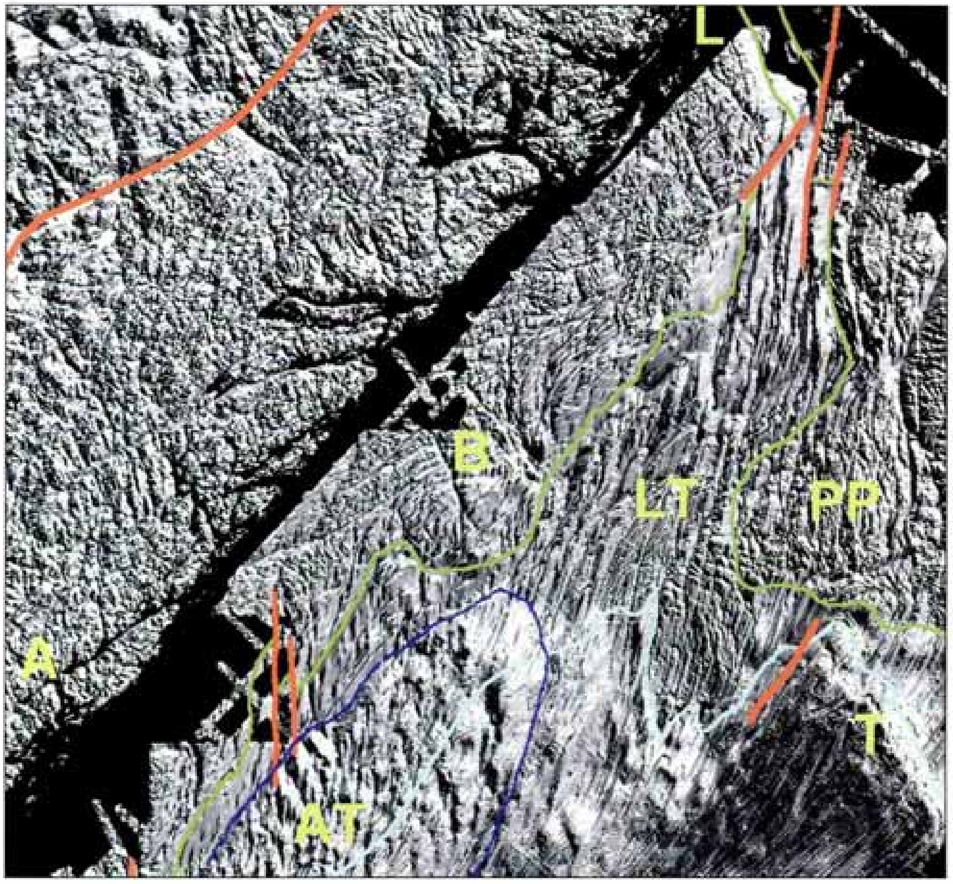

Fig. 2.3 Shaded relief image of the northern part of the Skagerrak, produced by generation of a 3D terrain model from offshore water depth and onshore height data, subsequently artificially illuminated by a «sun» shining from the northeast. A: Arendal; AT: Arendal terrace, an area of more than 200 m thick Quaternary deposits masking the bedrock features, outlined by dark blue line; B: end of lineament extending northeastwards from Arendal; L: Langesund area, LT: Langesund trough with Lower Palaeozoic rocks; PP: Permian plutonic rocks; T: Triassic rocks, escarpment. Red lines show major faults and lineaments. Solid green lines outline the base of Palaeozoic sedimentary (and possibly volcanic) rocks, while the blue lines outline the base of Mesozoic rocks. The fault onshore is a segment of a major fault zone running from Kristiansand to Porsgrunn (for location, refer to Fig. 2.1).

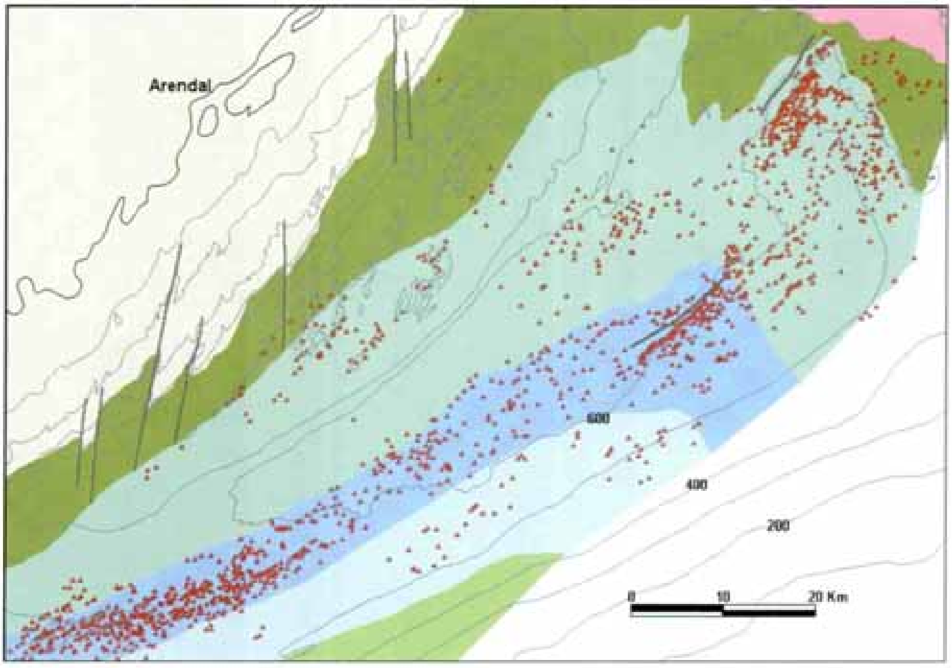

Fig. 2.4 Distribution of pockmarks (red triangles) in the inner parts of the Skagerrak. Many of the pockmarks occur above an Early to Mid Jurassic sandstone interval. For legend, see Fig. 2.1.

glacial erosion, together with other features (gneisses, for example, are commonly rather massive, while sedimentary rocks are layered) has caused the different, characteristic surface morphologies (landscape forms) on the sea bottom, just as on land. Image processing of detailed bathymetric data from the Skagerrak and height data from the land (Fig. 2.3) reveal a number of features. Precambrian gneisses with a characteristic rugged appearance occur on land, and in the shallow coastal areas between Arendal and Langesund (Fig. 2.3). Lower Palaeozoic rocks crop out in a belt from Langesund through the Langesund trough (Fig. 2.3) and into the Skagerrak. Long ridges partly reflecting layering, partly reflecting faults and fracture zones, are evident in the northern part of the Langesund trough. A characteristic escarpment is related to the lower boundary of Triassic rocks (Fig. 2.3). In the northeastern part of the image (Fig. 2.3), it is thought that dominantly Permian plutonic rocks crop out, though both Precambrian gneisses and Palaeozoic rocks may be present. Some of the major faults and fracture zones (lineaments) are shown, but several others can be seen as narrow, elongated, shaded zones. A link between faults onshore and offshore is illustrated by the lineament extending northeastwards from Arendal (A-B, Fig. 2.3). The bedrock morphology is most clearly seen where the Quaternary sediments overlying the bedrock are thin or absent, which is the case for most of the area in Fig. 2.3. Thick Quaternary deposits occur in the Arendal terrace (Fig. 2.3), and the sea-bed morphology here reflects glacial processes, and not bedrock features.

Another example of how bedrock structures have influenced the shaping of the Skagerrak is seen in the southeastern slope of the Norwegian Trench. A prominent seismic reflector representing the base of the Late Cretaceous rocks (Fig. 2.1) probably represents a layer with high resistance to glacial erosion. This layer comes quite close to the seabed in the uppermost part of the slope, and largely coincides with the southeastern termination of the Norwegian Trench.

Gas seepage and pockmarks

Pockmarks form prominent features on the sea bottom in the Skagerrak. These are depressions which may be circular or elongated, varying in diameter from fifty to several hundred metres, and with depths up to 16 m. Such depressions are commonly interpreted to be due to seepage of gas through the sediments at the sea bottom. This gas may be of biogenic origin, i.e. produced by bacterial breakdown of organic matter in the sediments, or it may be related to seepage of gas from the underlying bedrock. The origin of the pockmarks in the Skagerrak is not yet fully understood, but some clues are given by the distribution pattern (Fig. 2.4). More than 90% of all pockmarks occur in sediments above Mesozoic sedimentary rocks, and appear to be due to gas seepage from specific horizons in these rocks, particularly Early to Mid Jurassic sandstones. This is important for future oil and gas prospecting, and is also valuable information in connection with underwater engineering.

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3 The birth of the Skagerrak and the Norwegian Trench - the Quaternary period - 2.7 million years of ice ages

Fig. 3.1 Icebergs break off glaciers at the sea's edge and may drift for long distances under the influence of wind and currents. Rock fragments incorporated in the ice drop to the sea bottom as the ice melts. The photo shows drifting icebergs off Greenland. Photo: Oddvar Longva.

At the beginning of the Quaternary Period, 2.7 million years ago, the Skagerrak area was covered by sedimentary rocks forming a continuous blanket from the North Sea, across Denmark and onto the Norwegian mainland. Uplift of the Norwegian mainland and the surrounding offshore areas had started in the Late Tertiary Period and continued into the Quaternary (see Fig. 2.2). This may have caused soft sedimentary rocks of Mesozoic and Tertiary age to be lifted above the sealevel, as seen in Denmark today, and such sedimentary rocks probably covered the coastal areas of Norway. Thus, at this time the Skagerrak was a shallow basin with water depths possibly up to 100-200m, much like the present North Sea. The Norwegian Trench, as we know it today, did not exist.

3.1 The ice ages in Scandinavia during the last 2.7 million years - when and why?

From 2.7 million years before the present, drifting icebergs (Fig. 3.1) were periodically common in the Norwegian Sea, off Mid-Norway (Mangerud et al. 1996). The icebergs dropped sand and gravel which are now found in the sediments from that time period and indicate that large glaciers were established on the continents bordering the Norwegian Sea. The presence of glaciers introduces the last era of ice ages, the Quaternary Period (Fig. 3.2). Similar glacial Periods occurred on Earth 700 million and 270 million years ago.

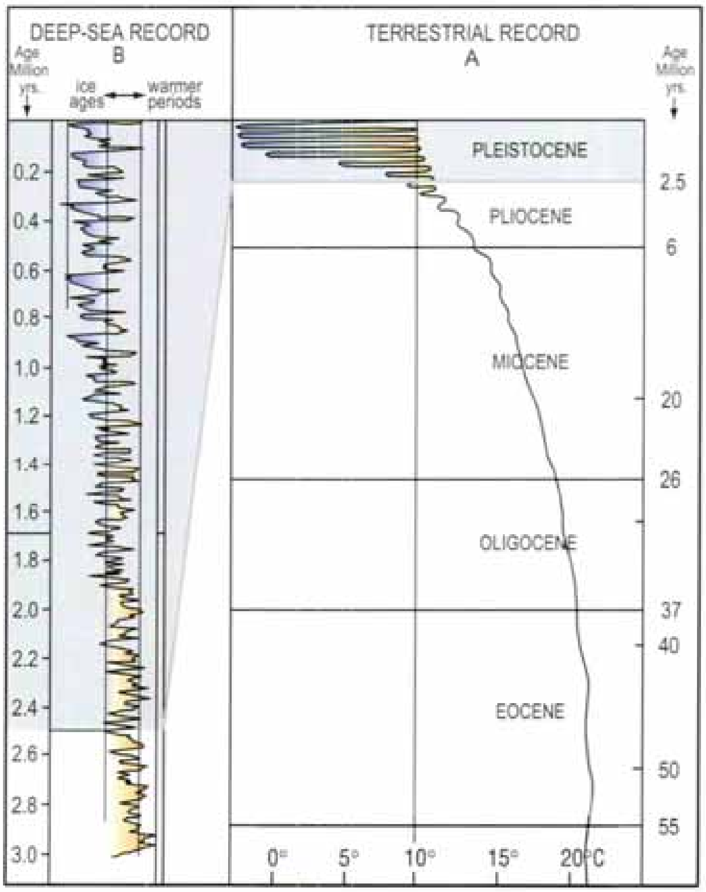


Fig. 3.2 Climate fluctuations over the last 50 million years, from the Tertiary to the Quaternary (Modified from Andersen and Borns 1994).
Column A: Mean annual temperatures in central Europe;
Column B: Fluctuations of the deep sea oxygen-isotopes through the last 3 million years.
$\delta^{18}O$ fluctuations correspond both with global ice-volumes and global climate fluctuations.
Blue: Glacial periods with large ice-volumes;
Red: Warm periods;
Yellow: The Pleistocene or Quaternary.

Fluctuations in the climate

The change from a tropical to a colder climate started in the middle of the Tertiary Period (Oligocene) approximately 30 million years ago. Possibly as a result of this climate shift, the great ice shield covering the Antarctic continent had already formed at this time. The Quaternary Period was characterised by dramatic changes of the climate. At high latitudes such as Norway, this resulted in several cold or glacial periods (ice ages), interrupted by periods of warmer climate and melting of the great ice sheets (interglacials), which characterise our present climate. Within the glacial periods, the climate might improve temporarily (interstadials) and parts of Norway would then be ice free.

The climatic fluctuations from glacials to interglacials have occurred at fairly regular intervals. The fluctuations are considered to be due to variation in the eccentricity of the earth's orbit (which follows 100 000-year cycles), the variation of the tilt of the earth's axis (40 000-year cycles) and precession of the earth (21 000-year cycles). The changes in the earth's orientation relative to the sun lead to small shifts in the intensity of solar radiation at high latitudes. These shifts are considered to be large enough to trigger these sorts of climatic variations.

During glaciations, the zone where cold polar water meets warmer subpolar water, known as the polar front, was forced southwards. The Gulf Stream turned southwards approximately outside Portugal and the oceans to the north became covered by winter pack ice. Over Great Britain and Scandinavia more snow fell during winter than that which melted during the summer and ice caps formed. The location of glacier growth depends upon where the majority of snow falls. Snowfall, in turn, depends on the tracks of atmospheric low pressure systems that may alter course during an ice age.

During the growth of large ice caps, more and more of the world's water resources freeze in glaciers, and global sea-level decreases. When the glaciers reached their maximum size, about 20 000 to 18 000 years B.P. (before the present), the level of the oceans was 100-150 m lower than today. The «British Isles» did not exist, but had a land connection to the Continent, and the Mediterranean Sea was much less extensive.

Glaciers flowing into the North Sea

Atmospheric temperatures since the start of the Quaternary Period have been relatively cold; thus, amplitudes in climate change increased in Europe one million years ago and gave rise to larger glaciations and warmer interglacials (Fig. 3.3). One million year old tills are found in the Norwegian Trench, west of Bergen, and demonstrate that glaciations were rather extensive at this time.

Large boulders of rock types confidently identified as deriving from localities in Scandinavia, have been found in tills and meltwater (glaciofluvial) deposits in England, Holland, Germany and Poland. These glacial deposits show that large ice sheets originating on the Scandinavian mainland had advanced onto the surrounding shelf and land areas (Fig. 3.4), and at least one of these early glaciers reached the European continent. The two most severe glaciations, the Elster and Saale ice ages, occurred between 300 000 and 130 000 years B.P. (Fig. 3.3). During these ice ages, the ice sheets covering Scandinavia and the British isles grew large enough to flow together, and at least at one occasion, Norwegian ice reached England (Fig. 3.5). The Elster ice age was followed by the Holstein interglacial and Saale by the Eem interglacial (Fig. 3.3). These interglacials represent periods with climates slightly warmer than today.

THE QUATERNARY

2,7 million years ago to the present

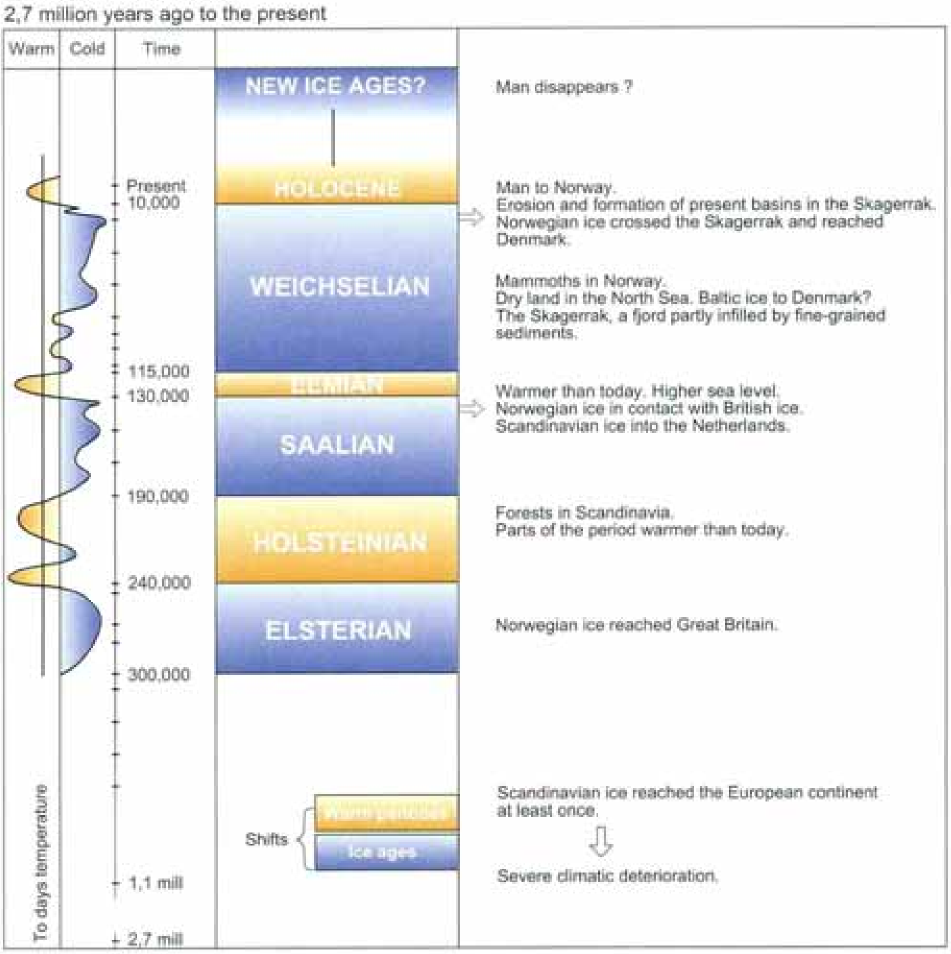


Fig. 3.3 Temperature variations during the last 300 000 years (see Fig. 3.2) and the subdivision in ice ages and warm periods. The age curve of ice ages and warm periods as shown in the figure is well documented. Debate exists, however whether or not the Holsteinian and Elsterian should be linked to periods older than those indicated here. The warm period that began 10 000 years B.P. our time, is called the Holocene. (Modified from Andersen and Borns 1994).

3.2 Weichsel - the last ice age

The last major ice age, the Weichselian period, lasted from c. 115 000 to 10 000 years B.P. (Fig. 3.3). Large areas of the northern hemisphere, including the Norwegian mainland, were covered by huge ice caps during most of the period from c. 70 000 to 10 000 years B.P., and large parts of the North Sea were above the sea-level. Even though the glaciers which formed during this period never grew as large as the glaciers during the Elster and Saale ice ages, they did for some time extend into

Fig. 3.4 Glaciers reaching into the sea at Svalbard. This was a common sight along the Norwegian coast during the ice ages. Photo: Arnt-Ivar Kverndal.

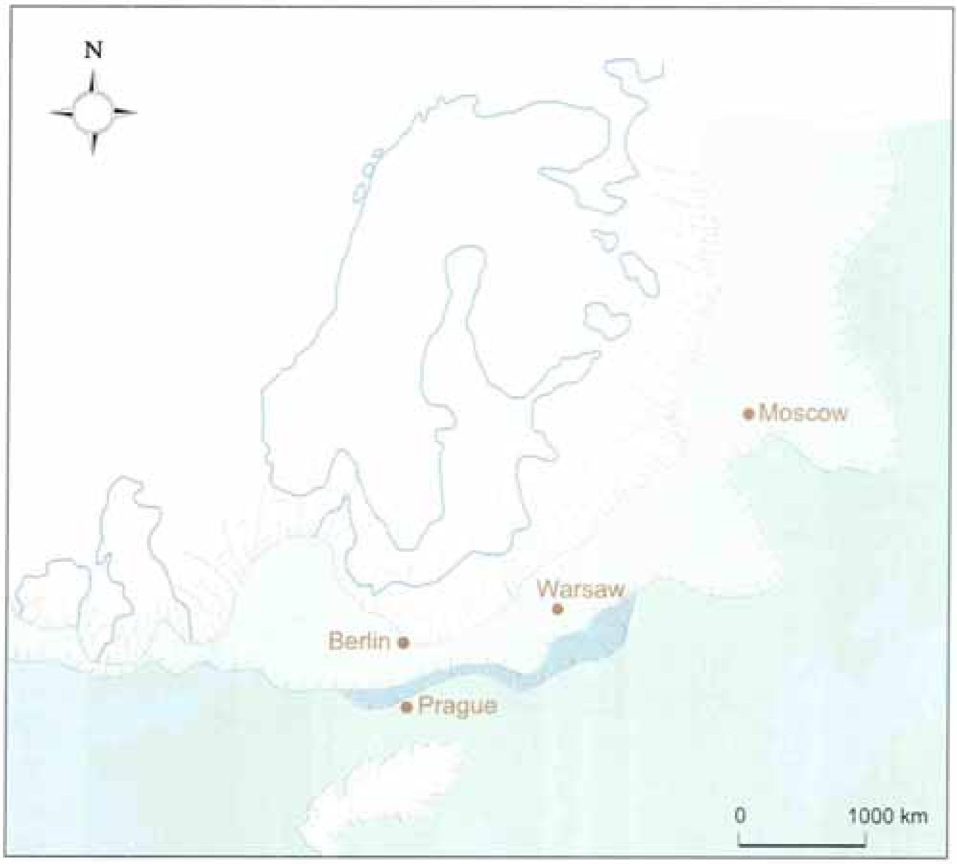


Fig. 3.5 The maximum extent of the European ice sheets during the Weichsel (white), Saale (light blue) and Elster (blue) ice ages. Modified from Andersen and Borns 1994.

Fig. 3.6 Mammoths like these lived in Norway 100 000 years ago.
Painting: Zdeněk Burian

the North Sea. The glaciers certainly had a large areal extent into the North Sea between 25 000 to 15 000 years B.P. and possibly also at 45 000, 65 000 and 90 000 years B.P. (Mangerud et al. 1996). During the three earliest of these ice advances the Skagerrak was probably either an open sea or was covered by an ice shelf which did not reach the bottom in the deepest part of the basin. Consequently, this period was probably characterised by more or less continuous sedimentation and no glacial erosion prior to c. 25 000 years B.P. at water depths exceeding a few 100 meters.

Mammoths in Norway

Climate fluctuations were standard even during ice ages like the Weichselian. The ice sheet which covered most of Scandinavia and perhaps the shelves melted away from parts of the Norwegian mainland during warmer periods (interstadials) at c. 100 000, 80 000, 55 000 and 35 000 years B.P. Mammoth skeletons from the one or two earliest of these interstadials have been found several places in southeastern Norway, and show that large areas of Norway were ice free (Fig. 3.6).

The later interstadials were colder. Bones of fish, birds and seals are found in a cave, Skjonghelleren, outside Ålesund on the west coast of Norway. These bones are dated to the interstadial 38 000 to 28 000 years B.P. and witness the existence of wildlife and hence, a climate, like that seen on Svalbard today (Larsen et al. 1987).

The last great ice advance

The interval between 28 000 and 18 000 years B.P. was the coldest during the entire last ice age (Fig. 3.3). This interval led to a new build up of the ice caps, which in northern Europe reached their maximum extent 25 000-18 000 years B.P. The ice cap covering Norway extended beyond the Skagerrak south- and westwards to Denmark and the northern North Sea during its maximum, and the Swedish and Baltic ice reached into Poland, Germany and Denmark (Figs. 3.5 and 3.7 A-C). The initial ice growth seems to have been fastest in the west (in the Norwegian mountains), but the ice «divide» - the highest parts of the glacier - slowly shifted to the east and into Sweden as the ice sheet grew. When the glacier first crossed the Skagerrak and the Norwegian Trench, the flow was directed straight towards the south into Denmark and southwest into the North Sea (Fig. 3.7 A). The Norwegian ice-sheet probably reached its maximum extent into the North Sea area as early as 25 000 years B.P. Debate still exists whether or not the Norwegian and the British ice were in contact. As the ice divide was shifted to the east, this resulted in a more westerly ice movement over the Skagerrak and Denmark (Fig. 3.7 B). The ice sheet continued to grow until c. 18 000 years B.P., when it reached its maximum extent towards the south and east. In the North Sea area, the sheet may have retreated somewhat. At this time, ice-flow from southeast Norway, Sweden and the Baltic Sea started to merge in the inner parts of the Skagerrak and to flow along the Norwegian Trench.

During this phase the glacier eroded deeply into bedrock and sediments. The ice followed the Norwegian Trench around southern Norway, northward along the west coast and calved into deeper waters at the mouth of the trench off Mid-Norway. Here it dumped its sediment load onto the continental slope. Along the outer margins of the glacier, on the North Sea plateau, local ice domes or stagnant ice probably existed (Fig. 3.7 C). More than

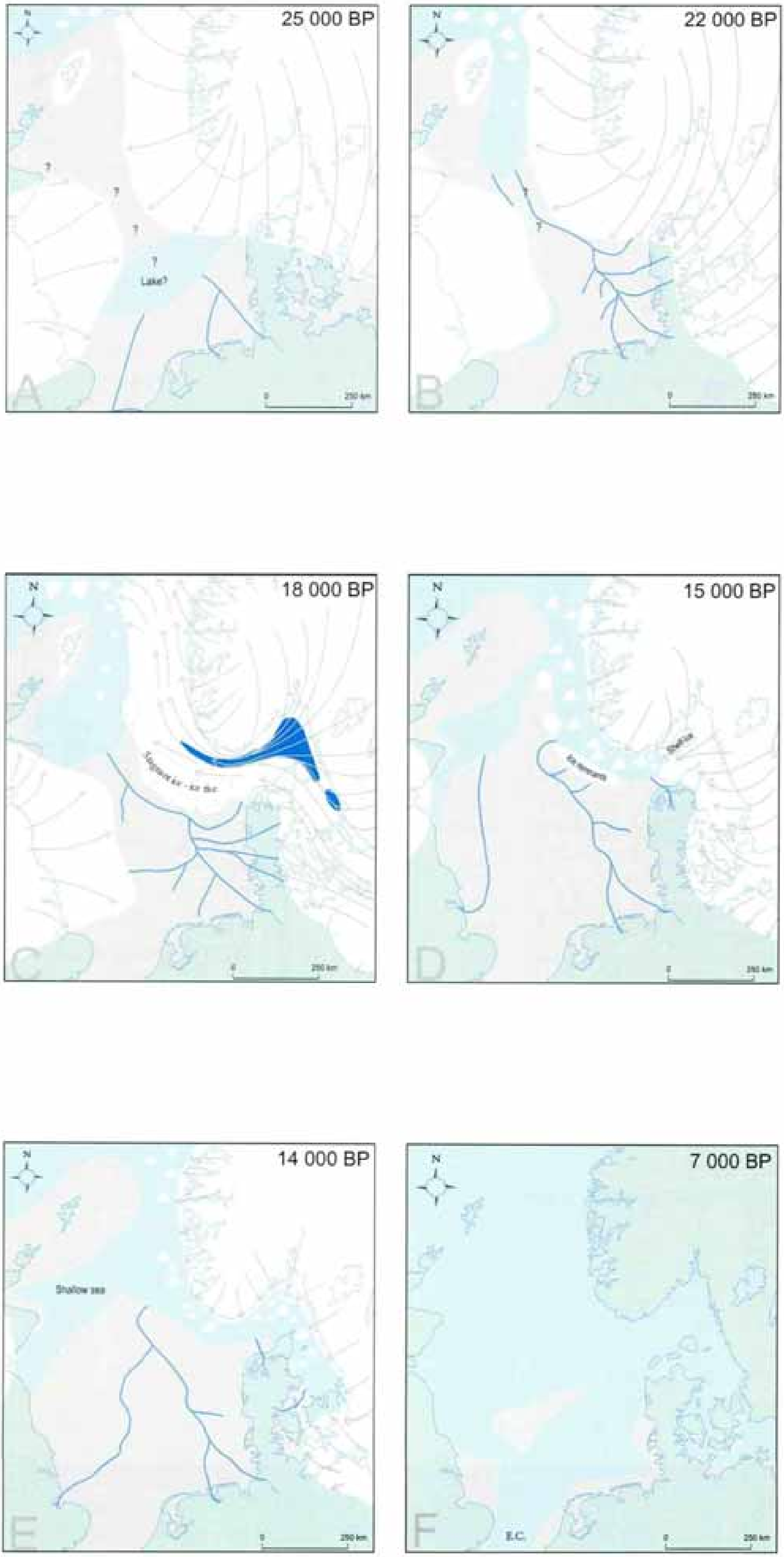


Fig. 3.7 The growth and decay of the Weichselian ice-sheet.

A: c. 25 000 years B.P. The initial growth of the Scandinavian ice cap was largest in the western Norwegian mountains, and the ice flowed westwards, crossing the Norwegian Trench, and southwards, crossing the Skagerrak. The maximum western extent was reached at this time. Debate still exists whether or not the Norwegian and the British ice were in contact. Ice-dammed lakes may have existed south of the ice-sheet.

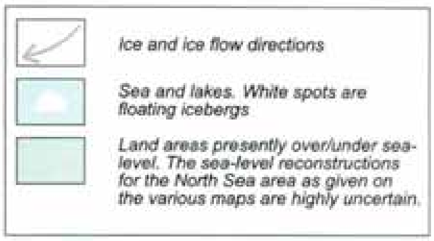
B: c. 22 000-18 000 years B.P. The maximum growth of the Scandinavian ice cap was shifted eastwards into Sweden. This resulted in more southwesterly ice flow in Skagerrak.

C: c. 18 000 years B.P. At the maximum extent of the ice cap, the ice-flow from Norway, Sweden and the Baltic Sea merged in the Skagerrak. The merging of the ice streams resulted in rapid ice flow and strong erosion. The present shape of the Skagerrak and the Norwegian Trench is a result of this erosion. The areas of maximum erosion are marked with blue.

D: c. 15 000 years B.P. The grounding line of the glacier is situated in the inner part of Skagerrak and actively calving shelf-ice floats over the deeper parts. The sea outside Norway is partly filled with icebergs from the calving ice front. Melt-water rivers, loaded with sediments from the ice-margin in Denmark and Germany flow into Skagerrak and the Norwegian Trench. Large quantities of sediments are deposited along the southern slope of the Skagerrak basin.

E: c. 14 000 years B.P. The shelf ice has broken up and the glacier is grounded in shallow water along the coasts of Norway and Sweden.

F: c. 7 000 years B.P. The inflow of melt-water from the glaciers to the sea led to a general sea-level rise. The flat plains which now form the sea-floor of the North Sea are almost flooded and the sea again flows through the English Channel (E.C.).



Shifting sea-levels (Box 3.1)
The stiff crust of the Earth rests on a softer interior. Glaciers are heavy and their growth leads to local depressions in the crust (isostatic depression). Over Scandinavia, the glaciers grew to be as much as 3 000 m thick. This depressed the crust 800-900 m, most at the centre of the ice sheet, less where it was thinner, and at a distance outside the ice margins it even bulged up slightly. At the same time, the sea-level of the world's oceans was 100-150 m lower than today because so much water was bound as ice in the glaciers.

When the glaciers started to melt, the oceans again rose from the input of melt-water (eustatic sea-level rise). From c. 13 000 years ago, when the climate warmed dramatically, the sea rose 15-20 m every thousand years. As the continental ice sheet melted, there was a reduction in the load of the ice on the Earth's crust and, consequently, the land surface elevation relative to sea-level started to rise slowly. The isostatic uplift was largest in central areas of the formerly glaciated region, and less along the margins where ice were not as thick. As a consequence of this isostatic uplift, Scandinavia is still rising: Bay of Bothnia still rises eight cm per 100 year, Oslo rises three cm per 100 year.

The reconstruction of former sea-level in the now-submarine parts of the North Sea area and Skagerrak is difficult due to the number of variables involved and the lack of complete datasets for some important factors. However, it seems clear that along the upper parts of the western slope of the Norwegian Trench, at present water depths of 130-160 meters, beach deposits did form 12 000-10 800 years B.P., when the sea-level was at least 120-130 meters lower than today. Despite the shortage of information, precise reconstructions of former sea-level stands can be made on land using relict shore features like terraces, beach ridges and marine sediments.

2000 m-thick sediment layers of glacial origin now lying outside the mouth of the Norwegian Trench indicate repeated deposition (King et al. 1996). From the amount of glacial deposits and the size of the glacially eroded Norwegian Trench, a phase with ice flow from Skagerrak to the continental slope, a «Skagerrak glacier», seems to be part of all major glaciations.

The ice sheets disappear

After c. 18 000 years B.P. the formation of new glacier-ice culminated. From this point onward, generally more ice melted during summers than was formed during winters. Between 17 000 and 15 000 years B.P. ice sheets all over the world had thinned by melting and calving and sea-level began to rise. Therefore ice on the shelves began to float and started to break up. When the disintegration had started, the ice front rapidly (within a few hundred years) retreated to the inner part of the Skagerrak. The Skagerrak and later on also the Kattegat received large amounts of fine-grained sediments from the melting glacier (Fig. 3.7 D). At c. 14 000 years B.P., the ice was grounded along the coasts of Norway and Sweden while large parts of Denmark were ice-free (Fig. 3.7 E) (Knudsen et al. 1996, Lagerlund & Houmark-Nielsen 1993, Lundquist 1994). The shrinking of the ice sheets continued except for a short, but very cold, period 11 000-10 000 years B.P. when the glaciers again advanced. This period is called the Younger Dryas. Along the margin of the ice at this stage, a prominent end moraine ridge formed. The ridge, called Raet in southeastern Norway, can be followed almost continuously from Finland through Sweden and along the Norwegian coast to Finnmark (Andersen et al. 1995). The last remains of the Scandinavian ice sheet disappeared around 8 500 years B.P. The sea-level continued to rise because of the melting glaciers and flooded parts of the North Sea which had previously been dry land. At around 10 000 years B.P., the warmer Atlantic water (the Gulf Stream) again reached the Norwegian coast and displaced the cold polar front to the north. This shift of the polar front measurably warmed the coastal climate within a few hundred years.

3.3 Holocene - the time of man

The rapid climatic change with the return of the Gulf Stream was the start of the present interglacial which is called the Holocene Epoch.

The sea-level changes

At the shift to the Holocene, 10 000 years B.P., the entire Skagerrak coast from Jæren to the Oslofjord was ice-free. The shoreline from that time has since been isostatically uplifted (see Box 3.1). Since Oslo lies closer to the centre of the former glacier than Jæren, this shoreline was elevated 220 m in Oslo, in contrast to only 10 m at Jæren. Most of the fine-grained sediments from the final disintegration of the ice sheet in central Norway were deposited in the coastal areas around the present Oslofjord. These sediments now largely lie exposed on land because of the post-depositional uplift. Throughout the Holocene, the fjords along the Norwegian and Swedish coasts have functioned as sediment traps for fine-grained sediments. Only when rivers are flooded do sediments of a certain volume now pass through to the open Skagerrak.

The North Sea plains were continuously flooded, and at c. 7 800 years B.P., the sea-level had risen sufficiently to flood most parts of the present North Sea. The English Channel opened (Fig. 3.7 F) and as a consequence the oceanographic pattern as we know it today came into existence.

Man arrives in Norway.

While Scandinavia was covered by ice, humans populated southern Europe. Beautiful wall-paintings of animals are found in caves both above and below sea-level in the Mediterranean. The flooded caves show that people lived in the belt of dry land that formed at these latitudes when sea-water was frozen in glaciers. The paintings illustrate large game like reindeer, wild oxen, musk oxen and mammoths. The artists possibly belonged to tribes of hunters who sustained themselves from these animals. When the climate started to warm after c. 18 000 years B.P., animals moved northwards and with them, also the people. After c. 14 000 years B.P., it is believed that hunters lived regularly on the wide plains of the North Sea area. They stayed here until Dogger Bank flooded as the last remnants of the North Sea continent 7 000 years B.P. (Fig. 3.7F). Remains of shelters used by these people have been found at present water depths of about 30 meters, and other human remains from this period have also occasionally been reported by fishermen.

Fourteen thousand years B.P. the Skagerrak was a fjord, and at its narrowest outside Lista only 60 km wide. During winter, the fjord was covered by sea ice and both animals and people could easily cross over to the narrow strip of land that was emerging from the ice along the Norwegian coast. At Rennesøy outside Stavanger, archaeologists have found traces of humans dating back over 10 000 years (Prøsch-Danielsen & Høgestøl 1995).

With the warmer climate at the onset of the Holocene, human populations dispersed as the ice disappeared. At 9 000 years B.P., humans probably existed all along the coast of southern Norway. The oldest skeleton of a human being in Norway so far reported was recently discovered at Søgne outside Kristiansand (Sellevold & Skar 1996). One nearly complete female skeleton and fragments of a second were discovered during the dredging of a small harbour close to shore (Fig. 3.8). Analyses of the bones show that these women lived nearly 9 000 years ago and had a diet consisting almost entirely of seafood. Thus the Skagerrak has been an important source for food for more than 9 000 years.

3.4 The Skagerrak - an ice-eroded basin

The Skagerrak and the Norwegian Trench are the result of repeated glacial cycles of alternating erosion and sedimentation. The geological history revealed from sediments and morphology is fragmentary because erosion has removed some of the old sediments (Fig. 3.9 B). The younger the story, however, the more pieces of the puzzle can be found.

In the following sections, we will chronicle the sequential evolution of the Skagerrak and the Norwegian Trench as seen through a cross section, from 2.7 million years B.P. to the present (Fig. 3.10). The location of the cross section is shown in Fig. 3.11 G. This story is somewhat incomplete, but yields as much detail as our present knowledge allows.

The Skagerrak and the Norwegian Trench - the result of repeated ice ages

At the onset of the Quaternary Period, 2.7 million years ago, soft sedimentary rocks of Mesozoic or Tertiary age covered much of the Skagerrak and may have extended over the coastal areas of the present Norwegian mainland (Fig. 3.10 A). The colder climate initiated glaciations of the Norwegian mountains, and the dramatic drop in temperatures 1.1 million years ago intensified the severity of the ice ages. The glaciers grew bigger and repeatedly extended into the North Sea area. Some time during every large advance of ice into the North Sea, an ice flow along the coast towards the Norwegian Sea was established. The glaciers eroded the soft sedimentary bedrock and the Norwegian Trench was formed (Fig. 3.9 A).

The formation of the trench probably started off the west coast, but with each glaciation the trench became longer, deeper and wider until the ice flow extended from Skagerrak to the Norwegian Sea. Such repeated erosion is very obvious in the Skagerrak. Troughs which were eroded into bedrock by glaciers flowing along the axis of the trench, cut sediments deposited during older glaciations and were again themselves covered by younger sediments (Figs. 3.9, 3.11). Prominent troughs made by glaciers older than the maximum ice-advance of 20 000-18 000 years B.P. are found outside Egersund, Lista/Mandal and Arendal (Profiles A,B,C, F and G Fig. 3.11). The troughs are parts of «Norwegian Trench(es)» older than the present Norwegian Trench, but their ages are uncertain (Fig. 3.9 A,B). However, in a 200 m-long core through the Quaternary succession in the Norwegian Trench west of Bergen (at the Troll oil and gas field), three till units are preserved. The oldest till is suggested to be 1.1 million years old and indicates that the erosion of the bedrock in the trench outside the west coast of Norway happened more than 1 million years ago (Sejrup et al. 1995). In Skagerrak the last glacier eroded deeply into bedrock. This shows that the final shaping of the Skagerrak morphology is considerably younger than the main morphologic development of the Norwegian Trench along the west coast of Norway.

During the last glaciations, the Skagerrak obviously served as a confluence basin where Norwegian, Swedish and Baltic ice flowed together. When large ice masses from a wide area merge in a narrower passage, the ice flow speeds up and erosion

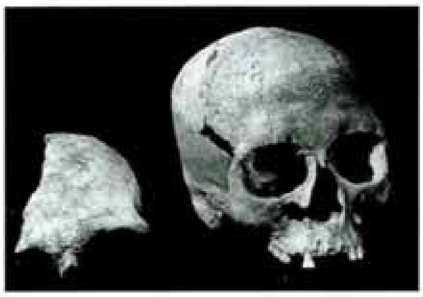
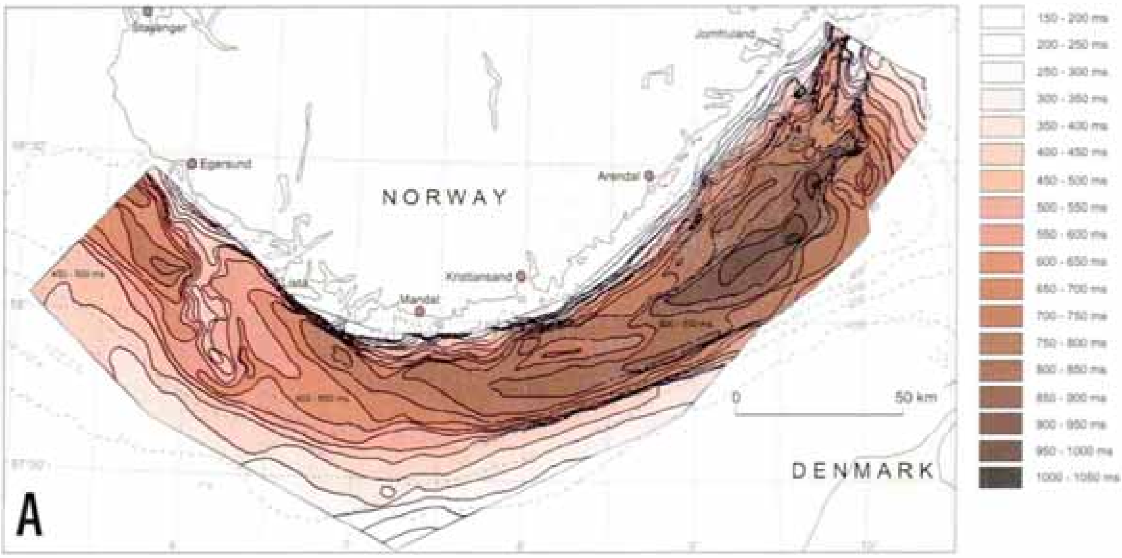


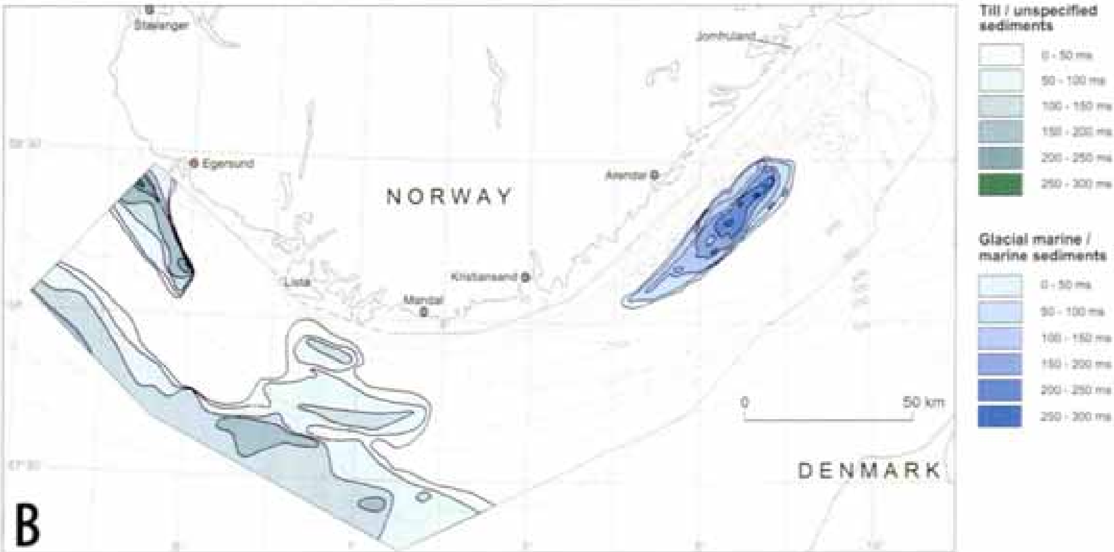
Fig. 3.8 Parts of the 9 000 year old skeletons recently found at Søgne outside Kristiansand. Photo: Anne E.T. Winterthun, NIKU.

Fig. 3.9: Isopach maps of the Skagerrak sediments and their bedrock substrate. The stratigraphy is presented in Fig. 3.11.

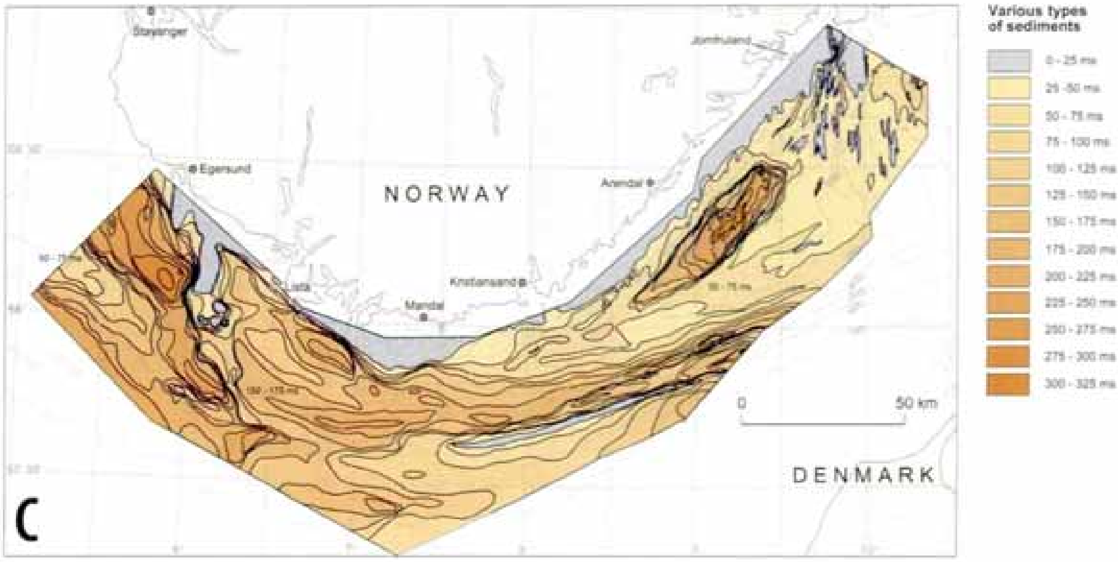
A: Bedrock surface. The map is based on interpolation between interpreted seismic lines (Fig. A1). The distance from the sea surface to bedrock is given in milliseconds (ms) two-way travel time, which is the time the sound takes to travel from the seismic equipment at the sea surface to the bedrock surface and back. In this case 100 milliseconds equals c. 80 meters.



B: Thickness (ms) of sediments older than the last glaciation (25 000 years). Green-coloured sediments are tills or unspecified sediments, and blue are marine or glacial marine sediments.



C: Total thickness (ms) of Quaternary sediments. The map includes all sediments deposited during the Quaternary, also the sediments shown in Fig. 3.9 B.



increases. This is the only part of the Norwegian Trench where such quantities of ice could have been confluent and explains why the Skagerrak is so deep compared to the rest of the trench.

Traces of older ice ages - sediments older than the last ice advance (c. 1.1 000 000 - 25 000 years ago)

The glacial troughs outside Egersund and Lista/Mandal are partly filled with old sediments (mostly tills) that were not removed by the last glacial erosion (Figs. 3.9 A, B and 3.11 A, B and C). These sediments cover large parts of the southwestern slope of the Norwegian Trench (Fig. 3.11) The tills are generally more than 100 m thick and made up of several units. The seismic signature shows that the tills were compressed by the weight of later ice sheets and the top surface was strongly eroded during later glaciations.

The trough southeast of Arendal (Profile G, Fig. 3.11) is covered by a thick (c. 250 m) sequence of nearly horizontally layered sediments which, after deposition, were eroded into a terrace shape. On the northern slope of the Skagerrak, the surface of the terrace is semi-horizontal at c. 400 m depth and has a steep margin towards the deepest parts of the Skagerrak. Because of its location and present shape we call it the «Arendal terrace».

The sediments were deposited in a marine and/or glacial marine environment during a period when the Skagerrak was ice-free. None of these sediments have been accurately dated, but it is likely that the sediments were deposited in the interval between Saale to Late Weichselian (140 000-25 000 years B.P.). Most of the sediments were probably deposited in a glacial marine environment, possibly as turbidites. This may have happened when the glacier either was grounded along the Norwegian Skagerrak coast or existed as a floating ice-shelf in Skagerrak during cold stages of the middle of the Weichselian Ice Age (70 000 and 45 000 or 30 000-25 000 years B.P.). The entire trough of the Skagerrak basin was filled with these sediments, similar deposits are also described from the Danish shelf (Knudsen 1994), which means that enormous volumes were removed by the ice later on.

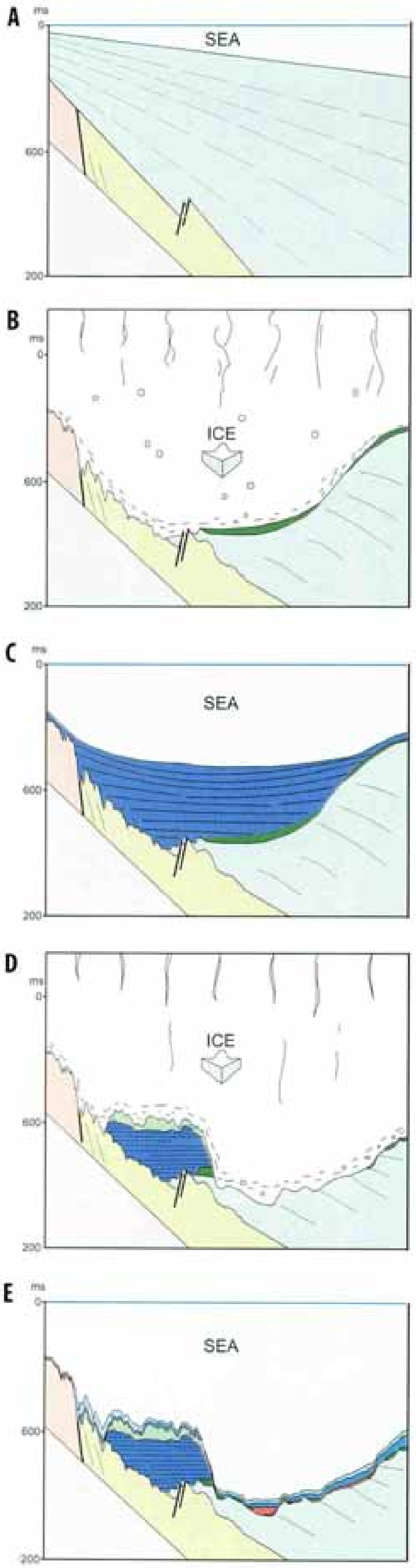


Fig. 3.10 The development of Skagerrak seen along a cross section between Arendal and Hirtshals. (Colours according to legend given in Fig. 3.11.)

A: c. 2,5 million years B.P. Mesozoic rocks covered the Skagerrak, and extended onto the coastal areas of the Norwegian mainland. The Norwegian Trench did not exist.

B: c. 135 000 years B.P. A Skagerrak basin has been formed by repeated glaciations. The glacier which flowed towards the southwest (arrow) eroded the trough that now is found below the «Arendal terrace». This probably happened during the Saalian Ice Age.

C: c. 130 000-25 000 years B.P. During this interval the deepest part of Skagerrak was filled with more than 250 m of fine-grained sediments (Arendal terrace sediments). Skagerrak was probably covered by shelf-ice in some periods, but the ice-sheet probably did not fill the Skagerrak basin enough to reach and erode the deeper parts of the bottom.

D: c. 25 000-15 000 years B.P. The Skagerrak was filled by thick ice during the main ice advance of the Weichselian Ice Age. In the later part of the interval the ice movements were directed along the axis of the trench (as marked by the arrow) and the glacier eroded through the sediments and deeply into bedrock. The top 20-50 m of the «Arendal terrace»-sediments were eroded by glaciers and deposited as till.

E: Present. The last ice disappeared c. 15 000 years B.P. and left an eroded bedrock surface and a thin, patchy cover of till. Immediately after the ice started to float and retreated, sediments flowed into the deep basin from meltwater rivers along the melting ice margin in Denmark. Later, this fluvial deposition was replaced by normal glacial marine depositional environments and finally, by purely marine sedimentation at 10 000 years B.P.

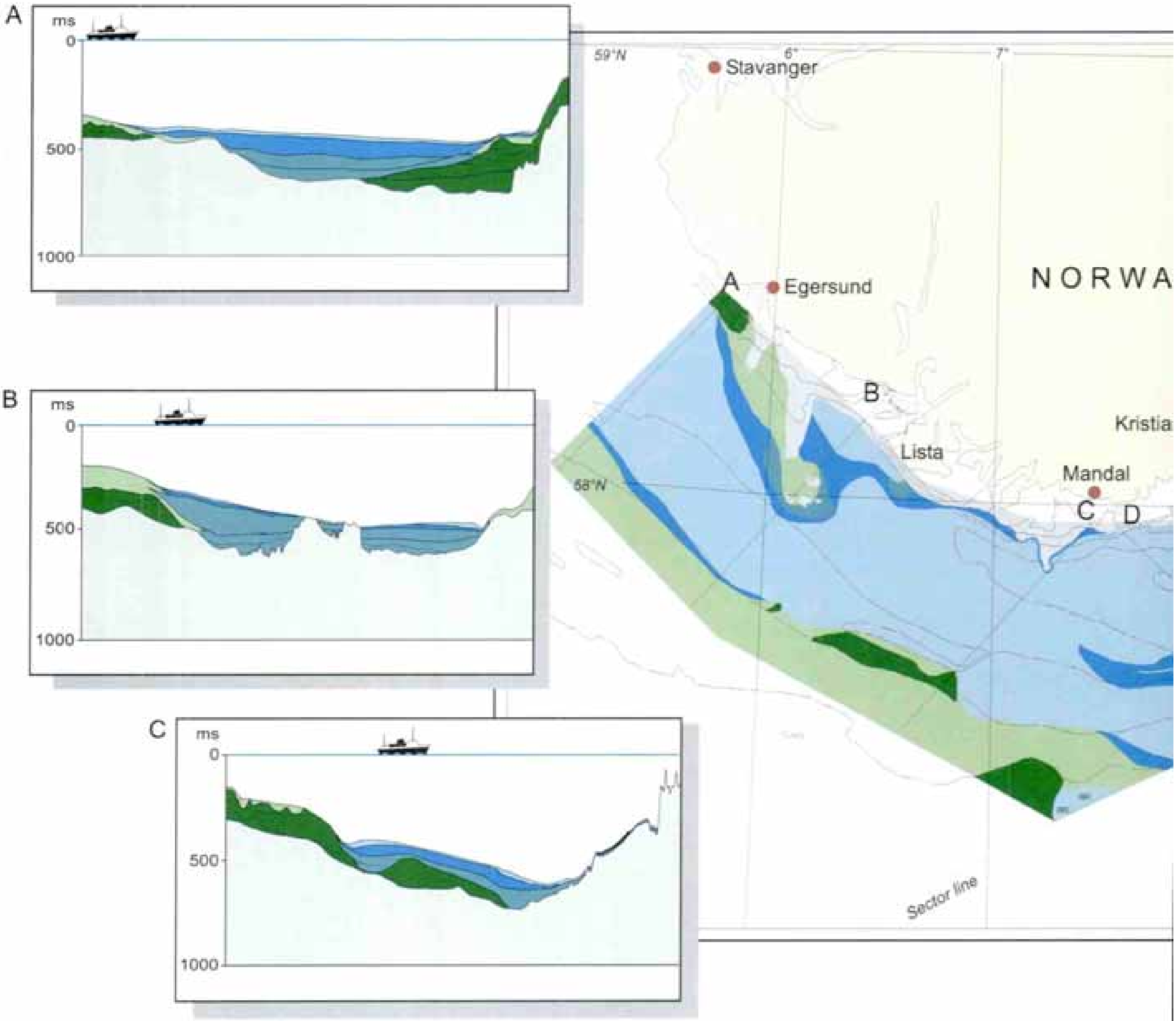


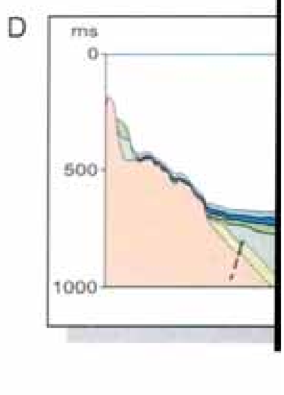
Fig. 3.11 Quaternary map and stratigraphic cross sections from Skagerrak.

The Quaternary map

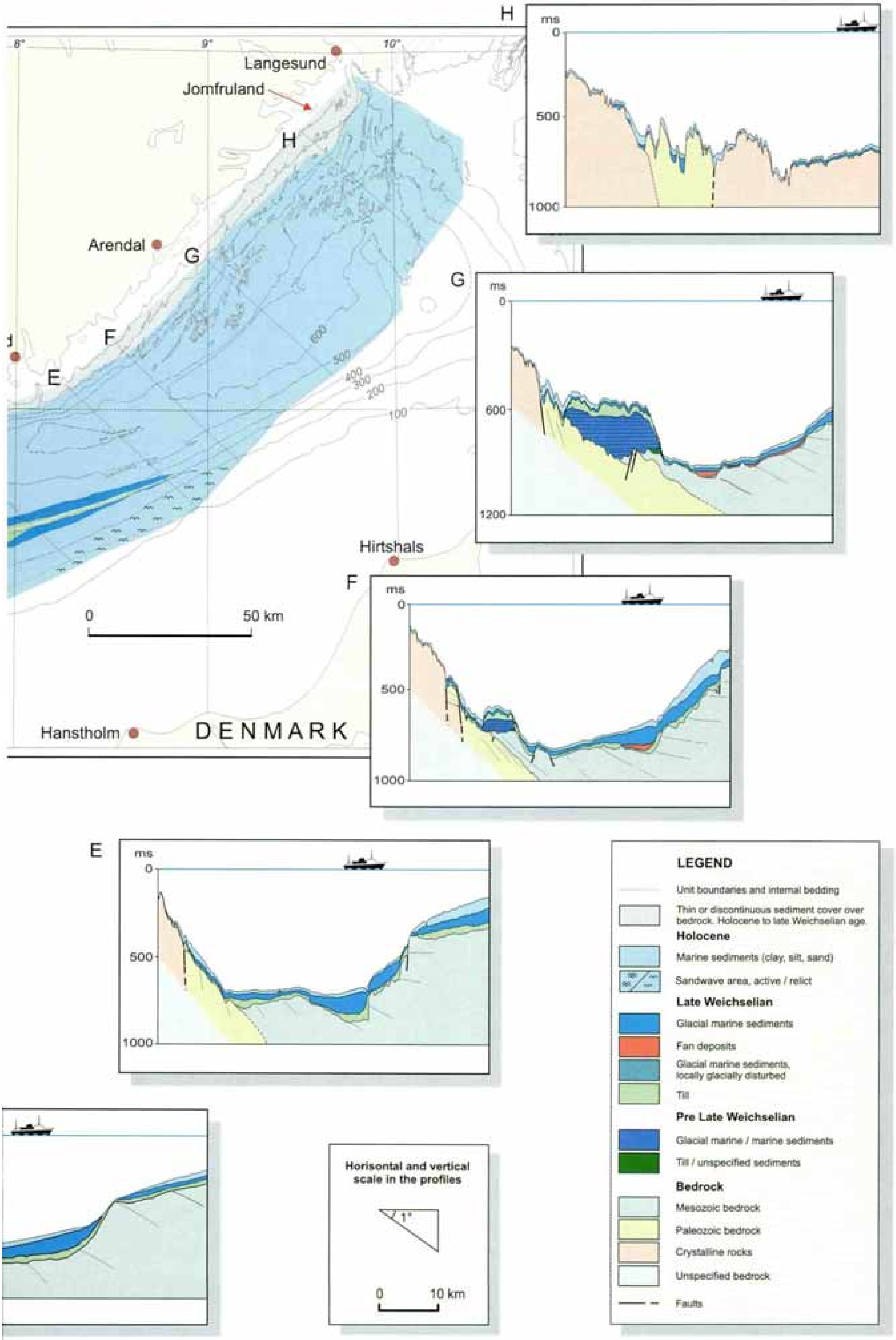
The map is generalised from interpolation between interpreted seismic lines (seismic grid given on Fig. A1 and may not contain all details from the profiles as presented here (A-H). The sediments exposed on the sea bottom are classified according to genesis, thickness and age. Blue colours refer to soft, fine-grained marine or glacial marine sediments. Green colours (dark green oldest) refer to tills deposited by glaciers, generally fine-grained, but stony and rather compacted. The till surface is uneven (Fig. 3.15) and may locally, or in depressions, have a patchy veneer of marine or glacial marine sediments. This is not shown on the profiles and hence the map, because the seismic resolution necessitates a sediment thickness of at least 2–5 m to be registered.

The profiles (located on the Quaternary map)

The profiles A–H are interpreted seismic lines. Both lithology and age relations are mainly based on seismic signature and with correlation to literature, some samples and a few dates. Vertical exaggeration is c. 40x. The bedrock interpretation for the profiles A–C is incomplete and left out. It should be mentioned however, that centrally in the trench (profile B) crystalline bedrock, the so-called «Hidra Mountains», tower through the Mesozoic sedimentary rocks.



NGU
Norges geologiske undersøkelse


8°
9°
10°
Langesund
Jomfruland
H
Arendal
G
F
E
600
500
400
300
200
100
Hirtshals
0
50 km
Hanstholm
DENMARK
H
ms
0
500
1000
G
ms
0
600
1200
F
ms
0
500
1000
E
ms
0
500
1000
Horisontal and vertical scale in the profiles
1°
0
10 km
LEGEND
Unit boundaries and internal bedding
Thin or discontinuous sediment cover over bedrock. Holocene to late Weichselian age.
Holocene
Marine sediments (clay, silt, sand)
Sandwave area, active / relict
Late Weichselian
Glacial marine sediments
Fan deposits
Glacial marine sediments, locally glacially disturbed
Till
Pre Late Weichselian
Glacial marine / marine sediments
Till / unspecified sediments
Bedrock
Mesozoic bedrock
Paleozoic bedrock
Crystalline rocks
Unspecified bedrock
Faults

Glacial processes and sediments (Box 3.2)

A glacier is a body of ice which flows from a centre of accumulation towards its melting margins. A glacier might either be cold (frozen to the ground) or temperate (at the melting point and fast flowing). The speed of flow along the base of a glacier varies from zero in a «cold» glacier to tens of meters per day in some temperate glaciers. Glaciers are effective agents of erosion, transportation and deposition of sediments and generates characteristic morphology and sedimentary deposits. The glacial environment leads to increased erosion by frost, wind and glacial rivers. **Glacial processes** are responsible for sculpturing the landscape by erosion and accumulation. Common glacial processes and resulting features are:

- **glacial grinding** - when a glacier flows over the ground, rock fragments are frozen to its sole. The sole acts like sandpaper and cuts into the ground that consists either of bedrock or sediments.
- **glacial plucking** - when a glacier tears off rock blocks at the lee-side of a rock lying at its base, water melts at the stoss side (facing the flow) of the rock and freezes at the lee side. The rock is then cracked by the freezing process and easily removed by the glacier flow.
- **glacial tectonism** - tectonic deformation of sediments or bedrock caused by glaciers. Glaciers are able to erode by displacing and deforming large bodies of sediment or bedrock.
- **u-shaped valleys and deep troughs** are typical morphologies after glacier erosion. Troughs in this connection are U-shaped closed depressions that can range from cm to hundreds of kilometres long and wide and from cms to hundreds of meters deep.
- **drumlins** are streamlined ridges, formed at the base of a glacier, that sometimes have a core of bedrock or older sediments. The ridges may be tens of meters high and several kilometres long; they are parallel to the flow direction of the glacier. The typical drumlin is cigar-shaped with a head and a tail the latter of which points in the flow direction. Drumlins may be formed either by erosion or accumulation.
- **fluted surface** describes a surface with narrow parallel ridges, generally less than 1-2 m high. The ridges are formed below the glacier, are parallel to the glacier-flow direction, and may be formed either in bedrock or sediments by erosion or accumulation. Flutes are related to drumlins.

Skagerrak 25 000 to 17 000 years B.P. - covered by thick ice masses

Most of Skagerrak is covered by shallow seismics and multibeam echo sounding (swath bathymetry) data which enables us to read the history of erosion and deposition of the last ice sheet in some detail. The multibeam echo soundings give a total coverage of depth measurements and a very detailed description of the morphology of the sea bottom. The youngest sediments in the Skagerrak are silty clays, from 10 -100 m thick. In the deeper parts of the Skagerrak, the currents are very weak and the deposition of the clay through the water column can be compared to quietly falling snow which evenly covers the ground. Therefore, the morphology of the sea bottom today reflects older surfaces from tills, slide deposits or bedrock 10-30 m below the sea bottom surface.

The till surface is fluted by 2 to 7 m high ridges which were deposited beneath the glacier in the direction of the ice flow (Figs. 3.12 and 3.14). Where the till lies directly on bedrock, the flutes of the last stage of ice flow are generally preserved. On top of the «Arendal terrace» however, where sediments have been moulded by ice, at least three distinct phases of ice-movement and their age relations can be seen and interpreted (Fig. 3.12). Most likely, all of these flow directions represent changing stages of the last glacier which reached its maximum 20 000-18 000 years B.P. and broke up in the Skagerrak c. 15 000 years B.P.

The first movements are represented by deep, diffuse furrows in a southerly direction. This represents the first flow of grounded ice into the Skagerrak after c. 30 000 years B.P.; it crossed the Skagerrak, reached Denmark and advanced to its maximum position in Jutland sometime before 20 000 years B.P. (Petersen & Kronborg 1988). As the ice culmination moved eastwards into Sweden, the movement dynamically shifted in a southwesterly direction, still forming deep furrows and drumlins (large flutes) with a total relief of up to 50 m, and later, to a very plastic type of ice flow that drained along the axis of the deep trench. Small flutes can be followed from the deepest part of the basin obliquely up the southern slope of the terrace onto the plain where they are bent in a more southwesterly direction. This illustrates how plastic ice from different parts along the coast flowed ogether along the trench. The nourishing of the ice on the North Sea plateau stopped as the Skagerrak glacier developed. The ice along the southern and western margins therefore became stagnant or «dead». An example of this is shown in Fig. 3.15.

The ice flow along the axis of the trench eroded through the older, more than 250 m-thick, sediments into bedrock in central parts of the basin and left the Arendal terrace as an erosional remnant (Profiles F and G, Fig. 3.11). The bedrock surface may have been lowered as much as 100 m and the deep trench shifted 25 km to the south during this erosion. The morphology of the deepest part of Skagerrak (Fig. 3.14 F) shows that erosion by glacitectonic (see Box 3.2) removal of many kilometres-wide and tens-of-metres-thick slabs of the soft Mesozoic bedrock has taken place. Such erosion has been an important process in excavating the Skagerrak basin.

Some of the eroded sediments and bedrock may have been deposited as tills along the Norwegian Trench, but most of it lies in the fan outside the trench off western Norway. Equivalents to ice streams like the Skagerrak glacier are found in Antarctica today. The ice streams moves typically with a speed of 1-5 m per day. The distance from the Skagerrak to the continental slope is 800 km. Thus, the ice and sediment would need 500 to 2 000 years to travel this distance and the glacier thousands of years to excavate the basin.

The Skagerrak glacier - confirmation of a 100 year-old theory

The idea of an immense Skagerrak glacier moving westwards, northwestwards and eventually, northwards along the Norwegian Trench, was introduced by Helland (1885). For some years this theory was generally accepted, but later became more controversial. The new bathymetric maps of the Skagerrak, together with observations of flutes in the trench outside Egersund and drumlins onshore in Jæren (E. Larsen, pers. comm. 1996), leave no doubt that such a large glacier did, in fact, exist, at least in a late phase before the glacier thinned and started to break up.

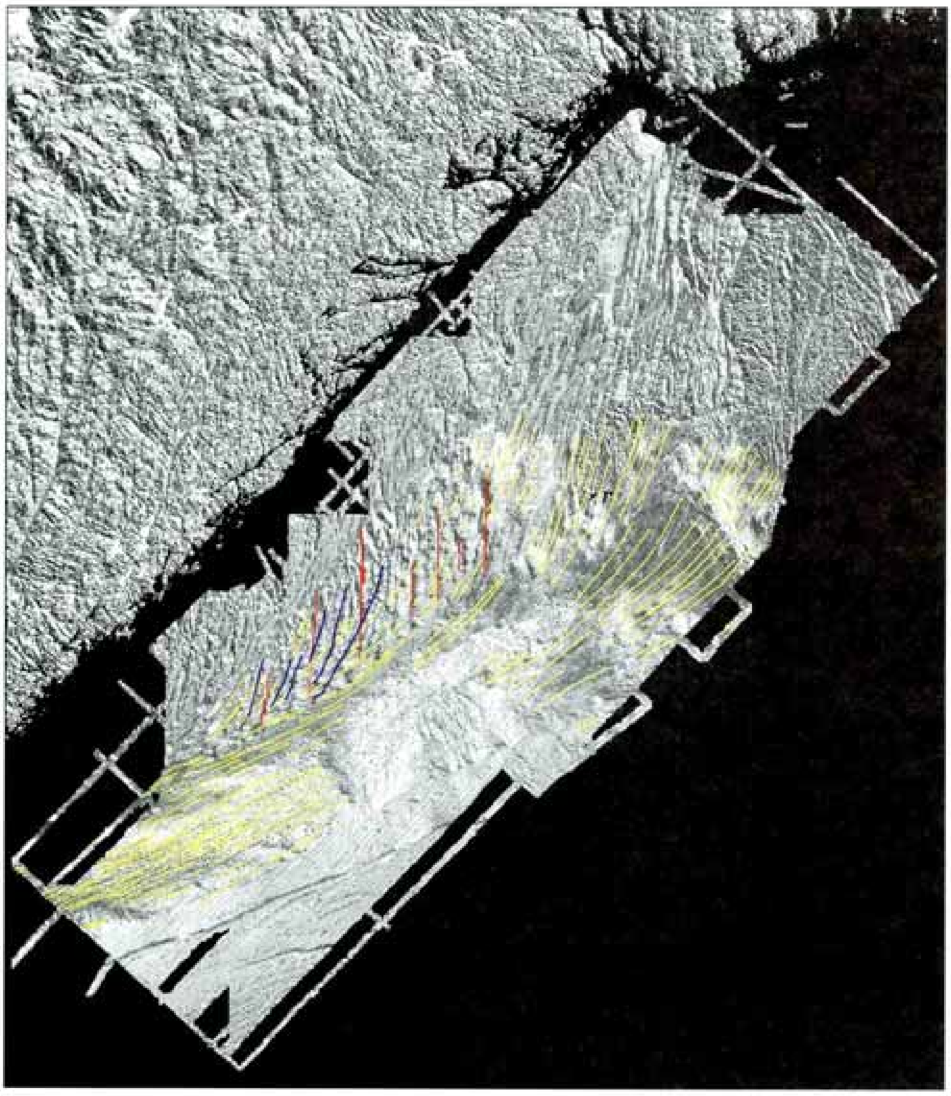


Fig. 3.12 Shaded relief image, processed to visualise the flutes. The image shows a radial ice flow in the deepest part of the Skagerrak basin. On top of the Arendal terrace three different ice movement phases can be separated. Red lines show the initial movements from a glacier crossing the Skagerrak. Blue lines indicate ice movements affected by pressure from Swedish ice. Finally, the yellow lines show the plastic flow of the «Skagerrak glacier». For location, see the index map in Fig. 3.14.

Deposition under floating ice outside Lista 17 000-15 000 years B.P.

After 18 000 years B.P. the Scandinavian ice cap started to melt and become thinner and finally fed less ice to the Skagerrak glacier. The glacier accordingly started to float and finally to break up. Evidence for the transition from grounded ice to floating ice is found in the seismic record of sediments across the trench outside Lista (Fig. 3.11, profiles A-C).

The sediments in the central part of the trench show acoustic layering, which changes into a chaotic seismic picture in shallower water. This is explained by grounded ice and till deposition on the slopes and floating ice and deposition of water-laid sediments over the deepest part of the trench. Grounding lines for this floating ice shelf can be seen as weak ribbons on the sea bottom (Fig. 3.15 D). The glacial marine sediments deposited in this way are disturbed by ice. Possibly the glacier oscillated and was periodically floating and grounded before it finally lost grip of the bottom, became a floating ice shelf for the entire Skagerrak and broke up by calving. The opening of the fjord outside Lista is, by correlation to sediments in the Norwegian Trench west of Bergen, relatively dated to 15 000 years B.P. The glacier therefore started to float prior to 15 000 years B.P. When it lost contact with the seabed outside Lista at

■ **iceberg scours** are shallow, generally 1-10 m deep furrows in sea bottom sediments made by ploughing icebergs. Such scours frequently occur as swarms of semi-parallel «furrows» on shallow-marine glaciated, or formerly glaciated, shelves.

■ **plastic forms (p-form)** are shallow smooth grooves or winding smooth channels on a rock surface, formed underneath a glacier, supposedly by abrasion of sediment-loaded water under high speed and pressure.

Glacial sediments are sediments deposited either directly by the glacier or in the vicinity of the glacier and characterised by the glacial environment.

A till is a sediment with a variety of grain sizes from clay to large blocks that is carried and deposited by a glacier (Fig. 3.13). There are several types of till depending on the depositional processes:

■ **lodgement** till is a till plastered onto the ground from the base of the glacier. It usually contains a high percentage of fine-grained clasts and is often very compacted.

■ **melt-out till** is melted out of a glacier and the finest clasts have usually been washed away.

Glacial marine sediments are generally clayey, stratified sediments deposited in the sea; the fine-grained clasts are supplied by meltwater from glaciers flowing either directly into the sea or via glacial rivers (Fig. 3.13). The clay falls out of suspension and drapes the sea bottom. The sediments may contain ice-rafted debris, especially sand-sized particles. When the glaciers melt away the fine-grained marine sediments are normally less stratified and contain more organic matter.

Glacial marine fan deposits are fans of fine-grained glacial-marine sediments deposited from debris flows or turbidite currents. The debris flows and turbidites may originate from deltas of rapidly depositing glacial rivers or from deposits along the ice margin which slide out when the ice-support disappears (for an example, see Fig. 3.16).

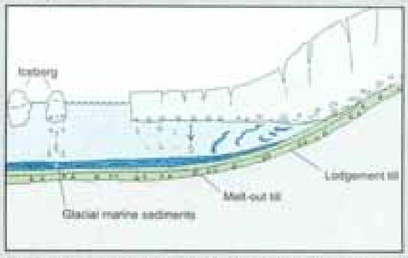


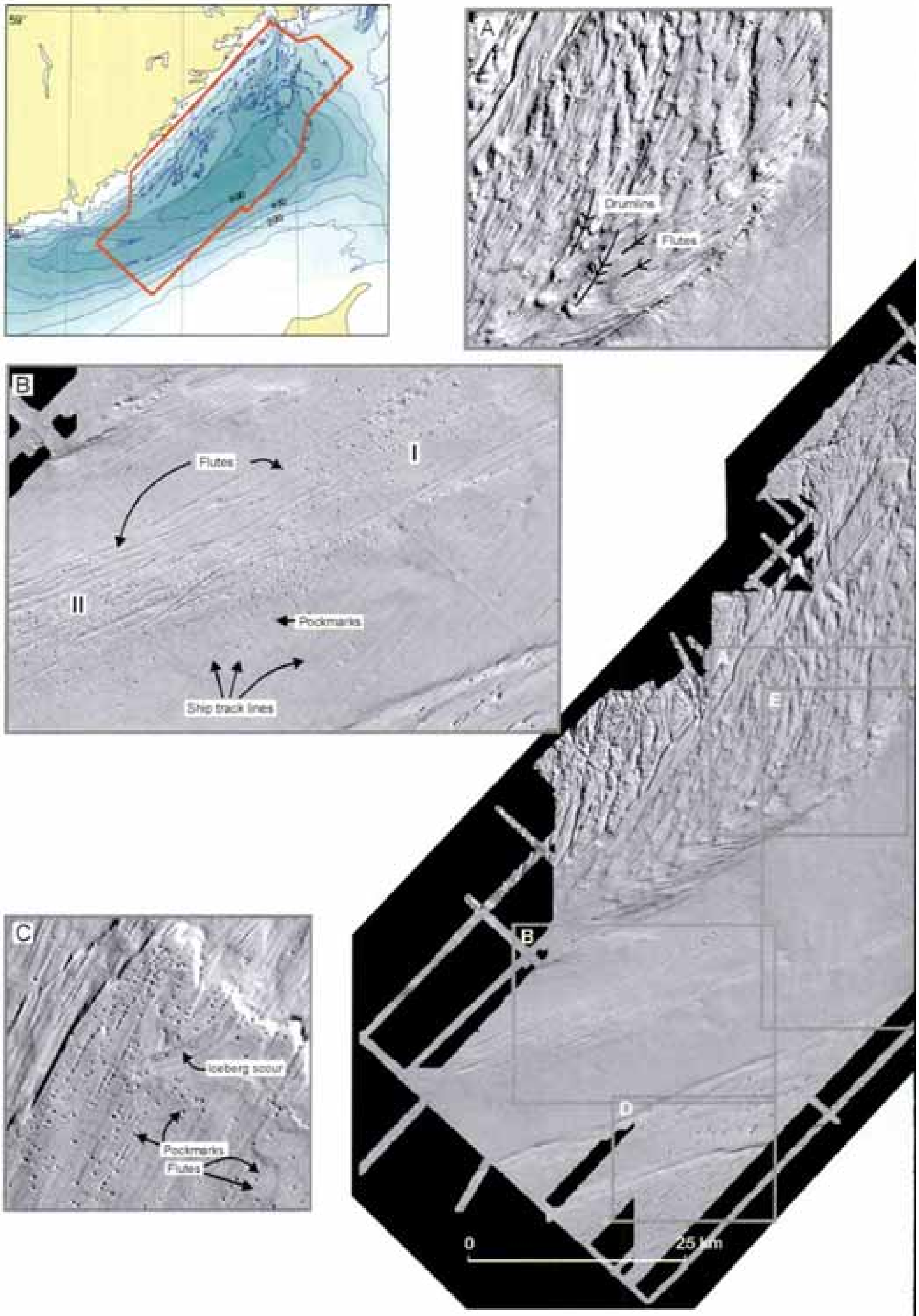
Fig. 3.13 Deposition of glacial sediments in the sea. See above for explanation.

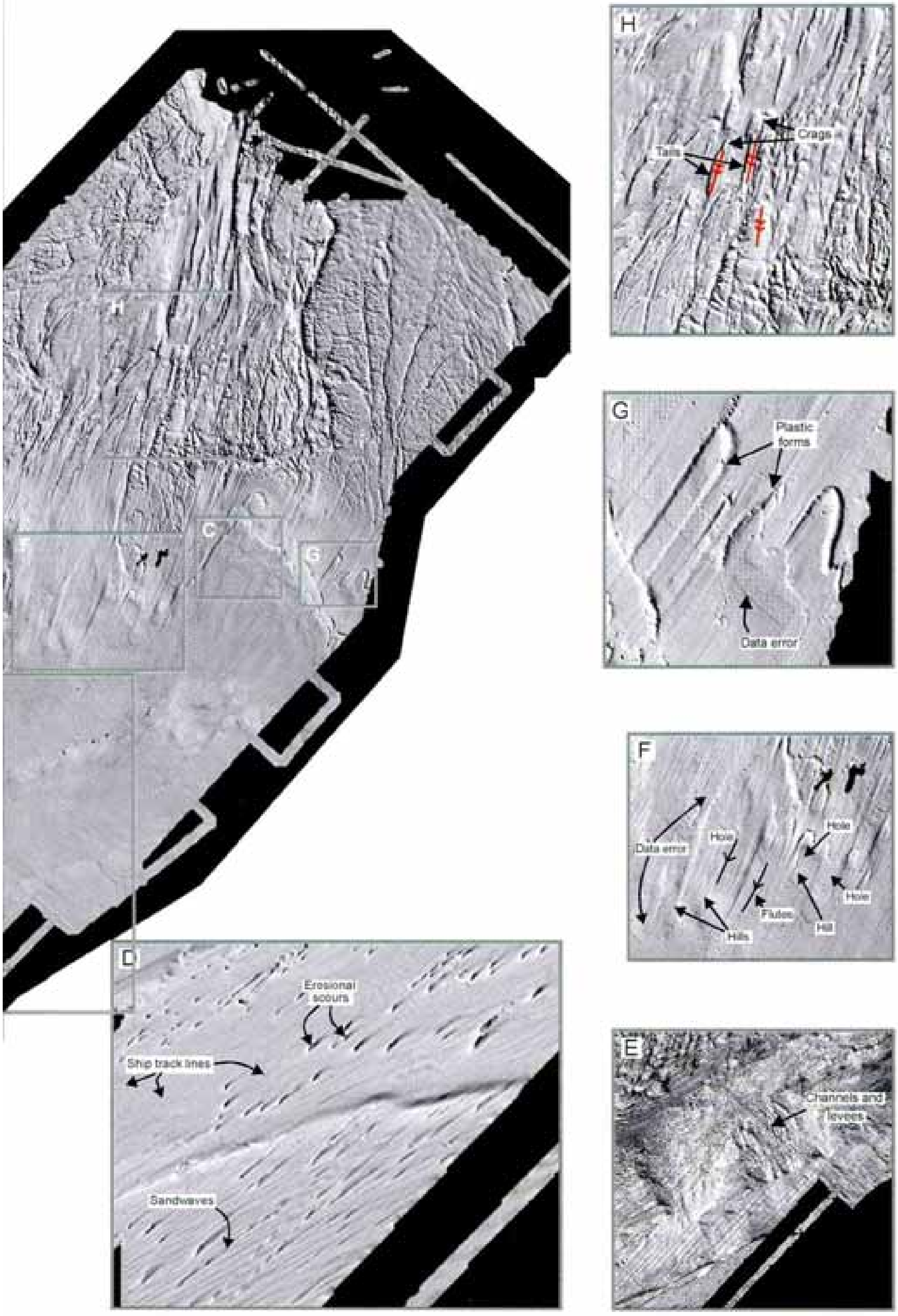
Fig. 3.14 Morphology and Quaternary geological processes in the Skagerrak. The main, central figure shows a shaded relief image of processed multibeam echosounding data from the Skagerrak. The smaller images (A-H) are magnified to highlight morphology resulting from different geological processes (for location, see the main figure). During processing, some noise generated during the data acquisition could not be removed, and this appears on the images as ship track lines and data errors. The area covered by the shaded relief image is outlined in the index map, upper left corner.

A: Flutes and drumlins from different ice-movement directions can be seen on top of the «Arendal terrace» sediments. See also Fig. 3.12.

B: Flutes and pockmarks. The flutes form ridges and furrows with a relief of 2 to 7 m and reflect the ice flow along the axis of the Norwegian Trench. Flutes from two different ice flow phases can be seen. I; regular flute pattern formed by the Skagerrak glacier during an active phase II; irregular flute pattern from the deglaciation period. The central part of the picture forms a ridge. When the irregular pattern was formed the glacier had become a floating ice-shelf which still had bottom contact over this ridge. Some of the grooves in area II may be iceberg scours. The small «dots» on the surface are pockmarks or depressions in the bottom sediments made by the seepage of gas from sediments or bedrock, in this case by gas seepage from the underlying sandstone. The pockmarks are generally 50-150 m wide and <15 m deep.

C: Flutes, iceberg scour and pockmarks. The scour in the centre of the image was probably formed by an iceberg or deep part of the ice-shelf that touched and ploughed the sediments. The scour cuts the fluted surface and was formed when the glacier in the inner part of Skagerrak disintegrated.





D: Sandwaves and erosional scours. The sandwaves, trending ENE-WSW, were active in the period following the deglaciation, at a time when the sea-level was lower and the ocean currents different from the present. The NE-SW trending scours have been formed by gas seepage and erosion by turbulent currents. The scours are elongated in the direction of the predominant currents, and can be up to 45 m deep.

E: Submarine fans. Fan complex formed by sediments flowing downslope from the Danish side of the Norwegian Trench. Channel and levee systems can clearly be seen. An isopach map of the fan deposits is shown in Fig. 3.16.

F: Glacitectonic hill-hole features. Under the steadily flowing Skagerrak glacier wide slabs of bedrock or sediments were tectonically disrupted and dislocated. This erosion can be identified from the holes where the rock was removed and the hills where it was deposited.

G: Plastic forms (p-forms). Grooves, with a maximum depth of 20 m, eroded into the bedrock by water under high pressure below the ice. The p-forms were cut into benches of rocks weaker than those surrounding them.

H: Crags and tails. Elongated structures formed in bedrock and sediments by glaciers moving towards the south-south-west. Note the streamlined shape of the crags and tails.

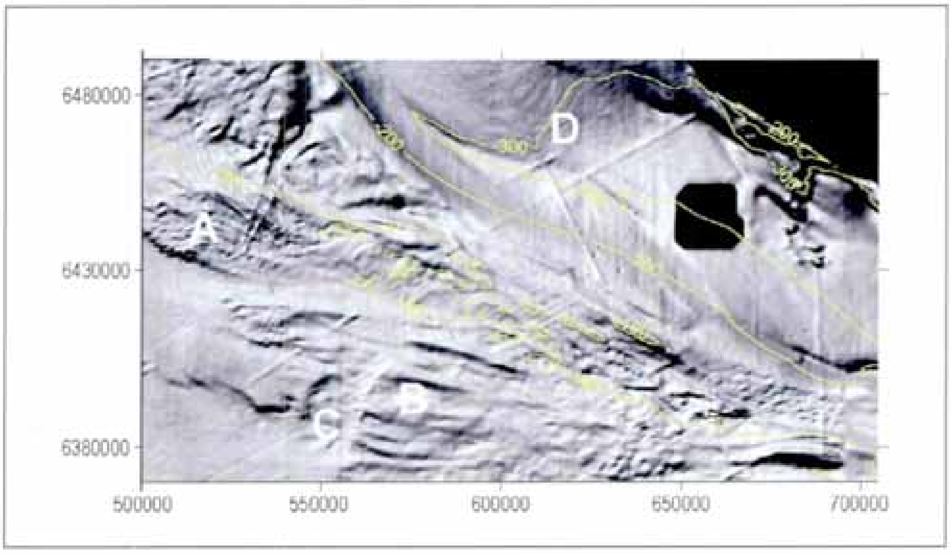


Fig. 3.15 Shaded relief image of the Egersundbank and the Norwegian Trench. The location of the relief image is shown on the index map (right). The relief image illustrates the glacial morphology of the Egersundbank, with hummocky terrain (A) indicating stagnant ice, end moraines/ flutes (B) and glacial meltwater channels (C). This morphology is covered by clay in the trench below c. 150 m. The weak ribbons that can be seen above the 300 m contour line in the upper middle of the image (D) are probably grounding lines from the time when the glacier was partially floating in this area, c. 15 000 years B.P. The «Hidra mountains» (Fig. 3.11 B) can be seen east of the black rectangle (where data are lacking). The relief is based on single-channel echosounding data from the Norwegian Hydrographic Service and is far less detailed than the morphologic map of the inner part of the Skagerrak.

c. 15 000 years B.P., the ice shelf retreated rapidly all the way to a grounding line south of Langesund.

The glacial marine beds deposited during the deglaciation are thickest on the southern slope of the trench (Fig. 3.11 profiles A-F). Most of these sediments were possibly delivered by continental rivers fed by melt water from the southern margins of the Scandinavian ice cap (Fig. 3.7). Limited amounts of glacial marine sediments were deposited in the area west of Lista after the ice withdrew (Fig. 3.11 B).

Skagerrak 15 000-10 500 years B.P. - an open fjord-like basin with huge floating icebergs

From the time when the glacier started to break up until it finally retreated ashore, the fjord was filled with icebergs. Some of the icebergs must have been enormous since plough marks made by one drifting iceberg can be seen at water depths of c. 400 metres. This shows that the calving ice front must have been nearly 400 m deep, and 40 m high. One of the plough marks is more than 5 km long, 150-200 m wide and up to 16 m deep, and cuts through a previously fluted surface. From Antarctica, icebergs the size of Vestfold county (c. 2200 km2) have been reported, and the largest Skagerrak icebergs may have been of comparable sizes.

Large rivers, originating from the margin of the melting glacier in the Baltic Sea area including Sweden, crossed the North Sea plains. The rivers brought with them large amounts of fine-grained material which were deposited in the Norwegian Trench fjord, probably in deltas and fans along the southern shore. This is assumed to be the most important source for the sediments deposited in the Skagerrak in this period.

The rapid deposition resulted in instable deposits, which frequently collapsed and slid into the fjord. From the Danish side of the Skagerrak north of Hirtshals, turbidites from such avalanches or from density currents directly from the meltwater rivers, have made prominent fans reaching into the deepest part of the trench (Fig. 3.16). In that part of the Norwegian Trench which is mapped in detail, such deposits have a volume of 16 km³ and cover 875 km².

The fan deposition must have occurred immediately after the ice disappeared, because the fans rest on tills formed when the ice started to float and disappear. The fan deposition was followed by deposition of clayey glacial marine sediments with iceberg dropstones. The glacial marine deposits are up to 100 m thick on the southern slope of the trench (Fig. 3.11)

The ice front retreated rapidly towards the coast, and by c. 12 000 years B.P. the coast was ice free. By 11 500 years B.P., the ice front was c. 20 km inland, north of Langesund. A short period of colder climate (11 000-10 000 years B.P., Younger Dryas) initiated a new growth of the ice sheet; the glacier made a rapid advance and formed a prominent end moraine ridge, the Ra moraine. The ridge can be followed below

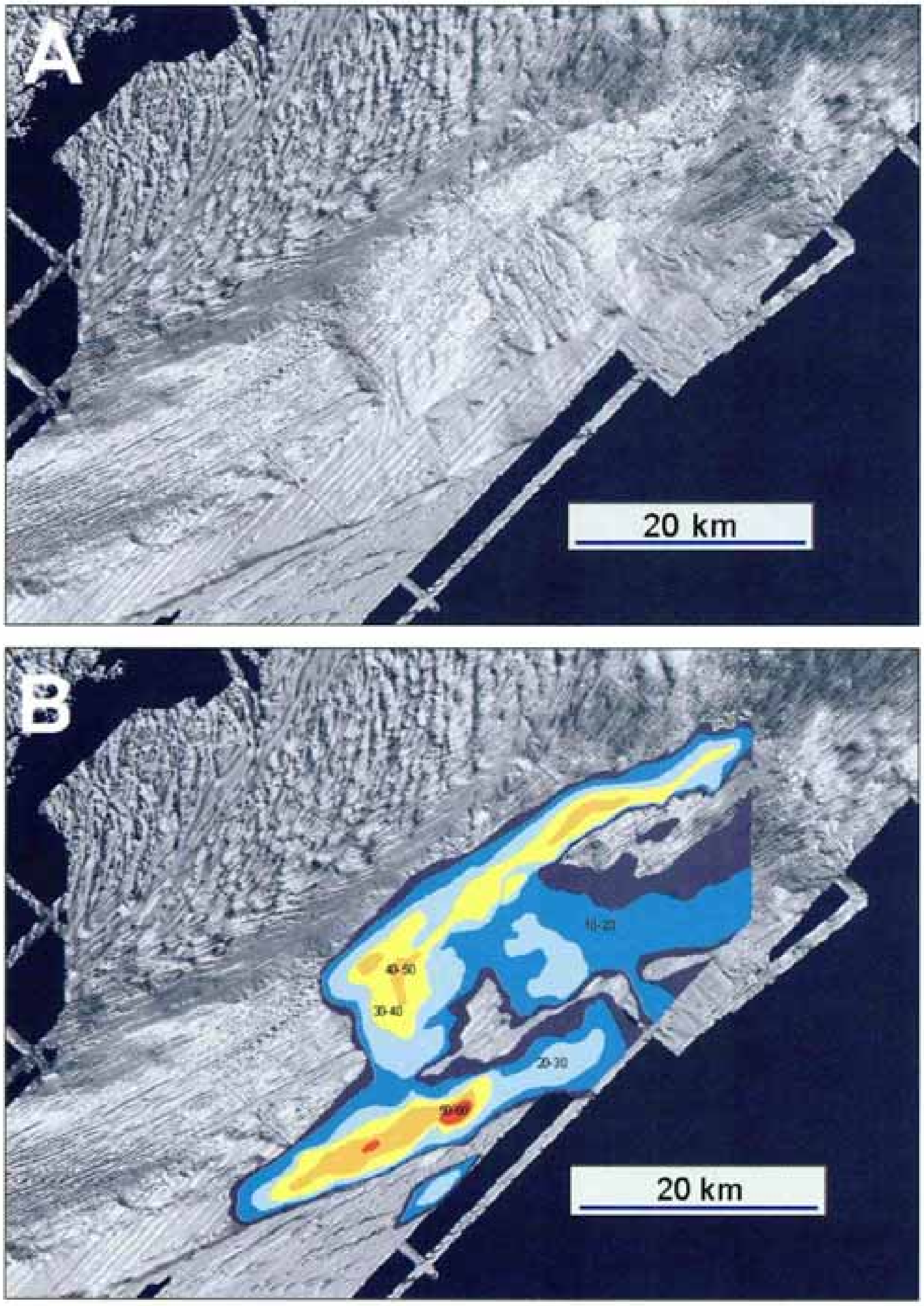


Fig. 3.16 Submarine fans in the deeper part of Skagerrak. For more detailed location see Fig. 3.14. The fans originated in the upper parts of the slope, in the Danish sector north of Hirtshals. A: shaded relief image showing the fan morphology. B: an isopach of the fan deposits. Note that the fans camouflage the fluted surface which otherwise is reflected through the cover of glacial marine and marine sediments.

the sea-surface from Langesundfjord to Arendal. The island of Jomfruland is an exposed part of this ridge (Fig. 3.17).

The glacier comes ashore 10 000 years B.P. - changed deposition in the Skagerrak

When the glaciers retreated ashore along the Norwegian and Swedish coasts 12 000-10 000 years B.P., most meltwater sediments were deposited in the coastal zone and no icebergs calved into the sea. Since then, the fjords have been effective sediment traps and relatively little of the rivers' sediment load reaches the deep Skagerrak. This change in sedimentary environment is clearly seen on seismic registrations. The post-glacial sediments have low reflectivity compared to the acoustically layered glacial marine sediments and the reflector between them can confidently be followed over most of the trench.

The thickest Holocene deposits are found in the southeastern slope of the Norwegian Trench north of Denmark, where they locally are c. 100 m thick and constitute some of the thickest Holocene marine sediments in the world (Fig. 3.19); further west along the upper part of the slope these marine sediments are absent. At the bottom of the trench, the Holocene sediments are 7.5-15 m thick to the east of

Fig. 3.17 The island of Jomfruland (for location, see Fig. 3.11) is an exposed part of Raet, a 10 000 year old end moraine ridge. Photo: Fjellanger Widerøe A/S.

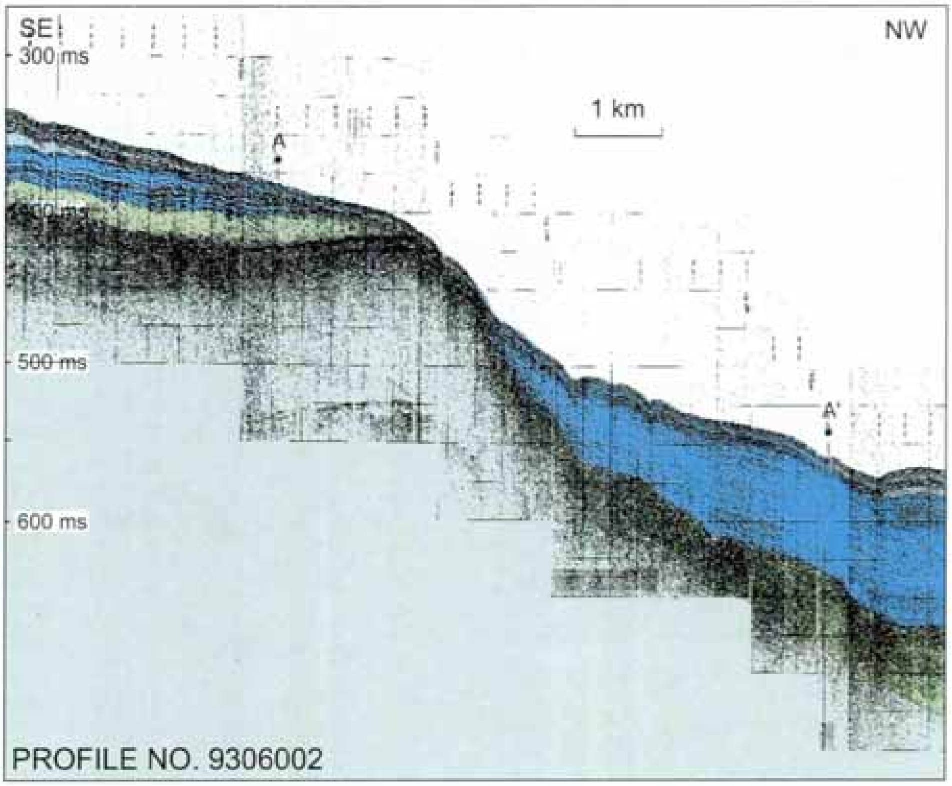
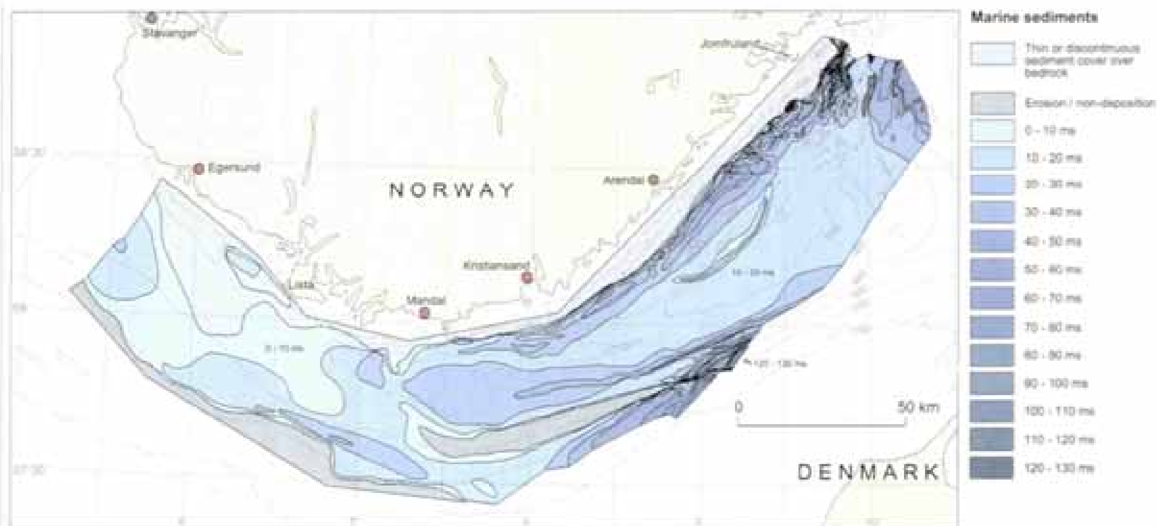


Fig. 3.18. Erosion of Early Holocene sediments on the southeastern slope of Skagerrak. A-A' gives a cross section of the area where the Early Holocene sediments have been removed by erosion.

Fig. 3.19 Thickness of Holocene deposits (Rise et al. 1996).

Lista and less than 7.5 m thick to the west. The Holocene deposits are mainly formed by sediments brought into Skagerrak early in the Holocene Epoch by European rivers which fed into the fjord and later also, when the North Sea was flooded, by sediments eroded from the sea bottom. In the deepest part of the trench, the Holocene sediments are typically 10-20 m thick. At the same time the recent sedimentation rate is 10-20 cm/100 years and this indicate that the deposition in the central part has been stable and continuous throughout the last 10 000 years. However, on the southeastern slope, there is an extensive area of erosion or non-deposition. This area is traceable for 100 km and has thick modern sediments both to the north and to the south (Fig. 3.19). The area occurs close to a steep bedrock scarp and cuts through Holocene sediments into older deposits (Fig. 3.18). This non-depositional feature shows that currents along the slope became stronger sometime during the Holocene, perhaps in the middle or late part of the period. The increased erosion and instability can probably be explained by an increased influx of Atlantic water as a result of a change of the large-scale circulation patterns of the North Atlantic, c. 4 000 years B.P. Since then, the climate has deteriorated over northern Europe. On land this has manifested itself in increased activity of slides and river erosion which ultimately has increased the flux of sediments into the North Sea and Skagerrak. In the following chapters it is shown that 50-70 % of all fine-grained sediments that are brought into the North Sea, finally end up in the Skagerrak basin and the Norwegian Trench. The increasing load of contaminants that has been released to the nature the last century, easily associates with fine-grained matter and sinks out with the sediments in this area - the «dustbin» of the North Sea.



Selected references

Quaternary geology has experienced enormous scientific advances over the last few decades, and an impressive amount of important scientific data has been published. 'The Birth of the Skagerrak and the Norwegian Trench' is intended as a popularised, easily readable version of the geological history of the Quaternary of the Skagerrak area. Therefore, literature citations have been kept at a minimum. On special topics which are treated in the text, we have cited some of the latest publications. These papers, and the references therein, will serve as an entrance to the vast literature that exists and which is relevant to the Quaternary history of the Skagerrak. A good review and bibliography for the area are given in Holtedahl (1993).

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4 The modern sedimentary environment

Facts about the Skagerrak (Box 4.1)

The Skagerrak: Sea area between Norway, Sweden and Denmark east of the line Lindesnes-Hanstholm.
Area: 36 000 km²
Water volume: 7 000 km³
Maximum water depth: c. 710 m

The Skagerrak is the deepest part of the North Sea as a result of the intense glacial erosion that carved the Skagerrak and the Norwegian Trench during the last ice ages (see Chapter 3). The waters in the North Sea are in constant motion, and nearly all water in the North Sea eventually passes through the Skagerrak carrying some sediment load. Because the Skagerrak is so deep compared to the rest of the North Sea, it acts as a sediment trap and is the main area for deposition of fine-grained sediments in the North Sea. The mechanisms of sediment transport and deposition in the area has a fundamental effect on the spatial distribution of contaminants in the Skagerrak (see Chapter 5).

Fig. 4.1 Bathymetry of the North Sea (modified from North Sea Task Force 1993).

4.1 Bathymetry and ocean currents

Bathymetry

The North Sea can be separated into three parts: a very shallow sea with depths shallower than 50 m from the Dogger Bank to the south and east, an area of intermediate depths (50-200 m) northwards from the Dogger Bank to the continental slope, and a deep water region with water depths exceeding 200 m, in the Norwegian Trench and the Skagerrak (Fig. 4.1).

The Norwegian Trench runs parallel to the west coast of Norway and ends in the Skagerrak, where it reaches its greatest depth at c. 710 m (Fig. 4.1). The shallowest part of the trench (the sill) lies outside Jæren (for location of Jæren, see Fig. 4.2) and is c. 280 m deep. In the Skagerrak, the trench forms a streamlined, asymmetric basin, with an irregular northern, and a more regular and gentle southern, slope. On the northern side of the trench, the slope gradients average 2-3° and the sea bottom is deeply incised by narrow channels. Outside Arendal, there is a «terrace» (The Arendal terrace, Chapter 3) at c. 400 m water depth. The «terrace» is approximately 60 km long and 15 km wide and has a 150 m high slope dipping steeply (6°-8°) down to the bottom of the Norwegian Trench.

The southern slope of the trench has gradients of c. 1° at water depths deeper than 250-300 m and of less than 1° at water depths shallower than 250 m. This slope changes into a gently dipping plateau towards Denmark at water depths shallower than 100 m. The eastern slope is semi-parallel to the Swedish coast and is dissected by several submarine channels extending into the deepest parts of the Skagerrak from the mouth of the Langesundfjord and adjacent areas. These very

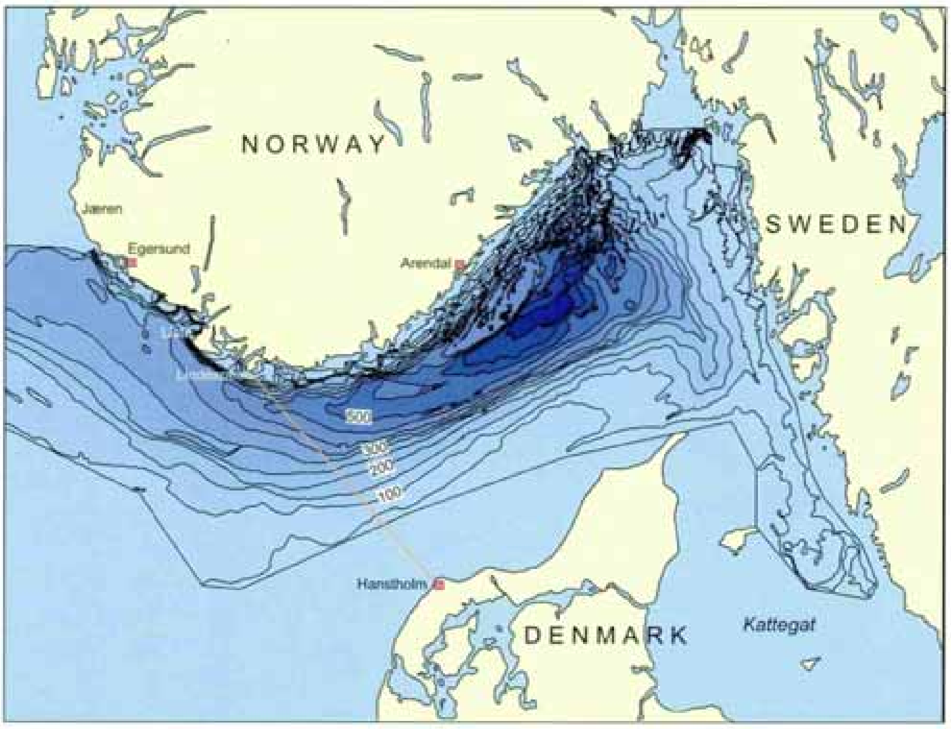


Fig. 4.2 Bathymetry of the Skagerrak and the southern part of the Norwegian Trench. The map is compiled from several data sources, of which recent detailed multi-beam echo sounding from the Skagerrak (Statens Kartverk Sjøkartverket - SKSK, is the most important. The bathymetry in the other areas is based on fishery plotting charts, sea charts and navigation maps in the scale 1:50 000 - 1:350 000 (SKSK, Kort og Matrikkelstyrelsen and Kungliga Sjökartverket).

steep-sided channels can reach depths of up to 300 meters (Fig. 4.2). The deepest parts of the Skagerrak basin have a nearly flat bottom that rises gently towards the southwest.

Oceanography - general circulation pattern of the water masses in the Skagerrak and adjacent areas

The water in the North Sea, including the Skagerrak, and the Baltic Sea consists basically of two components: salt water from the Atlantic Ocean and fresh water derived from precipitation and from rivers which drain large parts of Central and Eastern Europe, Fennoscandia and Great Britain. Most of the water entering the Baltic Sea and the North Sea passes through the Skagerrak (Fig. 4.3). Annually this water volume amounts to 56,700 km³, most of which flows near the surface or at intermediate depths (Fig. 4.4). When the inflow is compared to the volume of the Skagerrak (7 000 km³), this indicates that the water from intermediate depths to the surface is renewed at least eight times every year. This is in contrast to the renewal of the deeper waters, below the sill depth at c. 280 m, which occurs at one- to three-year time intervals.

Almost 90% of the inflowing water derives from the Atlantic Ocean, flowing through the northern North Sea and along the southern flank of the Norwegian Trench (Fig. 4.3). Approximately 9 % of the inflowing water comes from the central and southern North Sea, and c. 1 % is derived from the Baltic Sea (Fig. 4.3). All these water masses meet in the inner Skagerrak and subsequently flow out as the Norwegian Coastal Current (Fig. 4.3).

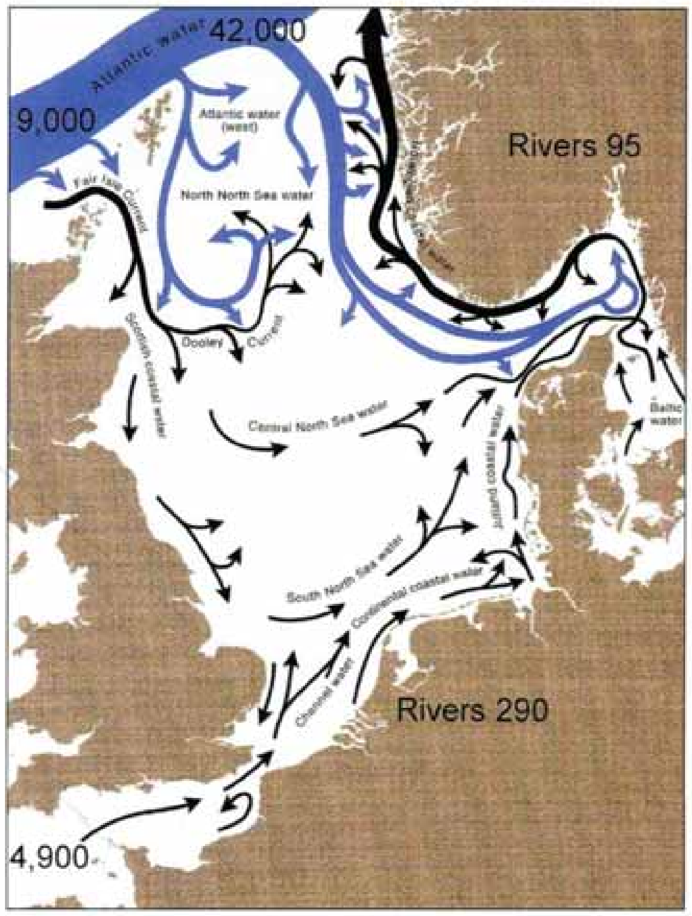


Fig. 4.3 General ocean circulation pattern in the North Sea and the Skagerrak. The width of arrows indicates the magnitude of volume transport. The part of Atlantic water which flows more or less directly into the Skagerrak is shown with blue arrows and those parts which flow in via the North Sea by black arrows. The thick black arrow along the Norwegian coast marks the Norwegian Coastal Current (modified from North Sea Task Force 1993). The numbers give average water inflow (km³/yr) for the different currents (Eisma & Kalf 1987).

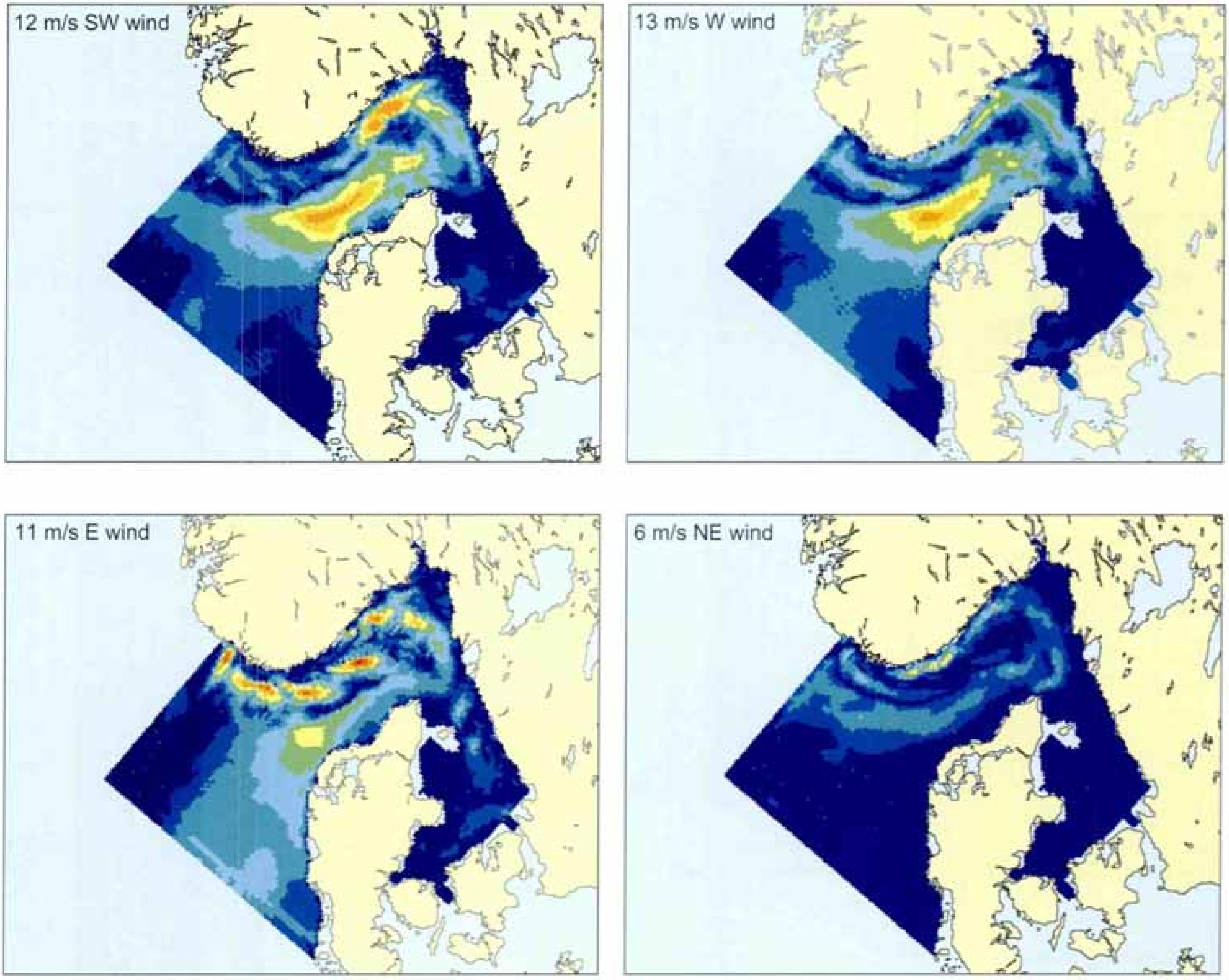


Fig. 4.5 Simulated bottom currents after application of a few days of typical, seasonal wind conditions in the North Sea modelled on the basis of the SKAGEX 1991 data (Svendsen et al. 1996). A: 12 m/s SW wind (early autumn). B: 13 m/s W wind (early autumn). C: 11 m/s E wind (December-April). D: 6 m/s NE wind (December-April).

The currents in the Skagerrak can be subdivided into surface and bottom currents that generally have the same flow directions, while the velocity of the bottom currents is lower than that of the surface currents. The two currents basically form a large-scale, anti-clockwise cyclonic circulation pattern, mainly regulated by the in- and out-flowing water masses and the shape of the Skagerrak basin.

Shifting winds (strength and direction) in the North Sea and the Skagerrak influence the ocean currents. This is particularly the case for the surface currents, but also for the bottom currents. Computer modelling of the bottom currents during four typical, seasonal wind situations in the North Sea (Svendsen et al. 1996 and references therein) illustrates the role of winds (Fig. 4.5 A-D). Westerly gales (SW-W, Fig. 4.5 A,B) are typical for the early autumn. These winds increase the water inflow into the Skagerrak from both the central North Sea and the Atlantic Ocean into the Skagerrak. This results in strong bottom currents along the southern margin of the Norwegian Trench and on the shallow banks north of Denmark. Bottom current velocities on the banks frequently reach 0.3-0.4 m/s with a maximum of c. 0.65 m/s. The strong currents continue into the inner part of the Skagerrak and out along the Norwegian coast in the same vortices pattern as the surface currents. Easterly and northeasterly winds (Fig. 4.5 C,D) are most common from December to April. Easterly winds tend to shift the core of the inflowing Atlantic water towards the north and into deeper water. Winds from the northeast (Fig. 4.5 D) result in weaker bottom currents (maximum 0.1 m/s) but do not influence the general circulation pattern.

4.2 Sediment transport and deposition in the North Sea and the Skagerrak

Although the strength and direction of the currents vary, a fairly constant water flux persists from the North Sea and the Atlantic Ocean to the north of Denmark into the Skagerrak. These currents function as a conveyor-belt to bring sediments to the area (see Box 4.2). The coarsest grains transported in the North Sea are normally sand-sized. Sand constitutes the seabed in the shallow areas where currents are strongest, whereas mud settles in the deep Skagerrak.

Sediment transport into the Skagerrak from the North Sea and the Atlantic Ocean

The North Sea is a highly dynamic water body with strong tidal- and wind-driven currents and strong wave action. These forces keep in suspension the fine-grained particles supplied to the North Sea by rivers and the atmosphere, and also lead to the erosion and resuspension of sea-bed sediments. Erosion of the sea-bed is especially strong in the central-southern parts of the North Sea and along the southwestern margin of the Norwegian Trench towards Denmark. Several areas in the southern North Sea and along the coasts from Britain to Hanstholm in Denmark exhibit annual erosion of up to 600 g/m^2 (North Sea Task Force 1993, Pohlmann & Puls 1994). Because of the frequent strong currents and waves, sediment particles are generally kept in suspension and only temporarily (days to centuries) deposited on the sea-bed. The Oyster Grounds and parts of the German Bight are such recent temporary depocenters.

Increased wind activity in the North Sea over the last 20 to 30 years (Svendsen 1991) may have intensified the strength of the bottom currents in the North Sea. Increased erosion of the sediments at the sea bottom in the North Sea and in the coastal areas and resuspension of previously deposited material are possible consequences of this. Transport of material to the Skagerrak by ocean currents is illustrated by a satellite image from the North Sea from March 1982 (Fig. 4.6).

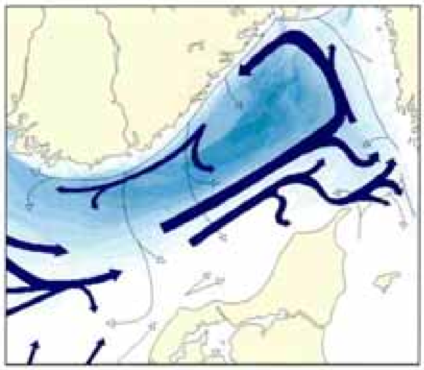


Fig. 4.4 General anti-clockwise cyclonic sea-water circulation in the Skagerrak. Thin lines show surface currents and thick lines the subsurface currents. The surface currents are periodically considerably influenced by the winds, and the situation where surface waters flow from the southeastern coast of Norway to Denmark is not typical. Modified from Danielssen et al. (1991).

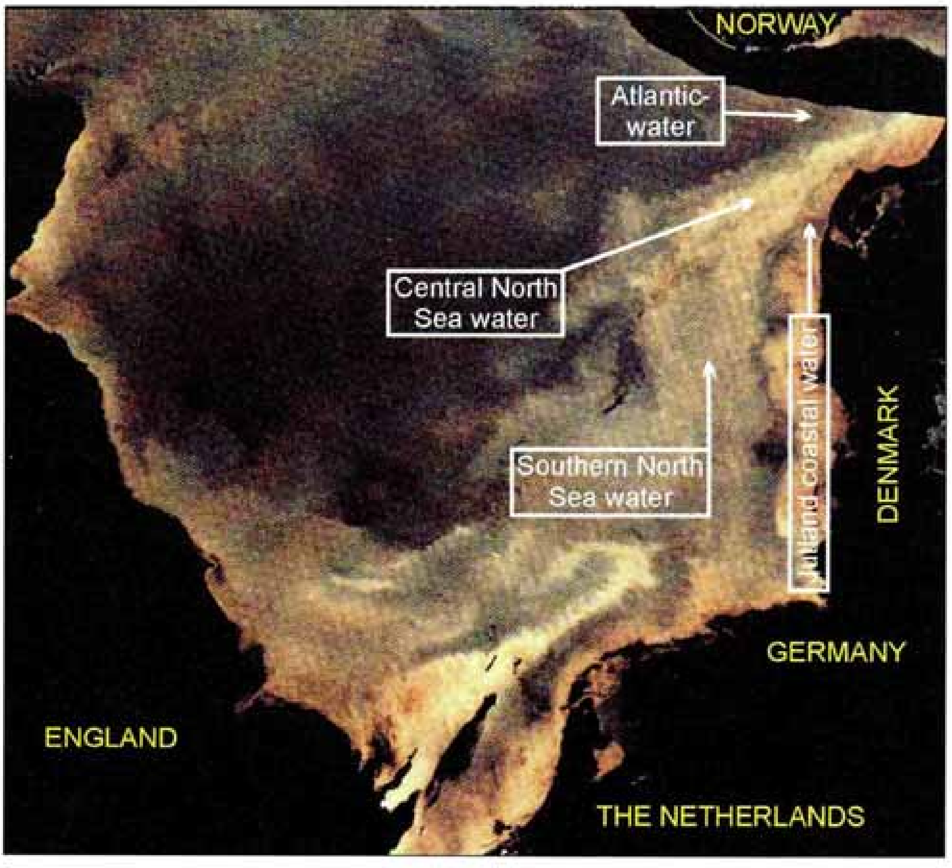


Fig. 4.6 Nimbus-7 satellite CZCS colour composite image obtained in March 1982 shows transport of solids and circulation patterns in the North Sea. Suspended matter distributions and light absorption by chlorophyll and dissolved organic materials are visible. The black field over the Skagerrak is due to lack of data (modified from the North Sea Task Force 1993).

General principles for sediment transport (Box 4.2)

Flowing water is capable of eroding and transporting sediment particles and sorting them by grain size prior to deposition. A sediment particle may be eroded and redeposited several times. The coarsest particles are found where the currents are strongest; sand is deposited where currents are somewhat weaker and mud settles in quiet waters.

When water flows over the sea-bed, the largest grains are moved by traction, during which grains roll or move by saltation (jumping) in a thin layer along the bottom. The second largest grains move in a near-bottom suspension, and the finest particles reside in suspension higher in the water column. As long as particles stay in suspension, they travel at the same velocity as the water, while the bed load travels more slowly than the streaming water.

As the current strength decreases, the capacity of the current to act as a transporting agent is reduced and the sediments are deposited. If the current strength increases, erosion of the sea-bed occurs and deposited particles may be resuspended.

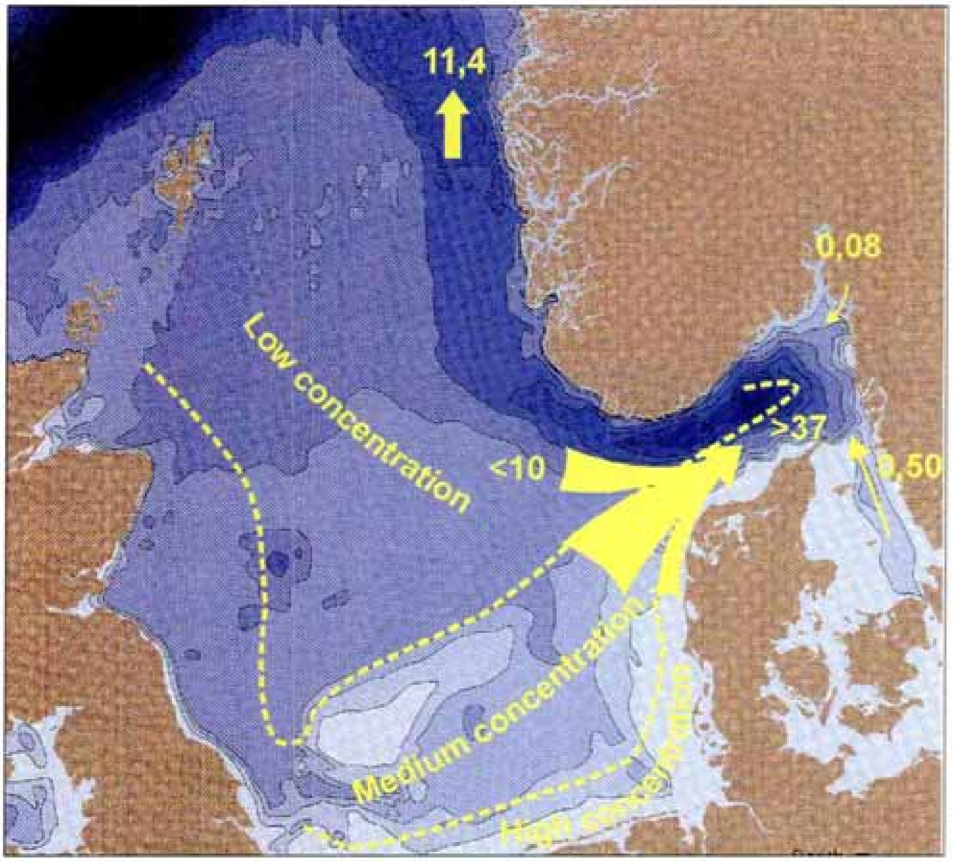


Fig. 4.7 Synthesis of sediment transport estimates (tons/yr) in the North Sea and the Skagerrak based on data from Eisma (1981). The sediment flow from Scandinavian rivers is exemplified by Glomma (0.08 tons/yr). The total annual input of sediments from rivers in this area is estimated to be less than 0.5 million tons.

The image (Fig. 4.6) demonstrates that suspended particles are concentrated in the various currents of the North Sea and are then carried into the Skagerrak to the north of Denmark (Figs. 4.3 and 4.6). The Jutland Coastal Water has the highest concentrations of suspended particles (Eisma 1981), but is a low-volume water body and consequently, delivers less sediments to the Skagerrak than do the waters from the rest of the North Sea (Rodhe & Holt 1996). The Jutland Coastal Water originates in the German Bight and is a mixture of continental river water and water from the southern North Sea. It flows relatively slowly northwards close to the western Danish coast, parallel to the South North Sea water. This current is highly instable; it may be blocked by inflowing Atlantic water for shorter or longer periods and may flow in pulses into the Skagerrak. Sediments brought into suspension in the southern Bight of the North Sea are suggested to take 10 to 15 years to reach the Skagerrak (Liebezeit 1991). The water in the rest of the southern North Sea has lower concentrations of suspended particles but faster flow; thus, it contributes with larger volumes of sediments to the Skagerrak. The water flowing in from the Atlantic Ocean has low concentrations of suspended particles, but since the water volume constitutes more than 90% of all water to the Skagerrak, a significant amount of material is transported in from the Atlantic Ocean and the northern part of the North Sea. Volume estimates for the transport and deposition of fine-grained sediments based on measurements of suspension load have been presented by a number of authors (Eisma & Irion 1988 and references therein). A synthesis of these estimates is presented in Fig. 4.7.

The transport of fine-grained material from the North Sea is demonstrated by studies of clay minerals (and chlorite) from the sea bottom in the North Sea (Zöllmer & Irion 1993). Three different mineral associations can be identified in the sediments: illite+chlorite, kaolinite and smectite. The distribution patterns show that the illite+chlorite association derives from erosion of glacial deposits in the northeastern North Sea, originally deposited by the glaciers from Scandinavia. The kaolonite association seems to originate from an area east of the Dogger Bank and represents sediment transport from Britain towards the Skagerrak over the central southern North Sea. The smectite

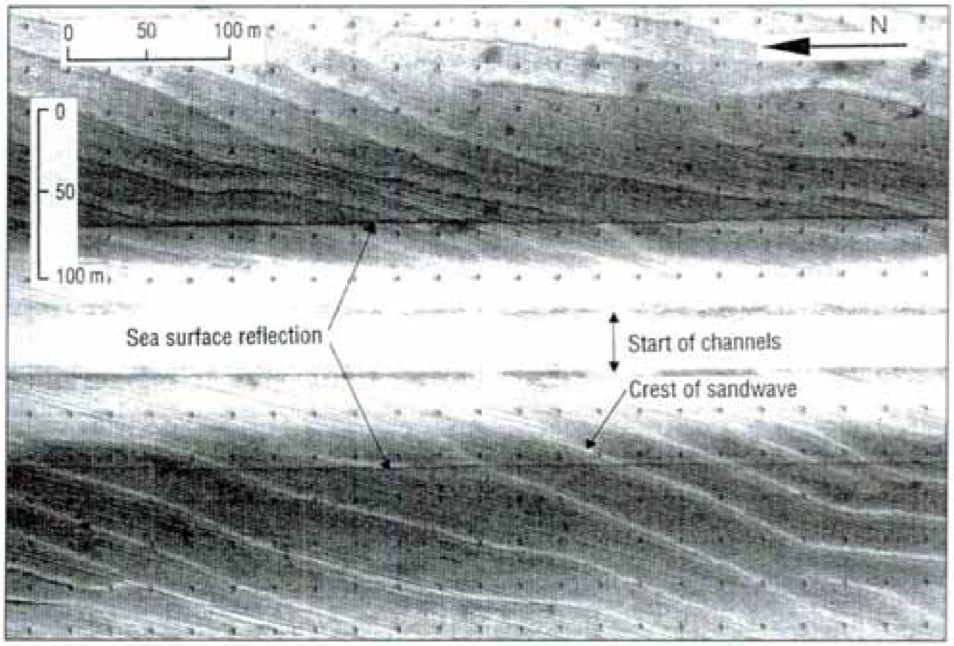


Fig. 4.8 Side-scan sonar example showing migrating sandwaves. The sandwaves are a few meters high with wavelengths in the order of tens of meters. Larger sand dunes with curved crests and broader wavelengths also occur in the area (not shown here).

association comes from erosion and dredging of Tertiary sediments in the southern North Sea and further transport northwards via the Jutland Current.

In addition to the suspension load brought into the Skagerrak, considerable transport of sandy sediments along the bottom occurs. The sand is mainly derived from sea-floor erosion, coastal erosion and rivers. The sand-sized material moves along the sea-bed in the general direction of the bottom currents. Locally, slowly migrating sand dunes and sandwaves are expressions of this sand transport. As an example, sandwaves and sand dunes, occurring in water depths of 85-105 m, have been identified with side-scan sonar data on the sea bottom on the upper southern slope of the Norwegian Trench to the southwest of Lista (Fig. 4.8). These bedforms are presently active and appear to migrate towards the southeast and east, i.e. in the same direction as the inflowing Atlantic water. Active sandwaves are also found in the southern North Sea and to the north of Jutland at water depths shallower than 70 m (Salge & Wong 1988, Kuijpers et al. 1993), from where they migrate towards the northeast with the Jutland Current.

Sediment transport to the Skagerrak from Norway, Sweden and the Kattegat/Baltic Sea

Waters flowing into the Skagerrak from the Baltic Sea and from Swedish and Norwegian rivers carry less suspended matter than the waters originating in the North Sea. This is mainly due to the catchment of sediments in local depocenters, particularly the fjords. Along the eastern and northern Skagerrak coasts, deep waters and hard bedrock prevent coastal erosion; in the Kattegat, the currents are weaker than those in the North Sea and cause less sea bottom erosion. Therefore, the input to the Skagerrak sediments from these sources is almost negligible in the overall sediment budget. The Baltic Sea is rather deep and has a very narrow and shallow sill between Sweden and Denmark. Thus, the Baltic Sea functions as a sediment trap and only minor amounts of suspended matter flow into the Kattegat. The sediment supply from the Baltic Sea to the Skagerrak is c. 0.5 million tons/yr (Eisma 1981), or approximately 1% of the total annual supply to the North Sea, Skagerrak and Kattegat.

The major rivers of Sweden and Norway discharge into sill fjords (fjords overdeepened by glacial erosion, which have a physical bedrock or glacial threshold in their outer parts) which trap most of the sediment load before the water flows into the Skagerrak. However, during spring floods, there is a contribution from rivers emptying their sediment load directly into the Skagerrak, e.g. the Glomma river. Glomma delivers an annual average of 160 000 tons of sediment to the sea. Approximately 50% goes into the Skagerrak, while the rest is deposited in the Glomma estuary (Helland 1996). The total annual contribution of sediments to the Skagerrak from the Baltic Sea and the Scandinavian rivers is less than 1 million tons/yr (Fig. 4.7). Much of this material is deposited in the outer Oslofjord area and along the coasts of Sweden and Norway.

Sediment dynamics within the Skagerrak

The currents in the Skagerrak form an average large-scale circulation pattern (Fig. 4.4), and the major part of deposition occurs below the core of these currents. Based on current velocities and gravitational settling velocities of clay particles, Rodhe & Holt (1996) estimated a settling velocity for clay particles in the Skagerrak water to be 10^{-4}m/s. This means that the time needed for most of the particles to settle to the sea bottom roughly equals the transport time of waters passing through the Skagerrak, thus allowing most of the sediment particles derived from the Atlantic Ocean and the North Sea to settle in the Skagerrak.

Distribution of sediment types in the Skagerrak and the spatial distribution of deposition and erosion areas are closely linked to water depths and the capability of the ocean currents to carry sediments or erode the sea bottom. When the currents entering the Skagerrak from the shallow North Sea (Fig. 4.4) meet deeper water along the southeastern side of the Norwegian Trench, their velocities are reduced. In this way, the currents reduce their capability to transport particles which then begin to settle to the sea bottom. This area is consequently one of the major deposition zones. Traction of sand along the bottom generally ceases in the upper parts of the slope at c. 200 m water depth (Fig. 4.9). In slightly deeper water, silt, transported by traction and in near-

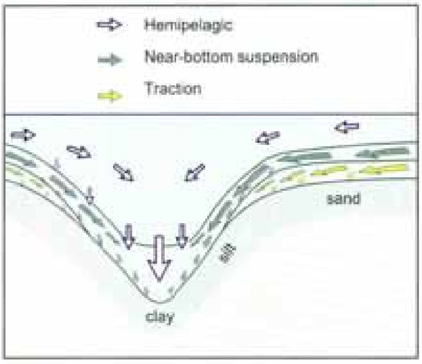


Fig. 4.9 Major sediment transport mechanisms deduced from the particle-size distribution in the sea-bed sediments. The reduction of current strength from the slope to deeper water leads to deposition of sediment particles according to size. With gradual transitions, the following scenario occurs: sand accumulates on top of the slope as traction along the sea-bed ceases; silt falls out of the near bottom suspension at slightly deeper water; clay settles from hemipelagic suspension in quiet water in the deepest parts of the Skagerrak. Modified from Lepland & Stevens (1996).

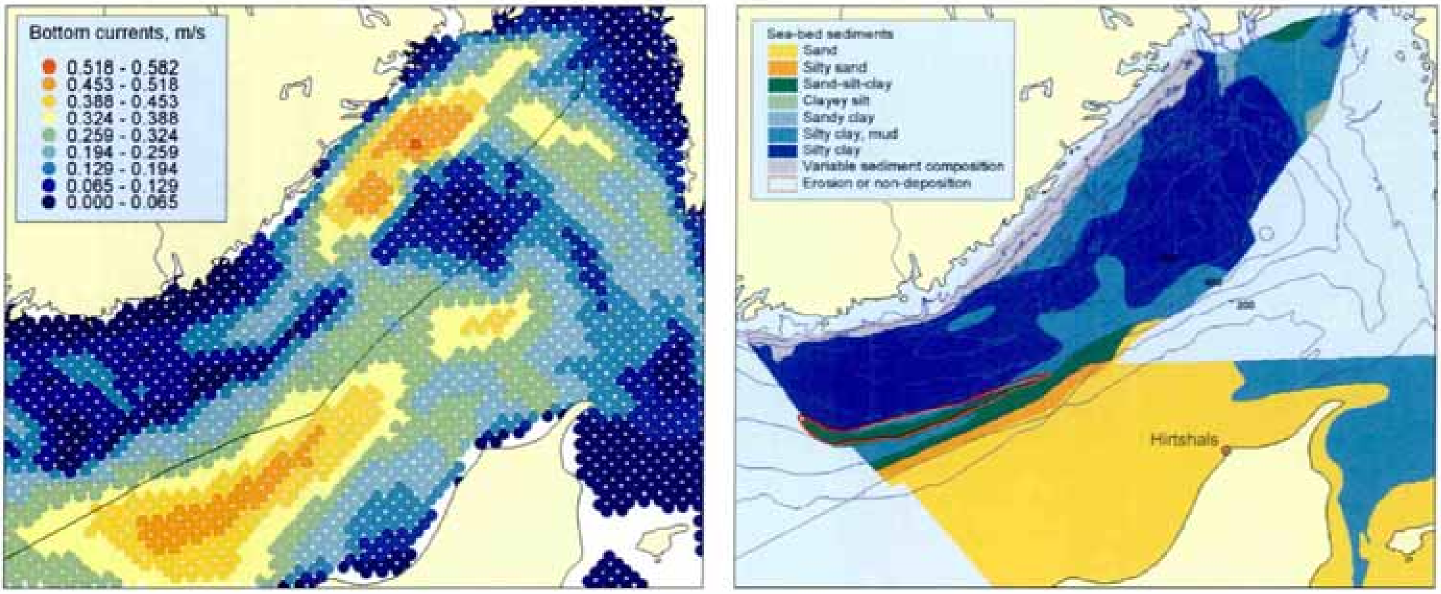


Fig. 4.10 Relationship between bottom currents and sediment types. A: Bottom currents after some days of SW-gales (Svendsen et al. 1996). B: Sea-bed sediment map of the Skagerrak. Note the close correlation between current strength and sediment type. The sea-bed sediment map is compiled from Bøe et al. (1996) and Nielsen (Ed.) 1992.

bottom suspension, occurs and becomes the predominant constituent of the sea-bed sediments. The finest grains slowly settle from suspension in the deeper parts of the Skagerrak basin where currents are weak.

During periods of strong westerly and southwesterly winds (Fig. 4.5), a body of fairly high velocity waters extends obliquely downslope from c. 100 m water depth into the Skagerrak deep, northwest of Hirtshals (Fig. 4.10 A). In the same area, sandy and silty sediments are deposited at water depths greater than average (Fig. 4.10 B), probably due to the periodic, high-velocity currents. In the same area of the southeastern slope, depressions are eroded into the sea bottom. These depressions (see Chapter 4.3 for further details) are elongated in a SW-NE direction and probably reflect a predominant NE flow direction. Erosion or non-deposition (Fig. 4.10 B) occurs between c. 270 and 400 m depth along the southeastern slope of the Norwegian Trench to the west of, and into the area with, the downslope currents described above.

As the water masses turn northward and northwestward in the easternmost part of the Skagerrak (Fig. 4.4), they form a large-scale anti-clockwise whirl where the current velocities are reduced and the waters mix with brackish water from Scandinavia and the Baltic Sea. The mixing of waters with different salinities may cause flocculation, intensifying deposition of suspended matter. The water masses carry a lot of suspended material, much of which is deposited in the northeastern parts of the Skagerrak under the large-scale whirl (Eisma & Kalf 1981). The water masses subsequently continue along the southeastern coast of Norway, become part of the Norwegian Coastal Current (Fig. 4.3) and deposit yet more fine-grained material, particularly in topographic depressions. Coarser-grained and poorly sorted sediments along the coast are interpreted as locally derived erosion products from topographic highs.

Organic matter, with total organic carbon content up to 2.8%, forms an important part of the sediment composition of the Skagerrak. The organic matter consists mainly of carbon from land-derived plants or erosion products from older sediments with a clear flux from the North Sea (Anton et al. 1993 and references therein). Marine plants and animals from the primary production of organic matter within the Skagerrak are generally recirculated within the water column or at the sediment surface (Aure & Dahl 1994), and consequently, are not incorporated into the sediments. The content of organic carbon in the sea-bed sediments has increased over the last decades, possibly indicating increased transport of organic matter from the North Sea or increased primary production due to euthrophication (for further details, see Chapter 5.4 and 6.1). A close link between the ocean currents and sediment distribution (see above) is confirmed by the distribution of organic carbon. There is a clear correlation between organic-rich sediments from the central and northern parts of the

Calculations of the amounts of deposited sedimentary material (Box 4.3)

Calculations of the amounts of deposited sedimentary material (ADSM) were made using the formula below. The calculations are based upon the assumption that each station is representative of a 100 km^2 area surrounding the station.

Formula:
ADSM = sedimentation rate * dry bulk density * 10^6
where the units are:
ADSM - tons pr. year
sedimentation rate - cm pr. year
dry bulk density - g/cm^3

The estimated annual deposition of sedimentary material using this method is 18.6 million tons in the Norwegian part of the Skagerrak.

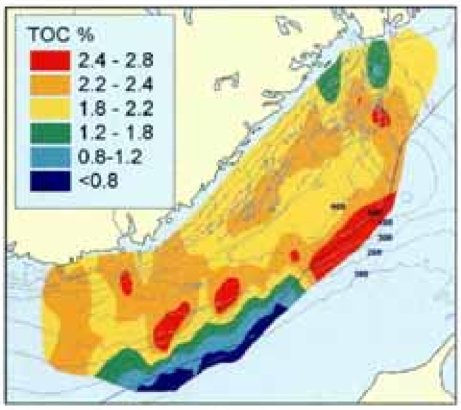


Fig. 4.11 Distribution of total organic carbon (TOC) in sea-bed sediments. The distribution in the central and northern parts of the Skagerrak demonstrates a clear connection between deposition of organic matter and the average large-scale current circulation pattern.

Skagerrak (exceeding 2.2 volume %, Fig. 4.11) and the average large-scale circulation pattern (Fig. 4.4).

The link between the ocean currents and sediment deposition is also demonstrated by studies of the magnetic properties of sediment grains which show a decrease in the grain-size of magnetic grains downstream along the axis of the current. The magnetic studies (Lepland & Stevens in press) also indicate a two-fold division with regard to sediment sources: the North Sea/Atlantic Ocean and the Scandinavian/Baltic provinces (Fig. 4.12). The North Sea/Atlantic Ocean province appears to be totally dominated by sediments deriving from the North Sea/Atlantic Ocean. The Scandinavian/Baltic province is also dominated by North Sea/Atlantic Ocean inputs, but with a significant contribution of sediments from Scandinavia and the Baltic Sea. The contribution from Scandinavia and the Baltic Sea has been estimated by Eisma (1981), and totals less than 15% of all deposited sediments, based on our calculation of sediment deposition in the province (for details with regard to this calculation, see Box 4.3). Therefore, it is likely that particles from the Atlantic Ocean and the North Sea constitute the bulk of the sediments even in the Scandinavian/Baltic province. The reason for the clear magnetic signature in the Scandinavian/Baltic province, despite the fact that the Baltic and Scandinavian sediments constitute just 15% of the bulk sediment, may be that the mineral grains from Scandinavia are,

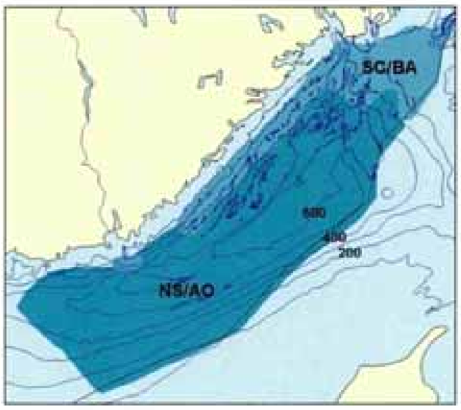


Fig. 4.12 Magnetic properties of the sea-bed sediments indicate two provinces. The North Sea/Atlantic Ocean province is totally dominated by sediments deriving from the North Sea and the Atlantic Ocean, while the Scandinavian/Baltic province receives an estimated c. 15% proportion from the Scandinavian countries and the Baltic Sea, and the remainder from the Atlantic Ocean and the North Sea.

to a large extent, derived from metamorphic and plutonic rocks, in contrast to the sediment particles from the Atlantic Ocean and the North Sea. Clearly, the province division represents a gross simplification of the complicated sedimentation pattern in the Skagerrak, but does provide a useful approach to the tracing of the sediment sources.

Sea-bed sediment densities and the calculated sedimentation rates (Fig. 4.13) suggest that the Norwegian part of the Skagerrak basin receives c. 19 million tons of sediments annually (dry sediment weight) (Box 4.3) of which c. 15 million tons are clay-dominated. This number accords well with estimates made in previous investigations that yielded 17 million tons as a minimum estimate for annual deposition of suspended particles in the Skagerrak and the Norwegian Trench (Eisma & Irion 1988).

Sediment deposition rates

Sediment deposition depends extensively on the ocean currents which may be influenced by meteorological events such as floods and wind. Therefore, sedimentation occurs to a certain extent episodically. Rapid deposition may occur over the course of a few days, and may be subsequently followed by long periods with very little to zero deposition. Through time periods extending over several decades, the sedimentation rates in the

Radiometric dating of sediments from lead and caesium isotope measurements (Box 4.4)

Radiometric dating methods are based on the radioactive properties of certain instable chemical elements. Atomic particles from these elements are emitted in order to achieve a more stable energetic state. Some radioactive elements such as uranium occur naturally and are commonly found in rocks, sediments and fossils. Radioactive decay (atomic transformation) is time-dependent, and if the rate of decay is known, the age of the host sediment or fossil can be established. Rates of radioactive transformation are extremely variable; some elements decay in days or even seconds, whereas others transform gradually over million of years. Two of the «short-lived» radionuclides which can be used to date young sediments are lead with atomic weight 210 (^{210}Pb) and caesium with atomic weight 137 (^{137}Cs).

^{210}Pb is a member of the ^{238}U decay series with a half-life of only 22 years. One product of the decay of ^{226}Ra (radium) is the gas radon which escapes into the atmosphere. Radon decays via a series of short-lived nuclides to ^{210}Pb which is eventually removed from the atmosphere by fall-out precipitation. This unsupported ^{210}Pb, which does not derive from decay of parent nuclides within the sediment, accumulates in lake or ocean sediments where it subsequently decays. Provided a continuous sediment deposition, measurement of ^{210}Pb content can be used to establish rates of sedimentation over a time-scale of the past 110 years or so.

^{137}Cs is a radionuclide that has been introduced to the marine environment by atomic bomb testing, from nuclear reprocessing plants and reactor accidents. The anthropogenic input started with the nuclear industry during the Second World War and large amounts of radioactive matter have been episodically released to nature. One tragic example of this is the Chernobyl disaster in 1986. Such episodes can be recognised in undisturbed sediments as peaks of high caesium activities and used for dating purposes. The caesium isotope has a somewhat greater half-life than the lead isotope (30 years) and can be used in age determinations spanning the last 150 years.

The Skagerrak cores have been dated by a method described by Kunzendorf et al. (1994,1996). The sediment cores were cut into 1 cm thick slices and the radioactivity measured by a gamma spectrometer. Based on the lead and caesium data, the annual sedimentation rates have been determined.

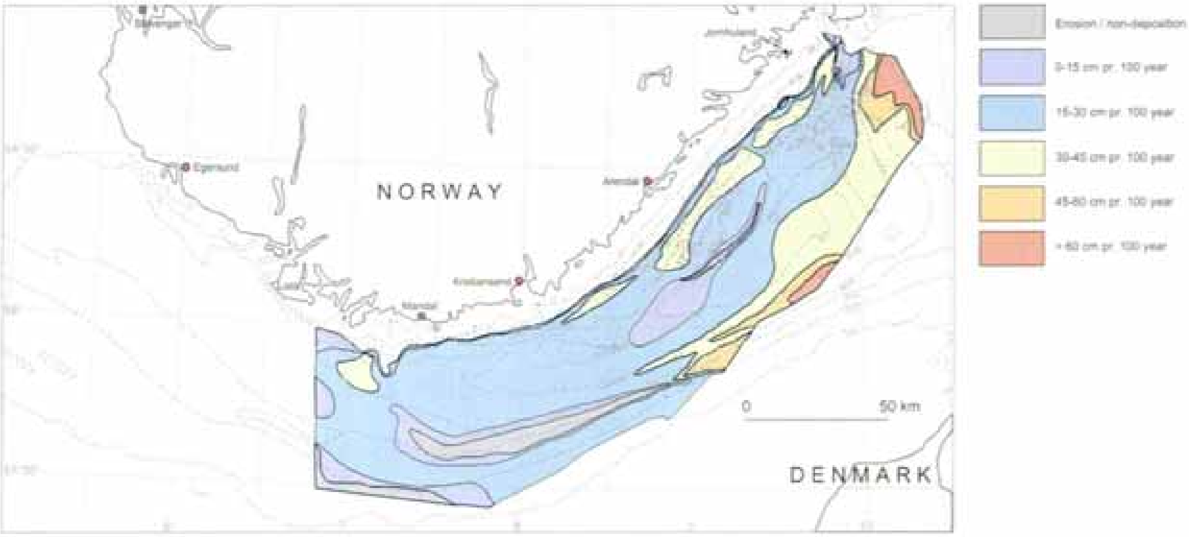


Fig. 4.13 Measured and estimated sedimentation rates in the Norwegian part of the Skagerrak. From Bøe et al. (1996).

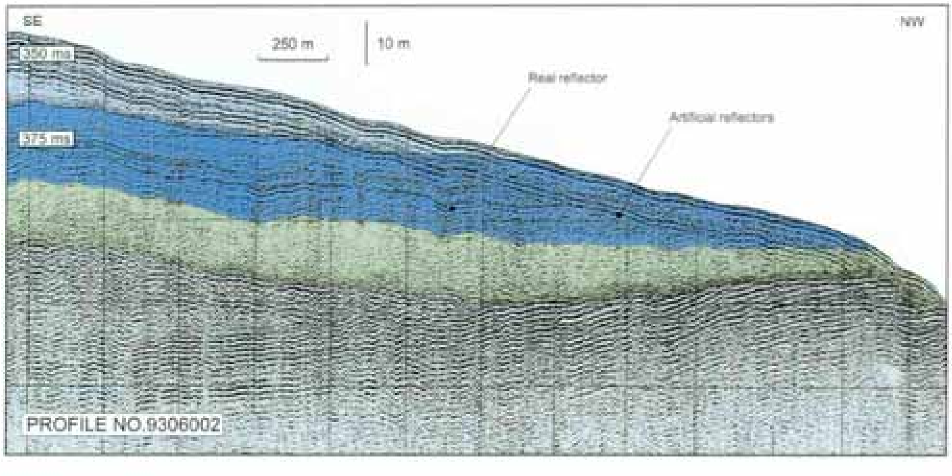
Skagerrak can be regarded as fairly constant; this has likely been the case over the last c. 4 000 years, although Hass (1993) has demonstrated locally large variations in sedimentation rates throughout the last 500 years. However, long-term climatic changes (for instance, glacial versus interglacial conditions - see Chapter 3) will affect the sedimentary environment, and influence the sedimentation pattern drastically (for an example of this, see Chapter 4.3).

Accurate estimates of average sedimentation rates can be achieved by measuring the content of the lead (^{210}Pb) and caesium (^{137}Cs) isotopes in sediments (Kunzendorf et al. 1996 and references therein) (Box 4.4 , Fig. 4.13). Pb- and Cs-radiometric dating was done on a selection of the Skagerrak sediment cores (c. 35 cores, including previously published results). The sedimentation rates for undated stations were derived by interpolation between the dated cores, aided by consideration of Holocene sediment thicknesses (Bøe et al. 1996 and references therein).

On the plateau towards Denmark, fine sands are typically deposited at a rate of 10-20 cm/100 years. Local depressions on the sea-floor indicate that erosion may occur within certain areas. On the southeastern slope of the trench, in Norwegian waters between 9°E and 10°E, recent sedimentation rates of more than 50 cm/100 years are common, and rates up to 98 cm/100 years have been measured. This area is located in the continuation of a major erosion area (Fig. 4.13), from which a certain contribution can be expected. High sedimentation rates further occur all along the southeastern slope of the Norwegian Trench in the inner part of the Skagerrak. Sediment accumulation rates in excess of 100 cm/100 years have been measured on the eastern slope of the Norwegian Trench (Fig. 4.13). In this area, the current velocities are low, likely due to the large anti-clockwise whirl, and are probably the main cause for the high deposition rates. It is also possible that the mixing of saline water masses from the southwest (Atlantic Ocean, North Sea) with dominantly brackish water masses from the Baltic Sea and mainland Norway and Sweden may cause increased flocculation and, therefore, increased deposition rates.

The sedimentation rates along the coast of Norway vary considerably; high sedimentation rates occur in small basins, whereas topographic highs have little deposition or are even sites for erosion. Outside the Norwegian coast, areas with sedimentation rates up to 30 cm/100 years (Fig. 4.13) are indicated by large Holocene thicknesses (Fig. 3.18). The sedimentation rates in the deeper parts of the Norwegian Trench are on the order of 10-20 cm/100 years.

Fig. 4.14 Seismic profile demonstrating the truncation of internal layering in Quaternary and Early Holocene sediments at the sea bottom. Pale green: Cretaceous bedrock; green: Quaternary tills; dark blue: Quaternary glacimarine sediments; light blue: Holocene sediments.



In conclusion, most of the suspended sediment particles that enter the Skagerrak north of Jutland are deposited prior to passing the trench sill west of Jæren (Rodhe & Holt 1996). The Skagerrak is thus the major sink for fine-grained matter in the North Sea; the sediments remain there until, perhaps, new ice ages give rise to glaciers that transport sediments back onto the North Sea plateau or along the trench to the continental slope outside western Norway.

4.3 Sea-bottom instability

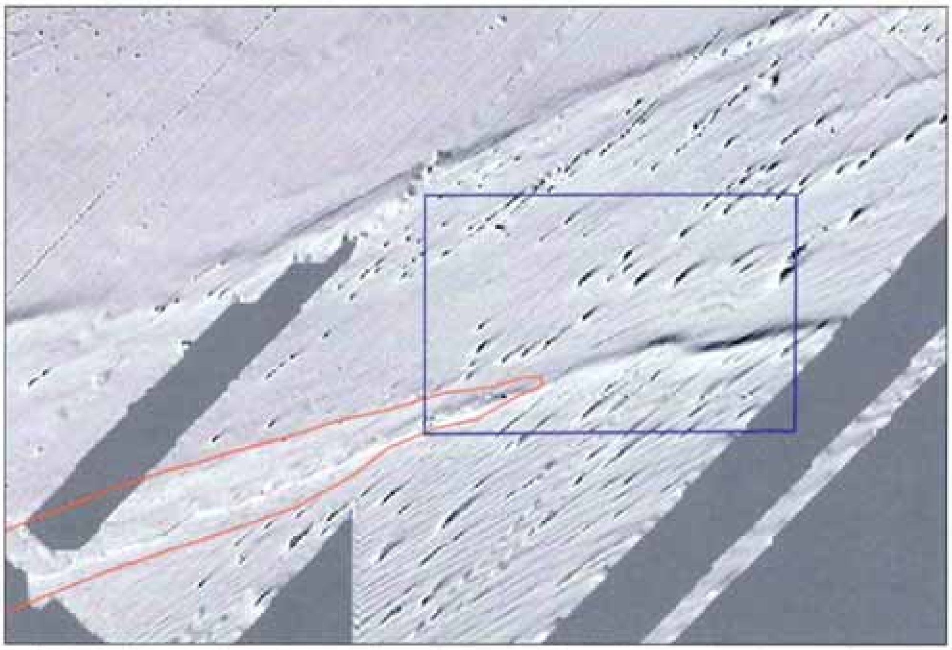
Most of the Norwegian Skagerrak has a net sediment accumulation and relatively stable depositional environment. An exception is located on the southeastern slope of the trench between 8.5° and 9.5° E and represents one of the most rapid deposition centres of recent marine sediments in the world; this area is located very close to another characterised by extensive erosion. Formation of mega-sized current scours occurs in the deposition area and indicates complex spatial and temporal variations in the sedimentary regime. The instability of the sea bottom in these areas with regard to erosion, rapid deposition and slides may represent hazards to technical installations. This should be taken into account when planning cables, pipelines or other offshore constructions in this region. Buried cables, for example, may be exhumed by erosion and made vulnerable to damage from activities like trawling.

Active erosion

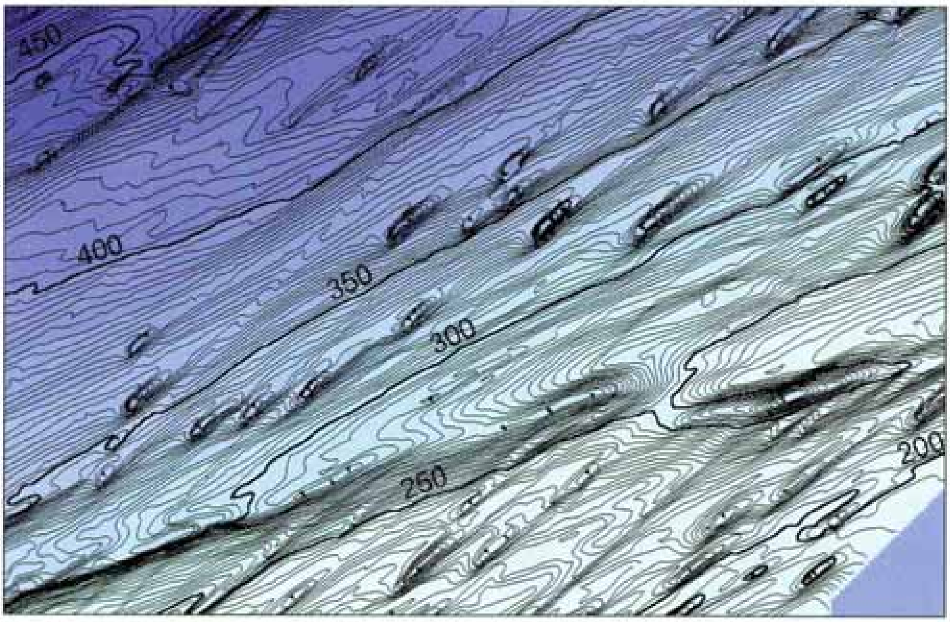
A large area of presently active erosion (c. 530 km²) occurs on the southeastern flank of the Norwegian Trench (Fig. 4.13). The erosion area is wedge-shaped, runs along the escarpment of an outcropping Cretaceous bedrock bench and ends towards the east in a trench more than 20 m deep (Fig. 4.15 A,B, see below). Within the erosion area, Cretaceous sedimentary rocks, Quaternary glacial marine clays and Early Holocene sediments are exposed at the sea bottom; the internal layering of the Quaternary and Early Holocene sediments is truncated at the sea bottom (Fig. 4.14).

The erosion of the Early Holocene sediments indicates a major shift in the sedimentary environment from one of deposition to one of erosion at some stage in the Mid Holocene (7 000-4 000 years B.P.). A significant part of the large sediment volumes deposited in the slope to the northeast of the erosion area may be derived from erosion within this area. This process was probably particularly important immediately after the shift from depositional to erosional conditions occurred, but is less important now. It is likely that the erosion of the sea-bed in this area, and the formation of mega-sized current scours (see below) are related to a complex

Fig. 4.15 Detailed bathymetry and morphology of the erosion/deposition area on the southeastern slope of the Skagerrak basin (for location, see Fig. 3.14 D).



A: Shaded relief image based on multi-beam bathymetry. The red lines outline the area of erosion (see Fig. 3.19), which ends in a channel and extends into an area of thick recent sediments. The current scours are the elongated dark spots on both sides of the erosion area



B: Detailed bathymetric map of the area outlined by the blue square on A (11.5 x 7.3 kilometres). The contour levels are 2 m.

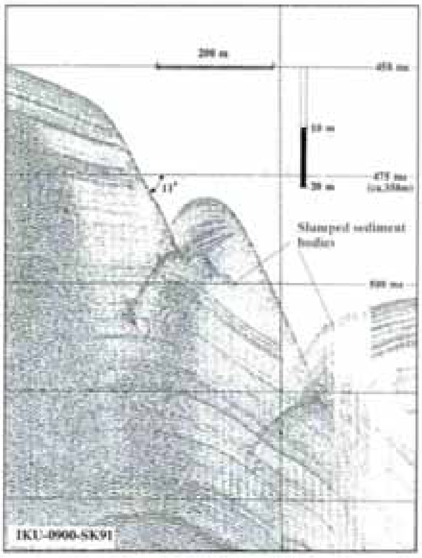


Fig. 4.16 Collapse structure from the upper part of one of the elongated, scoured pockmarks. Note the slumped sediment bodies. Reproduced with permission from IKU Petroleum.

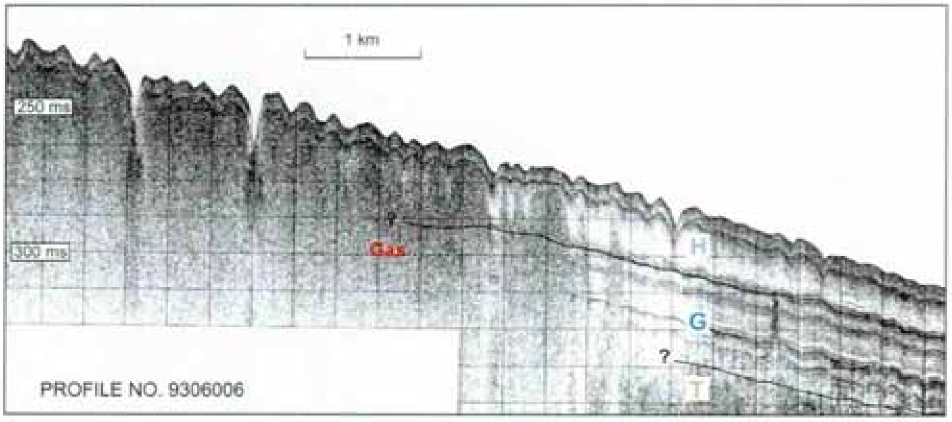


Fig. 4.17 Acoustic blanking caused by shallow gas in the sediment. Notice the deep depressions - the pockmarks - in the surface made by seeping gas. Note that only small amounts of gas in the sediments are needed to cause acoustic blanking on high frequency seismic records.
H: Holocene sediments; G: glacimarine sediments; T: till.

interaction between inflowing Atlantic water, waters deriving from the North Sea and periods of strong, wind-induced currents.

Sea bottom scouring

Very large, elongated, erosional depressions occur on the southeastern slope of the Norwegian Trench (Fig. 4.15 A,B). The depressions are 200-400 m across, and up to 2 km long and 45 m deep. The walls may be very steep, (up to 28°). These depressions have been incised into recent sediments and are oriented downslope in a northwesterly direction slightly oblique to the erosion area.

The depressions trend at an angle of about 20° to the depth contours. They are generally asymmetric, with the steepest scars in the southwestern end. The depressions open towards the northeast, become more gently inclined, and then widen. The morphology clearly indicates that the main current direction during formation of the scours was down-slope, towards the northeast. It is likely, but not demonstrated, that the erosion of the scours is related to the strong bottom currents induced by strong westerly or southwesterly winds. The occurrence of the deep depressions in this area has been related to gas seepage from the sediments or the bedrock beneath the sea bottom (Hempel et al. 1994). Such gas seepages make the sediments more vulnerable to erosion.

Instable slopes

The high sedimentation rates along the southeastern flank of the Skagerrak probably result in relatively high pore pressures and underconsolidated clays. Many of the erosional depressions (see above) of this area appear to have been subjected to sliding (Fig. 4.16), likely due to a combination of steep slopes and the high pore pressures/underconsolidation. The depressions frequently occur in pairs on the steepest sea bottom slope. This may be due to the sediment slides which change the morphology in the immediately surrounding sediments and thus can initiate further erosion.

4.4 Shallow gas and pockmarks

The term shallow gas refers to gas residing in the upper 1000 m of the sediment succession below the sea-bed. Shallow gas consists of methane, usually with minor amounts of heavier alkanes and carbon dioxide, and occurs in all types of sediments. The gas may either be petrogenic (thermogenic), i.e. formed by thermal disintegration of organic matter, or biogenic, produced by bacteriological activity. If gas is trapped in reservoirs of a certain size and permeability, it may represent a hazard to offshore drilling operations (blow-outs) and installations. Such reservoirs are generally associated with sand layers or sand pockets. The presence of gas in sediments or bedrock often causes acoustic blanking (fading of the seismic signals) on high frequency seismic records, and this may be used in the mapping of shallow gas (Fig. 4.17).

Gas in sediments and bedrock

Shallow gas has been mapped regionally both in the northern North Sea (Rokoengen & Tegdan 1983) and in the Skagerrak/Kattegat area (Van Weering 1982, Hovland 1991). Interpretations of seismic data (Fig. 4.17) collected during this project have located shallow gas in sediments in four regions in the Norwegian part of the Skagerrak (Fig. 4.18). These data confirm previous investigations, but also demonstrate the presence of previously unknown areas of shallow gas.

Southeast of Langesund and in the southeastern slope towards Denmark, the acoustic blanking reaches the sea-bed, and gas seems to be evenly distributed in the sediments. The gas occurs in areas of rapid sedimentation and is probably biogenic. In the southern slope, further to the west, the gas signal becomes less distinct and the distribution more discontinuous in the upper layers of the sea-bed. The gas is associated with various types of older Quaternary deposits. Pockets of gas in sandy sediments may exist. Acoustic blanking observed in Mesozoic sedimentary rocks in the Norwegian Trench is likely caused by petrogenic gas. Shallow gas of likely petrogenic origin also occurs in the Quaternary sediments directly above. It should be noted that this area is located just above the central part of the Farsund Basin, which is a potential oil and gas province (Fig. 4.18).

Pockmarks

Pockmarks may be formed where gas and/or pore fluids derived from underlying sediments (or rocks) erupt to the sea-bed. Pockmarks are generally rather circular craters with a diameter of 50-70 m, are commonly 5-8 m deep and are formed in clay, silt and sand (Hovland & Judd 1988).

Concentrations of circular pockmarks are found along three major belts which broadly coincide with the presence of sedimentary rock units of Triassic to Cretaceous age. The concentration of pockmarks in the central, deep portion of the trench coincides with a Jurassic sandstone bed (Sigmond 1992). Above the Farsund Basin (see above, Fig. 4.18), petrogenic gas is indicated in rocks of similar age. The concentration of pockmarks (up to 10 pockmarks per km^2) is probably caused by migration of petrogenic gas from the underlying Jurassic rocks, and seepage through the 20-40 m thick cover of Quaternary sediments (tills covered by glacial marine and Holocene sediments; for further details, see Chapter 3). The till surface is fluted in this area and the pockmarks tend to concentrate on top of the flutes or in the slopes, but not in the main depressions between the flute ridges. This is in contrast to iceberg scoured areas, where the pockmarks generally develop within the groove (Hovland & Judd 1988) as the gas focuses along faults formed in the sediment during scouring.

The elongated current scours on the southeastern slope (Fig. 4.19) are most likely pockmarks modified by ocean cur-

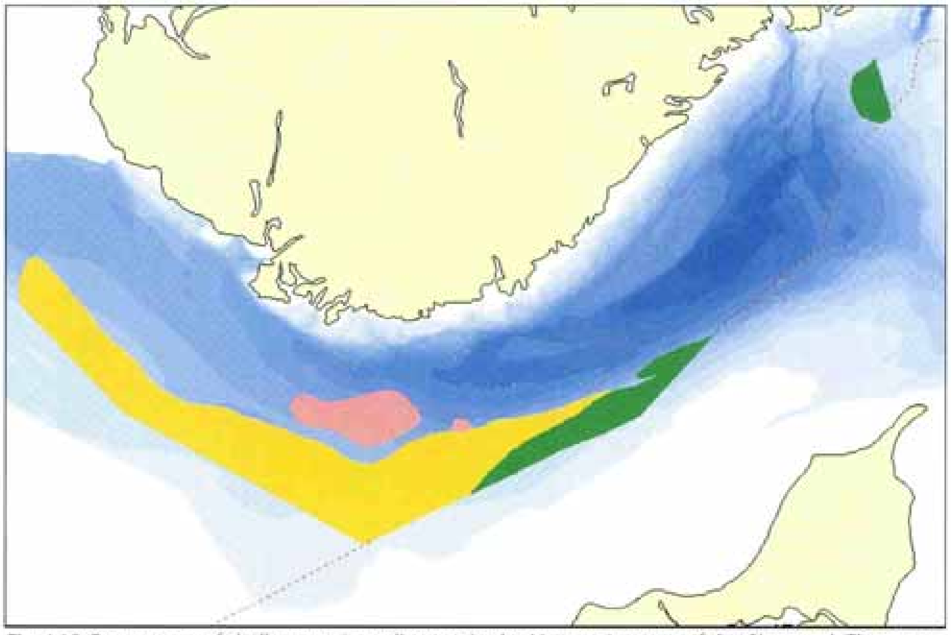


Fig. 4.18 Occurrence of shallow gas in sediments in the Norwegian part of the Skagerrak. The map is based on acoustic blanking determined from seismic data. Green: Shallow biogenic gas throughout the upper part of the sediment column. Yellow: Sporadic gas occurrences, probably biogenic gas derived from old Quaternary deposits. Pink: Petrogenic gas in the Mesozoic sedimentary rocks.

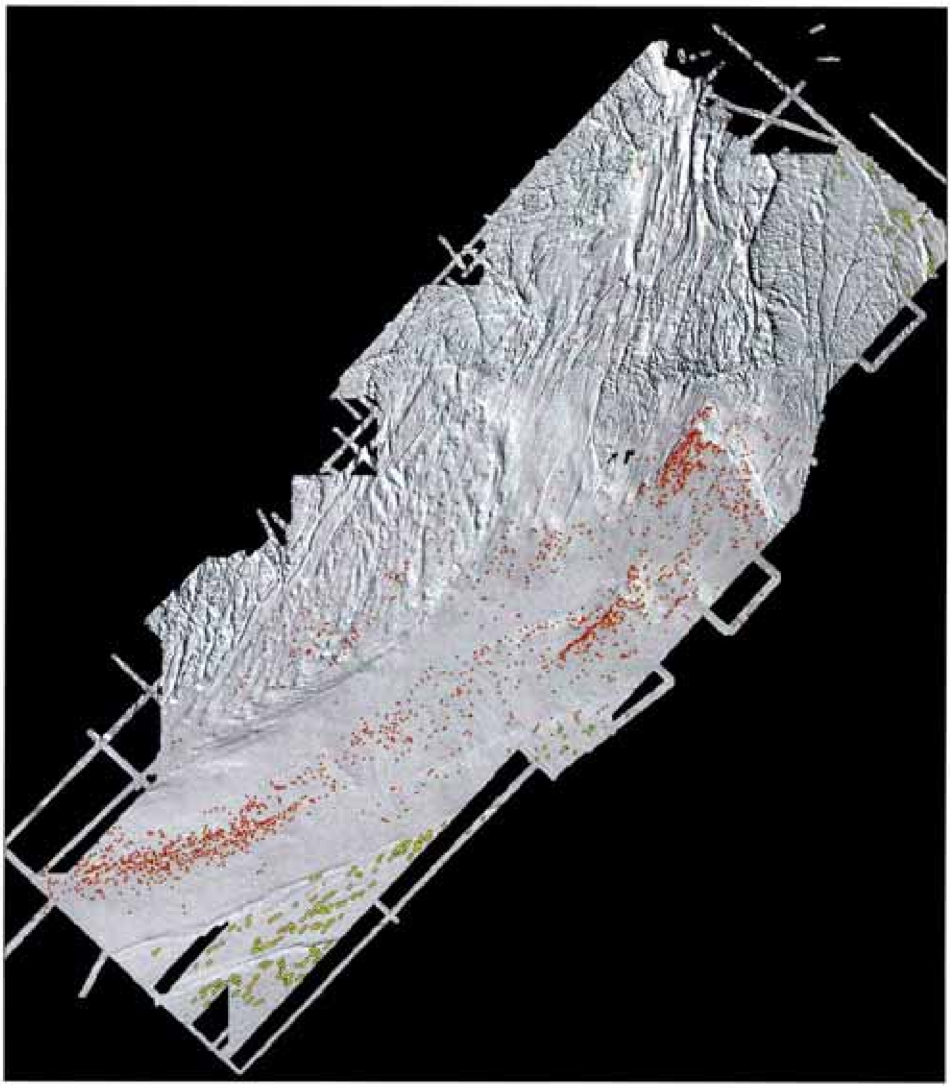


Fig. 4.19 Pockmarks in the Skagerrak. Red triangles represent «normal» pockmarks while the yellow lines show elongated pockmarks modified by current erosion. The majority of the «normal» pockmarks are concentrated along belts which coincide with the underlying Mesozoic rocks (see also Fig. 2.4). Note that the trends of the elongated pockmarks generally coincide with the ocean current directions.

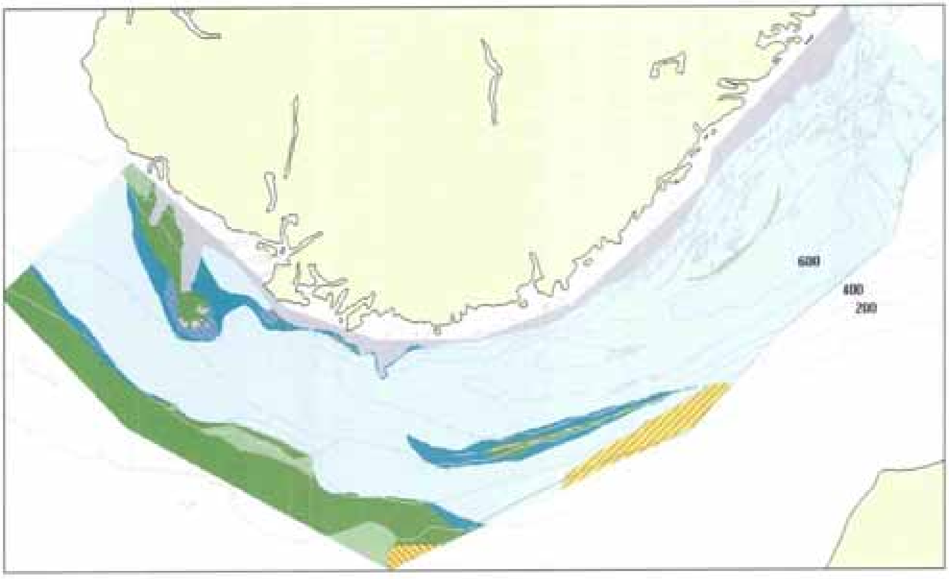


Fig. 4.20 Quaternary deposits in the Norwegian part of the Skagerrak, with division of soil classes relevant for the discussion of geotechnical parameters.

rents (indicated by the coincidence of the pockmark elongation and general current direction). They appear to be aligned along the strike of the underlying Cretaceous rocks, which indicates a petrogenic origin for these features. Deep, elongated depressions in the inner Skagerrak are similarly interpreted as pockmarks modified by ocean currents. These pockmarks are generally elongated in a NW-SE direction, in contrast to the pockmarks on the southeastern slope which have a SW-NE elongation. The pockmarks in the inner Skagerrak occur in acoustically blanked sediments overlying crystalline bedrock, and are likely formed by seepages of biogenic gas.

4.5 Hard and soft sediments - physical and geotechnical properties of the sea-bed sediments

The stiffness of the sea-bed sediments in the Norwegian part of the Skagerrak varies considerably. This has bearing on the design of projects involving sea-bed installations. For example, pipelines and cables usually have to be buried into the sea-bed to avoid damage either to the installations themselves or to fishing gear that is towed over the installations. Since trenching in hard (and stony) sediments is more expensive than in soft sediments, the geotechnical properties of the sediments may strongly influence project budgets.

Geotechnical and physical properties of sea-bed sediments have been investigated in detail during the Skagerrak Project on the basis of 0.5 m long cores (Bøe 1993, 1994, 1995, Rise & Bøe 1995). The marine sediments on the plateau along the Norwegian-Danish median line consist of fine and very fine sand with up to 10% silt and clay (Fig. 4.20). The sandwave succession in this area (sand, relict sandwaves - Fig. 4.20) was deposited at a time when the sea-level was lower (see Chapter 3.3 for further details). It is likely that the sandwaves (a 20-50 m thick succession) are covered by a thin veneer of sand that is more fine-grained than the material in the sandwaves.

At water depths in excess of 150 m, the silt and clay contents of sea-bed sediments increase. Below 300-350 m water depth, the sediments consist of silty clay with a clay percentage in excess of 50% and a sand content of 1-2%. Where silty clay constitutes the sea-bed, the sedimentary regime has probably been semi-stable for a long period (several thousand years), indicating similar sediment types at depth and at the sea-bed.

The undisturbed shear strength of sediments (measured at 30 cm depth below the sea-bed), with a clay content of more than 15% (cohesive sediments) varies from 3-7 kPa, while remoulded shear strength varies from c. 1 kPa to 5 kPa. The highest shear strength values (most compacted sediments) occur in the southwest and locally along the coast of Norway. Wet bulk density of silty clay generally varies around 1.4 g/cm^3, while in the sands along the Norwegian-Danish median line it is in excess of 2.0 g/cm^3. Corresponding values for dry bulk density are 0.5-0.7 g/cm^3 and 1.5 g/cm^3. The water saturation varies from 30 % in the sands along the median line, to 200% in the clays and silty clays; the porosity varies from 45% in the sands to c. 80% in the silty clays. In the thick Holocene succession on the southeastern slope, where the sedimentation rates are high, the pore pressures are probably high and may have resulted in underconsolidated sediments.

The glacial sediments along the southern and southwestern slope consist generally of glacial marine sediments and tills, in which large variations in terms of geotechnical properties may be anticipated. However, no available core information exists (at this time) from these areas, and consequently, it is premature to discuss these properties in any detail.

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5 Contamination of Skagerrak sediments due to man-made inputs during the last 200 years

The concentrations of selected trace metals and polycyclic aromatic hydrocarbons (PAHs) in the Skagerrak sediments are elevated. Although the sediments show normal concentrations of copper, zinc, nickel and chromium, present-day levels of lead and mercury in large parts of the Skagerrak are two to four fold higher than what are considered natural background concentrations. The PAH contents have increased two to four times since 1850. The state of pollution has not been the primary subject of this investigation, but large-scale environmental impact of contaminants and nutrients on the ecosystem has been demonstrated (North Sea Task Force 1993, Magnusson et al. 1996). A significant part of the contaminants derive from the North Sea, with minor contributions from Scandinavian rivers and the Kattegat. A certain input from the offshore oil and gas drilling activities is demonstrated by elevated barium concentrations. The contributions of other trace metals and organic compounds related to petroleum exploration is uncertain.

The sediments in the deepest parts of the Skagerrak will probably still receive high, or even increasing, contaminant loads in the next few decades. The area should therefore be of special interest for future environmental monitoring. Other parts of the Skagerrak, however, indicate a decreased contaminant load in the last few decades. This is probably the result of reduced contaminant discharges to the Skagerrak and the North Sea in this period. Nonetheless, estimates of the contaminant load deposited in the Skagerrak, compared with estimated riverine and airborne inputs to the North Sea, support the concept that the Skagerrak acts as a final sink for a substantial part of the contaminants discharged to the North Sea.

5.1 Contaminants in the Skagerrak and the North Sea - trace metals and PAHs

Contamination and pollution are key words in environmental assessments:

- contamination is defined as concentrations of natural substances clearly above the normal background levels, or elevated concentrations of purely man-made substances.
- pollution is defined as introduction of sufficient amounts of contaminants to the environment to cause negative effects on marine organisms.

The primary objective of this investigation has been to define the levels of contamination.

Metals are naturally occurring compounds which can be found in all parts of the environment. Even uncontaminated sediments contain a certain level of trace metals. At natural levels, metals play an essential role in many biochemical processes. Human activities have, however, increased the rates at which trace metals are introduced into the marine environment and caused elevated levels in water, sediments and biota. This is particularly so for areas close to industrialised countries, like the North Sea. Elevated levels of trace metals can cause negative effects on living organisms. Some trace metals such as lead, mercury and cadmium are readily accumulated in organisms, and are therefore of special concern. Lead and mercury can cause damage to the central nervous system (neurotoxic effects), and cadmium has been connected to the development of different types of cancer in humans. Despite these indications of the health effects associated with exposure to trace metals, the environmental effects are still not fully understood.

Major sources of metals come from activities like mining, the metallurgical industry and combustion processes. Mercury, cadmium, arsenic, lead, copper zinc and nickel are given special attention during investigations performed under the «Oslo and Paris Commissions» (OSPAR). In this report, we focus upon the same metals except for cadmium and arsenic.

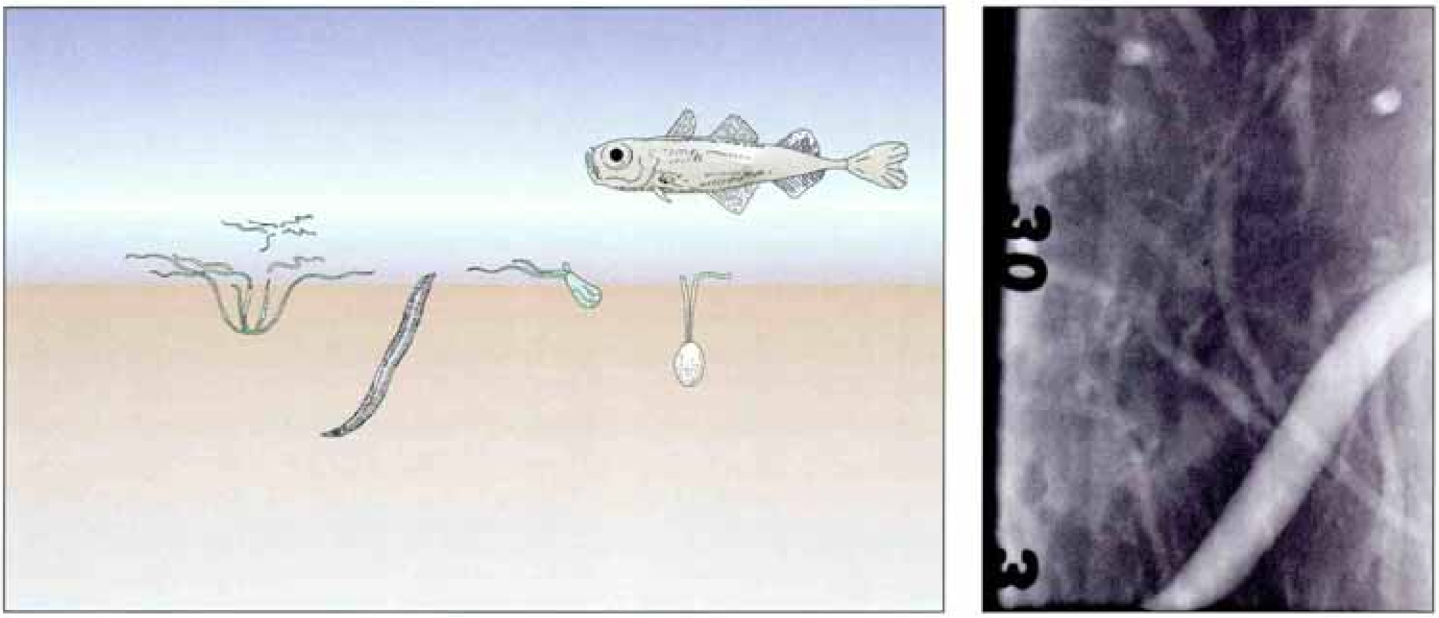


Fig. 5.1 Selected bottom organisms from various water depths in Skagerrak. A: A silvery pout *(Gadiculus thori)* swims above the mud bottom. Fauna in the sediment, from left to right: the brittle star *Amphilepis norvegica*, the polychaete *Orbinia norvegica*, the clams *Nuculuna pernula* and *Abra nitida*. B: The digging of organisms in the sediments leaves traces which can be seen as light grey elongated areas in X-ray photos. The X-ray photo is from c. 30 cm depth below the sea bottom, and is c. 5 cm wide and 8 cm high.

PAHs are recognised as hazardous environmental chemicals capable of inducing biological responses, and several PAHs are well known carcinogens (i.e. causing cancer). These compounds have both natural and anthropogenic sources, though the latter are far more important. Sources include: incomplete combustion of fossil fuels, discharges from manganese and aluminium melting plants and discharges of petroleum and petroleum-derived products. Different sources contribute characteristic mixtures of compounds, often with complex compositions. Low water-solubility and high fat-solubility are typical for PAHs, and these physico-chemical properties are of great importance for their behaviour, especially since highly fat-soluble compounds are readily incorporated into and stored by living organisms.

Polychlorinated biphenyls (PCBs) and some chlorinated pesticides are also important environmental contaminants, and formed part of the analytical programme in this investigation. Results from these analyses were not finished at time of publication of this report and will therefore be published elsewhere.

Sediments - agents for transport and archiving of contaminants

Suspended particulate material acting as a transport agent for contaminants often ends up in sediments, and sediments in deposition areas can be used as an environmental archive, reflecting the load of contaminants in the marine environment through time. Sedimentary basins like the Skagerrak function as traps or «final sinks» for contaminants released to the environment. In this way, large amounts of contaminated material are removed from the water column. However, if the sediments are exposed to mechanical disturbances like trawling, or changed chemical conditions in the near-bottom waters, parts of the contaminants may be released to the water-column and biota. Highly contaminated sediments may thus represent a potential future source of contamination. Since the industrial revolution, contaminants such as trace metals and PAHs from human activities have been extensively discharged to the marine environment through the air and rivers. Many important contaminants have a low solubility in sea-water, and will therefore in sea-water be readily attached (adsorbed) to organic matter, fine-grained particulate material or chemical compounds through complex physical and chemical processes.

The Chernobyl accident in 1986 is a good illustration of this phenomenon. The accident caused massive emissions into the atmosphere of radioactive material that was subsequently deposited over large parts of Europe. The radioactive material was extensively adsorbed to particles and

Bioturbation - a problem for environmental analyses (Box 5.1)

Bioturbation is the term for the mechanical mixing of sediments due to foraging fishes and sediment-dwelling macro- and meiofauna prevailing under aerobic conditions. Examples of such organisms are shown in Fig. 5.1 A. Different benthic organisms display different mixing activity. Because of the variety and complexity of the «turbation» processes it is extremely difficult to gain exact knowledge and quantitative description of bioturbation. The most active bioturbation zone is the upper few centimetres, but recent digging marks from large clams occur down to approximately 30 cm in the Skagerrak. Traces of digging channels/holes can easily be spotted in plexiglass cores or in X-ray photos of core samples (Fig. 5.1 B).

If the sediment has e.g. an upper zone of contaminated material with uncontaminated sediment below, bioturbation will tend to mix the sediments, giving lower contaminant content in the upper zone and «artificial» contamination in the sediments below. This represents a problem for environmental analysis when time trends for the contaminant content in the sediments are calculated.

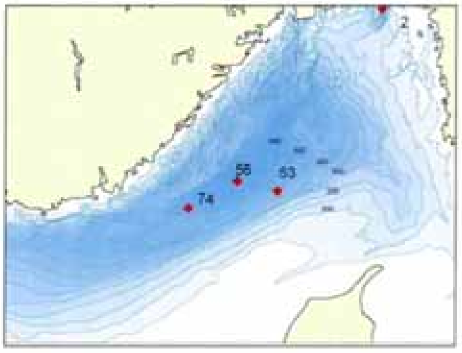


Fig. 5.2 Location of long cores used for definition of element background levels in the Skagerrak.

organic matter, transported to the seas, and finally deposited. In the Skagerrak, sediments deposited soon after the accident have shown clearly elevated levels of radioactive ^{137}Caesium. This example shows that the signal from increased or catastrophic discharges may be rapidly recognised in the sedimentary record.

Many contaminants discharged to the rivers running into the Skagerrak and the North Sea are rapidly adsorbed to particles or organic matter and transported to the marine environment. Most of the material with associated contaminants settles either in some sheltered estuarine areas, like the Wadden Sea or the inner part of the German Bight, or is transported into the Skagerrak and sinks to the bottom in the Norwegian Trench. The transport time for suspended particulate material from the North Sea to the Skagerrak may vary considerably. Water masses from the German Bight carrying suspended material may reach the Kattegat (and the Skagerrak) in less than one year (Kautsky 1985). On the other hand, a sediment transport time from the German Bight to the Skagerrak on the order of 10 to 15 years has been suggested (Liebezeit 1991) in a biomarker study. The wide spread in these estimates stresses the complexity of the particle dynamics in the North Sea. A possible consequence is a considerable delay in the contaminant load signal recorded in the Skagerrak sediments. This is particularly relevant for the detection of reduced contaminant inputs resulting from governmental regulations, because «older» contaminated sediments may still be transported to and deposited in the Skagerrak for several decades after initial contamination on land or in the sea.

In order to use the sediments as an environmental archive, a number of conditions have to be satisfied. The locations should have a continuous record of sedimentation, without major periods of erosion or non-deposition. The erosion area on the southeastern slope of the Norwegian Trench (Chapter 4.3) is one example of an unsuitable location for environmental investigations, as coring here may yield samples deposited 10 000 years B.P., and tell nothing about the present situation. Rapid deposition is required in order to get a sufficient resolution, and the sediments should be undisturbed, i.e. not slumped or disturbed by external activity such as trawling. Extensive bioturbation (see Box 5.1) may cause such a mixing of the sediments deposited at different times, and disturb the contaminant load signal. Well-defined Chernobyl ^{137}Caesium peaks in sediment cores from several stations (Paetzel et al.1994, Kunzendorf et al. 1994, 1996) indicates that sediment mixing caused by bioturbation is generally a minor problem in the Skagerrak, though variations do occur. Sediment cores which do not satisfy these conditions have been excluded from this investigation.

5.2 Background levels: an important basis for the evaluation of anthropogenic inputs

Prior to the start of the Skagerrak Project, only a few measurements of trace metal background levels from this area were available. Background levels are defined as the natural concentration of elements in sediments which have no anthropogenic inputs. Background levels vary, and are most often given as intervals for each parameter. In order to calculate contamination levels (Chapter 5.3), we have chosen one representative value within the intervals. Natural elements are defined as all elements produced by biosynthesis, or natural geochemical or chemical processes. Reliable background levels of natural elements in sediments were necessary in order to establish the level of anthropogenic input to the sediments. Furthermore, because differences in analytical methods may yield results that are not comparable, it was necessary to establish background levels using the same analytical methods for core samples as for recently deposited sediments. Sediments deposited in the region prior to c. year 1850 were analysed to establish these background values. Four three-meter long

Methods - sampling and analysis (Box 5.2)

In this investigation, a total of 133 locations were sampled using either a Niemisto corer or a Multicorer, both of which take c. 50 cm long cores of the sediments immediately below the sea bottom. This coring technique yields sediment samples from the last few hundred years, except in areas with high deposition rates. These coring devices take virtually undisturbed cores, and preserve the internal layering in the sediments and the sediment/water interface. Immediately after being placed on the shipdeck, the cores were sub-sampled according to pre-defined criteria and then frozen. The standard procedure for trace metal analysis in this work included grinding of the sediment sample, partial dissolution by strong acid (nitric acid - 7N HNO_3) and then analysis with standard instruments such as ICP-AES (Inductively Coupled Plasma - Atomic Emission Spectrometry) and AAS (Atomic Absorption Spectrometry). The analyses of trace metals were performed in the laboratory of the Geological Survey of Norway, Trondheim, which is accredited by the Norwegian Metrology and Accreditation Service according to NS-EN 45001, under accreditation number P020, for chemical, sedimentological and mineralogical testing. The analysis of a selection of PAHs was performed in the laboratory of the Institute of Marine Research, Bergen, using gas chromatography mass spectrometry (GC/MS)(Klungsøyr et al. 1988).

cores from the outer part of the Oslofjord and the deepest parts of the Skagerrak as far southwest as Arendal (Fig. 5.2) were analysed. The sediments in the cores were all fine-grained, with more than 90% clay+silt content, and a clay:silt ratio exceeding 1.

The depth of the cores has been converted to a time scale, based on measured and estimated sedimentation rates, starting at year 1500 and ending at the present - 1990 (Fig. 5.3) (for details regarding the conversion of core depths to the time scale, see Box 5.4 below). Sediments deposited before 1850 were selected for definition of the background levels and the median value of the analytical results was chosen (n=97) in order to obtain a discrete number (Table 5.1) which could be used for the calculation of the contamination levels. The intervals for the natural variation are shown by the minimum and maximum levels (Table 5.1). The concentration profiles (Fig. 5.3) show that the levels for copper, lead, zinc, and mercury were low and fairly constant prior to c. 1850, even though local variations did occur. From c. 1850, the concentrations of most elements show a variable, but steady, increase until present day. The reasonably constant levels of elements prior to 1850, i.e. prior to the industrial revolution, indicate consistent sediment input during the 1500-1850 time interval. Barium showed a different profile (Fig. 5.3), with fairly stable concentrations up to 1970, and subsequent strong increase towards present day. The observations with regards to the trace metals are in accordance with previous investigations in the North Sea and the Kattegat (e.g. Cato 1977, Förstner 1980).

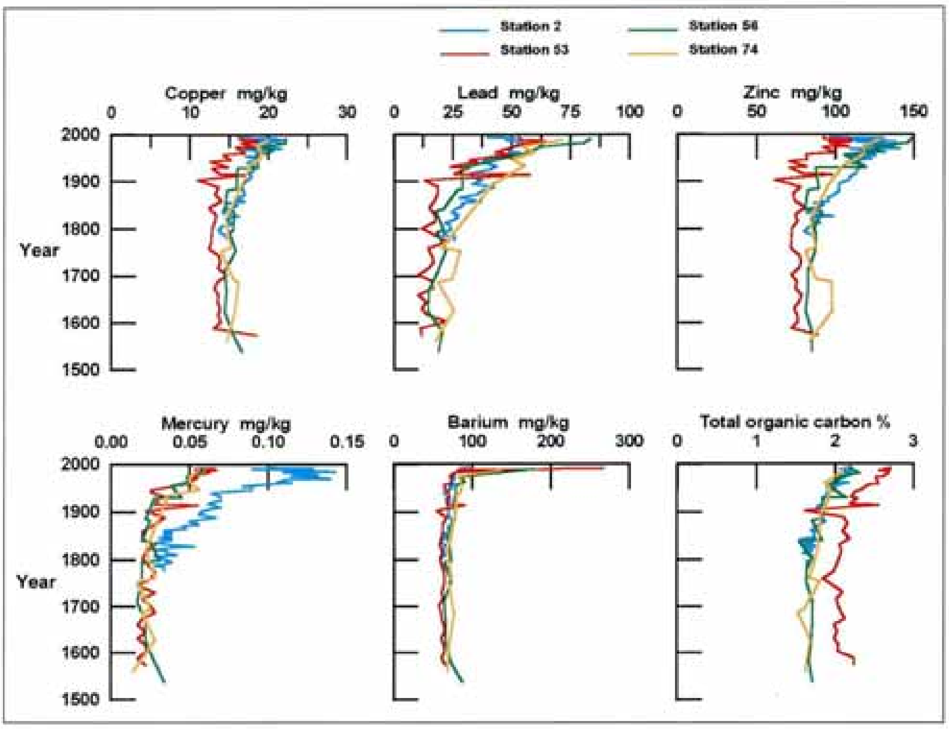


Fig. 5.3 Element concentration of copper, lead, zinc, mercury, barium and total organic carbon from four long cores, from year 1500 to present.

Trace metals

Based on the long cores, background values for copper, lead, zinc, mercury, nickel, chromium and barium were established (Table 5.1). In order to compare our data with other environmental investigations such as the 1990/91 Baseline Study of Contaminants in the North Sea (ICES 1995), the analytical results which used partial dissolution techniques have been recalculated to show the estimated concentration levels for total dissolution (for details see Box 5.3).

A comparison with values compiled by Laane (1992) and Müller & Irion (1984) shows that the background values from this investigation are generally equal to, or slightly higher than, previously reported background values for sediments in the Humber estuary, the Wadden Sea, along the Norwegian coast and earlier Skagerrak estimates (Table 5.3). It should be stressed that the values in Table 5.3 are not exact values, but approximations.

	Background value (mg/kg)	Minimum value (mg/kg)	Maximum value (mg/kg)
Copper	15 (23)	12 (20)	19 (27)
Lead	18 (27)	9 (19)	30 (38)
Zinc	85 (146)	72 (132)	99 (161)
Mercury	0.028 (0.047)	0.014 (0.035)	0.053 (0.069)
Barium	73 (392)	57 (375)	98 (418)
Chromium	51 (105)	44 (98)	59 (114)
Nickel	37 (45)	29 (39)	46 (52)

Table 5.1 Background values and intervals (minimum and maximum values) for selected trace metals in the Skagerrak. Numbers in parentheses give values recalculated to estimate results from total dissolution technique (see Box 5.3)

Comparison of partial and total dissolution techniques (Box 5.3)

Analysis of geological material based on partial dissolution, as in this investigation, will result in lower concentrations for many of the measured elements, in comparison to concentrations derived from total dissolution techniques that use hydrofluoric acid. In order to compare the effects of the different dissolution techniques, 25 samples were analysed using both partial and total dissolution methods. A good correlation was shown for all relevant metals except nickel and cadmium (Table 5.2). For cadmium, the poor correlation is due to analytical limitations, and is not a result of the different analytical techniques. For nickel, the low correlation coefficient is due to the limited value range.

A bivariate plot with the concentrations using partial and total dissolution techniques along the X and Y axes demonstrates a good correlation for the elements mercury and lead (Fig. 5.4). The total dissolution technique gave consistently slightly higher concentrations, than those from partial dissolution; this is apparent when concentrations from both methods are compared at different levels in one core (Fig. 5.5).

The good correlation and rather small difference in measured concentration levels for copper, lead, zinc, mercury and chromium is likely due to the fine-grained nature of the Skagerrak sediments (mainly clay and silt), which are nearly totally dissolved even with 7N nitric acid. For coarser-grained sediments like sands, a larger deviation can be expected, because larger proportions of the trace metals reside within the mineral grains themselves and are difficult to dissolve when 7N nitric acid is used. For fine-grained sediments like silt and clay, a high proportion of trace metals will be adsorbed to the surface of clay minerals, and are thus loosely bonded to the clay minerals or associated with the organic matter. A major part of the trace metals in this case are readily dissolved, also when using acids like 7N nitric acid. For barium, the results based on the total dissolution method are considerably, but consistently, higher than the results which used the partial dissolution method.

Table 5.2 Correlation coefficients, slopes and intercepts for selected trace metals, using partial and total dissolution techniques. Quoted errors are standard deviations (1σ).

	Correlation coefficient	Slope	Intercept
Copper	0.79	0.82 ± 0.13	11 ± 2
Lead	0.91	0.89 ± 0.08	11 ± 4
Zinc	0.91	1.10 ± 0.10	53 ± 10
Mercury	0.88	0.89 ± 0.09	0.022 ± 0.007
Barium	0.83	1.05 ± 0.15	315 ± 18
Chromium	0.82	1.13 ± 0.16	48 ± 8
Nickel	0.36	0.79 ± 0.41	16 ± 13
Cadmium	0.17	0.08 ± 0.10	0.09 ± 0.03

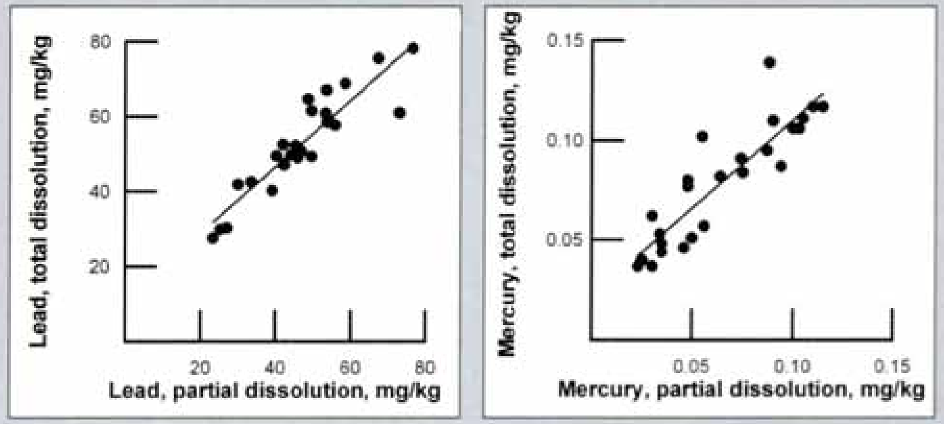


Fig. 5.4 Comparison of analyses using partial and total dissolution techniques for lead and mercury. The line of best linear fit is shown.

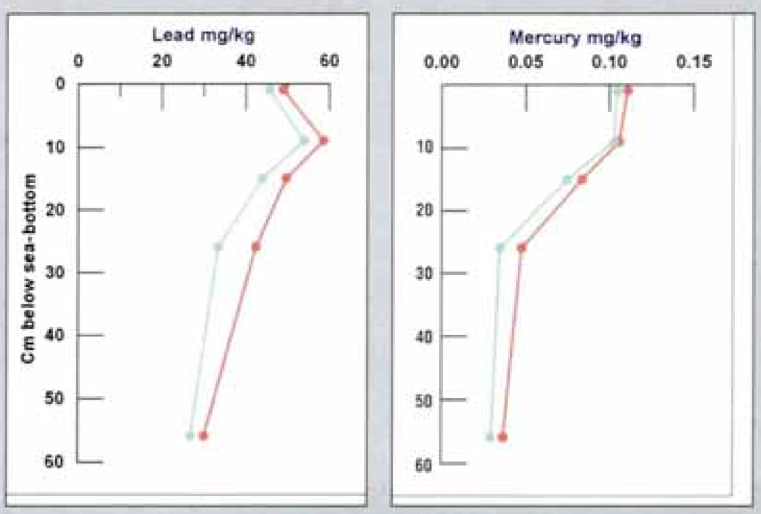


Fig. 5.5 Measured concentrations versus depth below the sea bottom from station 4 for lead and mercury levels using partial (green lines) and total (red lines) dissolution techniques. Note slightly higher values for the concentrations which used total dissolution techniques, and the consistency in the trends.

This analytical comparison implies that the results from the partial dissolution method can be meaningfully recalculated to produce numbers comparable to those in environmental investigations where total dissolution techniques were employed.

Table 5.3 Background values from other investigations in the North Sea and the Skagerrak (from Laane 1992[1] and Müller & Irion 1984[2]).

	Earth's crust (mg/kg)[1]	Sediments Humber (mg/kg)[1]	Sediments Wadden Sea (mg/kg)[1]	Sediments Norwegian coast (mg/kg)[1]	Sediments Skagerrak[2]
Copper	32	17	22±2.0	17±5.9	24
Lead	16	22	37±2.9	26±9.5	65
Zinc	127	84	103±5.2	110±27	137
Mercury	n.a.	n.a.	0.067±0.009	0.04±0.03	n.a.
Chromium	71	99	84±0.5	n.a.	83
Nickel	49	38	37±1.2	n.a.	55

n.a. - not available

PAHs

Incomplete combustion of organic material has been an important source of PAHs through history; volcanic activity and forest fires have been consistent PAH producers, while human use of fire has gradually increased the anthropogenic PAH input to the environment. True background concentrations of PAHs are thus difficult to define since these compounds have been transported to the oceans for thousands of years. Analysis of the short sediment cores collected in this study, therefore, do not represent «pristine» background concentrations, but rather facilitate comparison between pre-industrial PAH levels and those of the present day. The mean concentrations of PAHs in sediments deposited between 1750 and 1850 are shown in Table 5.4, and represent data from 21 stations in the Skagerrak. The stations selected contained fine-grained sediments (clay+silt >90 % and clay>silt) and were from water depths exceeding 400 m. Individual compounds had mean concentrations from 2.5 to 130 ng/g dry

	1850		1990	
	Mean	Range	Mean	Range
Naphthalene	13	2.0-20	43	19-83
C_1-Naphthalenes	40	8.1-65	120	42-190
C_2-Naphthalenes	67	17-97	180	71-250
C_3-Naphthalenes	54	15-77	150	56-210
Fluorene	5.6	2.1-7.3	16	6.8-25
Phenanthrene	33	13-49	100	49-140
C_1-Phenanthrenes	45	17-70	120	50-170
C_2-Phenanthrenes	40	15-56	120	53-180
Anthracene	2.5	0.8-6.0	13	7.8-17
Dibenzothiophene	3.3	1.0-13	9.4	4.7-14
C_1-Dibenzothiophenes	3.8	1.0-6.8	10	2.6-20
C_2-Dibenzothiophenes	7.3	3.2-10	46	15-320
C_3-Dibenzothiophenes	5.8	2.6-11	26	15-42
Fluoranthene	43	11-115	170	84-240
Pyrene	30	9.1-72	130	52-170
Benz[*a*]anthracene	20	5.2-50	82	34-110
Chrysene	30	10-67	130	60-190
Benz[*b/j/k*]fluoranthenes	130	32-320	490	280-950
Benzo[*e*]pyrene	52	16-110	180	110-260
Benzo[*a*]pyrene	24	6.8-54	100	60-140
Perylene	26	9.2-45	45	17-78
Indeno[*1,2,3-cd*]pyrene	54	10-160	270	120-980
Benzo[*ghi*]perylene	48	15-120	220	100-820
Dibenz[*a,c/a,h*]anthracenes	3.6	0.7-14	27	7.5-110

Table 5.4 Mean concentrations (ng/g dw) of selected PAHs in fine-grained sediments deposited between c. 1750 and 1850 (n=21) and in c. 1990 (n=39).

Fig. 5.6 A-F Contamination levels for selected trace metals. A: copper; B: lead; C: zinc; D: mercury; E: chromium; F: barium. Please note that only barium has contamination levels exceeding 5. Element concentration maps for selected elements in the surface sediments are shown in Chapter 5.5.

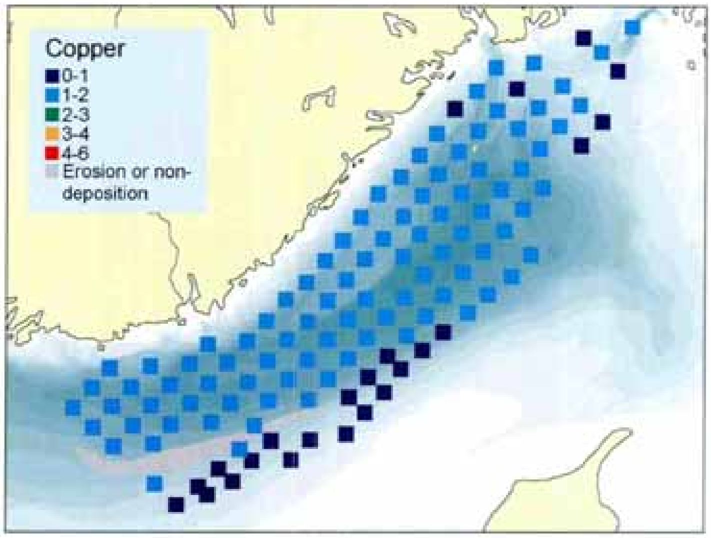


Fig. 5.6 A

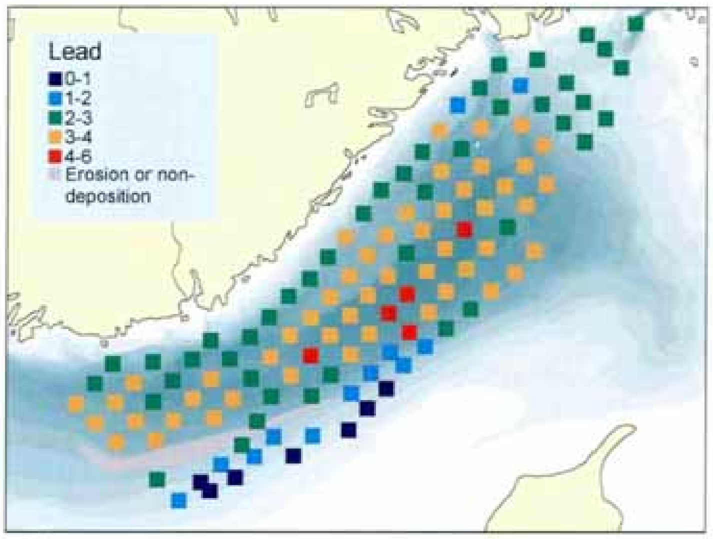


Fig. 5.6 B

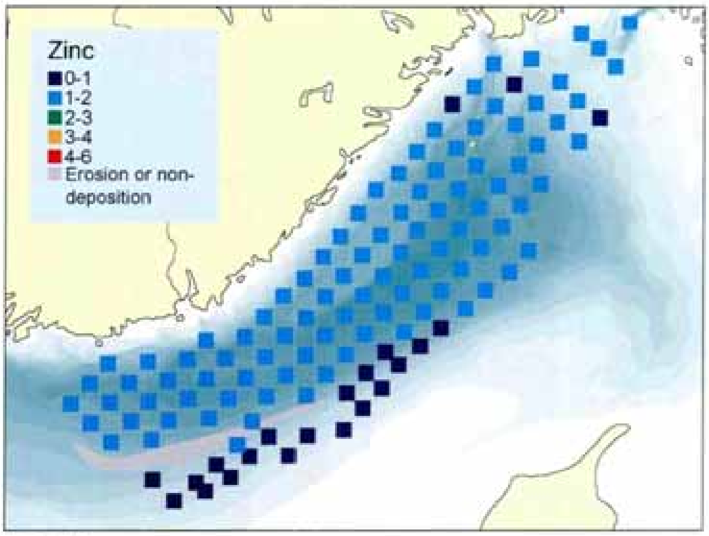


Fig. 5.6 C

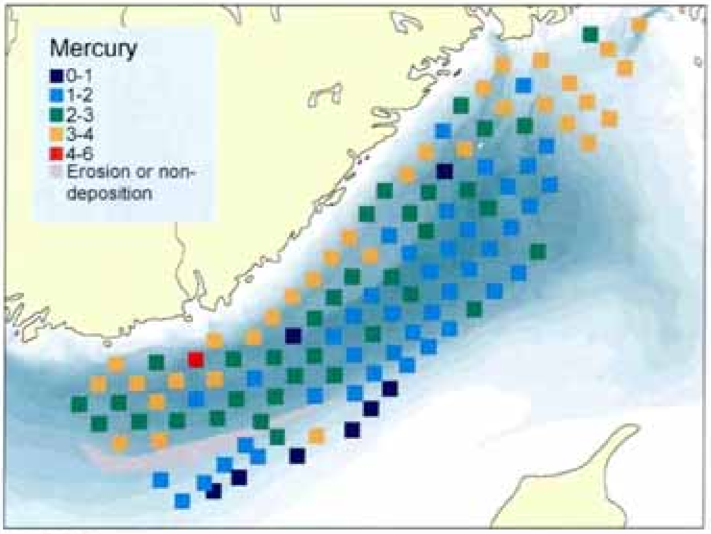


Fig. 5.6 D

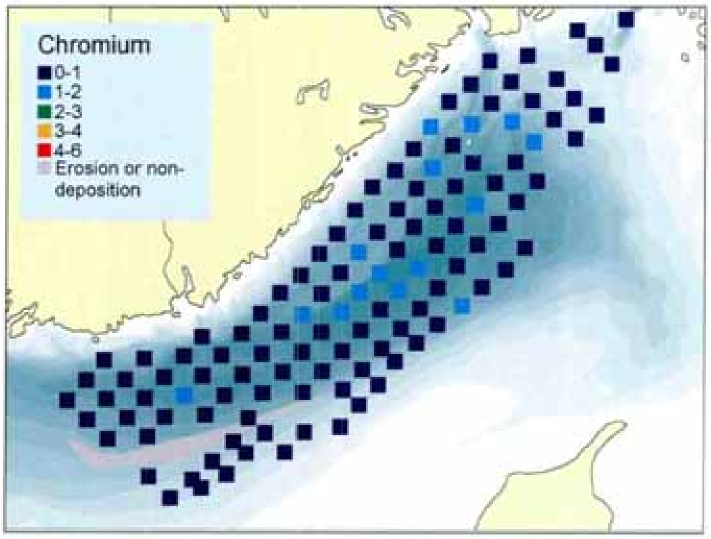


Fig. 5.6 E

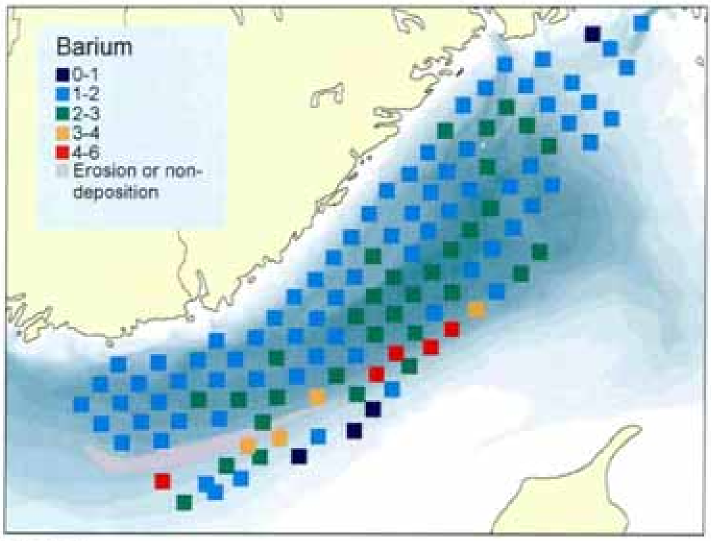


Fig. 5.6 F

Table 5.5 Trace metal contents corresponding to the contamination levels used in Fig. 5.6 A-F. The mean contamination level represents the average of all stations in the Skagerrak. The maximum contamination level is from the station with highest contamination for the particular trace metal.

Contamination levels	1-2	2-3	3-4	4-6	Mean	Max
Copper (mg/kg)	15-30	30-45	45-60	60-90	1.1	1.8
Lead (mg/kg)	18-36	36-54	54-72	72-108	2.8	4.7
Zinc (mg/kg)	85-170	170-255	255-340	340-510	1.2	1.8
Mercury (mg/kg)	0.028-0.056	0.056-0.084	0.084-0.112	0.112-0.168	2.3	4
Barium (mg/kg)	73-146	146-219	219-292	365-438	2	5.9
Chromium (mg/kg)	51-102	102-153	153-204	204-306	0.9	1.1
Nickel (mg/kg)	37-74	74-111	111-148	148-222	0.8	1.2

weight (dw). The relatively high levels of PAHs indicate that the sediments in the Skagerrak were already influenced by human activity as much as 150 years ago.

5.3 Contamination in the Skagerrak at present

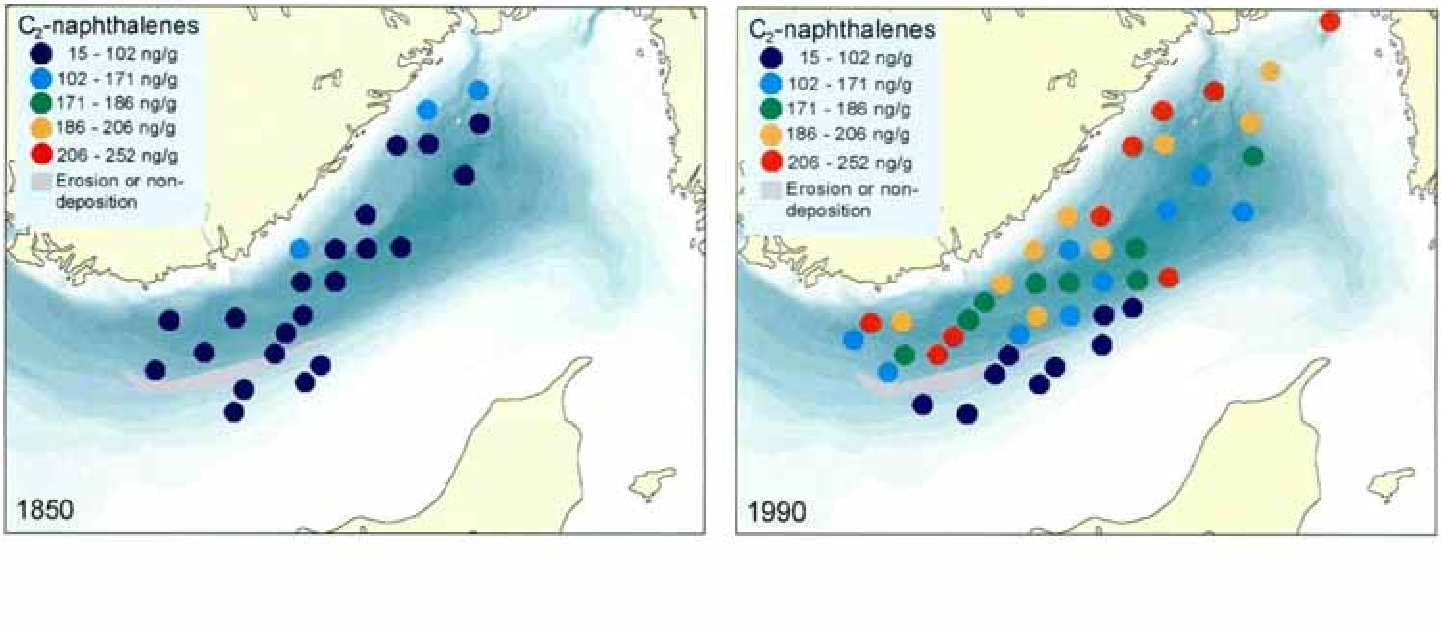
Recent environmental investigations in the North Sea under the Oslo and Paris Commissions (OSPAR) and the North Sea Task Force have focused on the trace metals mercury, cadmium, arsenic, lead, copper, zinc, chromium and nickel, and various organic compounds. In this chapter, focus will be on these metals, except for cadmium (excluded due to analytical limitations) and arsenic (not included in the analytical programme). We also included barium, since it serves as a tracer for transport of material derived from offshore drilling in the North Sea in connection with the oil and gas exploration and exploitation in the area. To illustrate the more detailed distribution of the PAHs, results for C_2-naphthalenes and benzo[*a*]pyrene were selected. These compounds can be regarded representative for the PAHs found in the Skagerrak sediments. C_2-naphthalenes are considered to be representative for petroleum and petroleum related sources. Benzo[*a*]pyrene is a compound mainly generated from incomplete combustion of fossil fuels (e.g. coal, oil, and petrol).

Which areas have the highest contamination?

In order to assess the contamination status in the Skagerrak, the background levels established from the long cores were used to define a **contamination level**, expressed as the ratio of the concentration of an individual trace metal in the surface sediment compared to the natural background levels of that trace metal. This is analogous to determining an enrichment factor (Olausson 1972, Cato 1977 and others). Intervals for the contamination levels are shown in Table 5.5.

An overview of contamination levels for copper, lead, zinc, mercury, barium, and chromium is shown in Fig. 5.6 A-F. Copper generally has a contamination level up to 2 in the surface sediments, ex-

Fig. 5.7 Changes in concentrations of C_2-naphthalenes (ng/g dw) in Skagerrak sediments from c. 1850 (A) to c. 1990 (B).



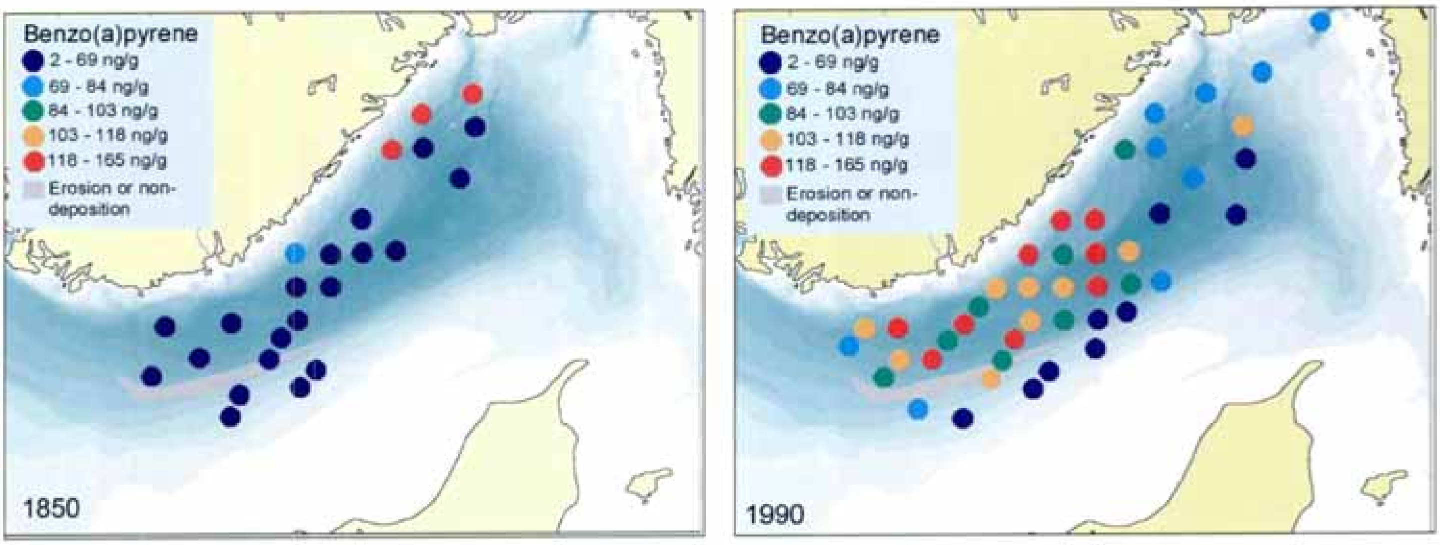


Fig. 5.8 Changes in concentrations of benzo[*a*]pyrene (ng/g dw) in Skagerrak sediments from c. 1850 (A) to c. 1990 (B).

Time-slicing (Box 5.4)

The model estimates of contaminant loads and element distribution at specified times are based on a combination of geochemical and geological data from 124 stations. Sedimentation rates have been measured or estimated for all of these stations, which have been sampled in a 10 x 10 kilometre grid (for details regarding sedimentation rates, see Chapter 4.2).

In order to simplify the modelling, we have assumed constant sedimentation rates. This simplification does not take into account temporal variations in the sedimentation rates.

For each station, a sediment core has been taken, and subsampled at regular intervals (0-2 cm, 2-4 cm ....45-47 cm, 55-57 cm). Using the sedimentation rates, we have calculated the deposition year of each sub-sample from all the cores, using the formula below:

$$\text{deposition year} = \text{sampling year} - \frac{\text{core depth}}{\text{sed. rate}}$$

In order to present estimates for specified years, a linear interpolation has been performed between the calculated years.

cept in the outer Oslofjord region and on the southeastern flank of the Norwegian Trench where the contamination is less than 1. The main reason for the low levels along the southeastern flank of the Norwegian Trench is that these sediments are coarser (silt to sand) than the rest of the Skagerrak sediments (clays, silty clays). This grain-size effect is seen also for the elements zinc, lead, mercury and chromium. In comparison, lead has higher contamination levels that generally exceed 2 and reach 5 in the central, deep parts of the Skagerrak. Zinc is similar to copper, with general contamination levels up to 2, but is elevated in most of the surface sediments, except those on the southeastern flank towards Denmark. Mercury has a markedly different pattern, with high contamination levels close to the coast, where contamination levels of 4 are recorded. Chromium and nickel (not shown) have generally low contamination levels that only just exceed 1 in the deeper parts of the Skagerrak. Barium has generally elevated concentrations in the surface sediments from most stations, with values up to two times the background. In the deeper areas and on the southeastern flank of the Skagerrak, the contamination level ranges from 2 to 6.

The present (c.1990) levels of PAHs in fine-grained sediments from the Skagerrak are shown in Table 5.4. The results indicate that the average concentrations have increased by a factor of three since the year 1850. The spatial distribution of the C_2-naphthalenes in sediments from c. 1990 has been compared to the levels found around 1850 (Fig. 5.7). The highest present-day levels of C_2-naphthalenes were found in fine-grained sediments from the deeper part of the Skagerrak and along the rather steep northwest slope towards Norway. The sediments towards the coast of Denmark are coarser and showed somewhat lower levels.

The spatial distribution of the combustion indicator benzo[*a*]pyrene in Skagerrak sediments (Fig. 5.8) differed slightly from that of the C_2-naphthalenes (Fig. 5.7). The highest levels of benzo(a)pyrene were outside the Arendal and Kristiansand areas with slightly lower levels in the inner Skagerrak.

5.4 Timing - when did the contamination signals in the sediments appear?

A central question in the assessment of the environmental condition of the Skagerrak is: At what time is the human input of contaminants to the sea detected in the sediment? The temporal and spatial trends for the lead content in the sediments, with a comparison between the lead concentrations in the sediments deposited at c. 1850, 1900, 1950 and 1990, reveals significant differences (Fig. 5.9). From generally low levels of lead in c. 1850, the concentration increased in the area south of Kristiansand in the Norwegian Trench (area 1, Fig. 5.10) up to c. 1950. From 1950 to 1990 there has been a distinct change, with the highest concentrations found in the deepest, central parts of the Norwegian Trench (area 2, Fig. 5.10).

The time-slice maps show that the load of contaminants to the Skagerrak has not been evenly distributed through time, particularly with regard to trace metals. Based

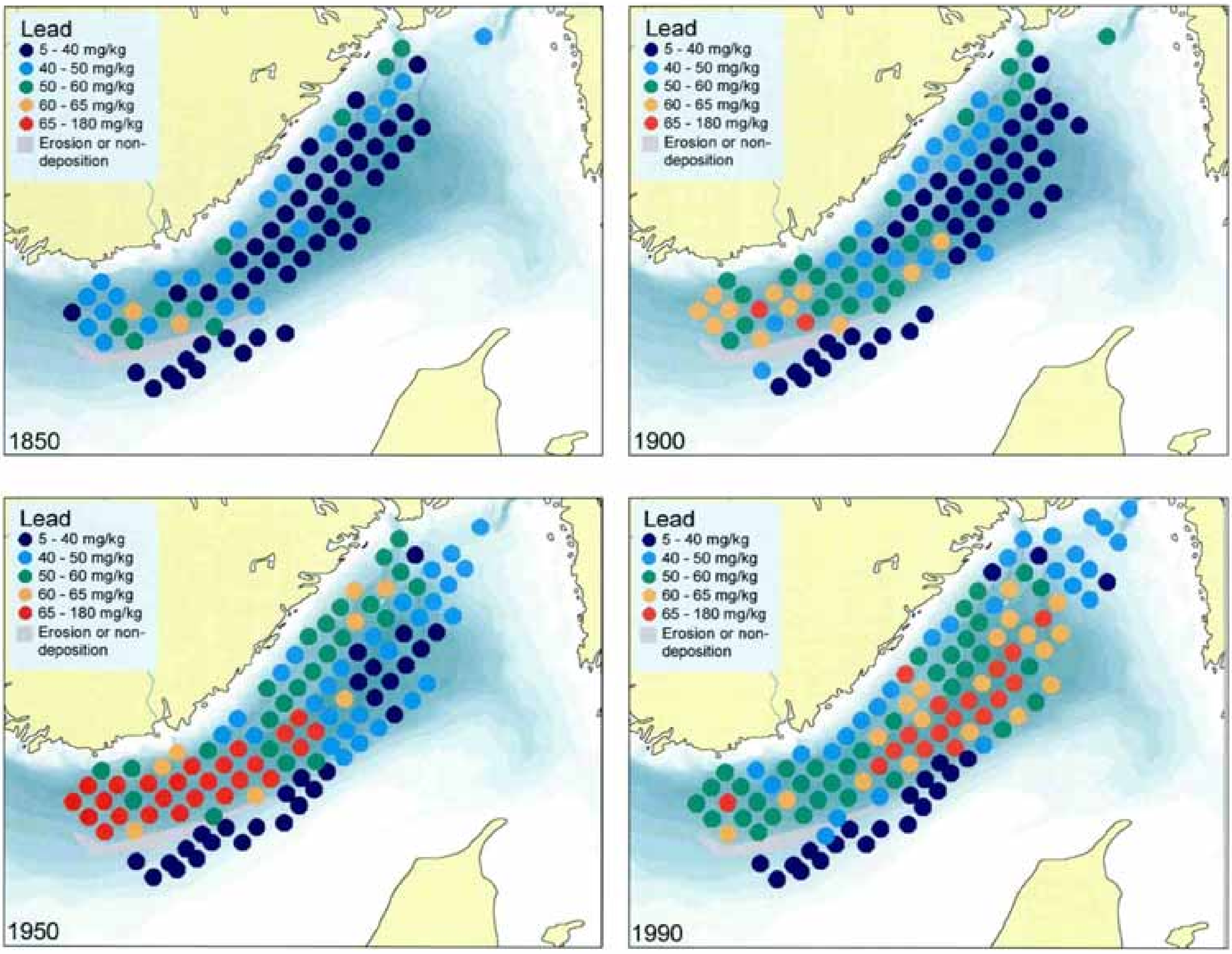


Fig. 5.9 Time-slice maps, showing the lead concentrations in sediments deposited at c. 1850, 1900, 1950 and 1990. Please note the northeastward change of high lead concentrations from area 1 to area 2 between 1950 and 1990.

on a dense net of stations and the time-slicing technique (see Box 5.4), areas with individual histories of contaminant load can be distinguished. In order to illustrate the time trends, special attention will be given to three areas (Fig. 5.10). Area 1 is located in the Norwegian Trench, south of Kristiansand, area 2 is located in the deepest parts of the Skagerrak, in the northeastern part of the Norwegian Trench, and area 3 is the Hvaler Deep Basin in the outer Oslofjord region.

Areas 1 and 2, in particular, show different trends for trace metal enrichment through time. Three cores from stations in the three areas have been selected and are presented in a stratigraphic plot in Fig. 5.11.

A similar stratigraphic plot of C_2-naphthalenes and benzo[*a*]pyrene from the inner Skagerrak (area 2) and the area outside Kristiansand (area 1) illustrates the development in load of PAHs to the Skagerrak in time (Fig. 5.12). The increased PAH levels from 1850 to 1990 for the whole Skagerrak are shown in Figs. 5.7 and 5.8.

In area 1, the Norwegian Trench south of Kristiansand, the sediment concentrations of copper, lead, zinc and mercury show a distinct decrease from approximately 1950 to the present, while the TOC content generally increases. The patterns for the two selected PAHs are different. Benzo[*a*]pyrene steadily increases from c. 1850 to the present, while C_2-naphthalenes increases from 1850 to c. 1950, and subsequently stabilises or decrease from 1950 onwards. This is similar to the trends for mercury and lead at these stations. The decreasing or stabilising trends displayed by copper, lead, zinc, mercury and C_2-naphthalenes, compared with the steadily increasing trend of TOC (and manganese

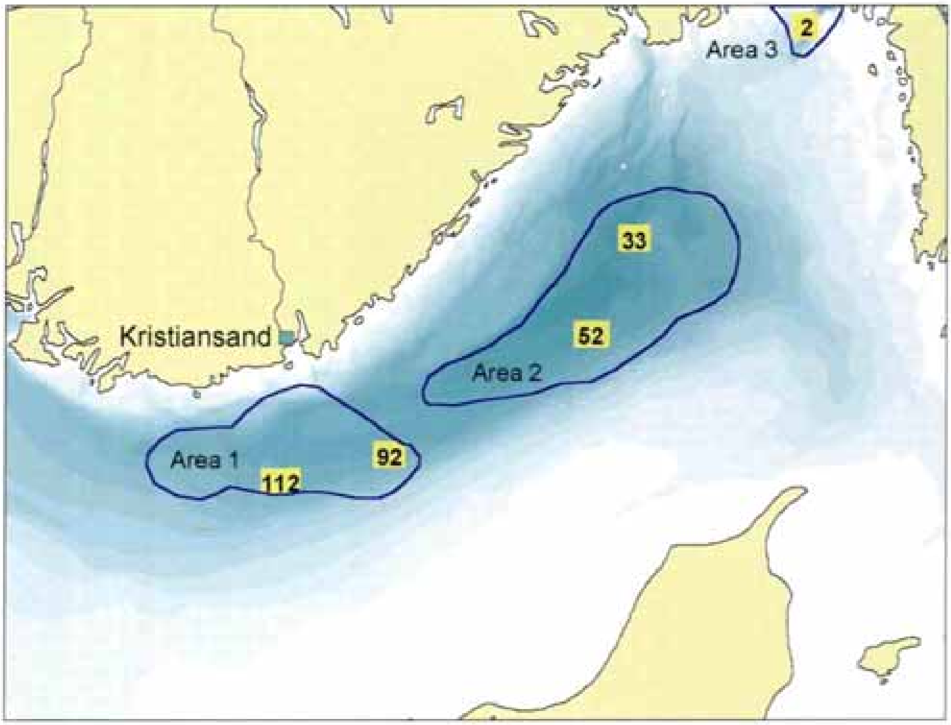


Fig. 5.10 Overview map of areas 1,2 and 3, with the stations 2, 33, 52, 92 and 122 indicated.

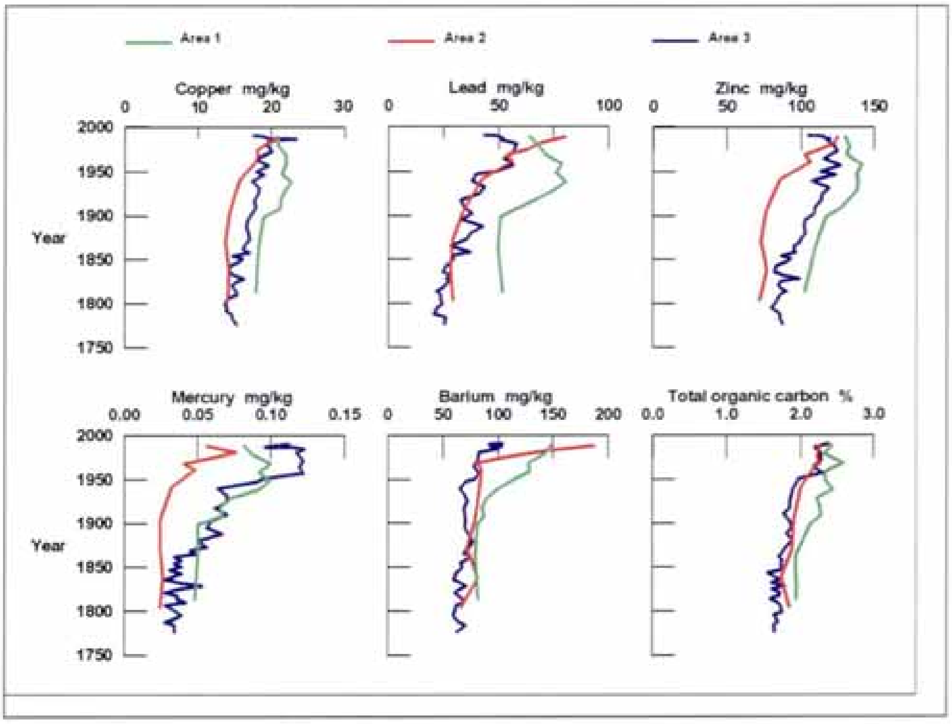


Fig. 5.11 Stratigraphic plot (i.e. with element concentrations versus a time axis) of selected contaminants and total organic carbon (TOC) for area 1 (station 112), area 2 (station 52) and area 3 (station 2). Please note the different trends of trace metal enrichment through time.

- not shown), indicate that the trends are not controlled only by the TOC content.

In the deepest part of the Skagerrak (area 2) copper, lead, zinc and barium increase significantly towards the surface. Mercury shows a decrease in the uppermost part of this particular profile. However, mercury increases steadily towards the present at nearly all stations of area 2. Barium shows a very strong increase since c. 1970. When all stations are taken into consideration, mercury shows a significant increase from c. 1950, while the lead increase begins somewhat earlier, at c. 1900. Benzo[*a*]pyrene and C_2-naphthalenes and other PAHs increase markedly from c. 1950 onwards, generally coinciding with the increase displayed by mercury, lead and barium.

In area 3, the Hvaler Deep basin, copper, lead, and zinc have increasing trends starting in c. 1850, with the highest levels from c. 1950 to 1975; these levels subsequently decrease towards the youngest surface sediments. Around 1850 mercury similarly starts to increase, with a stronger increase starting in c. 1940, followed by stabilisation or a weak decrease towards the present. These trends are in accordance with investigations within the coastal Hvaler area, which show that the riverine input of trace metals to the coastal Hvaler area was highest in 1960 - 1970, followed by a later decrease (Hektoen et al. 1992). Barium levels were low and stable until 1970, followed by a minor increase after c. 1970.

Barium behaves differently from the other trace metals. In areas 2 and 3 barium displays low and stable concentrations until c. 1960 - 1970, and then increases strongly in area 2 and more weakly in area 3. In area 1, the increase is more gradual, starting at c. 1925. Based on the results from area 2 and the distribution pattern of barium, the bulk of the barium in the young sediments in the Skagerrak is interpreted to be from the mineral barite, an important component of drilling muds discharged in large quantities to the North Sea since the late 1960s (see Chapter 5.5 for a more detailed discussion). However, the stratigraphic trends for barium in area 1 do not directly fit with this interpretation, since the increase begins prior to 1960 - 1970. Possible causes for these high pre-1960 barium levels could be extensive bioturbation (see Box 5.1) which brings barium-enriched material deeper into the sediments, or inaccuracies in the estimated (or varying) sedimentation rates, or diagenesis. A visual inspection of the degree of bioturbation using X-ray images of the sediment cores shows a fairly high degree of bioturbation in some areas, and these generally coincide with the areas where the barium increase starts before c. 1960 - 1970 (Fig. 5.13). Based on the general coincidence of the areas, the most likely cause for the early barium is apparently an increase in bioturbation. Other processes can also be involved. Diagenetic processes in some cores have possibly influenced the stratigraphic trend of barium, but these effects are considerably less important than the concentration changes caused by increased anthropogenic input.

The contaminant load to the different areas in the Skagerrak has varied considerably in the last few decades, and a number of factors must be taken into consideration. These factors may include changes in contaminant and organic matter supply, oceanographic changes affecting sediment transport, the euthrophication of parts of the Skagerrak, and environmental changes in the deeper parts of the Skagerrak. Euthrophication in the inner parts of the Skagerrak and the outer Oslofjord as a result of nutrient input from the southern parts of the North Sea and the Kattegat has been indicated by a number of investigations (see ANON 1996 for a recent review).

A substantial portion of the contaminants is associated with organic matter, and some of the differences between areas 1 and 2 may be explained by an increased load of organic carbon during the last few decades. The concentration levels of TOC in the surface sediments are on average c. 5% higher than in the sediments deposited in c. 1950. This downward decrease is generally due to the breakdown of organic material by microbiological and chemical processes. However, in area 2 the difference in TOC between 1950 and 1990 sediments is higher, ranging from 10 to 50%. This difference is found both in stations with low and high sedimentation rates, indicating that variations in the rate of burial and withdrawal from microbiological or chemical processes cannot explain the upward increase of organic carbon

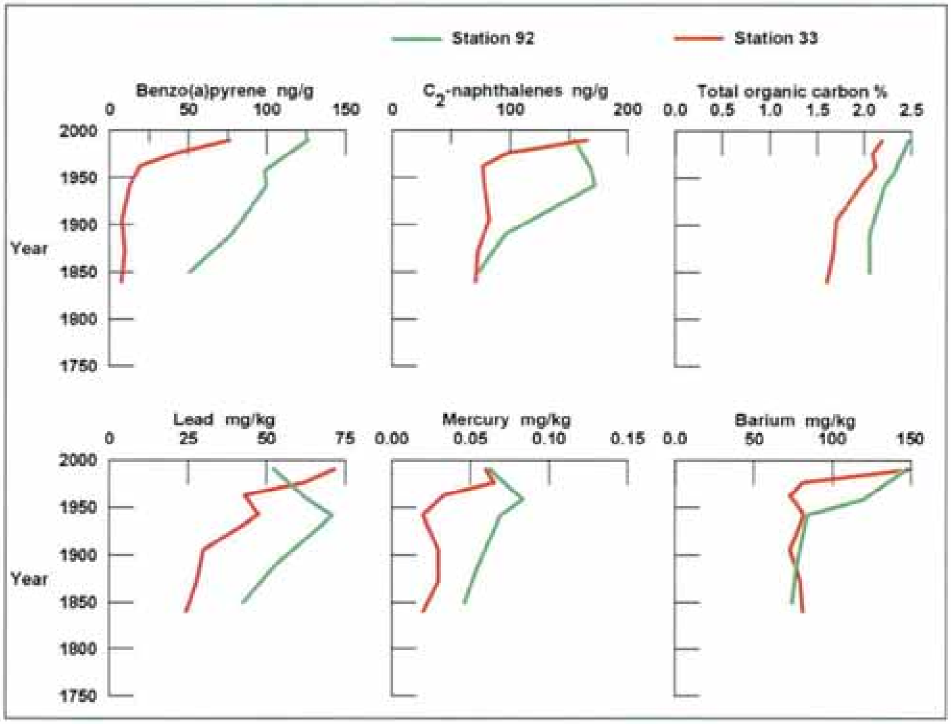


Fig. 5.12 Stratigraphic plot of benzo[*a*]-pyrene, C_2-naphthalenes, TOC, mercury, lead and barium for area 1 (station 92) and area 2 (station 33).

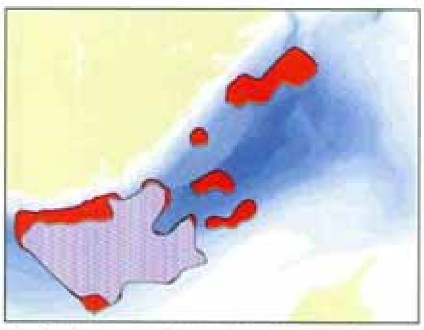


Fig. 5.13 Areas of fairly high degree of bioturbation (hatched area) and areas of barium increase before 1960 in Skagerrak sediments (red areas).

content. The increased organic carbon content in area 2 probably indicate a higher supply to this area, compared to the rest of the Skagerrak. This is possibly a result of higher production of organic material and increased transport of this to the Skagerrak region. The apparent increase in the TOC content is smaller relatively to the increase of trace metal content from 1950 to 1990, but elevated TOC levels may be partially related to the trace metal increase over the same period.

The role of changes in the ocean currents, and thus in the transport of sediment particles during this century is difficult to quantify, but may be important when evaluating contamination levels. This includes change in the influx of water (and thereby suspended matter) from the Atlantic Ocean, increased erosion and sediment transport from the North Sea and environmental changes. Of these factors, influx of Atlantic water into the Skagerrak is apparently not significant, since the Atlantic influx to the Skagerrak actually decreased between 1940 and 1989 (E. Svendsen pers. comm. 1996). This would imply reduced supply of (relatively clean) sediments for the same period, particularly for area 1, which may increase the relative portion of contaminated material deriving from the North Sea. This is in contrast to the observed decrease in contaminant content in the sediments in this area (1). Rather, increased erosion and environmental changes in the North Sea (see below) seems to correlate more closely to the observed overall contaminant trends. Increased erosion and sediment transport from the North Sea have possibly occurred during the last 20- 30 years (see Chapter 4.1 for details), and this may have resulted in increased contaminant load from the southern and eastern parts of the North Sea, particularly to the deepest, central parts of the Skagerrak (area 2). Likewise, environmental changes, reflected by changes in the benthic foraminiferal assemblages, have occurred in the deep parts of the Skagerrak since the early 1970's (Chapter 6.1), suggesting increased input of organic material. A possible consequence of this input is to change the pore water chemistry of the upper few centimetres of the sediments, and thereby influence the physical processes governing the behaviour of the contaminants.

Are the stratigraphic trends of trace metals and barium heavily influenced by diagenetic processes? (Box 5.5)

Diagenesis involves the chemical, physical and biological processes that bring about changes in a sediment subsequent to its deposition. The recent marine sediments are affected by early diagenetic reactions (depth of sediment burial less than 100 meters) which are primarily controlled by the character of the decomposition of organic matter in the sediments. In order to break down and oxidise organic matter, a variety of oxidants are used to supply the necessary oxygen. The sequence of oxidants used is determined by the energy gained in the particular reaction. Although there is a considerable overlap in the sequence of early diagenetic reactions, the oxidants are generally exhausted in the order:

oxygen >nitrate >manganese oxides >iron oxides> sulphate.

Accordingly, the following early diagenetic zones can be recognised:

1: oxic zone, 2: sub-oxic (or post-oxic) zone, which is divided into sub-zones of denitrification, manganese reduction and iron reduction, 3: sulphate reduction zone, 4: methanic zone

Components released in the early diagenetic reactions are either transported by diffusion through the interstitial waters to the sea-water, or they can be trapped in the sediments by *in situ* mineral precipitation. In Skagerrak the stratigraphic trends are fairly uniform of potentially diagenetically sensitive elements like manganese, iron and sulphur. Surface and/or subsurface enrichment of manganese is widely documented in previous studies, both from the Skagerrak and other parts of the world. After exhaustion of porewater oxygen and nitrate within the upper centimetres of the sediment, organic matter is oxidised using the oxidant manganese oxide. The released manganese does not form a solid phase in a reducing (i.e. oxygen-lacking) environment. Dissolved manganese is transported by upward diffusion back to the oxygenated, upper zone where it precipitates as oxides or oxyhydroxides.

The trace metals are mostly associated with surface oxyhydroxides (manganese and iron). When these oxyhydroxides are buried and dissolved in the sub-oxic zone, the metals may be released to the pore water. As a result of this release, the metals may be transported upwards to the oxic zone, where they can reprecipitate in connection with manganese and iron oxyhydroxides. Released metals (particularly cadmium, copper, nickel and zinc) can also migrate downwards and precipitate in the sulphate reduction zone as metal sulphides. Thus, trace metal trends may reflect diagenetic processes rather than variations of supply of trace metals to the sediments. However, the lack of correlation between trace metals and diagenetically sensitive elements in the Skagerrak sediments indicates that early diagenetic dissolution-precipitation processes are not the major factor controlling the stratigraphic distribution of trace metals, even though they may influence their occurrence to a certain extent.

5.5 Inputs and transport routes for trace metals and PAHs

Inputs via large rivers in densely populated and highly industrialised areas on the European Continent are major contributors to the total load of contaminants to the North Sea (Table 5.6). The riverine input of trace metals to the Skagerrak from Norway and Sweden is small in comparison to the total North Sea inputs (Table 5.7). A substantial input to the North Sea also derives from the atmosphere (Table 5.8). Direct discharges, disposal of dredged material, dumping of wastes from industrial establishments and cities and operational discharges from offshore industry and shipping also contribute to the total load. Dredged material from harbours, rivers and channels dumped in the North Sea contains considerable amounts of trace metals and PAHs.

An extensive offshore petroleum industry in the North Sea results in discharges. In 1991, the discharges of trace metals were estimated at 40 tons of copper, 12 tons of lead, 85 tons of zinc and low amounts of mercury and associated compounds. These

Table 5.6 Riverine inputs to the North Sea, including the English Channel, Skagerrak and Kattegat in 1990 (North Sea Task Force 1993). The data include both dissolved and suspended matter.

	Copper tons	Lead tons	Zinc tons	Mercury tons	SPM thousand tons
Belgium	29[5] - 41[6]	14[5] - 21[6]	170[5] - 250[6]	3.1[5] - 4[6]	340[5] - 700[6]
Denmark	10.5	5.1	75.8	0.042	n.i.
France	170	240	680	3.4	n.i.
Germany[1]	280	210	1 700	10.5	2 500
Netherlands[2]	380	340	1 900	3.1	1 700
Norway[3]	126	40[5] - 41[6]	580	0.08[5] - 0.19[6]	219
Sweden	36.7	7.8	226	0. 072	170
United Kingdom	187[5] - 202[6]	109[5] - 131[6]	1 010[5] - 1 020[6]	0.93[5] - 3.5[6]	501[5] - 502[6]
Total[4]					
Lower estimate[5]	1 200	970	6 300	21	5 400
Upper estimate[6]	1 200	1 000	6 400	25	5 800

[1] and [2] - including loads from countries upstream.
[3] - using 1991 data on inputs from Norway.
[4] - total rounded to two significant figures.
[5] - lower estimate: for concentrations less than the detection limit, a value of '0' was used when calculating loads.
[6] - upper estimate: for concentrations less than the detection limit, the value of the of the detection limit was used when calculating the loads.
n.i. - no information.
SPM - suspended particulate matter.

Table 5.7 Riverine inputs of selected contaminants to the Skagerrak and Kattegat in 1994 from Norway and Sweden. Data from Denmark are not available. Source of data: OSPAR (in prep.)

Country	Sea area	Copper tons	Lead tons	Zinc tons	Mercury tons
Norway	Skagerrak	67	27	300	0.1
Sweden	Kattegat	34	9.4	160	0.06
Sweden	Skagerrak	5.1	1.2	24	0.004

Table 5.8 Estimates of atmospheric inputs to the North Sea (to 59° N including the Kattegat and Skagerrak, but not the Channel) in 1990, based on deposition measurements at coastal stations and calculated for an area of 525 000 km^2 (North Sea Task Force 1993).

	Copper tons	Lead tons	Zinc tons	Mercury tons
Minimum	320	960	2 700	3.3
Maximum	740	1 700	5 500	6.9

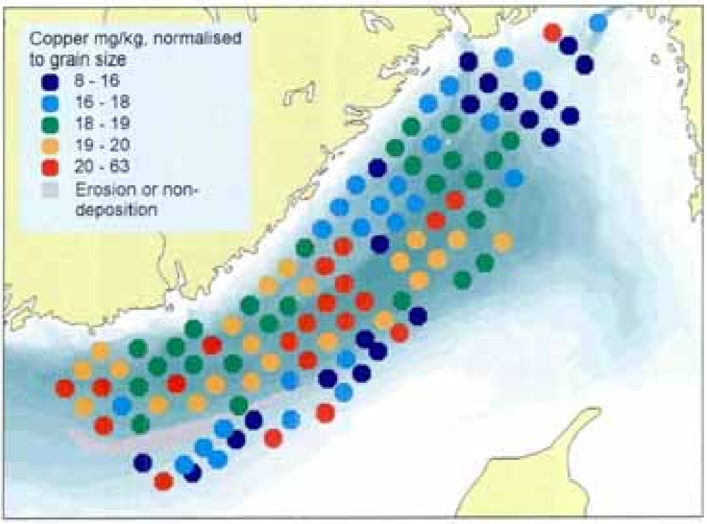


Fig. 5.14 Distribution map for copper in surface sediments in Skagerrak, normalised to the clay+silt content.

Normalisation of contaminant content to organic matter and grain-size

(Box 5.6)

Some groups of contaminants are primarily associated with TOC and/or fine-grained particles (clay and silt). Elevated levels of contaminants are therefore often found in fine-grained, organic-rich sediments. In order to reduce the effects of this variation, «normalisation» is often performed (see e.g. Wiesner et al. 1990 and references therein for further details). This may involve:

- division of the contaminant content by the content of TOC, to give a ratio; further division by a reference sample regarded as close to the background level yields an estimate of the contaminant enrichment for a given region.
- recalculation of the contaminant content, using the content of clay and silt, whereby a sediment with, e.g., 20 mg/kg lead that contains only 50% clay and silt, will be recalculated to double the original lead value, i.e. the normalised lead value will be 40 mg/kg.

Normalised data provides a more coherent picture if large variations exist in the sediment types involved in the assessment. However, in the Skagerrak the sediments are generally fine-grained, with the exception of the south-eastern slope of the Norwegian Trench, where slightly more coarse-grained sediments occur. Except for this specific area, the normalisation of contaminant content to organic matter or grain-size does not bias the data.

figures are based on estimates of discharges from Denmark, the Netherlands and the United Kingdom (North Sea Task Force 1993) and are minimum estimates. It should be noted that the main sources of trace metals in discharges from the offshore industry are trace metals associated with the barite and bentonite minerals used in drilling muds, the levels of which are highly dependent upon the quality of the drilling muds (North Sea Task Force 1993).

Copper

The copper contamination in the Skagerrak is low, with a mean contamination level just above 1, i.e. the copper concentrations in the surface sediments are close to the background level. Still, anthropogenic input can be recognised, with elevated levels in the coastal areas south of Arendal, in the southwestern and central parts of the Skagerrak (Fig. 5.14). The distribution pattern for copper in surface sediments in the North Sea shows that elevated concentrations occur in an area in the easternmost part, extending northwards from the mouth of the Elbe along the Danish coast (Zöllmer & Irion 1993). High concentrations also occur in nearshore sediments between the mouth of the Rhine and the island of Texel (Irion & Müller 1990). The highly contaminated sediments in the German Bight can be traced northwards to an area off the Danish coast, where «dilution» by less contaminated sediments from the central and northern North Sea takes place (Zöllmer & Irion 1993). The diluted, but still contaminated sediments, are subsequently transported to and deposited in the Skagerrak. In Kattegat, the input of copper-contaminated sediments is dominated by inputs from the Gøteborg area (Olausson 1975, Cato 1983), while inputs from the North Sea are considered to be less important (Kuijpers et al. 1993, Cato in press). The input from Norway appears to be restricted to the coast south of Arendal. A possible source may be copper-rich boat coatings extensively used in this busy shipping zone. The distribution of copper in the Skagerrak thus points towards a component of input both from the North Sea (southwestern and central parts), and a contribution from the Norwegian coast south of Arendal.

Lead

The concentration of lead in the surface sediments indicates considerable anthropogenic input to the Skagerrak that derives mainly from the North Sea. Investigations of the lead content in the surface sediments of the North Sea (Irion & Müller 1990) show that lead (and manganese) have a generally patchy distribution without clear spatial zonation; however, elevated concentrations do occur in nearshore sediments north of the Humber estuary, off the mouth of the Scheldt river, between the mouth of the Rhine and the island of Texel, and in the eastern part of the German Bight. According to Irion & Müller (1990), the patchy distribution shows that atmospheric transport rather than rivers is likely the dominant pathway for lead contamination to the North Sea. The atmospheric input of lead to the Skagerrak in 1989 has been calculated to 73 tons (Ross 1990). Considering the surface area of Skagerrak (36 000 km^2), compared with the surface area of the North Sea (525 000 km^2, used in Table 5.8) this estimate seems reasonable. This shows that the direct airborne input of lead to Skagerrak is small compared to the riverine and airborne inputs to the entire North Sea (estimates for 1990 range from 1930 to 2700 tons). According to Kuijpers et al. (1993), the major input of lead-enriched material into the Skagerrak and the northern part of the Kattegat is by the Jutland Current from the North Sea, with a minor and local source allocated in the eastern Kattegat (Varberg area). Other investigations, however, do not show this trend (Cato in press).

The spatial distribution of lead in Skagerrak surface sediments is influenced, but not controlled, by various physical and chemical parameters, like grain-size varia-

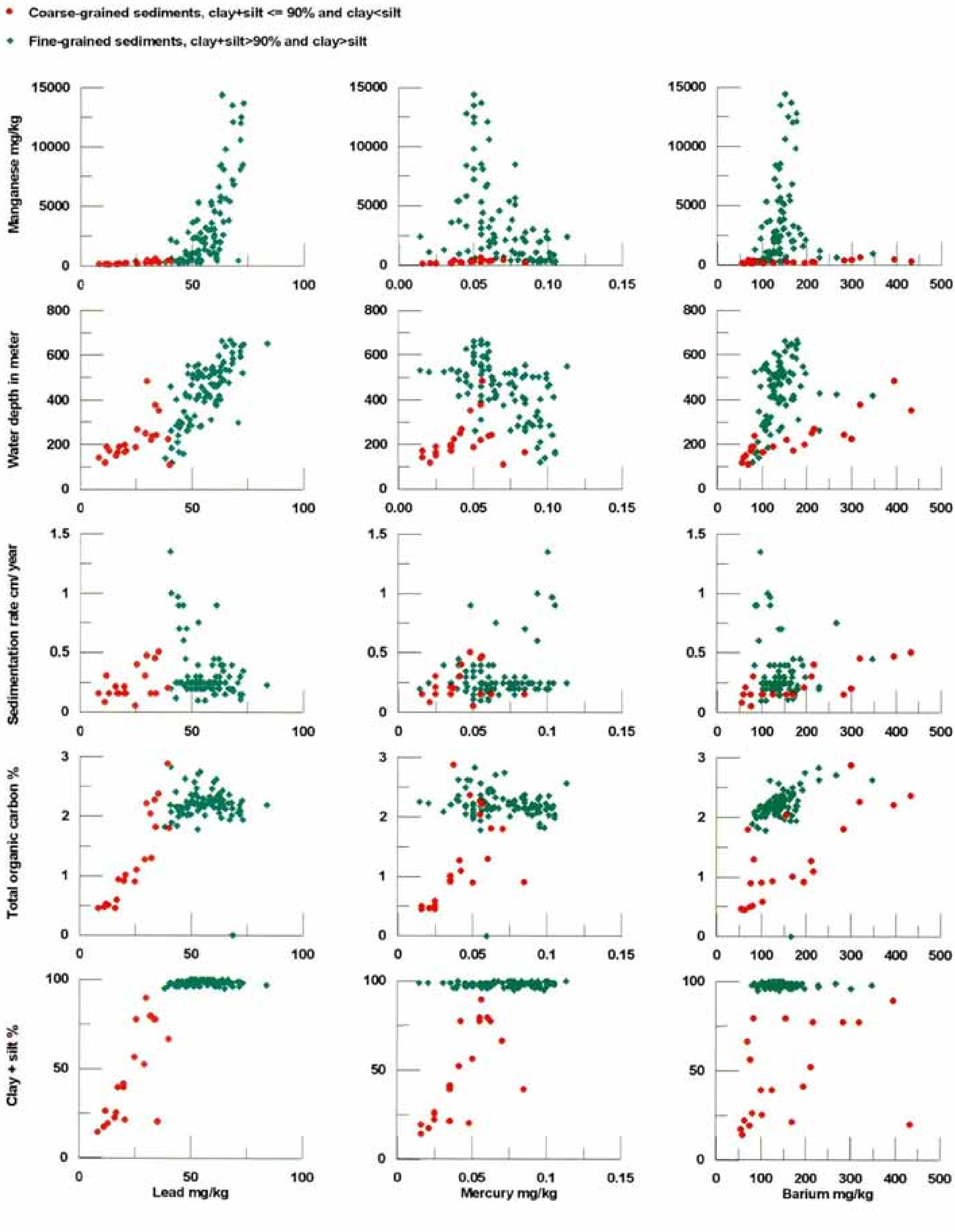


Fig. 5.15 Bivariate plots of lead, mercury and barium against clay+silt content, TOC content, sedimentation rate, water depth and manganese content. The red dots show the most coarse-grained sediments (less than 90% clay+ silt and more silt than clay), while the green diamonds show fine-grained samples (more than 90% clay+silt and more clay than silt).

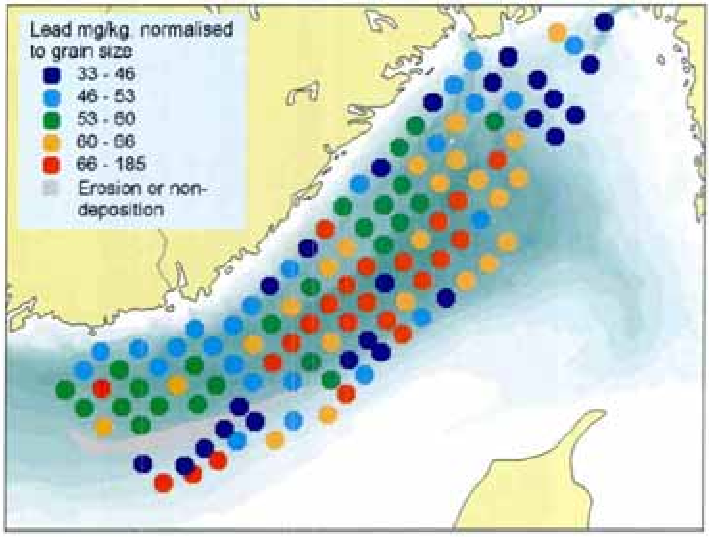


Fig. 5.16 Spatial distribution of lead in the surface sediments. The lead content has been normalised to the content of clay and silt.

tions, TOC content, sedimentation rates, water depth and manganese content (Fig. 5.15). In order to visualise the effects of grain-size variations, we have made a classification of comparatively coarse sediments (less than 90% clay+silt and more silt than clay), and fine-grained sediments which comprise the major part of the Skagerrak sediments.

The content of lead is correlated with the clay+silt content for low clay+silt values (Fig. 5.15). However, for fine-grained sediments (more than 90% clay+silt, and more clay than silt), the lead content is not only dependent on grain-size. A similar pattern is seen for the TOC content, where the lead content is correlated with the TOC content when the latter is less than c. 1.8%. For TOC values greater than 1.8%, there is no obvious correlation. Sedimentation rates do not affect the content of lead, but the content of lead generally correlates with water depth.

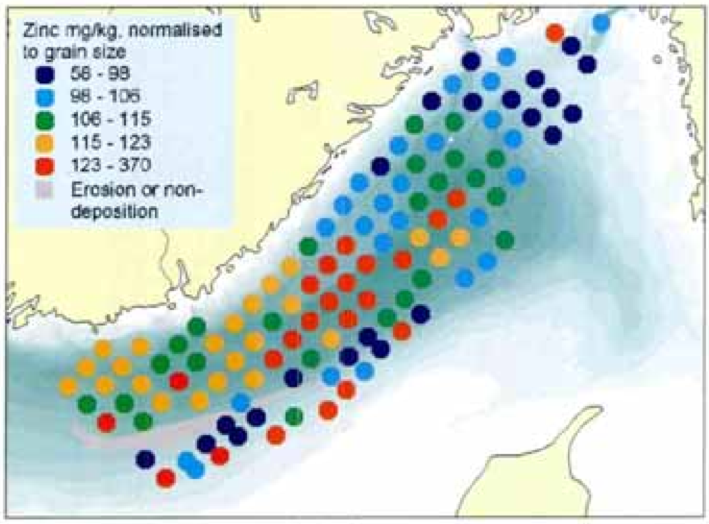


Fig. 5.17 Spatial distribution of zinc in surface sediments in Skagerrak and Kattegat. The zinc content has been normalised to the content of clay and silt.

The lead content in the surface sediments is strongly correlated with iron content, and when a logarithmic scale is used for manganese, the same is the case for manganese and lead. Irion & Müller (1990) reported correlation between lead and manganese in surface sediments in the North Sea. This may indicate that the lead distribution in the North Sea is connected to the distribution of manganese, and quite possibly, that lead is transported to the Skagerrak associated with manganese-iron hydroxides. The close connection between lead, manganese and iron in the surface sediments contrasts with the trends emerging when concentrations from all levels in the cores are compared. Particularly in area 1, no correlation between lead and manganese/iron is evident, indicating that diagenetic processes (manganese scavenging) in Skagerrak are not significant with regard to lead. The absence of a correlation between lead content and clay+silt content (in fine-grained sediments), and TOC content (sediments with more than c. 1.8 % TOC) shows that the spatial distribution of lead in Skagerrak is not only controlled by these factors, i.e. the spatial distribution of lead reflects variations in contaminant loads. The lack of influence by sedimentation rates indicates that lead is not diluted by rapid deposition of particles to the sediments. If lead deposited from the atmosphere above the Skagerrak was a dominant source, then the highest lead content should occur in locations with low sedimentation rates (i.e. in locations with minimum dilution by suspended matter transported from e.g. the North Sea), and vice versa. The lead must rather be transported to Skagerrak associated with suspended particles (adsorbed to the sediment particle surface), organic matter or manganese-iron hydroxides that form part of the sediment composition.

The highest concentrations of lead are found in the deepest parts of Skagerrak (area 2), and also on the south-eastern flank of the Norwegian Trench when the latter are normalised against the clay+silt content. Together with the other information presented, this indicates that the dominant input of lead to the Skagerrak is from the North Sea. Minor contributions by riverine inputs from Scandinavia and local atmospheric deposition may exist but appear to be lost in the signal from the North Sea inputs.

Zinc

The zinc concentrations in the surface sediments of Skagerrak are only slightly elevated, but an anthropogenic input can still be recognised. The elevated concentrations are found in the southwestern and deepest parts. In the North Sea, zinc shows a distinct zonation with the highest zinc concentrations (> 300 mg/kg) occurring in a narrow band of nearshore sediments between the mouth of Scheldt and the island of Texel and in a broader area off the Ems-Weber-Elbe estuaries that extend northward across the German Bight (Irion & Müller 1990). In addition, smaller isolated areas with increased zinc values

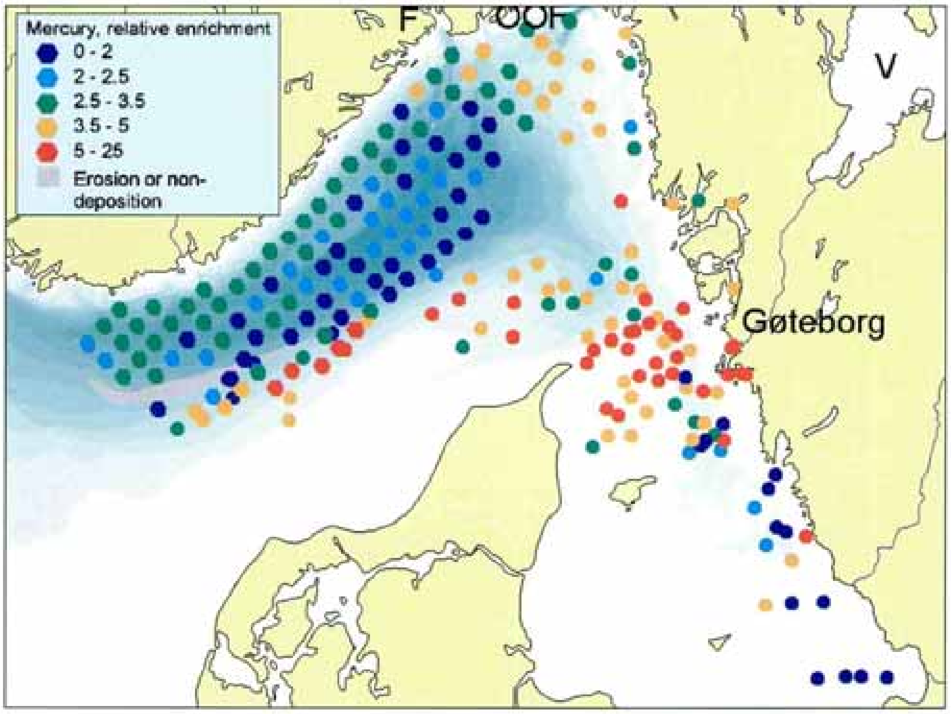


Fig. 5.18 Spatial distribution of mercury in surface sediments in the Skagerrak and Kattegat. The concentrations are normalised against the content of TOC and a reference sample. Data from Kattegat and parts of the Skagerrak (circles) are from Kuijpers et al. (1993). F - Frierfjord; OOF - Outer Oslofjord; V - Vänern.

are found off the English and Scottish coasts and in the northern part of the eastern North Sea. In the Kattegat, there is a major input from the Swedish coast (Cato in press). According to Kuijpers et al. (1993), the input from the North Sea is only secondary. However, the distribution map of zinc in surface sediments shows that the zinc content is high in the deepest and southwesternmost parts of Skagerrak which receives sedimentary material dominantly from the North Sea (Fig. 5.17). High values of zinc are also evident along the southern part of the southeastern coast of Norway, possibly indicating input of zinc-contaminated material from local sources along the coast, such as zinc anodes on boats.

Mercury

Fairly high levels of mercury are found along the Norwegian coast and along the southeastern flank of the Norwegian Trench, indicating that inputs both from the North Sea and from the Scandinavian mainland may be important. A regional survey of mercury content in sea-water outside the river Elbe in the German Bight (Schmidt 1992) showed very high levels of mercury near the river mouth, and decreasing contents away from the river mouth/estuary. According to Schmidt (1992), c. 99.5% of this mercury originated in the former German Democratic Republic and former Czechoslovakia. Similarly high levels of mercury were found in the offshore region east of Scotland, and a possible connection with production of natural gas in the North Sea has been suggested (Schmidt 1992). The riverine inputs of mercury to the North Sea were estimated at 21-25 tons in 1990 (Table 5.6), while the Norwegian and Swedish discharges through rivers in 1994 were estimated to be less than 0.2 tons (Table 5.7). The atmospheric inputs to the North Sea, on the other hand, are estimated to be 3.3 - 6.9 tons for 1990 (Table 5.8).

The spatial distribution of mercury in the surface sediments (Fig. 5.18) shows that high concentrations of mercury are found in the eastern part of the Skagerrak, Kattegat, coastal areas of Sweden, the outer Oslofjord and the southeastern flank of the Norwegian Trench. Medium-high levels are found in the near coastal areas of Norway and in area 2 (for location of area 2, see Fig. 5.10).

The spatial distribution of mercury in Skagerrak surface sediments is influenced by various physical and chemical factors (Fig. 5.15). The mercury content is controlled by the clay+silt content for coarser sediments. However, for fine-grained sediments, the mercury content is not correlated with the grain-size. A similar pattern is seen for the TOC, where the mercury

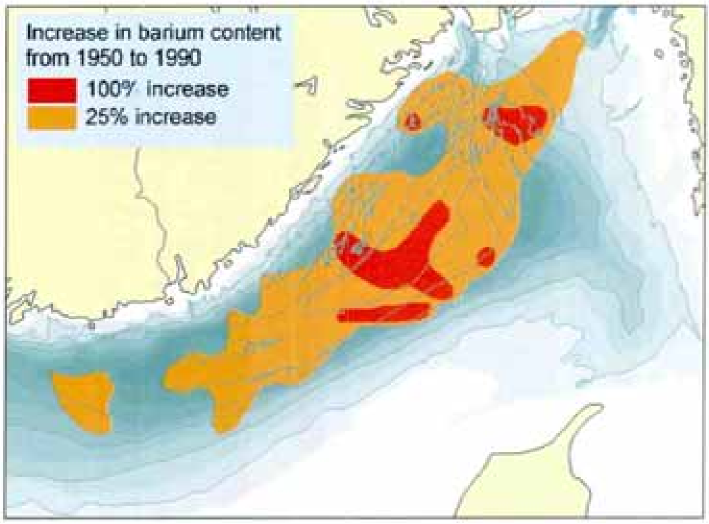


Fig. 5.19 Increase of barium content in Skagerrak sediments from c. 1950 to c. 1990.

content is controlled by the TOC when the latter is less than c. 1.8%. For TOC values greater than 1.8%, there is no correlation. Sedimentation rates does not affect the content of mercury. Likewise, water depth and manganese do not correlate with mercury. The lack of a correlation between mercury and clay+silt, TOC above 1.8%, sedimentation rates, water depths and manganese shows that the spatial distribution of mercury in the Skagerrak may be influenced, but is not controlled simply by these factors, i.e. the spatial distribution of mercury reflects variations in contaminant input.

The elevated mercury levels in Kattegat and along the Swedish and Norwegian coasts points towards an origin from the surrounding landmasses through riverine input. Rognerud & Fjeld (1990) have calculated the contamination factors in sediment cores collected from 210 lakes in Norway, using the minimum values recorded in the respective sediment cores as a reference value. This shows considerable (3-6 times higher mercury concentrations in the surface sample) to severe (surface enrichment exceeding 6 times) mercury contamination in south Norwegian lakes. Rognerud & Fjeld (1990) also present data from Sweden that shows significant mercury contamination in south Swedish lake sediments. Based on correlation with the sulphur contents of lake waters and previous studies by others, they conclude that the majority of atmospheric mercury pollutants today originate from the European continent, even though small inputs from point sources in Norway and Sweden must be anticipated. Wide dispersion of mercury along the Swedish coast is interpreted to be the result of air emissions (Cato 1992). Riverine inputs from urbanised areas along the Swedish coast, particularly the Göta river, contribute significantly to mercury contamination of the coastal areas in Kattegat (Cato 1992). A major source for these riverine inputs are discharges from chemical industries and pulp mills along the river and the Lake Vänern (Cato 1992).

One contributor of mercury contamination to Skagerrak is the Norwegian river Glomma which drains c. 50% (Pederstad et al. 1993) of the catchment area of the outer Oslofjord (Fig. 5.18). Since c. 1890, a number of factories, including large pulp and paper mills and chloralkali factories have discharged both organic and inorganic contaminants (trace metals) to Glomma. These sources may represent an important input to the Skagerrak. However, Helland et al. (1990) have shown that the surface sediments outside the Glomma estuary are only slightly contaminated by mercury. This contrasts with the situation inside the Glomma estuary, where the surface sediments are markedly contaminated by mercury (Hektoen et al. 1992). During the summer 1995, a major flood in the Glomma river occurred, and as much as 75% of the total suspended material from the Glomma river passed through the Glomma estuary and was brought into the Skagerrak (Helland 1996). In contrast, during normal river conditions, the majority of suspended particles settle within the estuary. Another potential point source for mercury contamination is a now-abandoned chloralkali factory on Herøya in the Frierfjord. The discharges from this factory appear to have been effectively trapped in the Frierfjord by a physical (bedrock) threshold in the outer parts of the fjord (Næs & Oug 1991). This is supported by the mercury concentrations shown in Fig. 5.16, where no plume of high mercury concentrations can be identified outside the Frierfjord. Pohlmann & Puls (1994) have demonstrated in a modelling experiment involving contaminant inputs from the rivers Rhine, Elbe/Weser, Tyne, Firth of Forth, Thames and Humber (with inputs in descending order) that contaminated material from these rivers is transported towards the Kattegat and the Skagerrak. The resulting concentrations were shown to be higher in the Kattegat and the coastal areas of Sweden and Norway, than in the central, deeper parts of the Skagerrak.

In conclusion, a major source for the elevated mercury concentrations along the Swedish coast, outer Oslofjord, and Norwegian coastal areas appears to be riverine inputs particularly from urbanised areas along the Swedish coast. Atmospherically transported mercury originating from the European continent, together with local emissions, also contribute to the mercury input. Input from the North Sea is indicated by elevated mercury concentrations on the southeastern flank of the Norwegian Trench and the eastern parts of Skagerrak and Kattegat, most probably related to transport of contaminated sediments by the Jutland Current. A certain North Sea contribution to the coastal contamination of the Skagerrak is also likely. It should be noted that the strongest increase of mercury content in the Skagerrak sediments during last 40 years has occurred in the central, deeper parts of the Skagerrak (area 2), while the levels in the coastal regions have been stable or have even decreased, except for one station in the outer Oslofjord. This indicates that the relative contribution of mercury contamination from the North Sea has increased during this period, and may even continue in the future.

Chromium

The chromium levels in the surface sediments show that only slight contamination is recognisable in the deeper parts of the Skagerrak, and a figure for chromium distribution is therefore not shown. Elevated chromium contents in North Sea surface sediments occupy an area extending from the Northern English coast into the central and northern North Sea, and a small area occurring between the mouth of the Rhine and the island of Texel (Irion & Müller 1990). Investigations from the sediments in the Rhine and Elbe rivers (Müller 1985) show a moderate enrichment of chromium (enrichment factor 2-3). The contaminated sediments in the German Bight can be traced northward to an area off the Danish coast where «dilu-

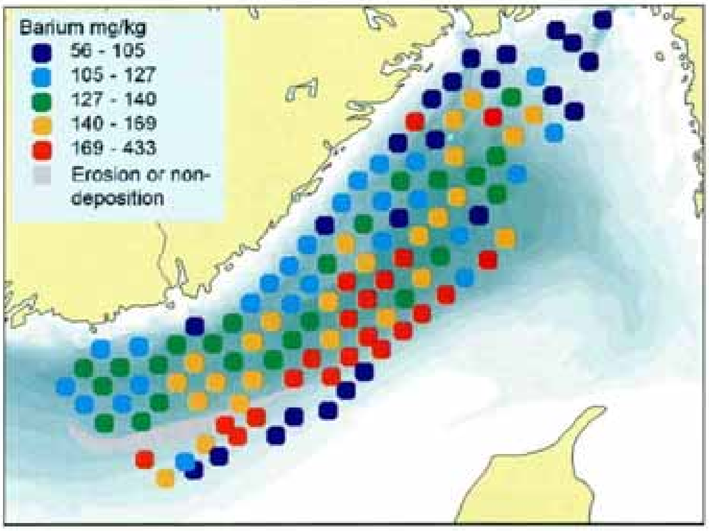
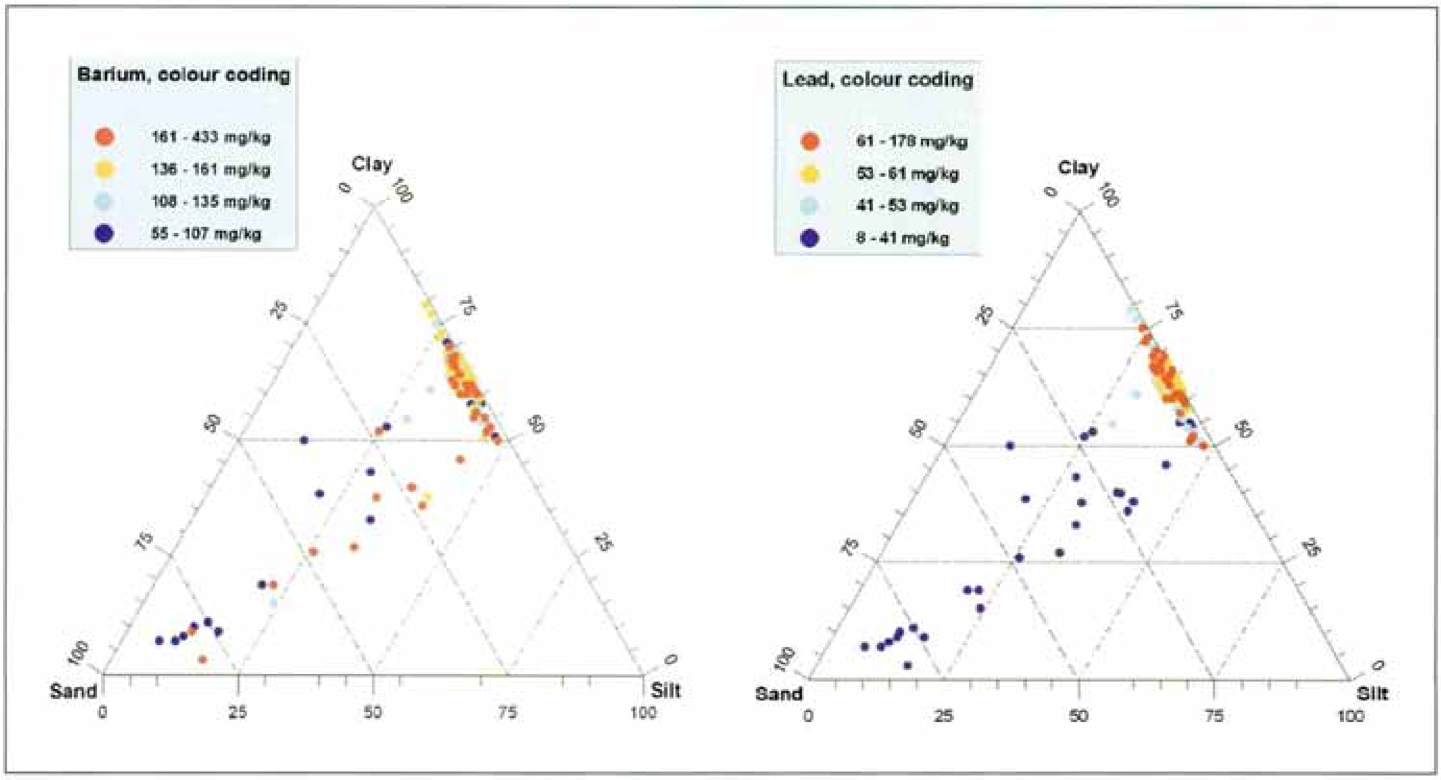


Fig. 5.20 Content of barium in surface sediments. No normalisation against clay and silt content.

Fig. 5.21 Colour-coded barium (left) and lead (right) concentrations in Skagerrak surface sediments plotted against the content of clay, silt and sand from surface sediments in a triangular grain-size diagram. Sediments with high sand content plot in the sand corner, and sediments dominated by clay and silt plot along the clay-silt axis.



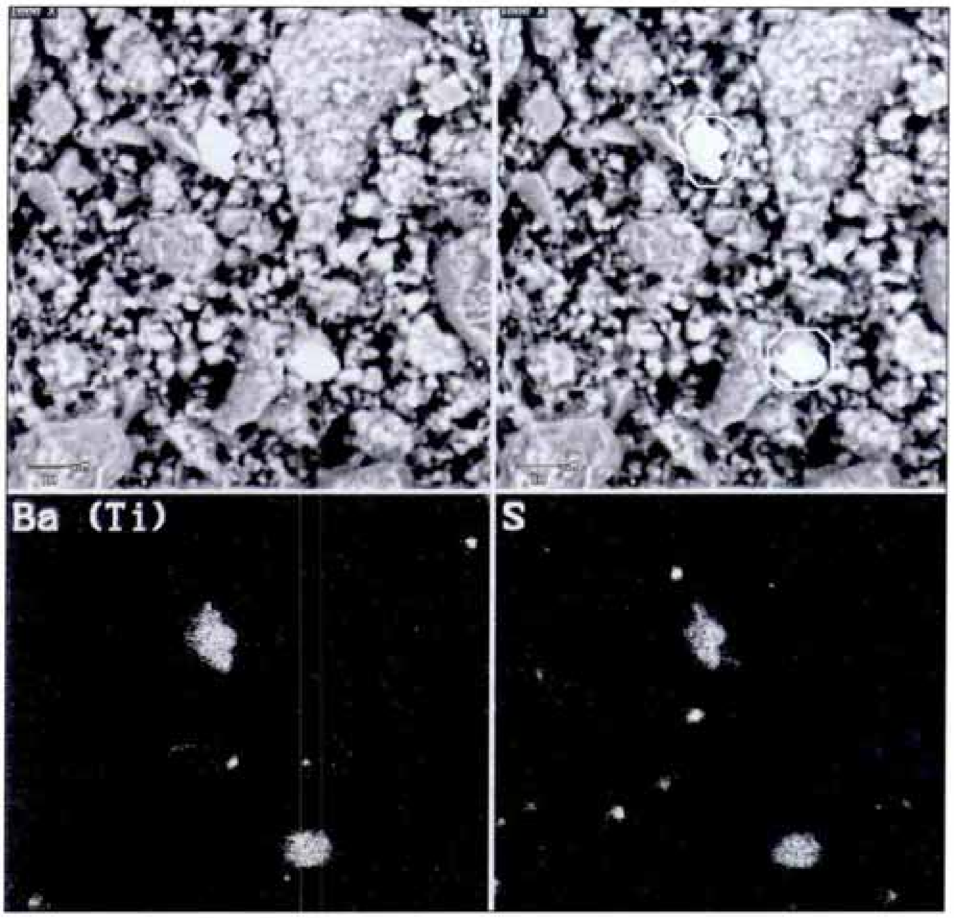


Fig. 5.22 Scanning electron microscope (SEM) images matched below by a back-scatter image of grains of barite ($BaSO_4$) (circled) in sediments from about 3 cm below the surface in the south-central part of the Skagerrak (station 54). Scale bar is 10 micron.

tion» by less contaminated sediments from the central and northern North Sea takes place (Zöllmer & Irion 1993). The diluted, but still contaminated, sediments are subsequently transported to and deposited in the Skagerrak. Figure 5.5F shows slight enrichment of chromium in the deepest parts of the Skagerrak. The enrichment trend is indicative of contaminated sediments that derive from the German Bight and become the major contributors to the (minor) chromium contamination in the Skagerrak.

Nickel

Only slight enrichment of nickel in the surface sediments in the deeper parts of Skagerrak has been observed (a separate element distribution map is therefore not shown). Only minor anthropogenic nickel input to the Skagerrak has occurred. The distribution of nickel in North Sea surface sediments gives a patchy and irregular pattern, and no obvious inputs can be identified (Irion & Müller 1990). Investigations of nickel contents in lake sediments in southern Norway (Rognerud & Fjeld 1990) have shown a large variation in nickel content, mainly caused by natural nickel variations in the superficial deposits and bedrock in the catchment areas. Significant nickel contamination is documented in the fjord outside Kristiansand (for location, see Fig. 5.10), where discharges from the Falconbridge factory in Kristiansand are the likely source (Knutzen et al. 1991); however, no nickel enrichment is found outside this fjord. This indicates that the sediments contaminated by nickel are effectively trapped within the fjord basin.

Barium

The barium content in the Skagerrak has increased markedly in the last decades (Fig. 5.19). This is most likely the result of huge discharges of barium-rich drilling muds from the petroleum industry since c. 1960. Barite (a barium mineral) is a primary component of drilling muds extensively used in the offshore petroleum industry since the late 1960's. Barite is virtually insoluble in sea-water and is therefore a good tracer for the dispersion of drill cuttings discharged from the oil and gas platforms; these drill cuttings have been a primary source of environmental disturbance around oil and gas platforms in the Norwegian sector of the North Sea. A large portion of the barite accumulates close to the platforms. Observations from the Valhall and Gyda platforms (Olsgaard & Gray 1995) show a decrease in barium and associated trace metals in the sea-bed sediments after cessation of drilling mud discharges. This indicates that parts of the drilling muds deposited close to the platforms may be resuspended within a few years and spread over large areas away from the platforms. Modelling shows that barite grains smaller than 35 microns (i.e. fine silt) can be transported in suspension. As much as 50% (weight%) of the discharged drilling mud occurs as particles smaller than 35 microns (Rye 1996). Discharges of drilling muds are by weight the most important discharges from offshore oil and gas activities. The composition of drilling muds varies from area to area, but all have a weighting agent, usually barite ($BaSO_4$), viscosity agents such as benthonitic clays, swelling controllers (potassium chloride - KCl), pH controllers (potassium hydroxide KOH), filter loss components, dispersants, defoamers, drilling lubricants, (such as fatty acids and hydrocarbons), gypsum to increase the calcium content, and biocides (GESAMP 1993).

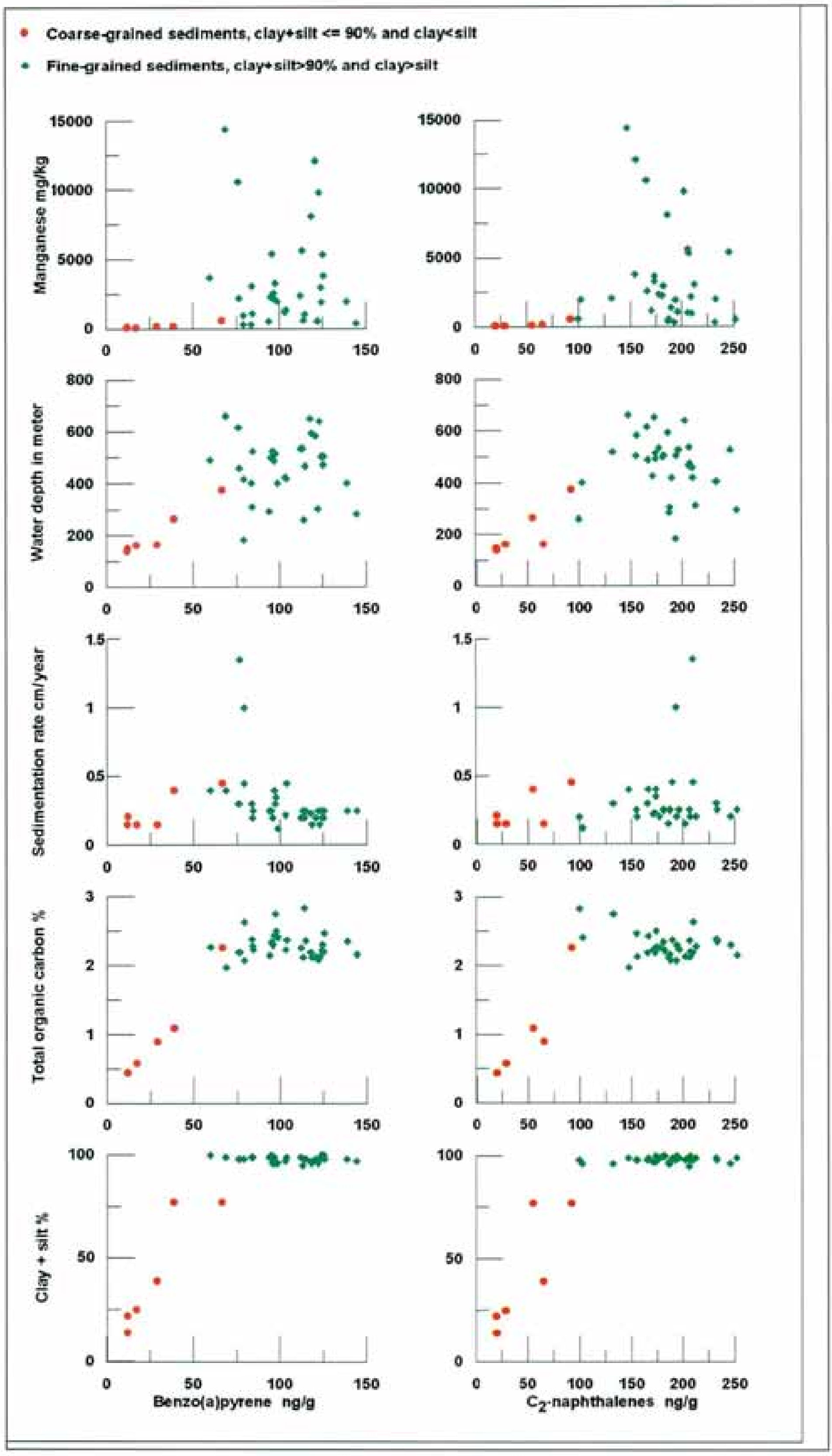


Fig. 5.23 Bivariate plot of benzo[*a*]pyrene and C_2-naphthalenes against clay+silt %, content of TOC, sedimentation rate, water depth and manganese content.

The total discharge of drilling muds to the North Sea in 1991 was c. 310 000 tons tons, of which c. 156 000 tons went into the Norwegian sector, while the discharges in 1993 and 1994 were c. 124 000 and 96 000 tons, respectively (P.E. Iversen, pers. comm. 1996). The composition of such drilling muds is complex. The content of barite varies between 60 and 90%, but can be assumed to be 80% on average (P.E. Iversen pers. comm. 1996). Using the 80% estimate, the total amount of barium (the

Calculation of contaminant loads

(Box 5.7)

Calculations of contaminant loads were performed by multiplication of the elemental concentrations in the sediments by the estimated amount of sediment deposited annually for each station (ADSM - Annual Deposition of Suspended Matter, see Box 4.3), and subsequently summing the figures for all stations.

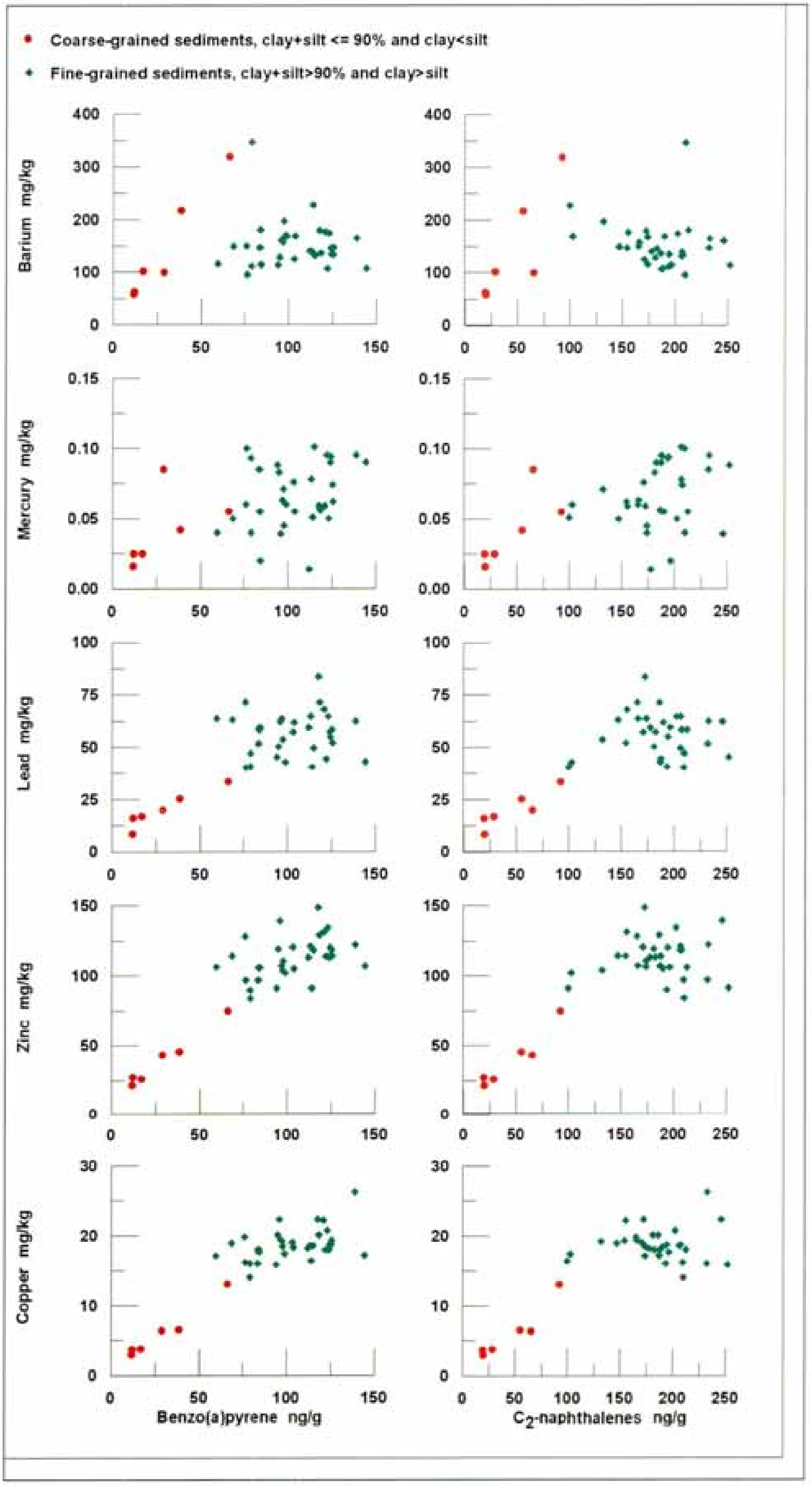
The fact that not all cores penetrate sufficiently deeply to reach e.g. the 1850 level (only 71 cores penetrated down to the 1850 level) influenced and weakened the statistical assessment of the data. The lack of complete datasets for some stations was compensated by first calculating the total amount of sediment deposited using the 71 cores, and second, by calculating the ratio of 1990 ADSM and 1850 ADSM. This ratio was then multiplied by the contaminant load calculated using the 71 stations. In this way, comparable numbers are produced, even if some stations are not represented in the pre-1990 levels.

In the model, the following assumptions have been made:

- the sedimentation rate has been stable during the last hundred years
- the effects of diagenesis are minor
- the effects of bioturbation are minor
- for calculation of 1990 levels, the surface sediments (0 - 2 cm) have been used
- for calculation of 1500 levels, the background levels have been used

This method introduces some uncertainties in the model, and the time estimates should not be looked upon as absolute numbers. However, the time trends and proportions of contaminant loads to different regions are regarded as reliable indicators of the degree of contamination.

Fig. 5.24 Bivariate plots between selected PAHs and trace metals in coarse- and fine-grained sediments.



main component of barite) discharged in 1991 was c. 145 000 tons, of which c. 62 000 tons went into the Norwegian sector. Another possible source for barium in the Skagerrak is from the natural cycling of barium in the watermasses by biochemical processes. Discrete barite particles, about 1 micron in diameter, are the most common manifestation in the open ocean of barite produced by these biochemical processes (Dehairs et al. 1980). Increased supply of nutrients to the sea may increase the production of organic matter, and thus also increase the rate of the biochemical processes responsible for the formation of discrete barite particles from dissolved barium and sulphate in the watermass. Elevated levels of barium in the sediments may therefore also be a signal of increased nutrient supply, i.e. the content of barium may be used as an indicator for the organic production in the overlying watermasses. The spatial distribution of barium in surface sediments (Fig. 5.20) shows that elevated barium levels are found on the southeastern flank of the Norwegian Trench, in the deepest parts of Skagerrak and at water depths greater than 200 meters south of Langesund.

The barium content of the surface sediments is not correlated with grain-size variations, as is evident from Fig. 5.15, and thus barium data have not been normalised to clay+silt content. Barium is not correlated with TOC content, sedimentation rate, or manganese (Fig. 5.15). There is a weak correlation with water depths, where the highest concentrations occur at intermediate water depths. These trends indicate that barium is transported differently than are the trace metals mercury and lead. High barium contents even in sediments with low clay+silt content imply that barium is partly associated with slightly coarser particles in the silt and very fine sand fractions (median diameter 5 to 105 microns; very fine sand, for example, has particle sizes of 62 - 125 microns). This is illustrated in Fig. 5.21, where the barium content is plotted against the content of clay, silt and sand in a triangular diagram. For comparison, a similar plot for lead content versus clay, silt and sand content is shown.

Scanning electron microscope studies of sediments with high barium content (Fig. 5.22) reveal grains (10 - 20 microns in diameter) of the mineral barite which display mechanical abrasion on the grain edges. This type of abrasion is characteristic of grains that have been transported over some distance (from a few to several hundred kilometres), and is not the result of chemical processes in the sediment.

Stratigraphic profiles show that the barium content increases markedly from 1970 to the present. The profiles overlap in time with both the onset of major petroleum exploration and increased euthrophication in the North Sea. The fact that barite grains larger than 10 microns are found in sediments with high barium contents, and that high barium contents are associated even with sandy and silty sediments, is consistent with the theory that a large part of the barite in the Skagerrak derives from discharged drilling muds. The findings of Olsgaard and Gray (1995) and the modelling of barite grain transport (Rye 1996) certainly shows that a large part of the barite grains discharged together with the drilling muds can be transported by suspension or near-bottom suspension. The lack of a correlation between barium content and TOC content indicates that euthrophication processes are not a major cause for the elevated barium levels in the Skagerrak. However, a certain contribution from such biochemical processes related to euthrophication is to be expected, but cannot be clearly distinguished from the barite derived from the drilling mud discharges.

PAHs

The pattern of PAHs in Skagerrak sediments indicate that the PAHs are derived from several sources. The levels of both petroleum- and combustion-related compounds are elevated in the time period studied (from c. 1750 to 1990). The concentrations of the selected two PAHs were related to some metals and normalising factors like sedimentation rate, grain-size, water depth and TOC (Fig. 5.23).

Benzo[*a*]pyrene is relatively well-correlated with copper, zinc and lead, but have poor correlations with mercury and barium (Fig. 5.24). C_2-naphthalenes are correlated with copper, zinc and lead in coarse-grained sediments, while the correlation in the fine-grained sediments is weak or even negative. The wide scatter in the diagrams limits the conclusions to be drawn from this comparison, but significant differences in the pattern between benzo[*a*]-pyrene and C_2-naphthalenes are suggested. Further investigations are needed in order to verify and explain these trends.

This information together with plots of PAHs against sedimentation rates, indicates that PAHs to a great extent are associated with fine particulate clastic material (clay and silt) and organic matter. Most of this material enters the Skagerrak from the North Sea. A significant contribution may also come from urbanised areas along the Swedish coast (Cato in press). Other contributors include atmospheric inputs to the sea surface in Skagerrak from the European continent and local sources (Brorström-Lundén 1996). The solubility of PAHs in sea-water is low. The compounds entering the water are quite rapidly associated with particles. Particle dynamics are thus important for the distribution and inputs of PAHs to the sediments.

5.6 Contaminant loads - quantitative modelling

Quantification of the amounts of hazardous substances transported to and deposited in the Skagerrak annually is an important part of the assessment of the environmental condition. The Norwegian part of the Skagerrak basin receives c. 19 million tons of sediments annually (dry sediment weight). Of this, c. 15 million tons comprise fine-grained material (clay dominated, and with more than 90% clay + silt). The annual contaminant load was modelled based upon measurements of contaminant elements and calculated annual sediment supply (Box 5.7) to the Skagerrak. The sediments deposited in the Skagerrak can be separated into two areas: the North Sea/Atlantic Ocean and the Scandinavian/Baltic Province (see Chapter 4.2). The North Sea/Atlantic Ocean province appears to be dominated by sediments coming from the North Sea and the Atlantic Ocean. The Scandinavian/Baltic province similarly receives the dominant input from the Atlantic Ocean and the North Sea, but with a significant contribution (c. 15 %) also from Norwegian and Swedish rivers, from the Kattegat and to some extent, from the Baltic Sea. Clearly, this province division represents a gross simplification of the complicated sedimentation pattern in Skagerrak. Still, the division is considered to provide a meaningful approach to the calculation of the contaminant load, respectively, from the North Sea/Atlantic Ocean, the Scandinavian landmass and the Kattegat.

The annual supply of contaminants from

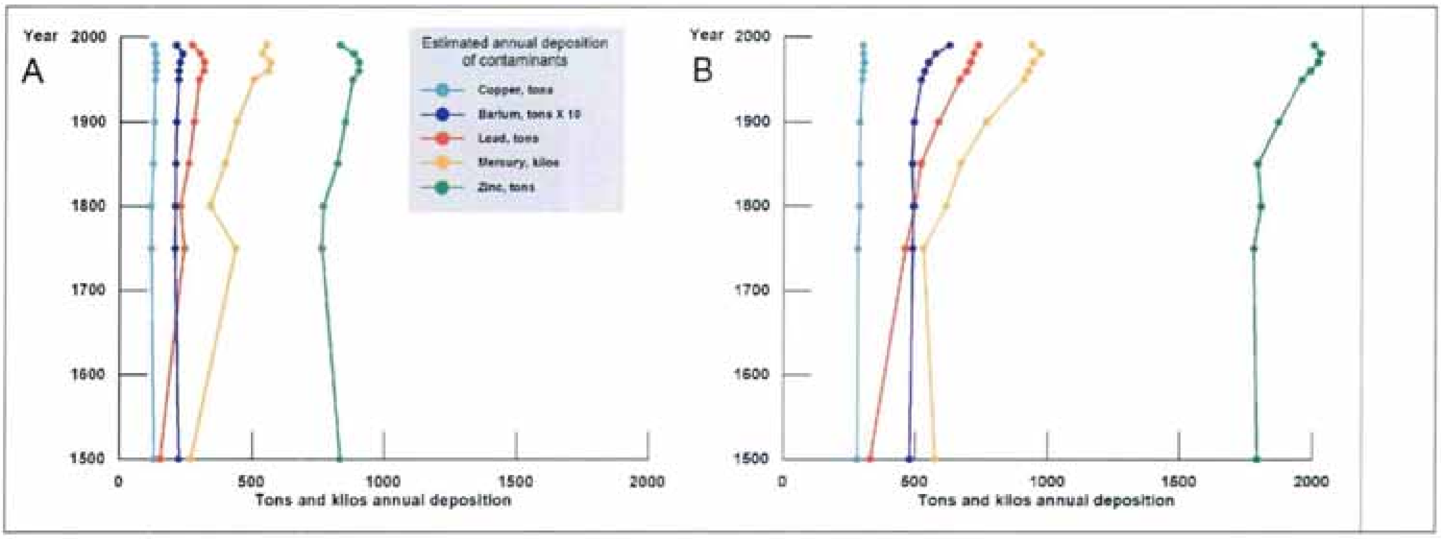


Fig. 5.25 Model estimates of annual deposition of copper, lead, zinc, barium (tons) and mercury (kg) for selected years from 1500 to the present. A: the load to the Scandinavian/Baltic province; B: the load to the North Sea/Atlantic Ocean province. The barium estimates have been divided by ten in order to use the same scale as for the other elements.

both natural and anthropogenic sources to the Norwegian parts of the Skagerrak is shown in Fig. 5.25. The modelling shows the load to the Scandinavian/Baltic province and the North Sea/Atlantic Ocean province.

Copper shows a very limited increase from the background levels in c. 1500 to the present day concentrations, and only minor copper contamination is evident on a regional scale. The trends for chromium and nickel are not shown, but have basically similar trends to that of copper. These trends agree with the results from the contamination level studies (Chapter 5.3) for copper, chromium and nickel. Lead, zinc and mercury, on the other hand, increase slowly from background levels in 1500 to c. 1850, increase more strongly from 1850 to 1950, and subsequently increase more weakly from 1950 to the present day concentrations. Barium is an exception, with moderate increases from background levels from c. 1500 to c. 1970, followed by a very strong increase towards present.

An interesting question is «How much of this material is derived from geogenic (natural) sources, versus that quantity derived from anthropogenic sources (man-made)»? Another important question is «How much of the annual contaminant input to the North Sea is deposited together with the sediments in the Skagerrak?» In the following, we provide an attempt to define a budget for the flux of contaminants in the Skagerrak. The first step was to estimate the anthropogenic and geogenic proportions of the contaminant load to the Skagerrak in 1990 (Fig. 5.26). This was done by subtracting the natural background levels from the actual concentration at any time, thus arriving at the combined anthropogenic and geogenic components. The second step was to compare the total input estimates for the North Sea (from Tables 5.6, 5.7 and 5.8) with our modelled contaminant load to the Skagerrak in 1990 (Fig. 5.27). In order to get an estimate for the entire Skagerrak, and not only the Norwegian part, 25% has been added to the model estimates (based on a very simple comparison of areas).

An amount equivalent to 52% of all lead input to the North Sea and the Kattegat annually is deposited in the Skagerrak which is higher than for the other contaminants. Half of this quantity is from anthropogenic sources, while the other half comes from geogenic sources. Copper and zinc exhibit very similar behaviour, with deposition of c. 30% of the annual North Sea and Kattegat inputs in the Skagerrak. It should be noted that c. 90 - 95% of the copper and zinc annually deposited in the Skagerrak is from geogenic sources, and does not represent any anthropogenic contamination. The deposition of mercury in the Skagerrak represents c. 7% of the estimated total inputs to the North Sea and the Kattegat. Approximately equal amounts of mercury are from geogenic and anthropogenic sources. No estimates for the total inputs of barium to the North Sea are available; only the estimates for anthropogenic inputs are calculated (c. 145 000 tons in 1990). The deposition of anthropogenic barium in the Skagerrak is less than 1% of this estimated input from the offshore industry. Approximately 15% of the barium deposited in the Skagerrak is from anthropogenic sources. This may appear to conflict with the contamination level described in Chapter 5.3 (the mean level is 2), but is due to the contamination analysis method that is based on partial dissolution technique data, while the numbers used in defining this budget are based on a recalculation of partial dissolution data to estimate numbers produced by total dissolution techniques (for further details, see Box 5.3).

The conclusion from these data is that the natural, geogenic sources dominate with regard to deposition of copper, zinc and barium in the Skagerrak. For mercury and lead, the proportions of geogenic and anthropogenic contributions are approximately equal. The reasons for this difference are not fully understood, but the fact that atmospheric transport and deposition are important for mercury and lead may be significant. For copper, lead and zinc, approximately 30 - 50% of the inputs to the North Sea are deposited in the Skagerrak, while less than 10% of the mercury inputs are deposited in the same area.

Skagerrak receives c. 50 - 70% of all the fine-grained material that enters the North Sea. A considerable amount of organic matter forms part of this. The Skagerrak area does not, however, receive 50 - 70% of all the contaminants (except lead). This may indicate that substantial parts of the contaminants either are trapped in the estuaries outside the rivers (e.g. Cato et al. 1980) and the fjords, are deposited in the North Sea, or are taken up into the food chain and removed from the sedimentary cycle. In recent sediments from the Lower Rhine, in excess of 90% of the copper, zinc, lead, mercury and cadmium contents are anthropogenic (Förstner & Müller 1973). The reason for the high proportion of lead deposited in the Skagerrak may be that lead to a large extent is deposited uniformly in the North Sea by atmospheric inputs. Lead can be transported to the Skagerrak by waters which derive from the Atlantic Ocean and the Central and Southern North Sea, and thus escape the estuarine traps. Complex processes take place in the estuarine mixing zones of river water and sea-water and thereby influence the fate of the contaminants. Small/low density particles have higher adsorption capacity than the coarser particles in an estuary. Such particles escape from the estuarine circulation and predominate in the coastal areas. Inputs from rivers result in elevated concentrations of contaminants in the coastal areas outside the rivers (Förstner 1980, Irion & Müller 1990), and may be partly due to flocculation processes as well as to the strong urbanisation of these areas. Studies from Norwegian fjords have shown that most of the trace metals and PAHs are trapped close to the input sources, inside the fjord sill (Næs & Oug 1991, Næs et al. 1995).

We emphasise that the calculated contaminant estimates for the Skagerrak show the quantity of contaminants deposited (and kept) annually in the sediments, while the input figures refer to the total influx of contaminants. These data do not account for processes which release the contaminants from the sediments to the water column. Estimates of the annual deposition of PAHs and other organic compounds like PCBs and chlorinated pesticides, e.g. DDT, will be calculated when all organic analyses are completed.

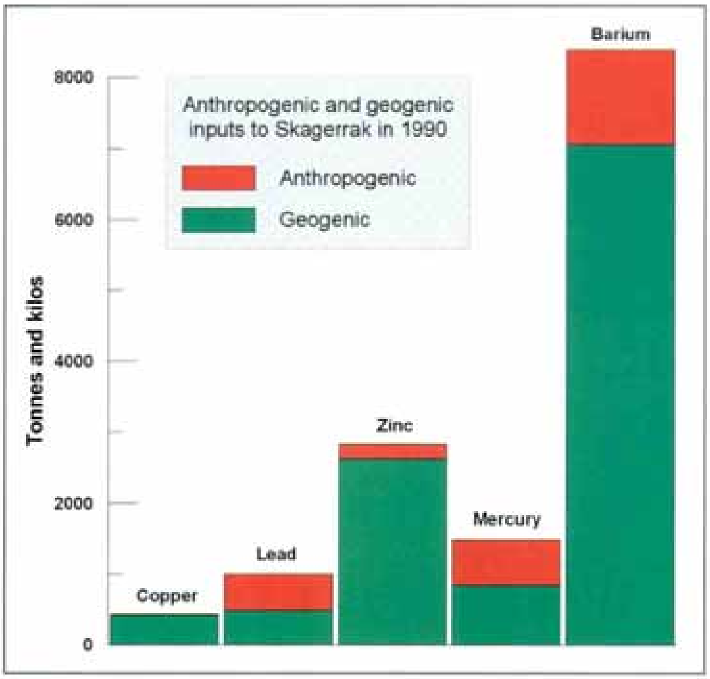


Fig. 5.26 Estimates of the geogenic and anthropogenic contributions of trace metals to the Skagerrak in 1990.

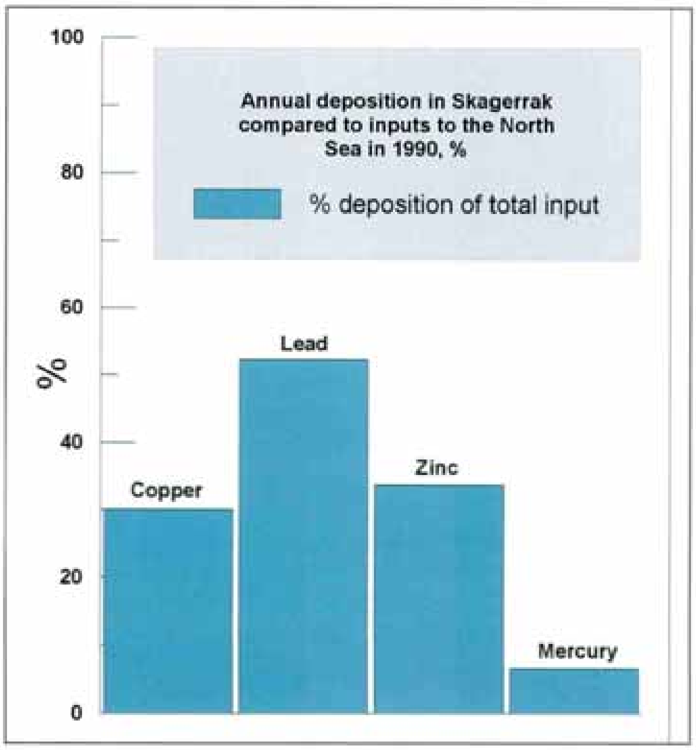


Fig. 5.27 Estimates of contaminant deposition in Skagerrak compared to the estimated total inputs to the North Sea and the Skagerrak in 1990.

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6 Micropalaeontological evidence of environmental conditions in the Skagerrak from the last few centuries

Analyses of benthic foraminiferal assemblages in the sediments of the Skagerrak allow division of the investigated area into basically three different depositional environments: one on the Norwegian slope, one on the Danish slope, and one in the deep Skagerrak basin. The NW areas of the Danish shelf and parts of the slope receive considerable amounts of particulate material (up to fine sand fraction) introduced from the southern North Sea. The Danish slope is considered an area of high benthic fertility and contrasts with the Norwegian slope.

Changes in benthic foraminiferal assemblages are evident in cores from the deep Skagerrak basin. The nature of these faunal changes suggests an increased input of organic material. In this relatively poorly flushed basin environment, such an increase may have enhanced the development of sediment porewaters undersaturated with calcium carbonate and caused an elevation of the redox boundary within the sediments. These changes in the deep Skagerrak have primarily occurred since the early 1970's. Although the historical data from the Norwegian and Danish slopes are too scarce to draw any firm conclusions, faunal data from 1937 and 1992/93 are in good agreement and do not suggest dramatic environmental changes through this period for the Norwegian slope; data from the Danish slope indicate development of a high benthic fertility regime. Overall, the faunal development, as reflected by the core data, is in good agreement with conclusions based on a comparative study of the surface assemblages collected in 1937 and 1992/93.

A pronounced reduction in the absolute abundance of planktonic foraminifera in the Skagerrak throughout the last several centuries is observed. Two possible explanations may be given for this reduction: 1) it may reflect an overall reduced influx of Atlantic water entering into the Skagerrak; 2) it may reflect some unknown changes in the hydrographic properties of the surface waters that have had an adverse effect on possible local planktonic foraminifera. In either case, the strongly reduced abundance of planktonic foraminifera implies some influence from environmental change. These changes are not simply linked to recent anthropogenic impact over the last decades. A separate study of dinoflagellate cyst assemblage in the deep Skagerrak sediments indicates changed climatic conditions at c. 1650; this is interpreted to be due to increased influence of colder surface water in the Skagerrak during the last few hundred years.

6.1 Foraminifera

This section represents a brief discussion and summary of the main conclusions derived from the foraminiferal analyses performed in connection with the Skagerrak Project. The study is based on the analyses of 56 living (stained) and 69 dead (unstained) assemblages recovered from 69 surface samples and on detailed stratigraphic analyses of six 0.5 m-long cores. For further details, see Alve (1996) and Alve & Murray (1995; in press) and references therein.

Benthic foraminifera as environmental indicators

Foraminifera are unicellular organisms (protozoans) that live either on the seafloor (benthic) or amongst the marine plankton. The planktonic and most of the benthic forms build tests (shells) which are preserved in large numbers in the sediments after death. There are two main types of benthic foraminifera: those with calcareous tests and those termed 'agglutinated foraminifera' with tests made from detrital material held together with a cement which is totally or partly organic. All planktonic foraminifera have calcareous tests.

The distribution of benthic foraminifera depends on variations in the local physical, biological, and chemical conditions (summary in Murray 1991). Examination of the sedimentary record for benthic foraminifera tests has revealed a significant response by these animals to anthropogenically-induced changes of their environment (reviewed by Alve 1995b). Benthic foraminiferal investigations in several fjord-basins on the Norwegian Skagerrak coast have provided detailed information about the environmental development, particularly effects of increased influx of organic material, from pre-industrial to present-day conditions (Nagy & Alve 1987, Alve 1991, 1994). Effects of environmental improvement, as shown by recolonization of formerly anoxic fjord bottom areas, have also been demonstrated (Alve 1995a, Bernhard & Alve 1996).

Present-day foraminiferal distribution

Although the classic taxonomic work on Skagerrak foraminifera is that of Höglund (1947), he did not publish his quantitative data (except for one station) so the present investigation represents the first detailed analysis of recent foraminiferal distributions and dynamics in the Skagerrak. Previous Skagerrak studies have generally been based on widely spaced samples, on samples that had not been stained (to distinguish live from dead specimens) or on samples processed on sieves of varying mesh size (63-150 micron). These factors complicated interstudy comparisons (for summary of previous studies, see Alve and Murray 1995).

Only scattered planktonic foraminiferal tests (mainly <150 micron, juvenile and stunted adult forms) are present in the surface samples. Benthic foraminifera, in contrast, are abundant and occur frequently throughout the area (Fig. 6.2) Some of these animals live epifaunally, attached or clinging to elevated objects, some live infaunally at depths down to 20 cm below the sea-floor, but the majority of species live infaunally in the oxygenated upper 5-10 millimetres of the sediment.

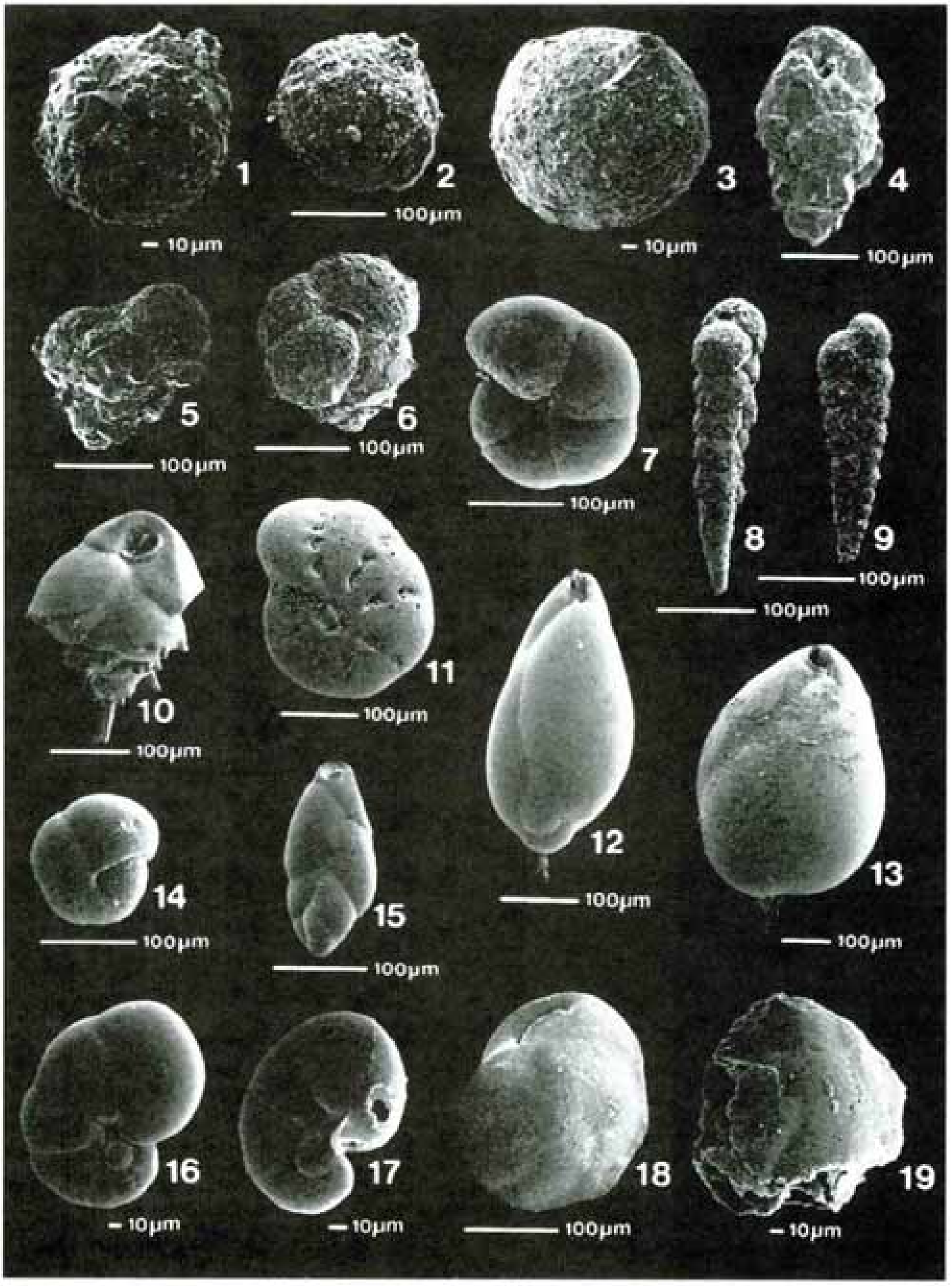


Fig. 6.1 Benthic foraminifera common in the Skagerrak. 1-9 are agglutinated taxa. 10 - 19 are calcareous taxa. For location of stations, see Fig. A2 (Appendix).

1. *Saccammina* sp., station 56.
2. *Saccammina* sp., station 56.
3. *Saccammina* sp., station 56.
4. *Eggerelloides medius* (Høglund), station 56.
5. *Trochamminopsis pusillus* (Høglund), station 56.
6. *Trochamminopsis pusillus* (Høglund), station 56.
7. *Haplophragmoides bradyi* (Robertson), station 75.
8. *Textularia tenuissima* Earland, station 108.
9. *Textularia tenuissima* Earland, station 108.
10. *Bulimina marginata* diOrbigny, station 114.
11. *Elphidium excavatum* (Terquem), station 114.
12. *Globobulimina auriculata* (Bailey), station 114.
13. *Globobulimina auriculata* (Bailey), station 114.
14. *Pullenia osloensis* Feyling-Hanssen, station 108.
15. *Stainforthia fusiformis* (Williamson), station 114.
16. *Nonionella iridea* Heron-Allen and Earland, station 56.
17. *Nonionella iridea* Heron-Allen and Earland, station 56. Partly dissolved test.
18. *Cassidulina laevigata* diOrbigny, station 114.
19. *Cassidulina laevigata* diOrbigny, station 56. Partly dissolved test.

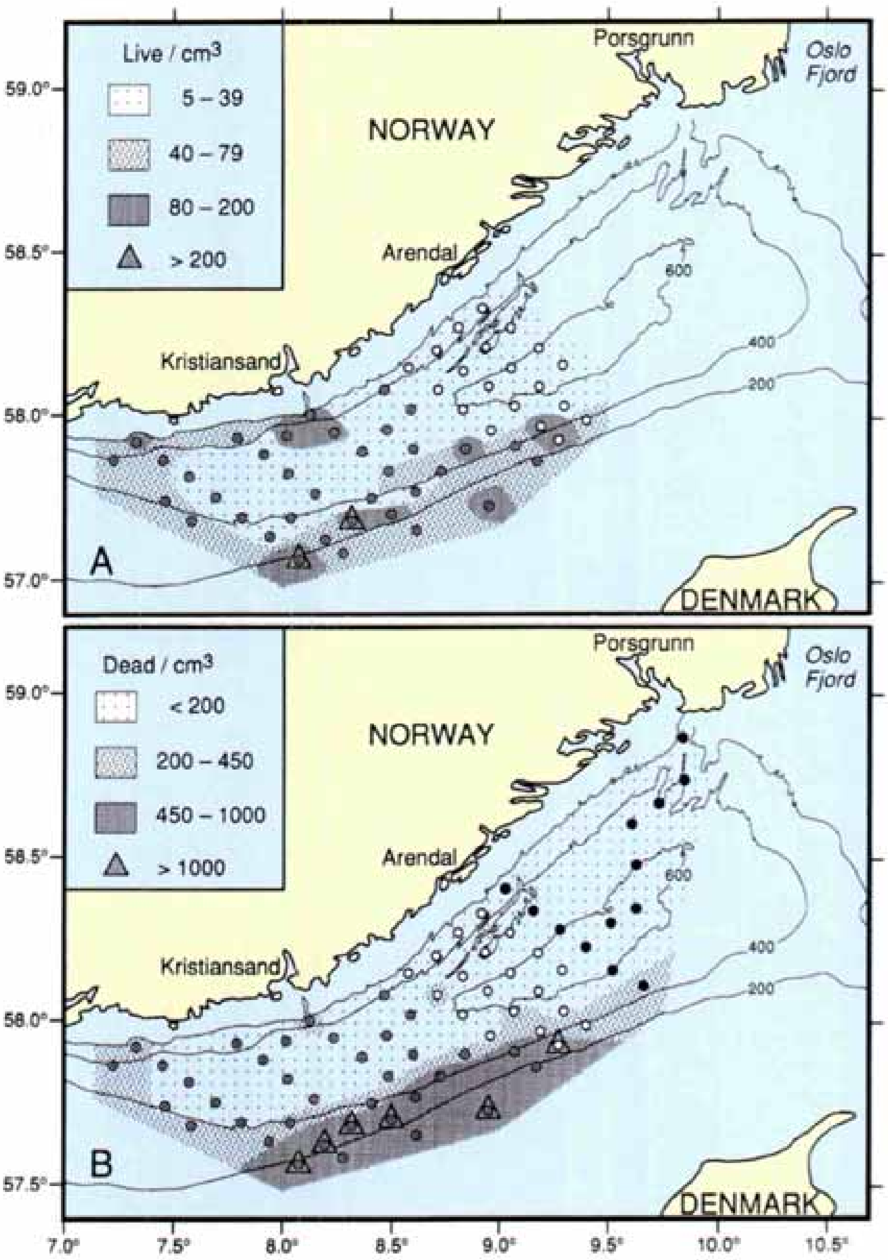


Fig. 6.2. Numerical density of benthic foraminiferal tests (no. tests/cm3). A: live assemblages; B: dead assemblages. Filled circles = 1992; open circles = 1993; double circles = 1994.

There are major differences between living associations when comparing the NE to the SW parts of the deeper Skagerrak basin (Fig. 6.3 A). On the other hand, the time-averaged dead associations have a relatively uniform composition throughout this deep water area (Fig. 6.3 B). This discrepancy between the distribution of living and dead associations may partly be due to different annual bloom events in certain species (NE and SW living assamblages collected in 1993 and 1994, respectively). However, there is clear evidence that the discrepancy is primarily due to contemporary dissolution of calcareous tests (discussed below), and to a lesser degree to destruction of fragile agglutinated forms. It seems reasonable that the end product of dissolution of either of the two living associations leads to essentially the same dead association. This may suggest that there is no long term significant environmental difference from one part of the basin to the other. On the other hand, if the two dissimilar living associations reflect real short-term environmental contrasts between the NE and SW deep areas, these differences are not well preserved in the dead association.

By contrast, the Norwegian and Danish slopes show uniform intraslope patterns, but distinctly different interslope associations; these differences between Norwegian and Danish slopes are primarily attributable to the differing influence of outflowing and inflowing water masses in the Skagerrak, respectively. On the Norwegian slope, the distribution of the living association resembles that of the dead. Most of the frequently occurring species are common in both associations but the maximum frequency of certain species differs, thus the difference in factor associations. Both the dead and living assemblages on the main part of the Danish slope are dominated by the opportunistic species *Stainforthia fusiformis* (Williamson). Distribution of this species generally correlates with the zone of sediments rich in organic detritus (maximum abundance at 200 - 500 m on the Danish slope) but it also extends to the top of the slope. At depths shallower than 200 m, the dead association is characterised by shelf species (discussed below) which are either not present or only rare in the living association.

Transport and high benthic fertility

The most likely explanation for the discrepancy between the living and dead associations on the Danish slope is that dead shelf tests are transported into the area. Source areas can only be determined on the basis of living distributions of species whereas total (living plus dead) assemblages, used by most authors in this geographical area, provide less reliable information, since they already include the effects of post-mortem transport.

The only study to distinguish live and dead assemblages in the southern North Sea is that of Murray (1992) who found widespread living and dead individuals of

Elphidium excavatum (Terquem) and *Eggerelloides scabrus* (Williamson). These and other examples of the shelf species found in the dead assemblages of the present study were recorded in total assemblages in the North Sea, adjacent to the west coast of Denmark (Jarke 1961, Gabel 1971). The same shelf species have also been recorded in total assemblages in the North Sea, also adjacent to the west coast of Denmark (Conradsen et al. 1994). However, *E. scabrus* was extremely rare so the Danish shelf cannot be the source area for this species. Therefore, the provenance of the transported species is most likely to be from the south under the influence of the north-flowing cyclonic current, shown to extend from the surface water to at least 400 - 500 m depths. (Rodhe 1996). This assumption is strengthened by the fact that both the relative and absolute abundance of transported tests systematically decrease downslope (Fig. 6.4).

Generally, the abundance of living foraminifera is related to the fertility of an area. In the southern North Sea the average standing crop values are 2-10 live individuals/cm^3, with occasional values >10 (Murray 1992). In the Skagerrak, the values are generally several times higher (Fig. 6.2 A). The general pattern is that the deeper areas (>400 - 500 m) have the lowest values (5-40 live individuals/cm^3), whereas all values of > 80 live individuals/cm^3 are on the Norwegian and Danish slopes. The maximum standing crop values (236-332 live individuals/cm^3) occur on the Danish slope between 200 and 300 m but high values (>120 live individuals/cm^3) are also present down to 500 m. The abundance of dead individuals shows a similar distributional pattern but the higher concentration of tests is even more clearly defined (Fig. 6.2 B).

Visual examination of organic detritus in the >63 micron fraction (wet sample) and of tubular foraminifera show patterns with maximum values between 200 and 500 m water depth on the Danish slope. This zone broadly correlates with the area of maximum numerical density of living benthic foraminifera (Fig. 6.2 A). These high densities of living foraminifera reflect elevated nutrient conditions and demonstrate that a high benthic fertility regime exists in this area. The presence of such conditions is due to high availability of organic material (e.g. organic detritus) and the associated bacteria that provide an additional food source for the foraminifera. The live numerical density on the Danish slope is comparable to that of the Mississippi delta (e.g., Lankford 1959).

Some of the organic detritus is probably transported northeastwards as indicated by the distribution of transported shelf species; this distribution suggests that parts of the Danish slope act as a sink area. Another indicator of provenance and deposition is the barium content of the sediments. The source areas are believed to be drilling platforms in the North Sea (Sæther et al. 1996) and barium analyses

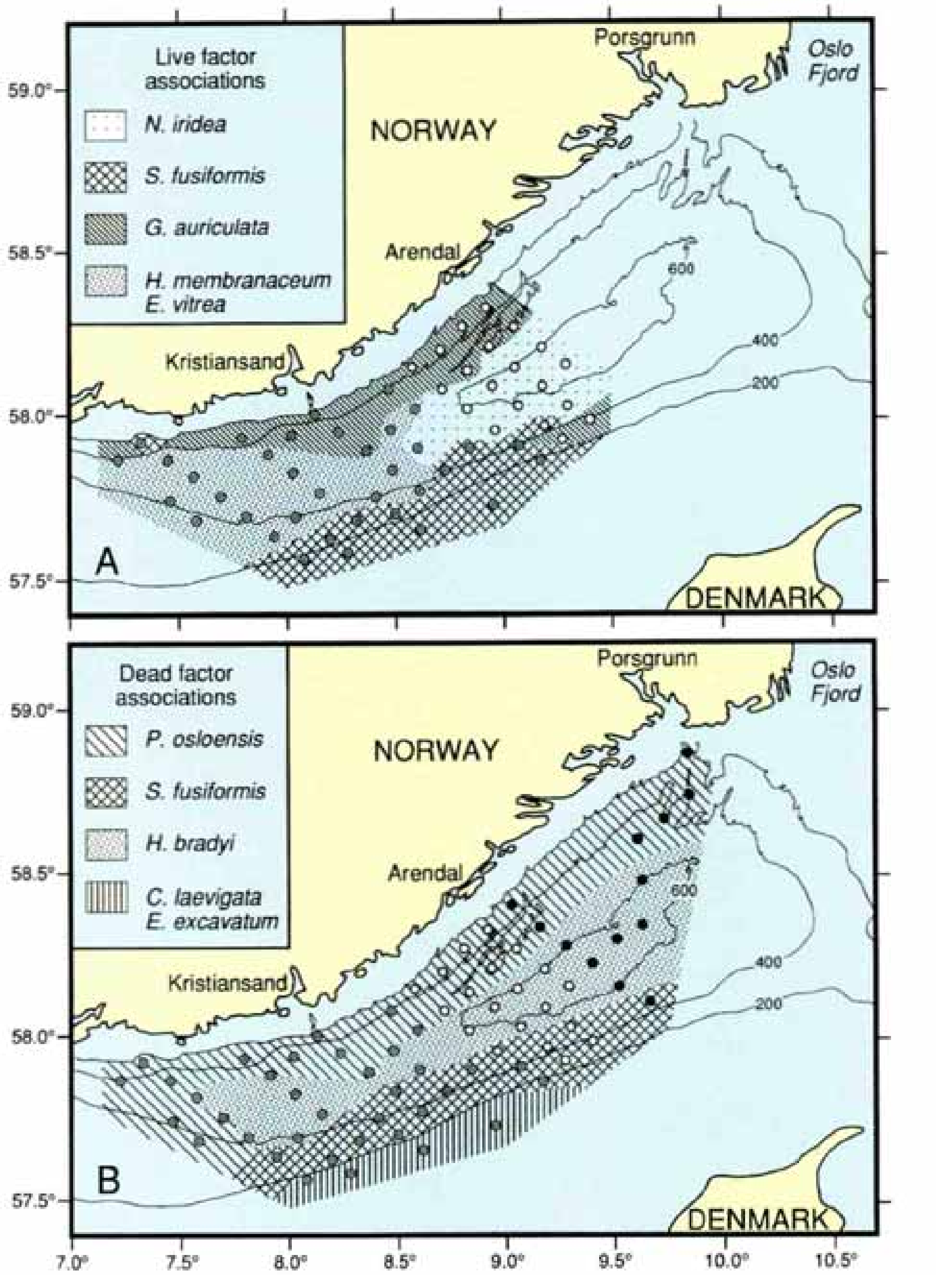


Fig. 6.3. Varimax factor associations. A: live; B: dead. Filled circles = 1992; open circles = 1993; double circles = 1994. Based on Q-mode factor analysis, four living and four dead foraminiferal associations are distinguished and their overall distributional patterns define 3 geographical sub-areas - the Norwegian slope, the Danish slope, and the deep Skagerrak basin (>400 - 500 m water depth) in between.

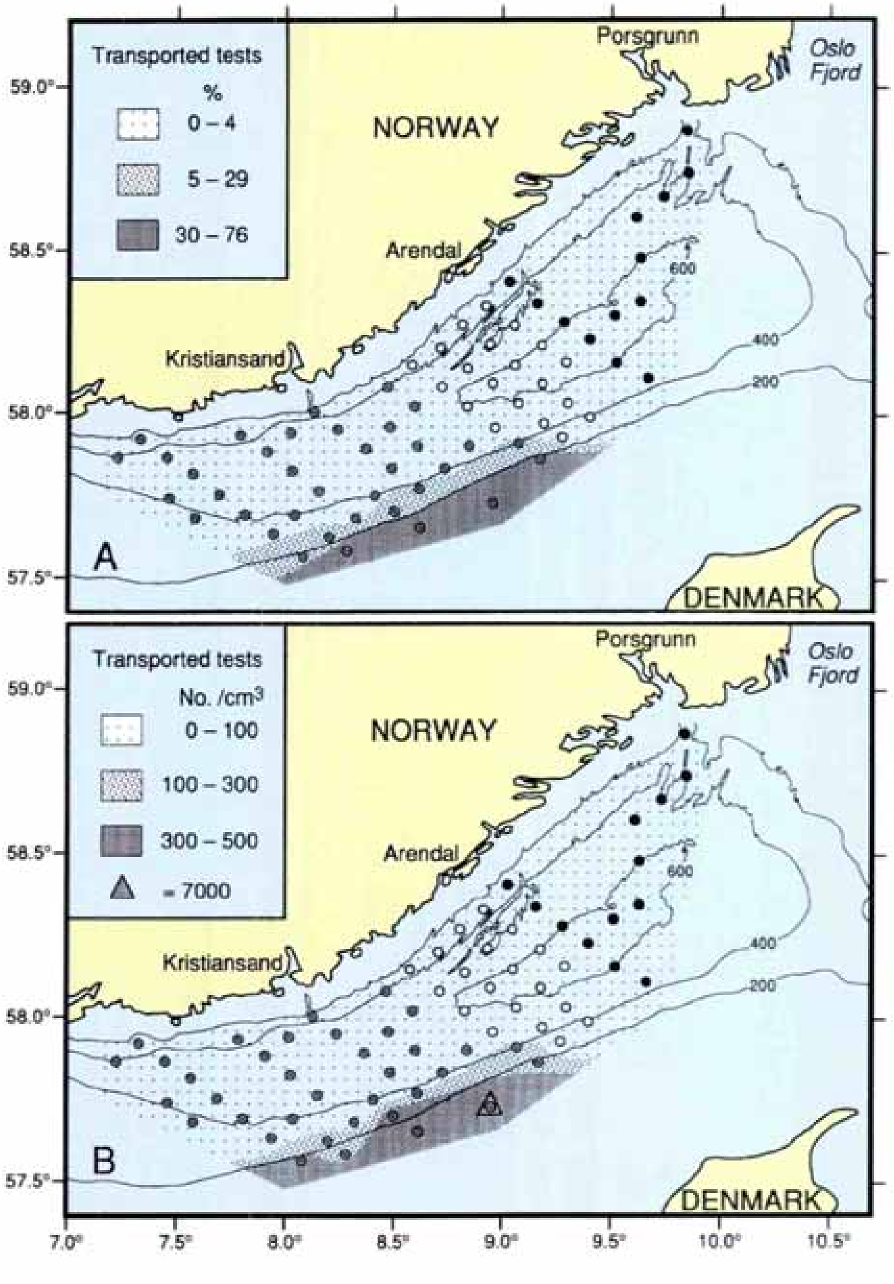


Fig. 6.4. Abundance of shelf/marginal marine species inferred to be transported into the area. A: percent; B: numerical density (no./ cm³). Filled circles = 1992; open circles = 1993; double circles = 1994.

of the surface sediments (see Chapter 5.5) have shown that the areas of maximum barium concentrations coincide with the areas of maximum organic detritus.

The upper Danish slope is also disturbed by the activities of trawlers scouring the sea-bed for prawns. This includes both physical disturbance of the sediment surface and the consequent resuspension of fine fractions, including organic matter. Some of this may be transported downslope into deeper areas not otherwise directly affected by the trawling.

The combination of physical disturbance and frequent supply of organic matter may be particularly favourable for opportunistic species which can easily recolonize and flourish in recently disturbed areas. This is probably the case for the opportunistic *Stainforthia fusiformis* (Alve 1994) which reproduces throughout the year (Murray 1992; Alve 1995a), and which is the predominant living species on the Danish slope. All these factors may contribute to the greater numbers of living foraminifera on the Danish slope.

Carbonate dissolution

The relative abundance of calcareous tests is generally higher in the living than in the dead assemblages in the deep Skagerrak basin. Dissolution damage, evident in many calcareous specimens (Fig. 6.1, no. 17 and 19), indicates ongoing calcium carbonate dissolution in the deep basin sediment porewater. Some dissolution damage is noted for the slope areas too but there it is much less evident. Dissolution of calcareous tests leads to a relative increase in agglutinated tests so that most deep basin dead assemblages are 50 - 79% agglutinated while the corresponding living assemblages only have occasional values > 50%.

Prior to 1970, *Nonionella iridea* was one of the most frequently occurring species in the deep basin but the accumulation rate of its empty tests has been more than halved since then. In spite of this reduction, *N. iridea* is still one of the most common living species (generally 10 - 30% of live assemblages) in the deep basin surface sediments whereas it is comparatively rare (generally 5%) in the corresponding dead assemblages. This strongly indicates that *N. iridea* has been an important species in the deep basin assemblages for a long time and that increased carbonate dissolution (i.e. unfavourable preservation conditions) over recent decades is responsible for its present reduced relative and absolute abundance in the dead assemblages.

Environmental development over the last couple of centuries

The stratigraphical data sets from the Norwegian and Danish slopes are too scarce to draw any firm conclusions. However, the available data suggest that the foraminiferal abundance on the Norwegian slope has been relatively stable with minor recent changes in the faunal composition. This suggests that no major environmental changes have occurred here. Data from the Danish slope strongly suggests that the absolute abundance of the opportunistic *Stainforthia fusiformis* has increased from 2 to >5 times over the past 50 - 60 years, suggesting increased nutrient availability (high fertility) and increased physical disturbance.

The sediment cores from the deep Skagerrak basin show that the accumulation rate of agglutinated tests was relatively constant from the last part of the 18th century until 1940 - 1950. Since the late 1960's, this rate has increased about 5-6 times compared to average pre-1940 values (Fig. 6.5). This increase is due mainly to increased production in four agglutinated species, *Haplophragmoides bradyi* (Robertson), *Eggerelloides medius* (Höglund), *Trochamminopsis pusillus* (Höglund), and *Saccammina* spp, of which the latter two were present only as accessory species prior to 1960. These results are in good agreement with the development as seen by the comparison between surface samples from 1992/93 and Höglunds data from 1937. According to Höglund (1947, p. 184), *Eggerelloides medius* had its maximum abundance between 150 and 250 m water depth in 1937. However, its modern distribution shows that its absolute frequency in the deep Skagerrak basin has tripled since 1937, indicating that it has moved its peak abundance towards water depths greater than about 550 m.

The consistent increase in these agglutinated species probably reflects that the environmental conditions have been modified in the deep Skagerrak basin, at least since the early 1970's. This area is the main depository of fine-grained particulate material in the North Sea (e.g., Van Weering et al. 1987). Additionally, because of its physical properties (sill at about 280 m water depth) and general water circulation patterns which prevent efficient deep water exchange (on average, deep water renewal is every 25th month; Aure & Dahl 1994), the bottom environment is probably more sensitive to increased fluxes of organic material than are the shallower, well-flushed areas. Dating with the ^{210}Pb method shows that the rate of sediment accumulation is lower in the deep basin compared to the slopes (except in the SW parts) with no indication that this accumulation rate has changed significantly over recent decades (see Chapter 4.2). However, an increasing, net influx of organic material might have occurred despite this stability in overall sediment accumulation rate.

Drastic changes in the benthic foraminiferal assemblages have also recently been noted at core levels dated to the early 1970's in the southern Kattegat (Christiansen et al. 1996). These authors suggested that the changes they recorded were due to wind-induced higher salinities and declining bottom water oxygen concentrations. At the present stage, it is too speculative to suggest that a link exists between these changes in the Kattegat and those recorded from the Skagerrak.

The faunal changes that have occurred in the deep Skagerrak basin over recent decades may, at least partly, be due to increased organic load that may have elevated the redox boundary in the sediments and made the habitat more favourable for agglutinated foraminifera. In this connection, it is worthwhile mentioning that a similar faunal change occurred in Frierfjord (a silled southern Norwegian fjord) during the 17th and 18th centuries, as a response to increased organic input (Alve, unpubl. data). In Frierfjord, increase of agglutinated foraminifera was the first of several faunal changes that preceded the development of nearly permanently anoxic bottom water conditions.

Evidence of environmental change from planktonic foraminifera

Throughout the 69 investigated surface samples, only scattered tests of planktonic foraminifera occur. On the other hand, all four cores from the deep Skagerrak basin show abundant occurrences (12-26% of the foraminiferal assemblages) of small (mainly <150 micron), juvenile or stunted adult planktonic foraminifera in the lower parts of the cores. Both the relative and absolute abundances of these small planktonic tests show a pronounced upward decrease, with minimum abundances (< 2%) registered in the surface sediments (Fig. 6.6). In the younger, upper parts of the cores, this is probably partly due to dissolution effects similar to those discussed previously for the benthic calcareous forms. For the lower (pre-1970) parts of the cores, dissolution is not considered to be an important factor affecting the

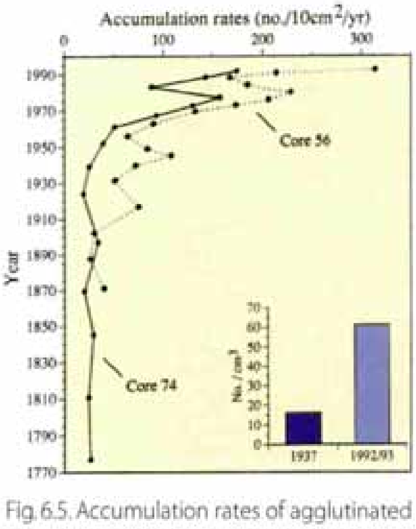
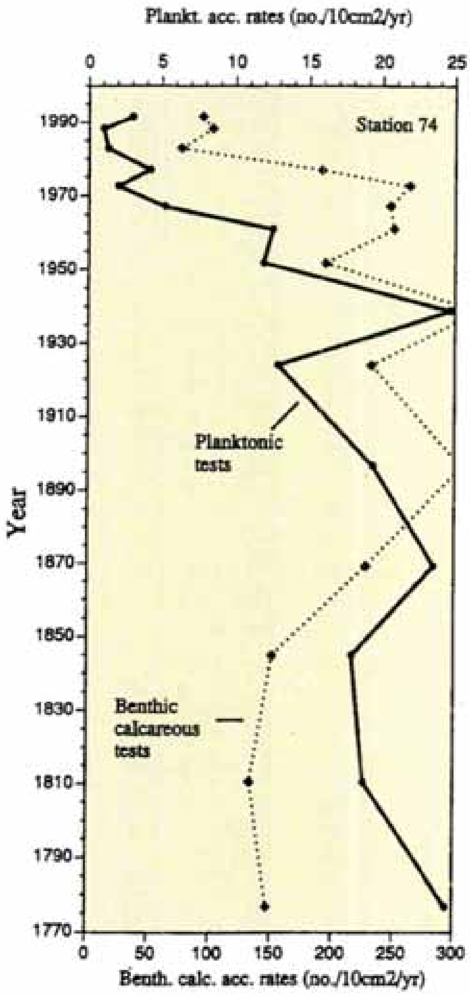


Fig. 6.5. Accumulation rates of agglutinated tests (dead assemblages) in cores from station 56 and 74. Histograms show the average concentration of agglutinated tests in deep Skagerrak Basin surface samples collected in 1937 and 1992/93.



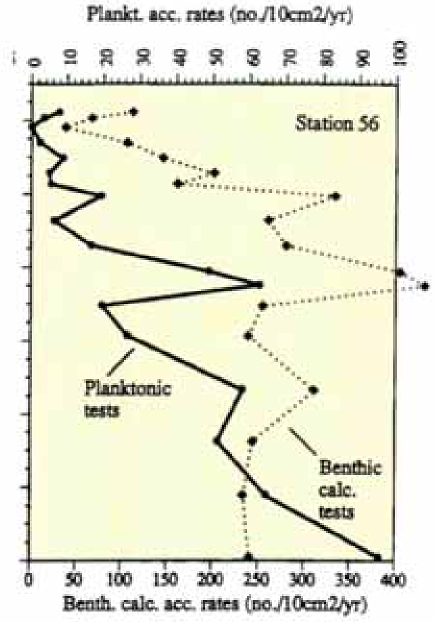


Fig. 6.6. Accumulation rates of planktonic and calcareous benthic foraminiferal tests (dead assemblages) in cores from station 56 and 74.

upward decrease. This is because it would also have affected the calcareous benthic tests, the abundance of which does not show a drastic reduction until after about 1970.

Planktonic foraminifera are essentially oceanic forms and do not thrive in coastal and shelf areas. Their distribution in ocean sediments are widely used to describe the circulation pattern of both modern and ancient oceanic surface water masses. In the Norwegian Sea, the northern North Sea, and the Skagerrak, their quantitative distribution reveals a zonation with steep decreasing gradients essentially perpendicular to the Norwegian continental margin (Qvale & Thiede 1980). For the coastal water masses of the Skagerrak and of the northern North Sea, abundances (>150 micron fraction) are <100 tests/g dry bulk surface sediment, whereas abundances of >10 000 tests/g are typical under the North Atlantic water. In the middle and southern North Sea, planktonic foraminifera are absent from most sediment surface samples (Jarke 1961, Murray 1992).

Renewal of the deep Skagerrak water may occur either by cooling of the water on the North Sea plateau or by inflow of denser Atlantic (Norwegian Sea) water (North Sea Task Force 1993, p. 14). Consequently, it is reasonable to assume that small, easily transported, planktonic foraminiferal tests are being carried into the Skagerrak area by subsurface, Atlantic water entering from the Norwegian Sea. If this is indeed the case, the concentrations of planktonic tests in the Skagerrak sediments may signal the influx of Atlantic water into the Skagerrak basin. On the other hand, we do not know if there have been (and perhaps still are) some local populations of small planktonic foraminifera living in the Skagerrak in the recent past. In either case, their drastic decline during the last couple of centuries signals environmental change.

6.2 Dinoflagellate cysts

Dinoflagellate cysts as environmental indicators

Dinoflagellates are single-celled, microscopic organisms that represent a major group of the marine phytoplankton. The autotrophic dinoflagellates, which utilise photosynthesis, live in the photic zone (0 - 50m). On the other hand, the heterotrophic dinoflagellates are not photosynthetic and prey on other phytoplankton such as diatoms or consume organic particles. Some dinoflagellates produce cysts which represent a resting stage in the life cycle; most cysts are composed of very resistant organic material that is insoluble either in the water phase or when buried in sediments. The geographic distribution of dinoflagellates is controlled by the complex interaction of a variety of environmental parametres like temperature, salinity, stability of the water column and the supply of nutrients (Dale 1983, Harland 1988). Most acid-resistant cysts are formed by dinoflagellates living in coastal waters, although acid-resistant cysts are also formed by some oceanic dinoflagellate species. The composition and the concentration of the cysts in the sediments are controlled by the cyst production, their transport in water, the sedimentation rate and the amount of sedimentary mixing caused by bioturbation and resedimentation. Recently, the distribution and abundance of dinoflagellate cysts in sediment cores from southern Norwegian fjords have demonstrated their potential as indicators of anthropogenically induced environmental change over recent centuries (Dale and Fjellså 1994). These investigations primarily focus on euthrophication signals. The dinoflagellate cyst interpretations from the Skagerrak are based on analyses of eight samples from a 50 cm-long sediment core collected at station 74, in the deep Skagerrak basin at 594 m water depth. For further details, see Grøsfjeld (1996).

Water mass characteristics over recent centuries

The analysed core represents sediments deposited since the late 17th century. The assemblage composition in the uppermost 40 cm of the core is dominated of *Operculodinium centrocarpum* (described by Deflandre & Cookson, and later by Wall) and is basically the same as that of Late Holocene assemblages in the NE Atlantic, off western Scotland (Harland & Howe 1995). The compositions of the cyst assemblages in this part of the core do not show any major changes, nor do the cyst concentrations change through the core. The dominance of *O. centrocarpum* (50 to 70 %) is in accordance with other studies from Skagerrak/Kattegat (Koniezcny 1983, Dale 1985, Thorsen et al. 1995). *O. centrocarpum* appears to tolerate wide ranges of temperatures and salinities, and it is found in great abundances in oceanic as well as in estuarine cyst assemblages. In the Atlantic Ocean *O. centrocarpum* seems to be associated with the North Atlantic Water and it dominates the assemblages in sediments underlying the Norwegian Coastal Current and the Norwegian Current (Matthiessen 1991, Harland 1983, Dale 1985); this species appears to be a good indicator for the modern, relatively warm North Atlantic current. The two lowermost samples of the core show reduced abundances of *Operculodinium centrocarpum* primarily related to elevated abundances in *Protoperidinium* spp. and *Gymnodinium catenatum* (described by Graham). The latter accounts for 15% of the assemblage in the lowermost 10 cm in the analysed core, whereas it is absent in the uppermost 40 cm of the core.

Gymnodinium catenatum is a toxic dinoflagellate only recently found in minor amounts of the plankton assemblage of Danish waters. It is today present in regions with supposedly warmer surface water (the Gulf of California, Venezuela, Argentina, Tasmania, Japan, around the Iberian peninsula and in the Mediterranean) than the Scandinavian waters today (Thorsen et al. 1995). *Gymnodinium catenatum* was, however, a numerically important species in the eastern part of the Skagerrak/Kattegat at 4 000 years B.P. and between 2 000 years B.P. and 300 years B.P. It had its maximum occurrence during the Medieval Warm Epoch, at 830 years B.P. At c. 300 years B.P. it disappeared from the Skagerrak. The disappearance of Gymnodinium catenatum is well documented in the analysed core at c. 40 cm depth. This extinction at c. 1650 indicates changed climatic conditions with an increased influence of colder surface water in the Skagerrak during the last few centuries.

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Appendix

Glossary

adsorption - the process by which a substance attaches itself to the surface of another.

agglutinated tests - foraminiferal tests (shells) made by particles from the surrounding sediment and held together with a cement which is totally or partly organic.

alkanes - a series of chemical compounds containing carbon and hydrogen linked in saturated chains like methane, ethane, propane, butane or octane.

anthropogenic - man-made or influenced by mans activity.

aragonite - a grey, harder, less stable and less common variant of $CaCO_3$ than calcite.

aromatic hydrocarbon - compounds in unsaturated ring structures containing carbon and hydrogen.

assemblage - in this context, the typical assembly of different foraminifera (or dinoflagellates) species which constitutes the local fauna (or flora) at a certain time.

background levels (concentrations) - natural levels of chemical elements in sediments which are not affected by anthropogenic contamination.

barite - $BaSO_4$, a barium mineral (barium is a heavy metal).

bathymetry - the measurement of ocean depths and the charting of the topography of the ocean floor.

bathymetric map - a map of the sea-floor which shows the water depths by means of contour lines (isobaths).

benthic foraminifera - unicellular organisms which live on the sea-floor.

bentonite - a sedimentary rock formed from the alteration in place of volcanic ash.

benzo[*a*]pyrene - a polycyclic aromatic hydrocarbon which is mainly generated from incomplete combustion of fossil fuels (e.g. coal, oil and petrol).

biota - all living organisms of an area, both flora and fauna.

bioturbation - mechanical mixing of sediments due to foraging fishes and sediment-dwelling fauna in the sediment (see Box 5.1).

C_2-naphthalenes - an aromatic hydrocarbon often found in oil and oil-derived products.

$CaCO_3$ - calcium carbonate

calving - the breaking off and floating away of pieces of ice from an ice front or ice shelf which rests in water.

Cambrian - the geological period from 540 million to 495 million years ago (see Fig. 2.2).

clay (mineral) - clay is both a size term and a mineral. The size term refers to particles less than 2 micron. Clay minerals are finely crystalline hydrous silicates of aluminium, iron, manganese, magnesium and other metals. The principal clay minerals are kaolinite, smectite (montmorollinite), illite and vermiculite.

conglomerate - a coarse-grained clastic sedimentary rock, composed of rounded to subangular fragments larger than 2 mm in diameter set in a fine-grained matrix of sand or silt, and commonly cemented by calcium carbonate, iron oxide, silica or hardened clay.

contamination - concentrations of natural substances clearly above the normal background, or elevated concentrations of purely man-made substances.

contamination level - the definition used in this report is the ratio of the concentration of an individual trace metal in the surface sediment compared to the natural background levels of that trace metal.

continental shelf - that part of the continental margin that is between the shoreline and the continental slope (between 0 m and 200 m depth). It is characterised by its very gentle slope of $0.1°$.

continental slope - the slope from the continental shelf and into deeper water. It is characterised by relatively steep gradients of $3\text{-}6°$.

Coriolis effect - the deflection of the path of a moving object, e.g. a current of the sea, as the result of the earth's rotation.

Cretaceous - the geological period from 142 million to 65 million years ago (see Fig. 2.2).

current - movement of water in a particular direction and with sufficient continuity to be distinguished from other water, e.g. surface currents, such as the

Gulf Stream, caused by a dominant wind.

$\delta^{18}O$ - see oxygen isotopes.

detritus - fragments of minerogenic or organic matter resulting from abrasion or disintegration.

diagenesis - the chemical, physical and biological processes that bring about changes in a sediment subsequent to its deposition (see Box 5.5).

dinoflagellate - single celled, microscopic marine phytoplankton (dominant).

drumlin - a streamlined ridge formed by a glacier at its base. The ridge lies parallel with the flow direction of the glacier, and it consists of subglacial till, sometimes with a core of bedrock or a core of older sediments. The typical drumlin is cigar-shaped with a head and a tail, with the tail pointing in the glacier-flow direction.

epifaunal - fauna living on the surface of the sea bottom sediments.

erosion - removal of material from any part of the earth's surface.

estuary - an arm of the sea at the mouth of a tidal river where the tidal effect is influenced by the river current.

eustasy - world-wide changes in world sea-level caused by variations in the ocean water column or size of ocean basins. Most scientists also include changes in shape of the globe, the geoidal changes, in the term; these include elastic deformation of the earth caused by shifts in load from the ice sheets on the continents to the water in the ocean basins. However, the most dominant factor for the Quaternary eustatic changes is the changing amount of water stored in the large ice sheets.

eustatic sea-level rise - sea-level rise due to eustasy.

euthrophication - enrichment of the sea by nutrients, causing rapid growth of marine organisms.

fault - in this context a fracture or a zone of fractures in rocks along which there has been displacement of the sides relative to each other.

faulting - adj. of fault.

Fennoscandia - abbreviation for Finland and Scandinavia.

flocculation - the physical process by which several particles join together.

fluted till surface - till surface containing parallel ridges that have a fairly constant height over long distances. The flutes may be formed either by erosion of grooves or deposition of ridges. The ridge axes are parallel to the flow direction of the glacier forming them (see Fig. 3.14).

foraminifera - see Benthic foraminifera.

gamma-ray spectrometer - an instrument for measuring the energy distribution, or spectrum, of electromagnetic radiation from an atomic nucleus whether from natural or artificial sources.

geogenic material - material derived from geological processes.

glacial trough - a term used in many different connections, also in glacial geology for a closed depression with a smooth «U-shaped» cross profile. Glacial troughs are characteristic forms in glacially sculptured landscapes. They can be from a few centimetres to several hundred meters deep and up to many kilometres long and wide, and they can be of regular or very irregular shape. The sides of some troughs are gentle and some are steep.

glacial - a term used generally for features and deposits related to glaciers and glaciations, but also used for a stratigraphic time period such as between two interglacials or between the last interglacial and the Holocene, for instance the Weichselian Glacial.

glacier - a body of snow, firn, and ice which flows or has flowed. According to Ahlmann's classification, there are temperate, subpolar, and high-polar glaciers. The ice in a temperate glacier is at the pressure melting point, except at the surface during the winter. No melting generally takes place on the surface of a high-polar glacier.

glaciofluvial - transported by melt-water rivers or the result of such transportation.

glacitectonic - term for complicated and deranged features and deposits found at glacial borders, and consisting of material which may have been overturned, inverted, folded, and/or transported by the shoving action of glaciers.

gneiss - a foliated rock made by regional metamorphic alteration of older rocks.

grain-size - particle size or granularity. Depending on size, particles are classified into gravels (2 cm - 2 mm), sand (2 mm - 0.063 mm or 63 µm), silt (63 µ m - 2 µm) and clay (< 2 µm). µm is symbol for micron (see micron).

grounding line - the line described by the shift from grounded ice to floating ice of a glacier that terminates in water.

half-life - the time necessary for a radioactive substance to loose half of its radioactivity by radiation. Each radionuclide has a characteristic half-life.

Holocene - the time period spanning from 10 000 years B.P. and until today (Fig. 3.3).

hydrocarbon - a compound of hydrogen and carbon only, e.g. petroleum, coal, asphalt.

hydroxide - a compound or an element with the radical or ion, OH, as e.g. manganese hydroxide $Mn(OH)_2$.

ice age - a glacial period in the earth's history when large glaciers covered areas which are ice free today. Best known are the ice ages during the last 2.7 million years.

ice cap - a more or less dome-shaped glacier which is smaller than an ice sheet.

ice front - the front (terminus) of a glacier.

ice shelf - the floating part of a glacier or many merging glaciers.

ice-sheet - a glacier which covers a wide area. The ice sheet may have outlet glaciers in valleys and fjords. The term is generally used for very large glaciers.

iceberg - slabs of floating ice broken off the front of grounded glaciers or ice shelves. Some icebergs are several kilometres wide.

infauna - those aquatic animals that live within the sea bottom sediments.

infaunally - adj. of infauna.

interglacial - the time between two glacials, when the climate, the regional vegetation zones and the glacial conditions on the earth's surface were approximately as they are today.

interstadial - a term generally used in connection with the Quaternary glaciations, meaning a relatively warm phase between colder phases. An interstadial is usually cooler and shorter than an interglacial. However, an interstadial can be as warm as an interglacial, but in that case it must be of so short a duration that the glaciers of the world were not reduced to interglacial sizes, and the regional vegetation zones did not reach the extent of the interglacial zones.

isopach map - a map that shows the thickness of a geological unit (bed, formation etc.) throughout a geographic area by means of isopachs (lines through points of the same true thickness) at regular intervals.

isostatic depression - depression of the earth's crust by the weight of ice caps or ice sheets (see Box 3.1).

isostatic uplift - rebound of the earth's crust after disappearance of ice caps or ice sheets.

Jurassic - the geological period from 205 million to 142 million years ago (see Fig. 2.2).

kPa (kilopascal) - unit for pressure.

macrofauna - living or fossil animals large enough to be seen with the naked eye.

marine - prefix for anything that has to do with the sea.

meiofauna - organisms ranging in size from 1 mm to 0.1 mm that live within sediments.

Mesozoic - the geological time span between 248 million and 65 million years before today (see Fig. 2.2).

metamorphism - the mineralogical, chemical and structural adjustment of solid rock to physical and structural conditions which have generally been imposed on the rock at deep levels into the earth's crust.

metamorphic - adj. of metamorphism.

methane - a hydrocarbon consisting of one atom of carbon and four atoms of hydrogen.

mg/kg - milligram per kilogram.

micron - unit of length, equal to one thousandth of a millimetre.

micropalaeontology - the study of microfossils.

minerogenic - consisting of or derived from minerals.

moraine - either synonym for till (sediment deposited by glaciers) or geomorphological term for an accumulation of till and formed by glacier action.

morphology- the science dealing with the surface features of landscapes, their shape and how they are formed. The terms is used also for the surficial shape of sediment grains and fossils.

multibeam echo sounding - mapping of the sea bottom with echo sounders that register depths by more than one (usually 36) beam simultaneously.

ng - nanogram, one thousand millionth gram.

normalisation - see Box 5.6.

oceanography - the study of the ocean, including its physical, chemical, biological, and geological aspects. In a narrower sense, the study of the marine environment.

organic compounds - pertaining or related to a compound containing carbon, especially as an essential component. Organic compounds usually have hydrogen bonded to the carbon atom.

opportunistic species - species (in this context foraminifera) which tends to be generalised in its adaptations, disperses and reproduces rapidly.

OSPAR - Oslo and Paris Commissions.

oxygen-isotope - oxygen atoms with different atomic weight (oxygen-18/oxygen-16) During ice ages, much oxygen-16 is bound with water in glaciers and the sea is consequently enriched by oxygen-18. The ratio of $^{18}O/^{16}O$ in marine fossils (shells) can be used to elaborate past times temperature history.

PAH - see polycyclic aromatic hydrocarbon.

pack ice - an area of floating sea ice (broken pieces) which is not attached to the shore.

Palaeozoic - the geological time span between 540 million and 290 million years before today (see Fig. 2.2).

petrogenic gas - gas originating from the disintegration of organic remains in sediments formed during the transformation from sediments to rocks.

phytoplankton - a flora of freely floating, often minute unicellular organisms that drift with water currents. Oceanic phytoplankton is the primary food source, directly or indirectly, of all sea organisms.

plankton - aquatic organisms that drift or swim weakly (mostly microscopic).

planktonic - adj. of plankton.

Pleistocene - geological time span from 2,5 million years to 10 000 years ago (see figs. 2.2 and 3.2).

plutonic rocks - rocks made by the crystallisation of melted rock at great depths into the earth's crust.

pockmarks - shallow, small, generally circular depressions on the sea-floor usually formed where gas or fluids from the sediments in deeper-lying beds escapes.

pollution - introduction of sufficient amounts of contaminants to the environment to cause negative effects on the marine organisms.

polycyclic aromatic hydrocarbon - compounds with three or more fused aromatic rings, containing carbon and hydrogen.

pore water - water filling small openings and channels in rocks and sediments.

postglacial - the term Postglacial has been used synonymously with the term Holocene. However, postglacial (without a capital P) is more commonly used in a wider sense for the time following the deglaciation of an area.

Precambrian - the geological time span before 540 million years ago (see Fig. 2.2).

primary production - the photosynthetic carbon fixation in water by plants and bacteria forming the base of the food chain.

protozoan - a single celled organism characterised by the absence of tissue and organs. Some protozoans have both plant and animal affinities.

Quaternary Period - time period spanning the last 2.7 million years (see Fig. 2.2).

redox - abbreviation for reduction/oxidation and refers to the shift in sediments where oxygen is present or not, normally two to five cm into marine sediments. The presence of oxygen has major impact on the life and chemical alterations in the sediment.

resuspension - erosion and transport by suspension of previously deposited particulate matter.

sand - see grain-size.

saline water - water containing dissolved salts at concentrations sufficient to allow precipitation of sodium chloride.

sandwave - a generally large and asymmetrical bed form in sand, with a wave like form but lacking the deep scour associated with dunes and mega-ripples.

sediment - material settled from a solution or a suspension, or material that has been transported by water, wind, ice or gravity, and has come to rest.

sedimentary rocks - rocks formed by petrifaction of sediments, including sediments resulting from precipitation from solutions or secretion from organisms. The most common are; claystone or mudstone, siltstone, sandstone, greywacke (an impure, dark sandstone). Conglomerate, breccia, tilllite, etc. are sedimentary rocks dominated by clasts. Limestone consists of more than 50% $CaCO_3$, frequently of cemented shells, but in some cases of chemical precipitates. Chalk is a very pure white limestone. Dolomite consist of $CaMg(CO_3)_2$ and is generally formed from $CaCO_3$ by adding Mg.

sedimentation - in this context, the act or process of forming and accumulating sediment in layers, including such processes as erosion of particles from rock or older sediments, the transportation of these particles to the site of deposition and the actual deposition or settling of the particles.

sedimentation rate - the amount of sediment accumulated in an aquatic environment over a given period of time, usually expressed as thickness of accumulation per unit time.

seismic - phenomena related to earthquake activity or to artificially induced vibrations of the ground produced in connection with the exploration of structures below the earth surface. (See shallow seismic recording).

shallow seismic recording - recording of the upper sediment beds below the sea-floor, or on land, by means of low-energy vibration (wave) sources like air-gun, boomer, sparker and penetration echo sounder.

shear strength - the internal resistance of the sediment to resist stress. This resistance consists both of friction and internal bonding - cohesion. The difference of shear strength of an undisturbed sediment sample (undisturbed shear strength) and the shear strength of the same sample after being mixed (remoulded shear strength) is used as descriptive parameters of sediment properties.

sill - a sub-marine ridge or rise at relatively shallow depth, separating a basin from another basin or from an adjacent sea and causing the basin to be partly closed. It is synonymous for a threshold (of a fjord).

silt - see grain-size.

Silurian - the geological period from 443 million to 417 million years ago (see Fig. 2.2).

stratigraphy - the part of geology dealing with the study of stratified rocks and sediments, their lithology, fossil content, depositional environment, age and correlation. In stratigraphy there are three main branches- lithostratigraphy (based on sediment/bedrock characteristics), biostratigraphy (based on the content of fossils), and chronostratigraphy (based on age).

suspension - a mode of sediment transport where the water is turbulent enough to support the weight of sediment particles and keep them floating in the surrounding fluid (such as silt in water and dust in air).

suspended particulate material - particles (minerogenic and organic) transported in suspension.

taxonomy - the theory and practice of classifying plants and animals.

terrace - in marine geology, a bench-like structure on the ocean floor.

Tertiary - geologic period from 65 million to 2.7 million years ago (see Fig. 2.2).

till - sediment consisting of all grain-sizes (diamicton) carried by, and deposited by, a glacier, generally in contact with the glacier. There are several kinds of till, determined by how the till was deposited (see Box. 3.2).

time-slice - properties of surfaces of the same age.

TOC - abbreviation for total organic carbon.

total organic carbon - all carbon in the sediment that derives from organisms.

trace metals - metals that occur in minute quantities either in minerals or organic matter.

Triassic - the geological period from 248 million to 205 million years ago (see Fig. 2.2).

trough - see glacial trough.

turbidity current - here, a submarine density current, consisting of a suspension of sediments, which is heavier than the surrounding water and travels downslope with high speed. Density currents can erode canyons and deposit large, flat submarine fans on the seafloor beyond the mouth of the canyons.

turbidite - sediment deposited by turbidity currents.

Appendix

Shallow seismic lines and seabed sampling stations

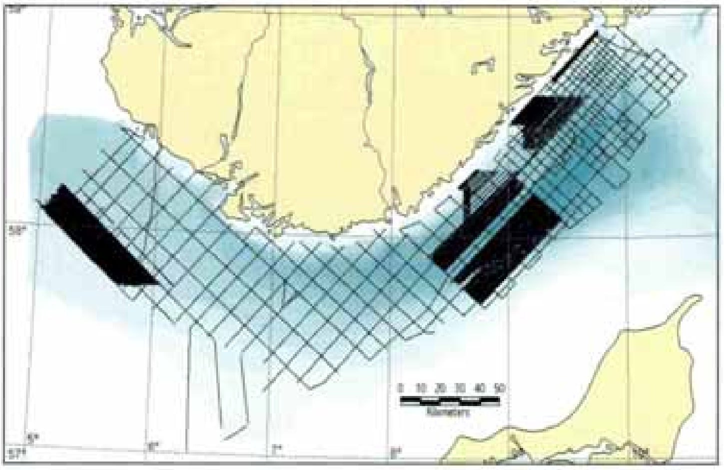

Fig. A1 Overview of shallow seismic lines collected during the Skagerrak Project, 1991-1994

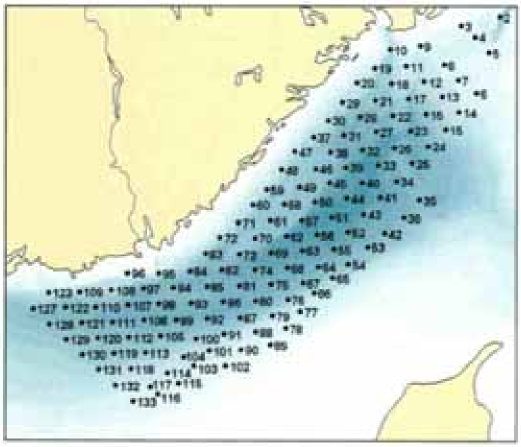

Fig. A2 Stations sampled during the Skagerrak Project 1992-1994.

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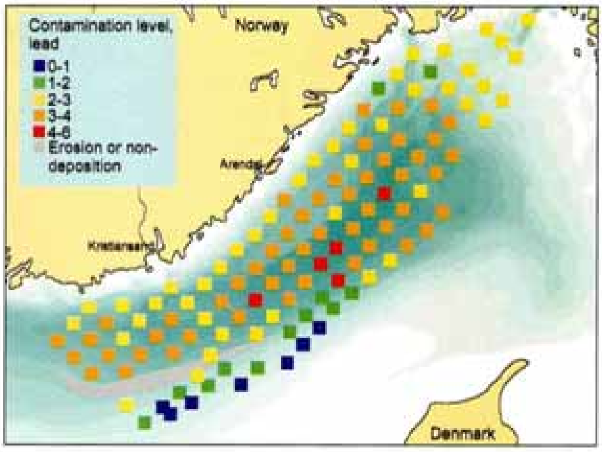

More than 100 cores from the Skagerrak have been analysed for environmental purposes. This example shows that the present levels of lead in the sea-bed sediments in the deepest parts of the Skagerrak are more than four times higher than the natural levels in sediments deposited prior to the industrial revolution.

The Skagerrak is an area of considerable interest, in terms of both environmental and industrial issues. Sedimentary rocks, generally of the same type as in the North Sea, provide a potential for economic hydrocarbon resources. Large glaciers have carved out the Skagerrak basin by repeated ice advances during the last ice ages, and because of this, the Skagerrak is now the deepest part of the North Sea. Major ocean currents transport sediments into the Skagerrak from the Atlantic Ocean, the North Sea, the Baltic Sea and the surrounding land areas. A large volume of the contaminants (e.g. trace metals and organic compounds) released into the marine environment of the North Sea is therefore deposited in the Skagerrak, which has popularly been termed «the dustbin of the North Sea».

This multi-disciplinary report gives an overview of the geological history and state-of-the-art knowledge of the sea-bed environment at the present day for use by a broad public. It should provide the basic knowledge needed in planning further utilisation (fisheries, underwater engineering, hydrocarbon exploration, etc.), in management by governmental bodies such as the Ministries of Environment, Industry, and Oil and Energy, and in future scientific investigation.

The project has demonstrated how governmental institutions with offshore tasks and academic institutions both in Norway and abroad can co-operate successfully with a considerable synergetic effect, achieving results beneficial to society in a cost-effective manner.

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