Marine Geology of Kiel Bay

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Geological and Hydrographic Setting

Kiel Bay, together with Mecklenburg and Lübeck Bays, forms the Belt Sea or Western Baltic Sea. The bay lies on the hinge-line between the upwarping Scandinavian Shield and the sinking North Sea Basin (tectonic zero line approximately through Fehmarn Belt; R. KÖSTER, 1961) and is itself a relative newcomer to the world's seas.

The Belt Sea is bordered in the east by the Darss Sill which rises to a depth of 18 m (small channels up to 32 m deep); Kiel Bay finds its eastern limit in Fehmarn Island. In the west the Little Belt (Kleiner Belt), minimum depth 10 m, and the hydrographically more important Big Belt (Großer Belt), minimum depth 20 m, form the connections to the Kattegat and thereby to the North Sea.

The morphology of Kiel Bay owes its origin largely to the Scandinavian ice sheet (For discussion see K. GRIPP, 1964). The ice deepened the Western Baltic Basin and covered the underlying Tertiary (mainly Eocene in the NE half and Miocene in the SW half) with ground and end moraines. All of these moraines resulted from the last glaciation and are therefore less than 25,000 years old. Rises in the bay suggest end moraines which, like their counterparts on land, have undergone compressional ice tectonism. Outwash plains border the moraines. The negative features are more difficult to interpret. They may represent hollows between end moraines, melt-water channels formed under or in front of the ice, or kettles from dead ice which persisted even into the Alleröd. Pre-existing negative features such as Kiel Fjord and Eckernförde Bay were further excavated by advancing tongues of ice. After the retreat of the ice sheet, the area remained above sea level and was, at least for a short period, subjected to periglacial conditions. The existence of sand dunes, however, has not as yet been proven. The drainage during this period flowed northward to the Big Belt cutting new, or deepening pre-existing, channels. Depressions were filled with lacustrine deposits, and peat layers testify to the rich vegetation which existed. Rising sea level during the Holocene led to the Litorina transgression (starting about 8,000 years ago) which, after an initial rapid rise, slowly covered the glacial landscape and carved out a highly variable coastline. Coastal cliffs were and are being eroded away at a rate of up to 1 m/year. Small bays and inlets were cut off by hooks and spits and rapidly returned once more to dry land. While the land forms were undergoing this process of equalization, a parallel development was taking place in the submarine environment — highs were being planed off (the "Flache" in Fig. 6) and depressions were filled in. The result is that today southern Kiel Bay exhibits a rather monotonous relief down to a depth of 20 m. In the northern half of the bay, the channels remained; their present depths of up to 39 m were, and perhaps still are, locally being deepened by current action. Recent salt tectonism may have played a role throughout the area but is particularly important in the western portion (see Fig. 9).

Archaeological and geological evidence indicate that tectonic subsidence along the southern coast of Kiel Bay since the Middle Ages can be measured in decimeters. (Inner Lübeck Bay has subsided over 1 m in the last thousand years, R. Köster, 1961). In addition, the eustatic sea level rise must be considered. This has averaged about 1 mm/year over the past 80 years.

Hydrographically (G. Dietrich, 1950) the Baltic Sea serves as a model for an adjacent sea in a humid climate. Fresh water inflow amounts to 183 km^3/year from precipitation and 479 km^3/year from rivers. Loss through evaporation, however, amounts to only 183 km^3/year. This imbalance leads to an outflow of surface water through the belts and sounds of 1216 km^3/year as opposed to an inflow (mainly through the Big Belt) of only 737 km^3/year. (Further details and geological implications can be found in E. Seibold, 1967, 1970). Kiel Bay forms the transition zone between Kattegat/North Sea and the main Baltic Sea, and is characterized by brackish water along with extreme variability in its hydrographic parameters. As opposed to the North Sea with its salt content of 35 ‰ and seasonal variation of 3-4 ‰, Kiel Bay shows variations in its surface water ranging from 9 to 22 ‰ and from 14 to over 30 ‰ in its bottom water. In the summer, surface water temperatures of 17 °C may be reached while the bottom water reaches only 12 to 13 °C. All of these parameters are dependent upon specific weather conditions which favor either outflow (E-wind, most often in spring and early summer) or inflow (W-wind, most often in summer). In addition, severe autumn and winter storms combined with cooling can destroy the summer water-layering, with the result that in February/March a homothermic water column forms with a temperatur of +2 °C.

The normally existing division of the water column into two layers with a boundary at −16 to −20 m is in marked contrast to the constantly mixed North Sea water. In the summer this layering can lead to an oxygen deficiency in the bottom water and in closed depressions even to H_2S development. The two water bodies are also reflected in the species distribution of the benthonic organisms. An example for the foraminifera can be seen in Fig. 5.

Bottom water inflow through the Fehmarn Belt can reach a velocity exceeding 120 cm/sec. Such strong surges of salt water, which take place only every few years, can reach the eastern Baltic some 16 to 18 month later. In Kiel Bay these strong inflow currents lead to erosion in channels, and are responsible for the megaripples on the sandy bottom north of Fehmarn and west of Lolland Islands (Fig. 7). These megaripples have a wave length of 40-70 m and a height of 1 to 2 m (F. Werner & R. S. Newton, 1970). Again in direct contrast to the North Sea, tides have practically no influence on sedimentation here. The average spring tidal range does not reach 20 cm in Kiel Bay.

The influence of wind is also quite different on Schleswig-Holstein's North Sea and Baltic coasts. On the North Sea, westerly storms with their long fetch have the greatest geological effect. In combination with tides, they both build and erode the tidal flats which exist nearly everywhere on the German North Sea coast. In Kiel Bay half of all winds and 3/4 of all storms (Beaufort $\geqq 8$) are westerly, but here the fetch is small and west winds lower the water level instead of raising it. The easterly winter storms with their long fetch, deeper working wave action and frequently radically increased water levels are particularly aggressive in eroding the coastal cliffs. Storm tides which increase water levels more than 1.7 m, occur along the Baltic coasts only on an average of once every 4 years, while similar storm tides are recorded in the North Sea 2 to 3 times a year. Extreme storms can, however, generate water level changes in Kiel up to 5.26 m (+2.97 and −2.29) and in Travemünde (Inner Lübeck Bay) up to 5.32 m (+3.30 and −2.02). Compensatory currents after high water periods are capable of transporting nearshore, medium grained sand from 6 m into 12 m water depth (tracer sand studies, E. SEIBOLD, 1963). As an aftermath of storm tides, seiches with a period of 27.3 hours can develop in the Baltic.

The maximum depth of wave action is reflected in small-scale ripples down to a depth of 22 m in Kiel Bay, as well as in the varying depths at which the facies boundaries are found. Breaking waves and longshore currents lead to the formation of 1 to 3 offshore bars, as well as hooks and spits along the gently sloping portions of the coast. Because of the pronounced variations in coastal morphology and the changeable wind directions, sand transport directions are far from uniform. A glance at some of the largest sand hooks in Fig. 6 confirms this variability. Tides and wind are responsible for the extreme differences in coastal morphology and nearshore sediment distribution in the North Sea and the Baltic — two seas which at places in Schleswig-Holstein are only 60 km apart.

Methods

The Geological Institute of the University of Kiel presently uses the equipment listed in Table 1 to investigate the sea bottom and its sediments.

Sediment Types

Present-day sediments are provided largely by erosion and redeposition of material from the sea bottom. Additional sediment comes from the erosion of coastal cliffs, which constitute about 1/3 of Schleswig-Holstein's Baltic coast. The proportion of sediment provided by sea bottom and cliffs is determined by effective wave base and cliff height in each area. For example, on the coast SW of Fehmarn Island, the shallow sea bottom provides some 84,000 m^3, and the cliffs some 19,000 m^3 yearly (G. SEIFERT, 1955). The freight of streams and winds is negligible in Kiel Bay, T a b. 1: Main ship-board marine geologic equipment used by Kiel University, Geol. Inst.

	Instrument	weight (kg)	Sample size a) surface (cm×cm) b) length of core (m)	For use primarily in
Grabs	Modified van-Veen (normal size)	45/60	a) 30×33	all but very coarse sediments
	Modified van-Veen (small size)	6	a) 20×20	all but very coarse sediments
	Modified van-Veen (large size with camera)	150	a) 65×60	all but coarse sediments
	Shipek sampler	50	a) 20×20	sand and very coarse sediments
	Constant volume sampler	12	a) 30 b) 0.02 to 0.06	fine sand to mud
	Constant volume multi sampler (in construction)	?	b) 0.02 to 0.06	fine sand to mud
Corers	Box sampler	700 (max.)	a) 20×28 b) 0.45	sandy sediments
	Box corer	1000 (max.)	a) 15×15 b) max. 10	soft sediment
	Gravity corer (with liner)	300 (max.)	a) 26 b) 1 to 5	soft and sandy sediments
	Conventional piston corer (with liner)	1000 (max.)	a) 56 b) max. 8	soft sediments
	Foram.-corer	10	a) 5 b) max. 1	soft sediments
	Vibro corer (small model)	250	a) 10×10 b) 1 to 2	sand
	Vibro corer (large model) (in construction)	2—2500	a) 15×15 b) 1 to 6	sand
Penetration	Gravity lance	300 (max.)	b) 0.8 and 1.25	sand and gravel
	water-jet lance		b) up to 10	sand
Acoustic/optic	Sediment echograph		acoustic penetration max. 40 m	
	Side Scan Sonar		horizontal width of recording: 600 m	areas with bottom relief
	Underwater television		normal field of view: 3 to 4 m^2 with camera. 1 to 15 m off bottom	all areas

Remarks on application	a) Concept b) Modified by	Construction
Can sample sediment surface by opening top of grab	b) E. Seibold u. E. Walger, Kiel	Hydrowerkstätten GmbH, 23 Kiel, Uhlenkrog 34
Can sample sediment surface by opening top of grab		dto.
large amount of sediment; allows determination of biomass, or study of bioturbation in combination with surface photo	a) Menzies et al., Woods Hole, U.S.A. b) F.-C. Kögler, Kiel	dto.
samples in gravels (eg. reef debris) where other grabs may not work	a) C. J. Shipek (Scripps U.S.A.)	Hydroproducts (San Diego, U.S.A.)
size of sample exactly defined; can be varied. Mainly used for microbiological purposes	a) K. O. Emery, U.S.A. b) H. Krumm, Kiel b) Meischner et al., Göttingen	Zentralwerkstatt GmbH., Univ. 34 Göttingen
Combination of three sample tubes for statistical studies in microbiology	b) F.-W. Haake and F.-C. Kögler, Kiel	Hydrowerkstätten, Kiel
large undisturbed cores; orientation and inclination photographically recorded; mainly for studying sedimentary structures	a) H.-E. Reineck, Wilhelmshaven	F. Leutert, Erbstorf b. Lüneburg
large undisturbed cores, good for study of sedimentary structures, sediment mechanics, lamination, etc.	a) F.-C. Kögler, Kiel b) F. Werner, Kiel (see F. C. Kögler, 1963)	Hydrowerkstätten, Kiel
Uncomplicated, especially useful for rapid reconnaissance work	b) F.-C. Kögler, Kiel	Hydrowerkstätten, Kiel
long cores	b) F. C. Kögler, Kiel	dto.
easy handling; collects defined surface area with overlying bottom water	b) F.-W. Haake, Kiel	dto.
cores relatively undisturbed; good for study of sedimentary structures; large sample cross section	a) F.-C. Kögler, Kiel	dto.
cores relatively undisturbed; good for study of sedimentary structures; large sample cross section	b) F.-C. Kögler, Kiel	dto.
measurement of sand/gravel thickness over glacial till	a) F. Werner, Kiel	dto.
measurement of sand thickness overlying harder base (here normally glacial till). Used by divers in up to 15 m water depth	a) K. Vollbrecht, Hamburg	Geological Inst. Kiel from standard components
areas with soft sediments, high resolution (0,3 m)	a) Elac-Kiel (see K. Hinz et al., 1969)	Electroacustic GmbH, Kiel, P. B. 68
resolution ca. 0,5 m	Geodyne	Geodyne/Boston U.S.A.
Allows continous profiling for mapping purposes. Video recording on tapes. Combination with photo camera	a) Ibak	Ibak, Kiel, Wehdenweg 122

and biogenic components from planktonic and benthonic organisms are also normally unimportant. For example, on the Mittelgrund (outer Eckernförde Bay) where strong erosion can be observed, the material in suspension on one occasion (B. ZEITZSCHEL, 1965) was found to be 85 % inorganic, 10 % organic detritus and 5 % living plankton.

By far the most important source of sediment in Kiel Bay is the Pleistocene till, which forms the sea bottom and builds the surrounding cliffs. This till consists mainly of rock debris, quartz, fedspar and clay minerals, and has a $CaCO_3$ content of about 20 % (occasionally up to 50 %). A typical grain size composition is: 1/5 $<$ 0.002 mm, 1/5 0.002-0.02 mm, 1/3 0.02-0.2 mm, 1/5 0.2-2 mm, and the remainder coarser. Other local sources of material are fluvioglacial sands, glacial-lake muds and Holocene sediments. Overall, an extremely broad grain size spectrum, from large boulders to mud, is available for sedimentation (see Fig. 1).

In general only wave-action in conjunction with morphology and wind directions plus exposure to these directions are of importance for reworking and distributing this material, although currents are of primary importance in the channels. Accordingly, a comparison of the maps in Figures 6 and 7 shows a relatively clear-cut relationship between sediment distribution and bathymetry.

Facies boundaries generally parallel isobaths unless fetch or bottom morphology change suddenly. In areas with little sedimentation, inherited sediments, laid down during the post-glacial transgression, must also be taken into account.

For practical reasons the sediment distribution map (Fig. 7) shows facies

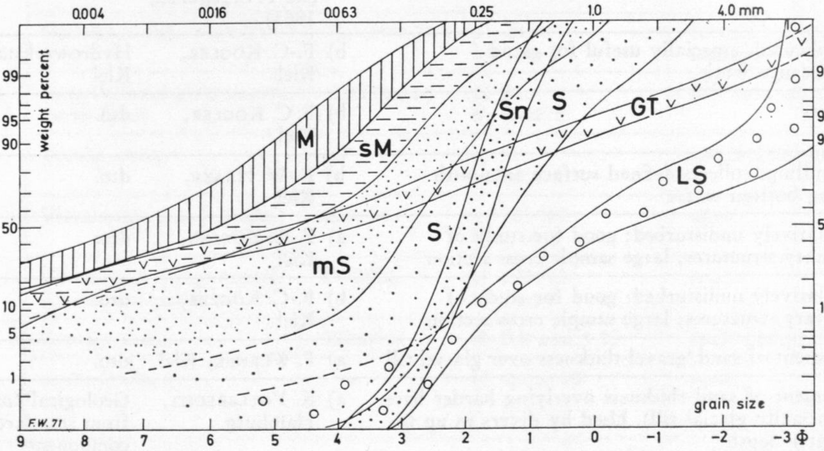

Fig. 1 Grain size distribution patterns of different sediment types on probability net. Legends as in Fig. 2. Shows sorting in relation to sediment source (GT = glacial till). The best sorted sediment is from near-shore bars (Sn). Data from G. SEIFERT (1955) (GT), U. BARNER (1965) (S and mS), and F. WERNER (1968, and unpublished).

types and not rigorously defined grain size groupings. The subdivisions mapped are: lag sediments, sand, muddy sand, sandy mud and mud.

Lag sediment

Almost everywhere along the coast, mostly between 5 and 15 m water depth, a strip of very coarse sediment forms a veneer (10-30 cm thick) over glacial till. In places the till itself is exposed. This sediment is typified by pebbles, cobbles and boulders, mostly covered with algae and sessile animals, mixed with poorly-sorted coarse sand and gravel. Diver and television observations show that the rocks are very unevenly distributed, partly because of the dredging of larger rocks for building material. Sometimes the pebbles and cobbles build a firm pavement, but often they occur in accumulations separated by small areas of coarse or medium grained sand. Isolated blocks ringed by scoured depressions are often found in areas of coarse grained sand. The irregular, sometimes isolated wave-formed ripple marks found in these areas have fine gravel and shell detritus in their throughs. Dense Mytilus banks and isolated Mytilus patches are widespread. These banks and patches slow the currents, sometimes allowing considerable fine grained material to accumulate along with the normal coarse sediment. On exposed coasts, this zone of lag sediment may extend down to 20 metres. Isolated till highs in deeper water are covered solely with lag sediment because the fines are constantly swept away. In such areas, observations by divers have shown that wave-action sometimes reaches very deep. For example near Boknis Eck (Fig. 6) in 14 m of water, numerous cobbles with diameters of up to 10 cm were found to have algae on their buried surfaces indicating that they had been recently turned by wave action. Lag sediment is an indicator of erosional areas where planation of the till surface is taking place. Erosion and sorting leave a protective pavement which limits further erosion. Although erosion has stopped, the water movement is sufficient to prevent deposition of fine sediment.

This pavement can be regarded as a typical transgressional conglomerate, and is sometimes clearly graded.

Medium and fine grained sand

Areas of well-sorted medium and fine-grained sand are grouped together in the sediment map (Fig. 7). Submarine erosional areas are normally surrounded by such sandy areas. Landwards the erosional areas are bounded by the "küstennahe Sandanhäufungszone" (zone of nearshore sand accumulation) of O. PRATJE (1948), in which the sediments are continually reworked by wave and longshore-current action. Seawards from the erosional areas is a zone where the eroded sand comes to rest, but where finer material is removed.

The offshore sand areas are nearly everywhere covered with small-scale ripple marks, and underwater-television profiles show that their orientation is controlled by the last storm. They are often indistinct and their troughs are filled with finer grained sediment. Each major storm rebuilds ripples; the deeper they lie, the less frequent the rebuilding. After each strong easterly storm (Beaufort > 8), fresh ripples can be observed down to 16-18 m near Boknis Eck.

The sand is predominantly quartz, with up to 20 % feldspar. Common heavy minerals (up to 3 %) are garnet, ilmenite and hornblende; these are most abundant in the fraction 0.06-0.2 mm. Grain size decreases with water depth in the offshore zone. Even more pronounced than the decrease in the median diameter is the increase in the silt fraction (< 40 μ) with increasing depth. Fig. 2 shows that the silt fraction/water depth relationship approaches an exponential function: the silt fraction increases steadily from ca. 0.5 % at 15 m to ca. 5 % at 20 m. A corresponding decrease in median grain size is only from 0·20 mm to 0.16 mm. The decreasing influence of water movement downward is also shown by the increase in sessile and semisessile benthonic organisms such as tube-building polychaete worms, and the ophiuroids. These organisms cause intensive bioturbation of the sediments, a characteristic feature of the lower part of the sand zone. Bioturbation distributes the finer material, originally confined to ripple troughs, throughout the sediment. Ripple cross-lamination seen in cores does not reflect the present day axial bottom current in Eckernförde Bay, and is presumably formed by waves.

In the nearshore sand areas the morphologically important near-

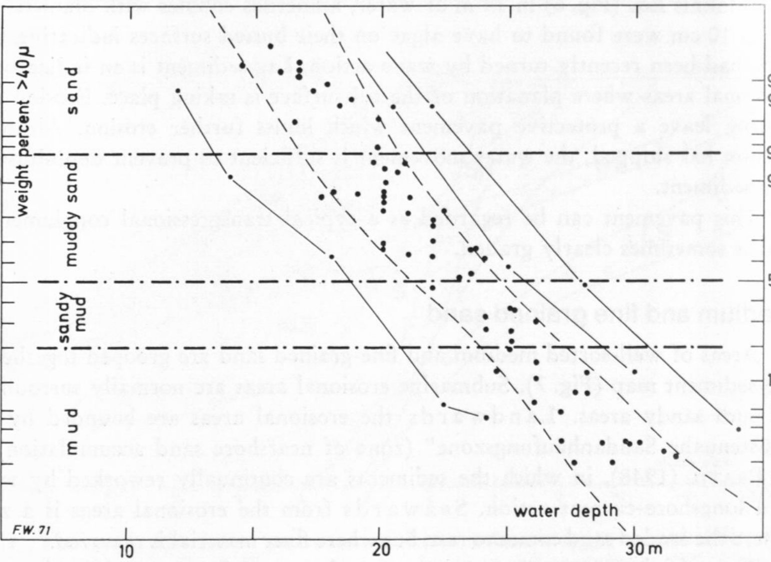

Fig. 2 Decrease of sand fraction (> 40 μ) with increasing water depth. Solid lines connect points on a single profile. Left-hand curve from sheltered area. (F. WERNER, unpublished).

shore bars are formed, but the sand zone often extends well seaward of the bars. The internal structure of the bars is complex, consisting of coastward dipping small-scale ripple laminae, decimeter thick units of foreset laminae from "bar steps" which form during low-water periods, horizontal laminae, and comparatively rare seaward-dipping laminae (R. S. NEWTON, 1968; F. WERNER, 1963). It is noteworthy that only the onshore-offshore wave direction is represented in the lamination, although the net sand transport is parallel to the bar. Tracer sand experiments (R. S. NEWTON, 1968) in small-scale ripple fields on the bars also showed this coast-parallel sand movement. Bar types other than longshore bars also represented. They include bars which run oblique to the coast, as well as arcuate bars. Largescale wave-formed ripples (height 20 to 40 cm, wave length ca. 25 m) are locally found in the nearshore sand area. These various forms are related to irregularities in the coastline and/or to competing wave directions. Attempts have been made to determine the direction of sand transport in these areas by means of median grain size, content of heavy minerals, quartz/plagioclase or garnet/hornblende ratios, rounding of quartz grains etc. (see E. SEIBOLD, 1963; E. WALGER, 1966).

The sand areas are particularly well developed a) adjacent to the Grosser Belt channel where currents are sufficiently strong to build megaripples, b) on the relatively even bottom lying between 15 and 18 m (Stoller Grund to Hohwacht Bay), and c) on the lee side of various shallows.

Muddy sand and sandy mud

Muddy sand contains between 50% and 95%, sandy mud between 20% and 50% material > 40 μ (Fig. 2). This subdivision can be easily and quickly determined a board ship immediately after the sample is brought on board. The previously mentioned increase in the silt fraction with depth continues in these sediments. Fig. 2 shows this effect for areas with varying exposures.

The sand/muddy sand boundary coincides roughly with the disappearance of ripple marks. The structure found in this facies, primarily a very thin alternation of sand, silt and mud layers, is also characteristic. Remarkably, the ratio of coarse to fine grained layers also decreases with water depth as an exponential function; a further indicator of the role of waves. The evaluation of X-ray photographs allows recognition of microcycles in this mm-thick layering, which suggest sedimentation during waning storms. Burrowing organisms, particularly polychaete worms, destroy the layering to vanying degrees (F. WERNER, 1968). With decreasing sand content the bioturbation reaches a maximum and then decreases, a trend which parallels that in the population density (see G. KÜHLMORGEN-HILLE, 1963).

Normally, sand-mud areas are confined to a narrow strip along the coastal slope or around local highs. However, when the necessary bathymetric level is widespread, as in Hohwacht Bay, it can cover large areas. In parts of Fehmarn Belt this facies lies very deep, due to the effect of strong bottom currents.

Mud

Sediments with less than 20 % $> 40\,\mu$ are indicated on the sediment map as mud. Depending on exposure, the upper boundary of the mud zone lies between 20 and 30 m. Beneath this boundary the sand content generally decreases rapidly, so that the greater part of the mud areas probably contains less than 10 % $> 40\,\mu$. Organisms are comparatively rare in these areas and, due to oxygen deficiency in sheltered bays, are sometimes even non-existent. The water-content of the uppermost 2 cm can be as high as 350 % of dry weight. As the deepest zones, the mud zones normally show closed contours. In the eastern part of Kiel Bay, where the water is shallower than in the west and northwest, the mud zone is seldom present. Investigations of the relative clay mineral frequencies in the Baltic Sea (H. KRUMM, in press) are summarized in Table 2 below:

Table 2: Clay minerals

Suspended matter (21 samples)	Recent sediments (about 520 samples)
micas + illite = 0—60 %	micas + illite = 0—60 %
smectites + mixed layer clays = 0—30 %	smectites + mixed layer clays = in places absent; in basins up to 15 %
chlorites = 0—15 %	chlorites = 0—10 %
kandites = 0—12 %	kandites = 0—10 %

% = Percent of total inorganic crystalline material in each sample

The variable source materials available in the adjacent land areas show no widespread influence on the clay minerals in the Baltic (about 600 samples of land sediments and soils were analysed). No regional trends are present for mica + illite and chlorite distribution, neither in suspended matter nor in the recent marine sediments. Smectites and mixed-layer clay minerals are relatively abundant in suspension, but yield no recognizable regional distribution pattern. However, in the recent sediments, these clay minerals are markedly more common in the deeper basins of the Baltic east of Kiel Bay. This is interpreted as a result of transport-sorting as the currents carry the clay minerals eastwards. These minerals, which are extremely fine grained and have low settling velocities, are transported further than mica, illite and chlorite.

No diagenetic changes in the clay mineral assemblage have been noted in cores up to several metres in length.

Mixed sediment

This sediment, which shows an unusual mixture of grain sizes, has limited distribution. It consists of abundant fine grained material (silt + clay) which is intimately mixed with coarse material of variable grain size. Gravel and coarser components are characteristic. This mixed sediment frequently appears as thin deposits on Pleistocene surfaces bordering mud areas, and is often transitional into sandy mud or muddy sand (see Fig. 7).

The surface of the adjacent mud sediment (which is generally a few meters thick) lies somewhat deeper. The sand sedimentation of shallower waters has not yet reached these areas, so that they form a no-man's-land between sand and mud areas, in which little sediment accumulates. The benthonic fauna, however, is rich and typified by large individuals; tubebuilding and vagile polychaete worms such as Terebellides strömi and Pherusa plumosa are characteristic and are responsible for mixing the slowly deposited fine sediments with the relict coarse sediments.

Mixed sediment can also form in other ways. Where the slope between an erosional area and a deeper-lying mud area is steep enough, gravel and small rocks are swept into the mud during storms, often with the aid of attached algal "floats". In other places mixed sediment is closely related to presentday currents such as those in the deep channels of the Grosser Belt (U. BARNER, 1965) and Fehmarn Belt. Because strong currents only occur under extreme weather conditions, it is understandable that fine material should be deposited on coarse sand and gravel during quiet periods. This fine material is then mixed in by bioturbation.

Geochemistry

Content of organically-bound carbon

Organic carbon (C_{org}) values vary between 1 and 3 % in muddy sand and sandy mud, and between 3 and 5 % in basins with mud deposition. Some beds, particularly peat and other horizons rich in plant debris, contain considerably more C_{org}.

No suggestion of decreasing C_{org} content with depth of burial (which could be expected to result from diagenetic destruction) has been seen in the cores examined. The material settling out of suspension contains considerably more C_{org} than the sediment itself, an indication that destruction begins immediately upon sedimentation.

Sulphur content

Sulphur values clearly parallel C_{org} values: sand-mud mixtures contain around 0.5-1 % total sulphur and mud 1-2 % total sulphur.

It is worth noting that near the sediment surface considerably less sulphur is present (1/2 to 1/3 as much) than in deeper parts of the same cores (under 5-10 cm). This clearly suggests early diagenetic changes, which are being further investigated through $S^{32}/^{34}$ determinations (see M. HARTMANN et. al., 1969).

Iron content

Iron values are also clearly related to C_{org} values: sand-mud mixtures < 1-2 % Fe and mud 2-5 % Fe.

The reasons for this relationship are complex: C_{org}-rich sediments are fine grained, and therefore contain considerable Fe on clay minerals. Reduction of fine grained sediments with a high organic content begins immediately upon deposition, giving rise to H_2S which fixes Fe as FeS. With further diagenesis in the uppermost decimeters, this is converted to FeS_2 (pyrite). Flocculated Fe-hydroxide in suspension in seawater (it originates mainly from Fe^{2+}, which is released into the overlying water by means of ionic diffusion out of the pore water as the sediments are reduced) behaves hydraulically as extremely fine grained sediment, and is only deposited in the very quiet water of the deeper basins. Up to now it has not proved possible to study this process in nature (M. HARTMANN, 1964).

Manganese content and manganese nodules

The manganese content of the sediments generally varies between 100 and more than 1,000 ppm; in a few thin mud horizons of the eastern Baltic Sea, contents of more than 10 % have been analysed. In general the near-surface layers (0-5 cm) contain considerably more Mn than the underlying sediments.

The cause of this phenomenon is presumed to be the high solubility of Mn under reducing conditions, in contrast to Fe. Values of over 30 mg Mn/l have been determined in pore water in Baltic Sea cores. The manganese deposited with the sediment goes into solution as Mn^{2+} (from Mn-hydroxides after reduction, Mn-carbonates through simple solution) and, because of diffusion exchange in the uppermost sediment layers, reaches the sediment surface and is released into the overlying water. Following renewed oxidation and flocculation it is preferentially redeposited in areas with little water movement. Areas with marked water movement and limited sedimentation accordingly contain Mn-poor sediments.

The bottom waters contain substantially more manganese in solution and suspension (up to $> 100\ \gamma$ Mn/l) than the surface waters ($< 5\ \gamma$ Mn/l). This is particulary noticeable in the deeper basins east of Kiel Bay (M. HARTMANN, 1964). Around the edges of basins, manganese nodules and crusts are formed in large quantities in the eastern Baltic, but only in limited quantities in localized areas in the western Baltic. Unlike the deep-sea nodules, these nodules are flat or concavo-convex with the concave side downward (the orientation is shown by sessile organisms). Furthermore, the Baltic nodules are more porous than deep-sea nodules, and contain only low concentrations of heavy metals, although their Mn content often reaches 30 %. Concretions with a cross-section of 12 cm occur in Kiel Bay in the southern Kleiner Belt. While such nodules have thus far been found only in mixed sediment, thin Mn crusts as coatings on molluscs

Tab. 3: Sediment core sequence
(Outer Flensburg Fjord, see Fig. 10; N. Exon, unpublished; present water depth around 28 m)

Part of core	Sediment	Average carbonate content (%)	Preserved macrofauna	Preserved benthonic forams	Solution[1]	Approx. age
upper 10 %	Sandy mud	1—2	Varied molluscs	Marine, calcareous	Marked	1500—2000 AD
next 30 %	Mud	0,1	Only worm burrows	Marine, arenaceous (Eggerella scabra)	Marked	1000—1500 AD BC
next 25 %	Mud	1	Only worm burrows	Brackish, mixed	None	1000—3000 BC
next 30 %	Mud	1—2	Thin shelled pelecypods (Abra alba)	Marine, calcareous	None	3000—5500 BC
lowermost 5 %	Mud	1	None	Brackish, arenaceous	None	5500—6000 BC
underlying sediment:	a) Reworked calcareous lake sediments	25	Freshwater snails	Allochthonous, marine, calcareous	None	6000 BC
	b) calcareous lake sediments	Not determined	Freshwater snails	None	None	6000—6500 BC
	c) peat	Not determined	None	None	None	9000 BC or older
	d) lacustrine- and fluvioglacial sediments	Not determined	None	None	None	

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[1] Strong carbonate solution, both on the sediment surface and in the sediment itself, is occuring at present in the deeper parts of the Baltic Sea. However, in the early phases of the marine transgression, the extremely shallow water allowed no halocline to isolate the underlying CO_2-rich bottom water, and carbonate solution was not marked.

(particularly on Astarte borealis and A. montagui) are more common. These crusts, which can be up to 2 mm thick on living molluscs, must form very rapidly.

Sediment Thickness

The thickness of the young marine sediments in Kiel Bay is particularly interesting in regard to the quantitative study of erosion and sedimentation, and in regard to diagenesis (see Tables 3 and 4). In muddy areas thicknesses can be readily determined with the help of a sediment echosounder or an air-gun, as the underlying till is an excellent acoustic reflector. Profiling using these methods has shown that the lower boundary of the young, acoustically "soft" sediments lies quite deep in some localized areas in northern Kiel Bay (Fig. 8; also K. Hinz et. al., 1969 and 1971). The lower part of these filled channel sequences, however, probably also contains some late and postglacial non-marine sediments (see Table 3).

Apart from these exceptions, the younger sediments in the central bay are not more than 8 m thick. However, in areas such as Eckernförde Bay and Flensburg Fjord they can be much thicker. In the narrow, deep channels which were inherited from the glacial topography, the bottom currents are sometimes strong enough to limit sedimentation or to cause erosion.

Thicknesses in sandy areas are more difficult to determine as no present-day acoustical method gives adequate definition of their lower boundary. Nevertheless, some values for sand thickness over till have been obtained through the use of a gravity lance, or a diver-operated water-jet lance. It appears that the sand bodies bordering erosional areas are of the order of 0.5 to 2 m thick.

Sediment balance

The mapping of erosional areas has allowed a rough estimation of the amount of material eroded since the beginning of the Litorina transgression. In addition, isopach maps allow a comparatively accurate calculation of the volume of mud which has been deposited. In Kiel Bay the estimated volume of till eroded is 5-7 $\times$ 10^9 m^3, whereas the wet volume of mud deposited is 4.5 $\times$ 10^9 m^3. This means that there is a considerable deficit of mud, as 1 m^3 of till provides roughly 2.2 m^3 of wet mud. The two values agree better for the northern part of Kiel Bay.

Accordingly it can be deduced that in the eastern part of Kiel Bay where large erosional areas around Fehmarn Island and south of Langeland Island are found, and where only small mud accumulations occur, most of the fine grained sediments are carried away in suspension. In the more intensively investigated outer part of Flensburg Fjord, it is possible to subdivide the sediment balance as shown in Table 4.

	Area (km²)	Million tons dry till eroded	Million tons $CaCO_3$ freed	Million tons of dry mud available for deposition	Mud deposited			
					Average thickness			
					present day (wet) (m)	waterfree (m)	Million tons (dry)	% mud carried out of area
a) Gelting Bay	46	260	50	138	7.5	1.3	82	38
b) Sonderborg-Falshöft-current area	68	230	46	102	3	0.5	44	58
whole area total	145	620	107	284	5.3	9.9	170	40

Tab. 4: Sediment Balance — Outer Flensburg Fjord (After N. EXON, 1971).

In the protected Gelting Bay (a) the effect of currents on sedimentation disappears and wave action is limited. In the area between Sonderborg and Falshöft (b), on the other hand, bottom currents of 30 cm/sec have been measured. The difference in conditions means that much more of the available mud is deposited in area (a) than (b).

Furthermore, these figures allow the calculation that at present up to 1 m of wet sediment/100 years is deposited in Gelting Bay (= 0.15-0.2 m fossil sediment), and that, in the area of Fig. 10 around 100 tons of $CaCO_3$/km² is dissolved from the sediments yearly. Direct measurements of the sedimentation rate in outer Eckernförde Bay gave values of up to 2.6 mm wet material/year (B. ZEITZSCHEL, 1965).

Organisms

The organisms show typical brackish environment characteristics: low species diversity, in part reduction of size, morphologic modifications, low reproduction rate. Whereas the Belt Sea, for example, still contains corals, pteropods, scaphopods, cephalopods, and 143 species of polychaetes, 34 of pelecypods, 55 of fish, and 12 of foraminifera, none of the former groups are present east of the Darss Sill, and the numbers af species in the latter are reduced to 15, 24, 30 and 5.

Benthonic vegetation

Is generally restricted to areas with lag sediment, but it may also occur on mollusc shells and on sandy bottoms. No vegetation is present on mud. Zonation

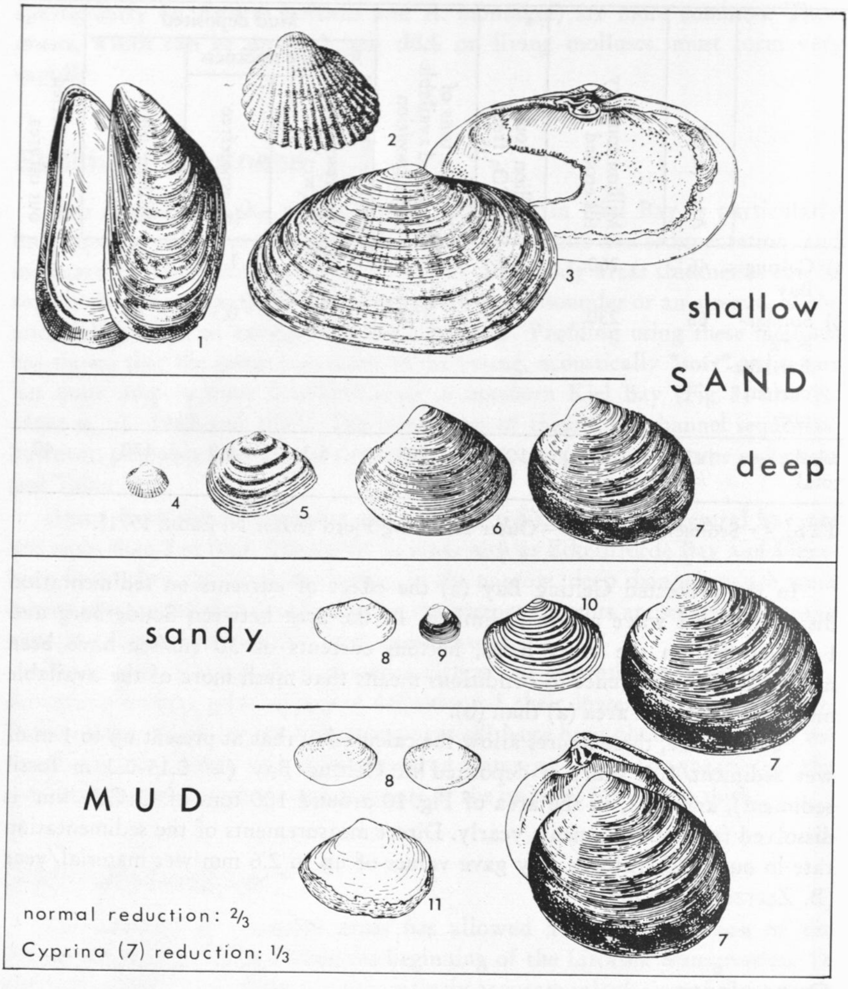


Fig. 3 Dominant pelecypods in Kiel Bay
Beach and nearshore area: 1. Mytilus edulis (in clumps and banks), 2. Cardium edule, 3. Mya arenaria.
Deeper-water sand areas (Macoma baltica coenosis): 4. Macoma baltica, 5. Cardium fasciatum, 6. Astarte borealis, 7. Cyprina islandica.
Sandy mud (Abra alba coenosis): 8. Abra alba, 9. Astarte montagui, 10. Astarte elliptica, 7. Cyprina islandica (here generally larger than in sand).
Mud (Abra alba coenosis): 8. Abra alba, 11. Macoma calcarea, 7. Cyprina islandica (here frequently corroded).
(Drawings partly from W. de Haas & F. Knorr, 1966, Franck'sche Verl.-Buchhdl. Stuttgart).

between different floral associations is indistinct. The most important associations are: Fucus crops (F. vesiculosus and F. serratus), meadows of seagrass (Zostera marina and Z. nana) and red algae associations of the sublittoral. The large brown algae (Laminaria sacharina and L. digitata) tend to be solitary (H. SCHWENKE, 1964. From a sedimentological point of view, the algae are important as floats for pebble transport, and the entire benthonic plant community acts as a buffer to water movement (especially where growth is dense). It also serves as a habitat for many organisms (mostly small gastropods, but also characteristic foraminifera) and as a source of organic matter.

Macrobenthos

Pelecypods are the most important biogenic contributors to the sediments of the western Baltic. Most species inhabit various sediment types. However, some are clearly dominant in specific sedimentary provinces; thus it is possible, for example, to speak of a Macoma-baltica-coenosis on sandy substrata between about 3 and 15 m depth, and of an Abra-alba-coenosis on the muddy grounds below approx. 15 m. The most common species are arranged in Fig. 3 according to sediment types and depth zones respectively. This situation is depicted in a diagram from the outer Flensburg Fjord (Fig. 4). Diagrams of this sort, to be sure, can claim but limited validity, since the pelecypod fauna is subject to

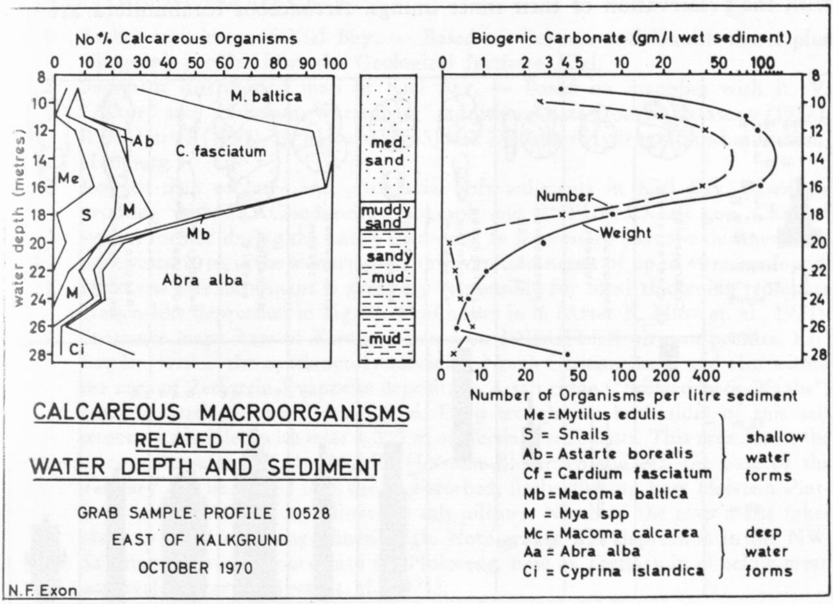


Fig. 4 Relationship of calcareous macro-organisms to water depth and sediment in a grab-sample profile. (N. EXON, unpublished).

strong seasonal and long term variations. The largest standing crops, and hence presumably in each case the greatest production of biomass and skeletal carbonates, are often found on muddy sand in moderate water depths (see G. Kühlmorgen-Hille, 1963), but can occur on any sediment with a considerable sand content (coarse sand to muddy sand), and the more sheltered the area, the shallower the largest standing crop (N. Exon, 1971). This suggests that, in the western Baltic, water properties are as important for the organisms as sediment types. The most favourable water properties are found a little above the halocline, at which depth muddy sand is the most common sediment. Besides pelecypods, other sedimentologically important members of the benthic fauna are: Sand Epifauna: crustaceans such as Crangon and Carcinus; Asterias on Mytilus-beds; Sand Endofauna: polychaetes such as Arenicola, Nereis, and Pectinaria; Mud Epifauna: semi-sedentary polychaetes.

Microbenthos (Foraminifera)

Due to the low salinities, only benthic foraminifera are able to survive in the Baltic. Their production of biogenic carbonate (G. F. Lutze unpublished, F. W. Haake, 1967) appears to be "normal", according to preliminary estimates; i. e. for the geographic and climatic situation approx. 600 mg/yr/m² can be expected. However, little of this production is preserved since most tests are already redissolved at a short distance below the sediment surface, sometimes with the preservation of their inner linings. Arenaceous foraminifera are not

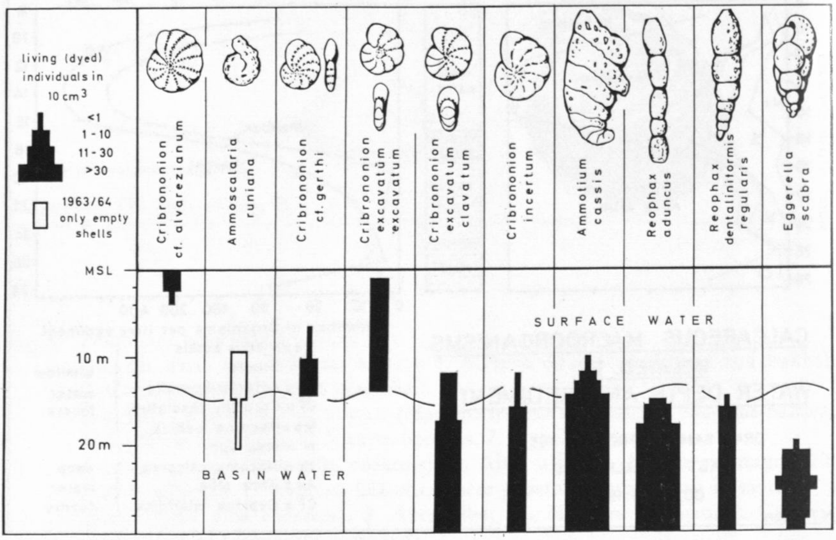


Fig. 5 Vertical distribution of the most important Belt Sea foraminifera. Absolute frequencies of living individuals. (G. F. Lutze, 1965).

always fully preserved; in many cases the organic structure of the test walls is destroyed, weakening the tests to the point where they disintegrate when mechanically stressed. These processes, which are important for the interpretation of fossil faunas, can be studied to great advantage in Kiel Bay (cf. J. Resig, 1965).

The surface sediment of Kiel Bay always contains a large number of reworked foraminiferal tests; these can serve as tracers to indicate the origin of the clastic sediment fractions: Trochammina tests indicate erosion of Holocene lagoon sediments or outwash from Recent lagoons (B. Grabert, 1971). Foraminifera from the Upper Cretaceous, now on their third site of deposition show clearly that the sand of Kiel Bay represents the coarse fraction of reworked marly till.

The Western Baltic shows that sharply separated faunal regions may also occur in a shelf sea with shallow depth. The causes should be sought in a combination of sediments and water stratification. According to G. F. Lutze (1965), the fauna of the more saline deep water is distinctive (Fig. 5). Marshes (arenaceous forms only) and lagoons also have their own characteristic species associations (G. F. Lutze, 1968). Another association, distinctly sediment dependent, consists of small, hour-glass shaped species which are attached to sand grains (Rotaliammina, Asterellina; only on coarse sands of the fore-beach region). Another group, rarely found in sediment samples, is formed by the species living on red algae (Crithionina, Tholosina and Ophthalmina).

Explanation of Figures 6-10

Fig. 6 Bathymetric map of Kiel Bay. — Based on German and Danish charts plus echograph profiles from the Geological Institute, Kiel.

Fig. 7 Sediment distribution map of Kiel Bay. — Based on mapping with R. V. "Alkor" and "Hermann Wattenberg", additional data from S. Bresslau (1957), R. A. Hintz (1958), U. Barner (1965) and Deutsches Hydrographisches Institut, Hamburg.

Fig. 8 Isopach map of late- and postglacial soft sediments in Kiel Bay. Based on profiling with ELAC-sediment echograph and PNEUFLEX-air gun. Channel system formed during the Late Pleistocene. In the eastern part the thicknesses do not exceed 10 m, in the western part, however, thicknesses of up to 40 m are found. Holocene salt movement is probably responsible for local thickening (compare graben-like depression in Fig. 9). Thicknesses in m (After K. Hinz et. al., 1971).

Fig. 9 Structure map: Base of Tertiary. Based on PNEUFLEX-air gun profiles. Kiel Bay lies within the continuously subsiding North German Basin and also within the area of Zechstein-Evaporite deposition. A salt ridge ("Schwedeneck-Waabs") extends north-westward from Kiel. Deep troughs on both sides of this salt structure are filled with over 1,000 m of Tertiary sediments. This area forms the eastern boundary of the Middle Holstein Block. To the NE the base of the Tertiary can be traced into the undisturbed, flatly dipping East Holstein Platform strata. The flat anticlines are salt pillows. North of the map a rise takes place to the Ringköbing-Fünen-High. Note graben-like depression in the NW. Salt movement continued into the Holocene. Base of Tertiary in m below mean sea level. (After K. Hinz, et. al., 1971).

Fig. 10 Isopach of Holocene sediments, bathymetry, and sediment distribution in outer Flensburg Fjord. Based on official charts, echograph profiles, grab samples and cores. (N. Exon, 1971).

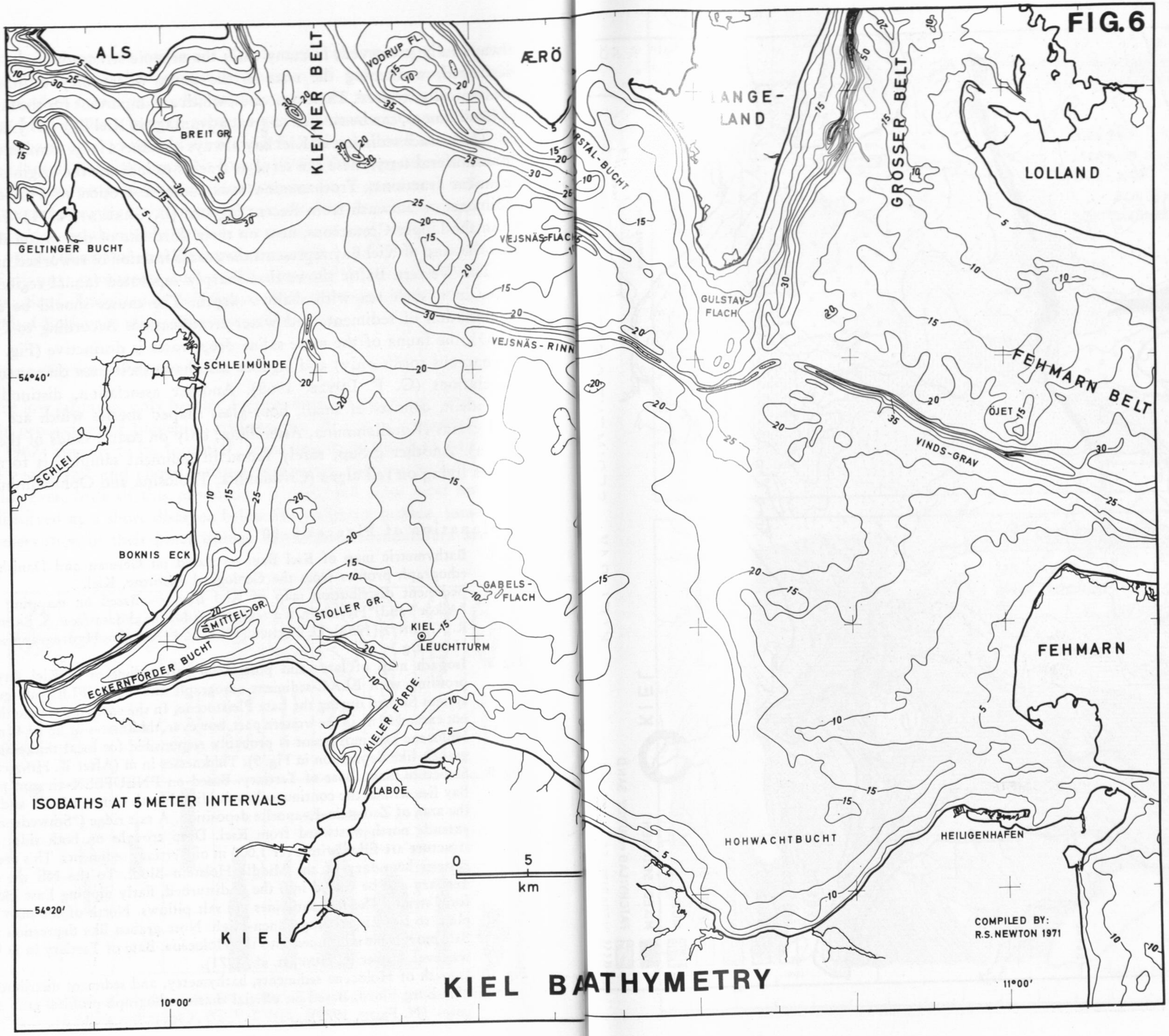
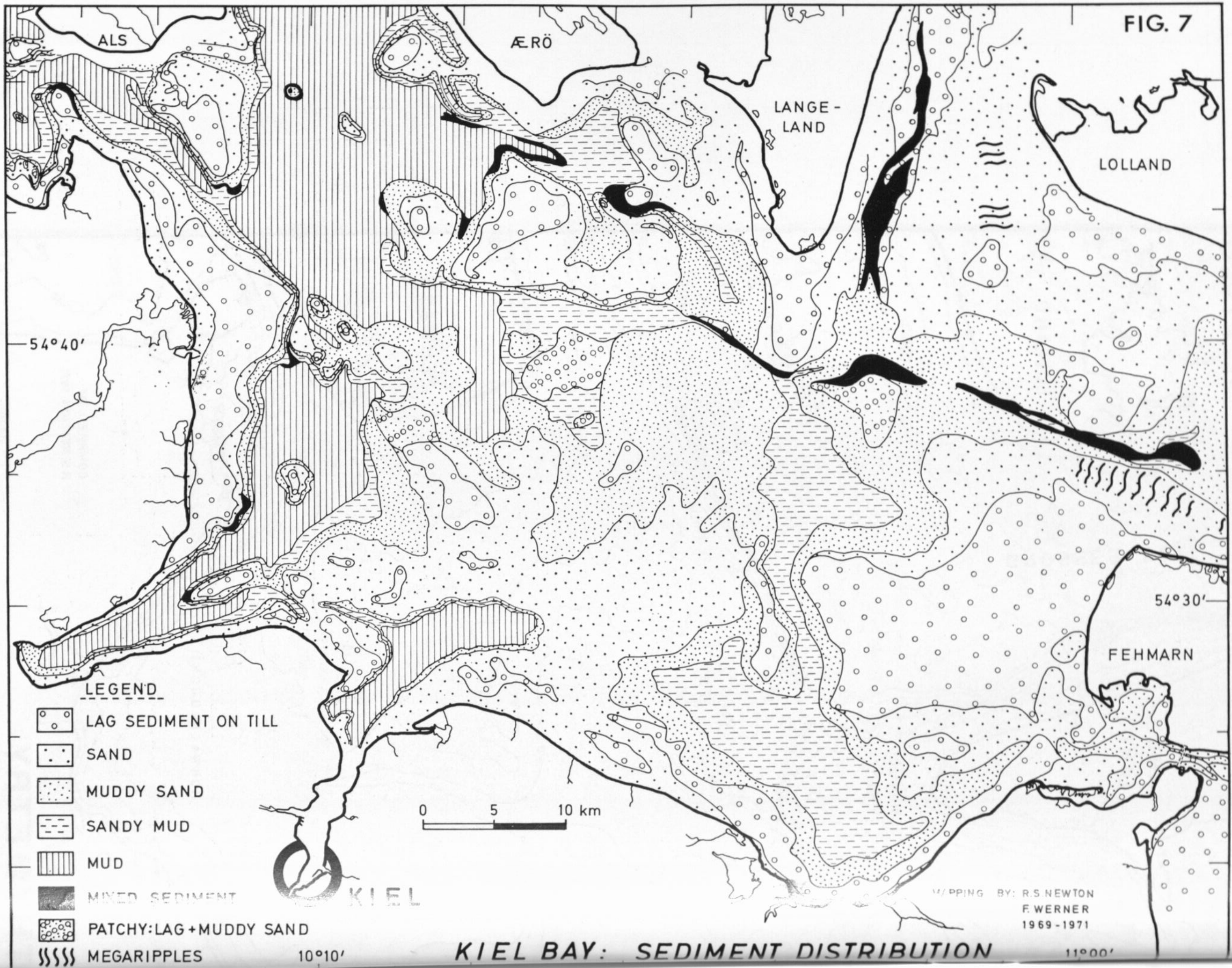


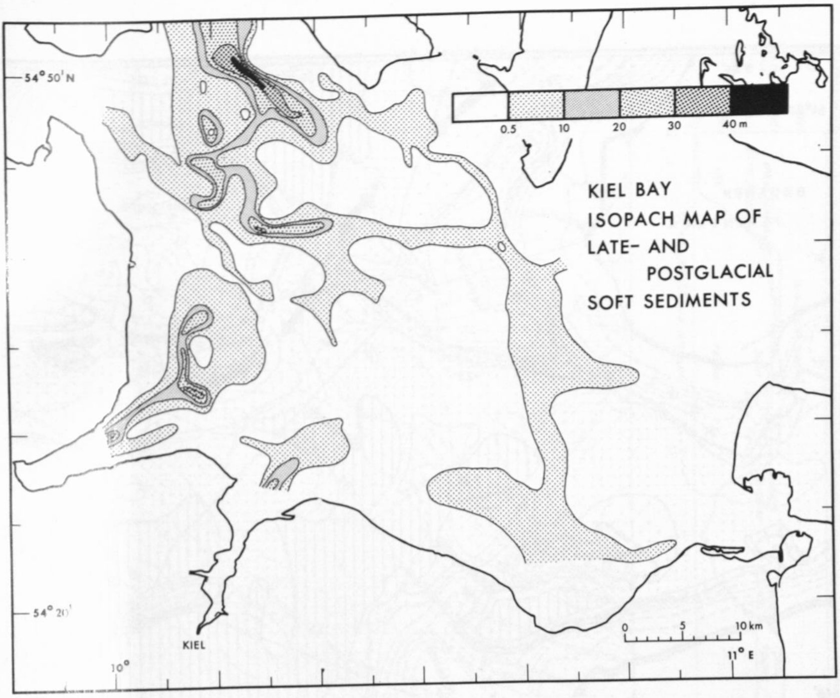
FIG.6

KIEL BATHYMETRY

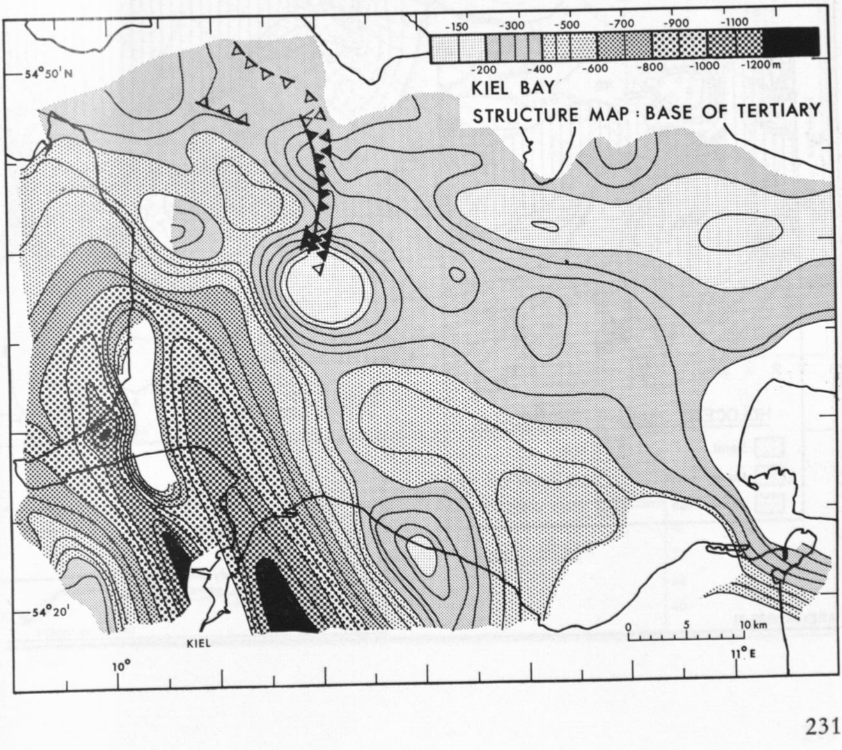
FIG. 7



KIEL BAY: SEDIMENT DISTRIBUTION


54°50'N
0.5
10
20
30
40 m
KIEL BAY
ISOPACH MAP OF
LATE- AND
POSTGLACIAL
SOFT SEDIMENTS
54°20'
KIEL
10°
0
5
10 km
11° E

8


-150
-300
-500
-700
-900
-1100
-200
-400
-600
-800
-1000
-1200 m
54°50'N
KIEL BAY
STRUCTURE MAP : BASE OF TERTIARY
54°20'
KIEL
10°
0
5
10 km
11° E

9

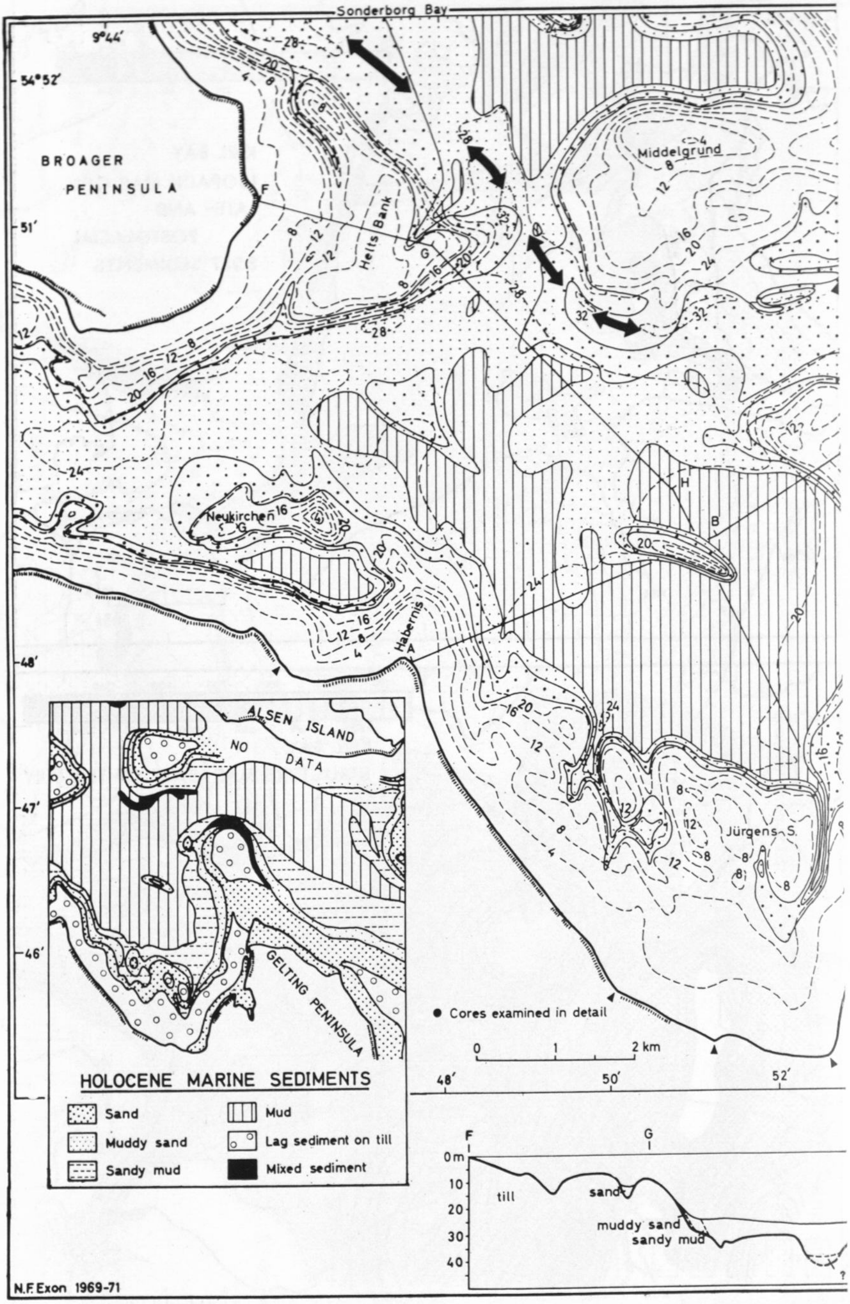
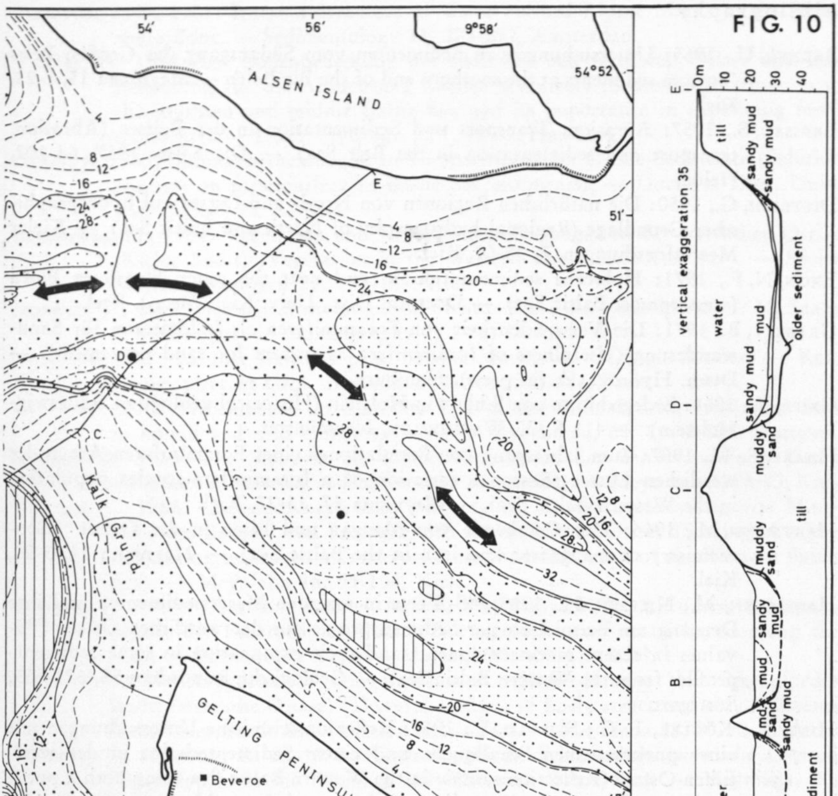

Sonderborg Bay
9°44'
54°52'
51'
48'
47'
46'
BROAGER
PENINSULA
F
G
Hells Bank
Middelgrund
Neukirchen
Habernis
A
B
H
Jürgens S.
ALSEN ISLAND
NO DATA
GELTING PENINSULA
● Cores examined in detail
0
1
2 km
48'
50'
52'
HOLOCENE MARINE SEDIMENTS
Sand
Muddy sand
Sandy mud
Mud
Lag sediment on till
Mixed sediment
0m
10
20
30
40
till
sand
muddy sand
sandy mud
?
N.F. Exon 1969-71

FIG. 10



OUTER FLENSBURG FJORD
HOLOCENE ISOPACHS
0·5–4m
4–8m
> 8m
Holocene sediment thickness
Boundary
Contour below water level: 4m spacing
Coastline
Cliff
Stream mouth
Bottom currents
54′
56′
9°58′
54°52′
51′
47′
54°46′
ALSEN ISLAND
GELTING PENINSULA
Kalk Grund
Beveroe
Falshoft
Gelting
E
D
C
I
4
8
12
16
20
24
28
32
vertical exaggeration 35
0m
10
20
30
40
water
till
sandy mud
mud
older sediment
muddy sand
sandy mud
mdy sand
? older sediment
A
B
C
D
E
H
I
sandy mud
muddy sand
mdy sand

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