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HOLOCENE DEPOSITS OF THE NORTHERN NORTH SEA: EVIDENCE FOR DYNAMIC CONTROL OF THEIR MINERAL AND CHEMICAL COMPOSITION[1]

THOMAS C. JOHNSON[2] & STEPHEN R. ELKINS[3]

ABSTRACT

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Tidal currents and waves have caused some reworking and redistribution of Holocene sediments in the northern North Sea, with preferential deposition of fines in topographic depressions. This has led to a patchy distribution of sediments in terms of their textural, mineralogical and chemical composition. Nevertheless discernable relationships are found to exist between mean grain size and composition of the sediments. The relative abundance of biogenic components (primarily benthic Foraminifera) in the sand-size fraction of the sediments increases as mean grain size decreases, thus biogenic components are relatively more abundant in bathymetric lows. Coarse-grained sediments rich in detrital quartz show higher values of Si/Al than do fine-grained sediments. Smectite is concentrated in the finest-grained sediments, whereas illite is relatively more abundant in coarser deposits. Thus clay mineral segregation processes previously reported to occur near river mouths also occur in an open shelf environment. Fine-grained, smectite-rich sediments show correspondingly higher values of Fe/Al and lower values of K/Al compared to the coarser deposits enriched in illite.

INTRODUCTION

Geological and geophysical investigations of marginal seas on the continental shelf have intensified in the last twenty years as man's need for mineral and food resources, and his awareness of environmental problems have increased. Excellent reviews of early exploration of the shelf are provided by EMERY (1966) and SCHOPF (1968). Many studies in the past decade have related bathymetric features and sedimentary structures to the dynamics of waves and currents on continental shelves (e.g., HOUBOLT, 1968; KENYON & STRIDE, 1970; SWIFT, 1974), and some recent investigations have dealt with the effects of dynamic sedimentary processes on the composition of Recent sediment (e.g., NAIDU ET AL., 1975; STUBBLEFIELD ET AL., 1975; FERENTINOS, 1975; FILLON, 1976).

The purpose of this investigation was to characterize Recent sediments of the northern North Sea in terms of their grain size, mineralogy, and chemical composition, and to determine if they reflect the dynamic processes at work in this area.

The work was concentrated primarily in the vicinity of the Fladen Ground in the northern North Sea (Fig. 1), and constituted one aspect of an internationally-coordinated study of the region. This study, *Fl*aden *G*round *Ex*periment 1976 (FLEX 76) is one part of the *Jo*int *N*orth *S*ea *D*ata *A*quisition *P*rogram 1976 (JONSDAP '76) (RAMSTER, 1977). The experiment is coordinated by the Sonderforschungsbereich 94 'Meeresforschung' of the University of Hamburg, and was designed primarily to study the spring phytoplankton bloom from March to June 1976, to model primary production and its complex interaction with the physical, chemical, biological and geological features of the area.

Previous studies on the sediments of the North Sea primarily concerned coastal areas and the predominantly sandy cover in the southern North Sea (e.g., LANGERAAR, 1966; EISMA, 1968; HOUBOLT, 1968; TERWINDT, 1971). LUDERS (1939) presented a comprehensive map of the surface sediments in the North Sea. In the northern North Sea seismic reflection surveys have been conducted by FLINN (1973) and JANSEN (1976).

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[2] Department of Geology and Geophysics, University of Minnesota, MINNEAPOLIS, MN 55455, U.S.A.

[3] Present address: Chevron Oil Company, NEW ORLEANS, LA, U.S.A.

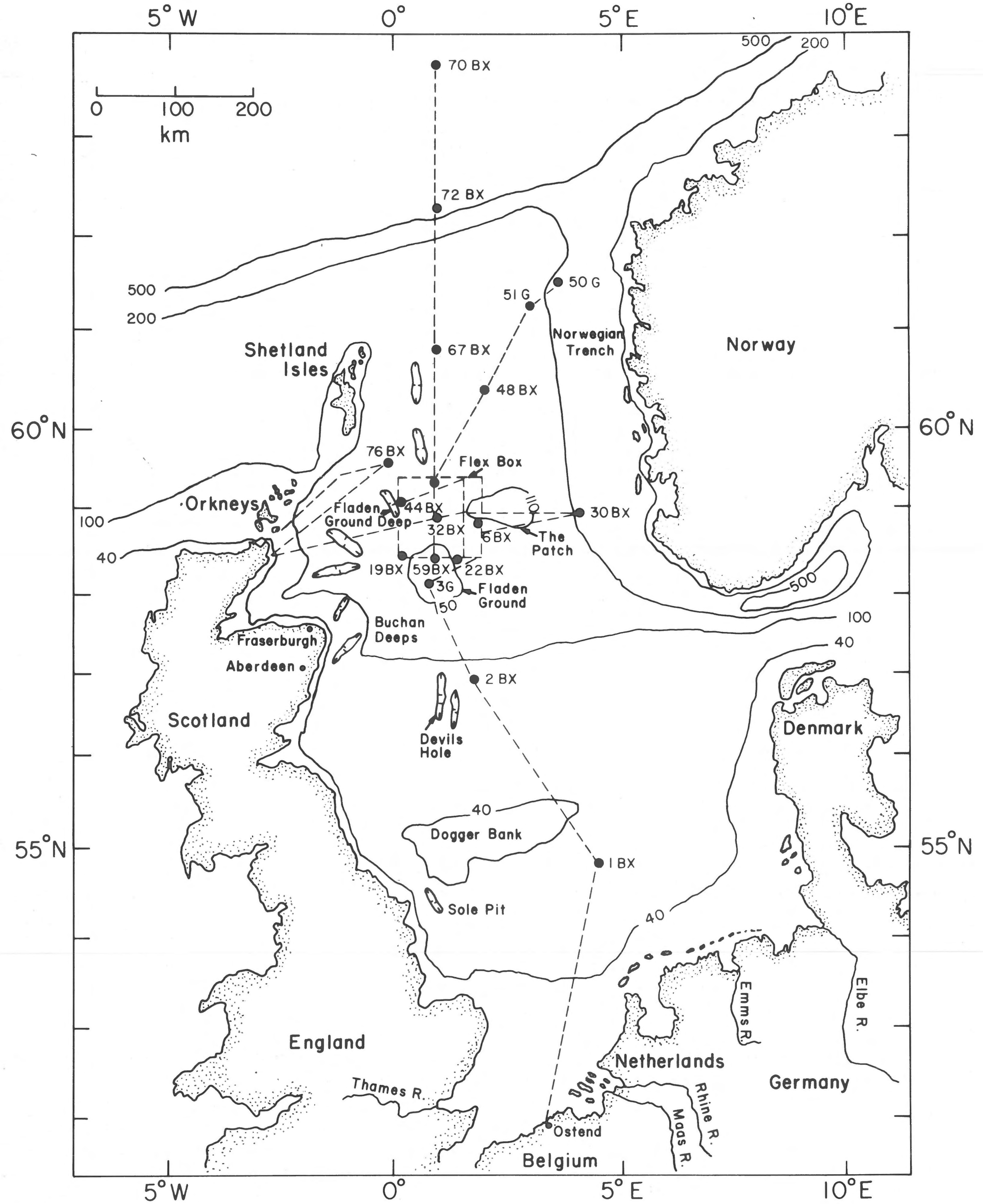

Fig. 1
Regional map of the North Sea, showing core locations (BX indicates box core, G indicates gravity core), ship track and major bathymetric features. Depths, in corrected metres, are represented by a non-uniform contour interval to clearly delineate the major bathymetric features.

METHODS

Field work entailed bathymetric profiling with a 12 kHz precision depth recording system, and sediment sampling with box and gravity corers in May 1976 aboard R/V KNORR of Woods Hole Oceanographic Institution. Satellite navigation was used throughout the survey, providing navigational accuracy typically within ±0.5 km.

Box cores and gravity cores were recovered at 18 locations (Fig. 1). Gravity cores were taken only in areas of rough bathymetry, at times of rough weather, or when there was insufficient time available for box coring. The box corer obtains a sample 50 cm by 50 cm by approximately 45 cm deep (HESSLER & JUMARS, 1974) and was used both to recover an undisturbed sediment sample and to provide enough volume of sediment for many different analyses. A subcore, 6 cm in diameter, was obtained from each box core for this study. Subscores were stored at room temperature aboard ship and were analyzed ashore. Each core was split longitudinally and visually described. Approximate percentages of biogenic and inorganic components were estimated microscopically in the top and bottom of each core, and in the biogenic fraction, relative abundances of benthonic and planktonic Foraminifera, sponge spicules, and other components were estimated. Subsamples from 10 cm intervals within each core were analyzed for grain size, bulk chemical composition, and clay mineralogy.

Grain-size analysis included separating each sample into fractions coarser and finer than 62 μm, with subsequent dry sieving of the coarse fraction and pipette analysis of the fines.

Clay mineralogy was determined on the $<2\mu$m fraction by x-ray diffraction, using a Phillips-Norelco diffractometer with machine settings at 40 kV, 20 mA, 2° 2Θ/minute scanning rate, 1° receiving slit, and Cu Kα radiation. Clays were glycolated to expand the smectite and the distinction between chlorite and kaolinite was determined by comparison of diffraction patterns after heating to 450 °C (JOHNS & GRIMM, 1954). Approximate weight percentages of the clay minerals were computed according to BISCAYE (1965), and considered accurate to within ±10% of the stated value.

Carbonate-carbon dioxide measurements were estimated by heating samples first at 550 ° C for one hour, weighing them, and then heating at 1000 ° C for one hour, and measuring the additional weight loss (DEAN, 1974).

Subsamples were heated to 1000 ° C for one hour and then pulverized in a mechanical agitator in preparation for bulk chemical analyses by x-ray fluorescence spectrometry. Pulverized samples weighing 0.9 g were mixed with 0.75 g of La_2O_3 and 5.25 g of $LiBO_2$, melted at 1000 °C for 20 minutes, and then fused into glass discs. One surface of each disc was polished, and irradiated with Cr Kα radiation at 40 kV and 20 mA. Weight percentages of nine major components (as oxides) were determined by comparing intensities of sample fluorescent radiation with those of discs made in the same manner from U.S. Geological Survey rock standards, as outlined in CLAGUE (1974). The elements analyzed and their corresponding standard deviations from the linear regression curves are as follows: Fe_2O_3 (±0.10), K_2O (±0.20), SiO_2 (±0.05), Al_2O_3 (±0.09), MgO (±0.34), MnO (±0.008), TiO_2 (±0.15) and CaO (±0.05). We could not analyze for Na with our instrument, and some phosphorous may have been lost from our samples during fusion.

GEOLOGICAL SETTING

Bathymetry

The North Sea bottom gradually deepens to the north, except in the middle of the southern region where the Dogger Bank extends east to west and rises to 15 m in some places (Fig. 1). In the rest of the North Sea, water depths range from less than 80 m over some submarine banks to more than 400 m in the Norwegian Trench. The sea floor is characterized by numerous broad, shallow, submarine banks, and circular to elongated depressions and troughs. The submarine banks have been interpreted as being morainic ridges and outwash fan complexes of the retreating Late Pleistocene Scandinavian ice sheet (MILLING, 1975). Other prominent features on the sea floor include narrow, linear depressions, or 'deeps' occurring in several localized groups, such as off Aberdeen and east of the Shetland Islands. Many of these 'deeps' are interpreted as being subglacial meltwater channels, or tunnel-valleys, emerging from beneath the Late Pleistocene ice sheet (FLINN, 1967; WOODLAND, 1970). The Norwegian Trench is by far the largest single feature in this area. It extends for approximately 600 km along the west coast of Norway, in water depths ranging from 250 to 400 m. Some consider it to be a glacial scour channel (SHEPARD, 1931), while others consider it to be of tectonic origin (O. HOLTEDAHL, 1950; H. HOLTEDAHL, 1958).

General description of the surface sediments

Surface sediments of the northern North Sea are primarily poorly-sorted, olive-grey silts and clays in topographic depressions, and fine, moderately-to-poorly-sorted sands on topographic highs. The sediments are uniform with depth in most cores, showing no stratification. They are highly bioturbated, and contain rich benthic communities of worms, sponges, molluscs and other invertebrates. A few of the cores showed a brown, oxidized layer at the surface, usually no more than about one cm thick, overlying the olive-grey sediment. The sediments are mostly terrigenous sands, silts and clays, but they contain a high abundance of calcareous microfossils, fragments of molluscs and echinoids and some whole megafossils. The most abundant megafossil is the pelecypod *Cyprina islandica,* but other pelecypods and gastropods were found as well. Pebbles and cobbles that probably were ice-rafted into the area during deglaciation are abundant in some cores.

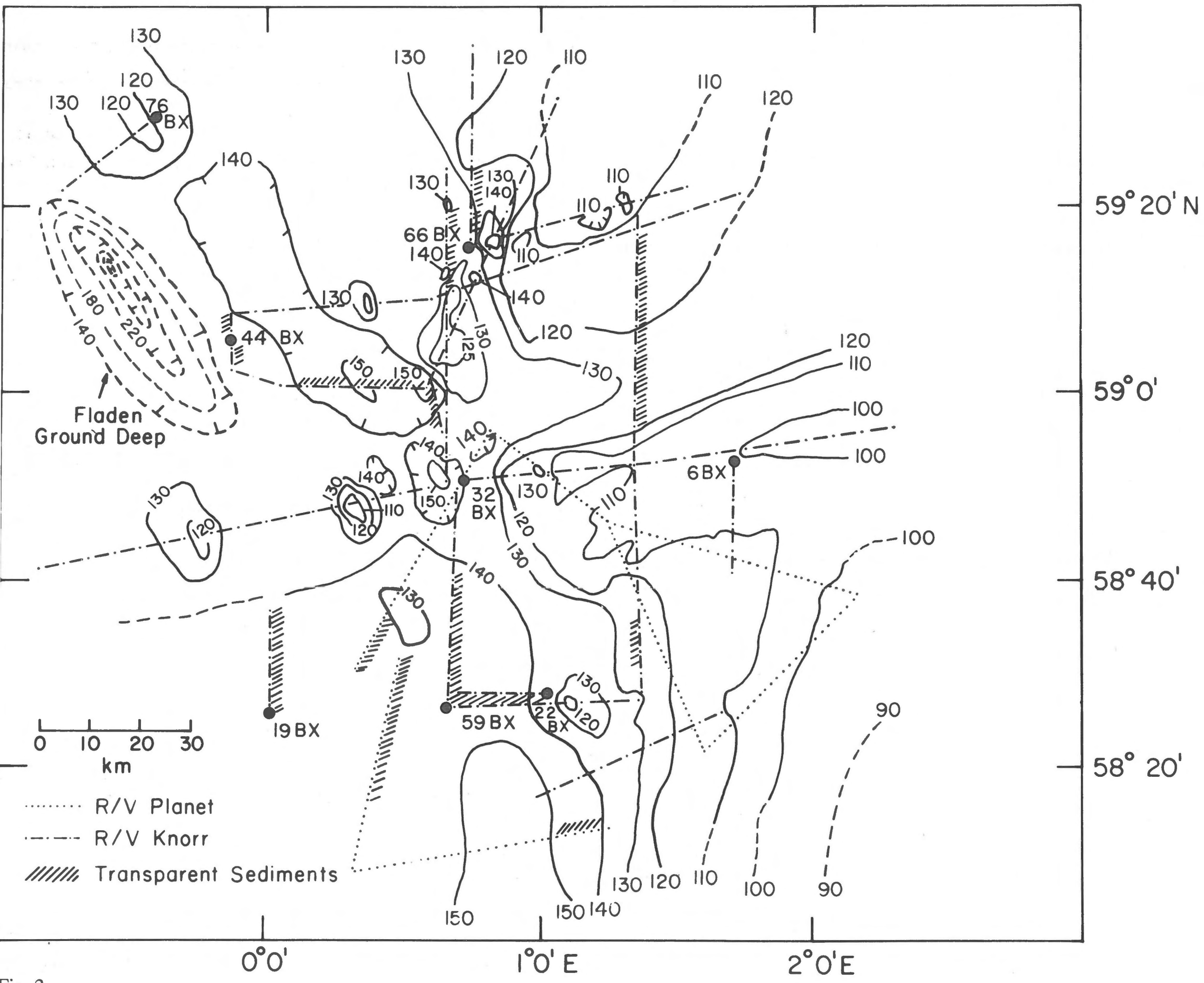

Fig. 2
Bathymetry in the detailed study area. Depths are in corrected metres, and are based upon echo sounding obtained by the R/V Knorr and the R/V Planet, and a preliminary map produced by the FLEX 76 project. The distribution of transparent sediments is indicated by shading along ship tracks.

Echo soundings of surface sediments

At certain locations the echo-sounding system penetrated surface sediments and showed reflectors below the sea floor. These 'acoustically transparent' sediments are the 'Witch Deposits' of JANSEN (1976). They vary in thickness, with up to 20 m ponded in some topographic depressions. The distribution of transparent sediments is influenced by depth of the sea floor, for they are present only in water depths greater than about 115 m (Fig. 2). The thickest transparent sediments often exhibit several reflection horizons. Few transparent sediments exist east of 1°E, where surface deposits are primarily sandy, particularly where the sea floor shallows to depths less than 100 m. FLINN (1973) shows the area west of 1°E to be covered by a large area of silt and clay-sized particles (mud), corresponding to the area of thickest transparent sediments.

Sedimentation rates

The transparent sediments are interpreted to be Late Pleistocene and Holocene in age. If it is assumed that they have been deposited continuously since sea level began to rise 18000 years ago, then the average sedimentation rate for these sediments is about 50 to 100 cm/1000 years. Sedimentation rates were estimated in two cores recovered from the acoustically transparent sediments in the study area. Two bivalve shells recovered from 21 cm in core 44BX were dated at 7480 ± 160 years BP, and a gastropod from 27 cm in core 59BX was dated at 4780 ± 130 years BP. No other datable material could be obtained from the cores to provide additional data. The dated shells correspond to sedimentation rates of 2.81 cm/1000 years in 44BX and 5.65 cm/1000 years in 59BX. The higher sedimentation rate in 59BX correlates with the thicker cover of transparent sediments in the basin from which core 59BX was obtained, than on the topographic high where site 44BX is located (Fig. 2). Assuming a maximum basal age of 18,000 years BP for the transparent sediments, the mean sedimentation rate for cores 44BX and 59BX is at least 33.5 cm/1000 years and 81.3 cm/1000 years, respectively.

The C-14 dates suggest that sedimentation rates of these transparent sediments have decreased by an order of magnitude during the late Holocene. The C-14 dates could be misleading if the shells were reworked into younger sediments by bottom current activity, or if they have been mixed upwards by bioturbation (BERGER & HEATH, 1968). The dated shells were large (5-15 cm across), however, so bioturbation effects should not have been extensive, and the comparable sedimentation rates for the two cores further suggest that no major amount of reworking took place. The difference between sedimentation rates determined from the acoustic records and the C-14 dates indicates that up to 15 m of transparent sediments were deposited in some deep areas at the beginning of deglaciation with only 20 to 30 cm of sediment being deposited within the last 7000 years. This corresponds to curves of relative sea-level changes for the North Sea during the Holocene as determined by JELGERSMA (1961). From 10,000 to 5,000 years ago, sea level rose at an average rate of 7 m/1000 years, and it slowed down to a rate of only 2 m/1000 years within the last 5,000 years. During deglaciation, when transgression proceeded and water depth increased, the distance from this area to the subaerial sources of sediment increased and the rate of sedimentation decreased to the contemporary rate of 3 to 5 cm/1000 years.

RESULTS AND DISCUSSION OF SEDIMENT ANALYSES

Grain size

The textural parameters for all samples are listed in table I. Most of the cores are of uniform grain size and sorting with depth. Obvious exceptions are cores 19BX and 72BX which exhibit decreasing grain sizes with depth. When plotted on a ternary diagram of sand-silt-clay, most samples fall into one of four classifications: silty-clay, clayey-silt, silty-sand, or

Table I
Textural parameters.

Core	Depth	%Sand	%Silt	%Clay	M_z(phi)	S_G
1BX	0-5 cm	86	7	7	3.5	0.5
	10-15	82	11	7	3.62	0.63
2BX	0-5	73	20	7	3.53	1.2
	10-15	80	14	6	3.45	0.95
3G	0-5	5	75	20	6.25	2.43
	10-15	2	74	24	6.7	2.8
	20-25	4	76	20	6.2	2.35
	30-35	2	73	25	7.33	3.0
	40-45	2	55	43	8.17	2.85
	50-55	2	50	48	8.47	3.2
6BX	0-5	93	2	5	2.73	0.8
	10-15	90	5	5	2.8	0.6
19BX	0-5	11	73	16	5.47	1.7
	10-15	11	75	14	5.45	1.6
	20-25	11	68	21	6.1	2.4
	30-35	1	59	40	8.05	3.25
22BX	0-5	47	38	15	5.05	2.4
	10-15	52	38	10	4.28	1.5
	20-25	44	41	15	5.05	2.5
30BX	0-5	6	36	58	8.93	3.0
	10-15	8	30	62	8.6	3.7
	20-25	4	28	66	9.03	3.5
	30-35	3	30	67	9.43	3.15
32BX	0-5	43	45	12	4.32	1.55
	10-15	58	30	12	4.32	1.8
	20-25	55	33	12	4.43	2.0
	30-35	58	30	12	4.17	1.55
44BX	0-5	41	47	12	4.62	1.25
	10-15	48	40	12	4.62	1.25
	20-25	44	44	12	4.78	1.5
48BX	0-5	97	2	1	2.27	0.43
	10-15	97	2	1	2.3	0.45
50G	0-5	11	27	62	9.1	3.5
	10-15	8	32	60	9.1	3.95
	20-25	4	31	65	9.02	3.55
	30-35	4	39	57	9.05	3.25
	40-45	4	36	60	8.9	3.55
	50-55	5	48	47	8.85	3.50
51G	0- 5	3	40	57	9.0	3.5
	10-15	3	42	55	8.27	3.45
	20-25	3	40	57	8.67	3.65
	30-35	3	47	50	8.23	3.38
	40-45	3	45	52	8.43	3.8
	50-55	3	50	47	8.58	3.5
	60-65	3	40	57	8.78	3.5
59BX	0-5	11	66	23	6.67	3.0
	10-15	10	68	22	6.58	3.1
	20-25	12	63	25	6.47	3.1
66BX	0-5	57	33	10	4.37	1.50
	10-15	52	40	8	4.25	1.68
67BX	0-5	89	7	4	2.63	0.58
	10-15	89	4	7	2.68	0.6
70BX	0-5	25	33	42	6.93	3.8
	10-15	24	33	43	7.18	3.9
	20-25	14	39	47	8.07	3.95
	30-35	12	27	61	8.95	3.6
72BX	0-5	85	9	6	2.58	1.0
	10-15	61	17	22	4.75	3.5
	20-25	29	35	36	7.25	4.2
	30-35	30	35	35	7.23	4.35
76BX	0-5	94	5	1	2.45	1.0
	10-15	90	8	2	2.68	0.95

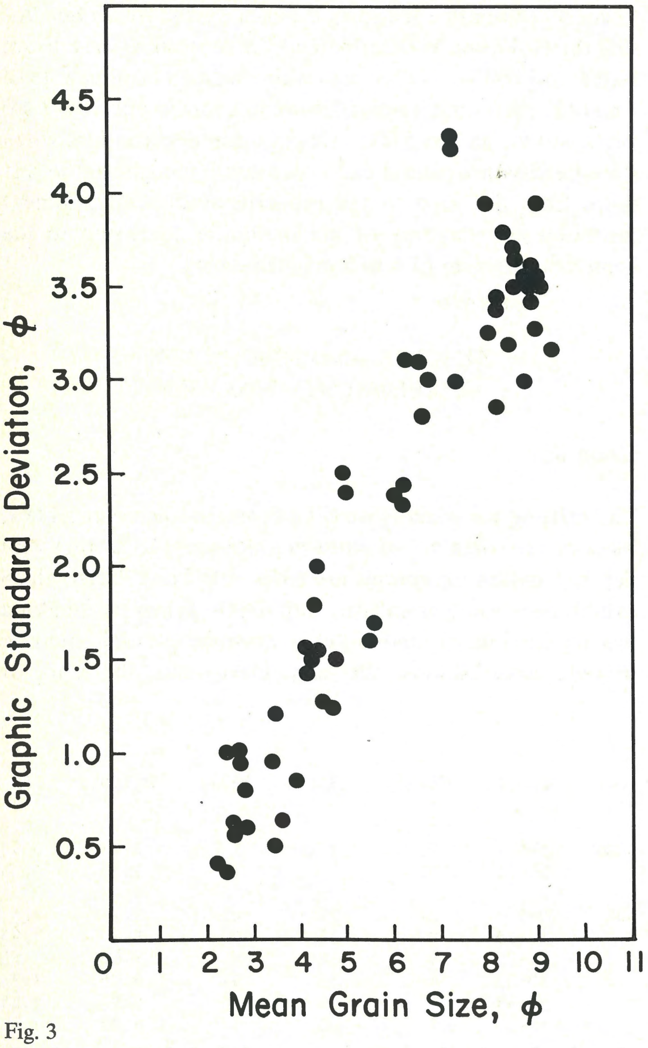

Fig. 3
Graphic standard deviation versus mean grain size, showing the better sorting in coarser sediments.

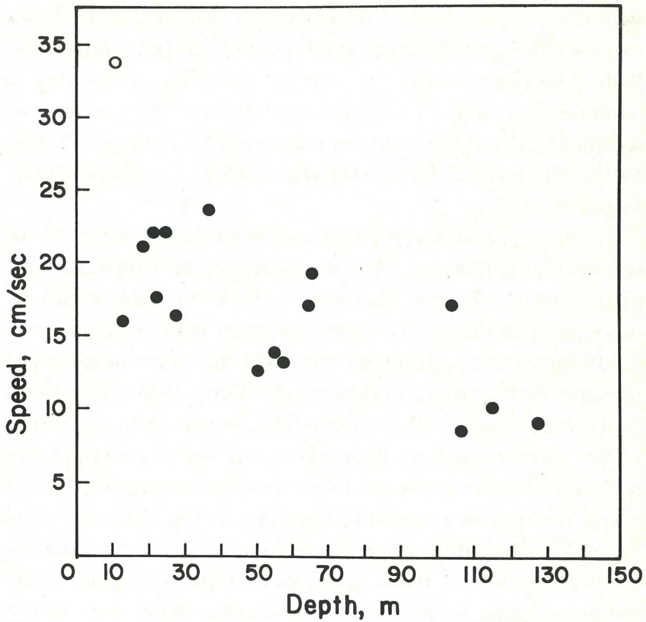

Fig. 4
Maximum current velocities measured in a two month period in the FLEX area, at various water depths, showing that the tidal currents are generally weaker at greater depth below the sea surface. Data were obtained by the Deutches hydrographisches Institut, Hamburg, and preliminarily presented in the Draft FLEX Atlas.

sand. A plot of mean grain size versus the graphic standard deviation for all samples shows that the coarser sediments are better sorted (Fig. 3), indicating winnowing action by currents (FOLK, 1974). The generally uniform distributions of sand-silt-clay ratios and sorting with depth in these cores implies that the depositional environment and hydrodynamic factors in this area have not changed significantly over the last 5 000 to 7 000 years.

Regionally, the grain-size variations of the surface sediments reflect the bathymetry of sea floor. All cores with mean grain sizes in the sandy range (0 to 4 phi) are at locations shallower than about 120 m. Cores from greater depths are either silty (4 to 8 phi) or clayey (over 8 phi).

Hydrodynamic processes associated with waves and currents probably force the preferential deposition of fine-grained sediments in topographic depressions. Currents in the northern North Sea are primarily tidal (NIHOUL, 1975) and are characterized by extreme directional variability, which may reflect passing eddies (HILL, 1973). Current velocities were measured continuously from March to June 1976, by the Deutsches hydrographisches Institut. Higher current velocities exist at shallower water depths, reaching a maximum velocity of 33.5 cm/s at a depth of 11 m (Fig. 4). The minimum current velocity required to erode unconsolidated silt and clay-sized material is about 26 cm/s (STERNBERG, 1972). This indicates that bottom currents of sufficient velocity to erode fine-grained particles were not observed near the sea floor during the period of *in situ* measurement.

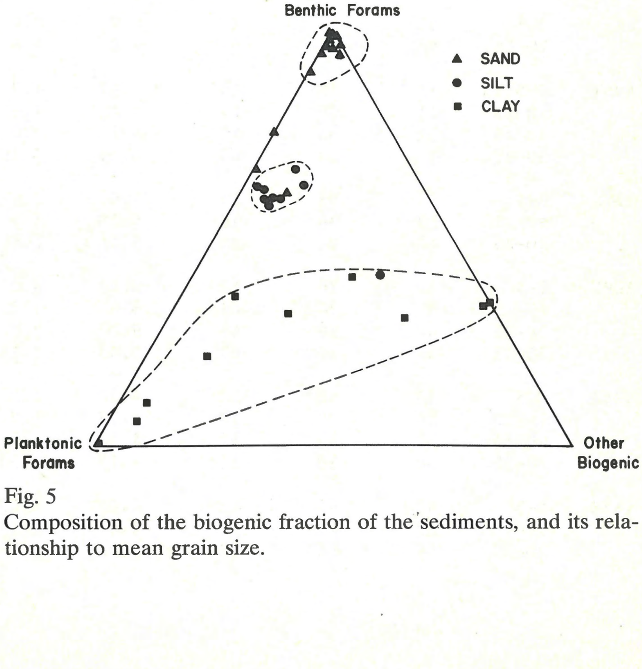

Fig. 5
Composition of the biogenic fraction of the sediments, and its relationship to mean grain size.

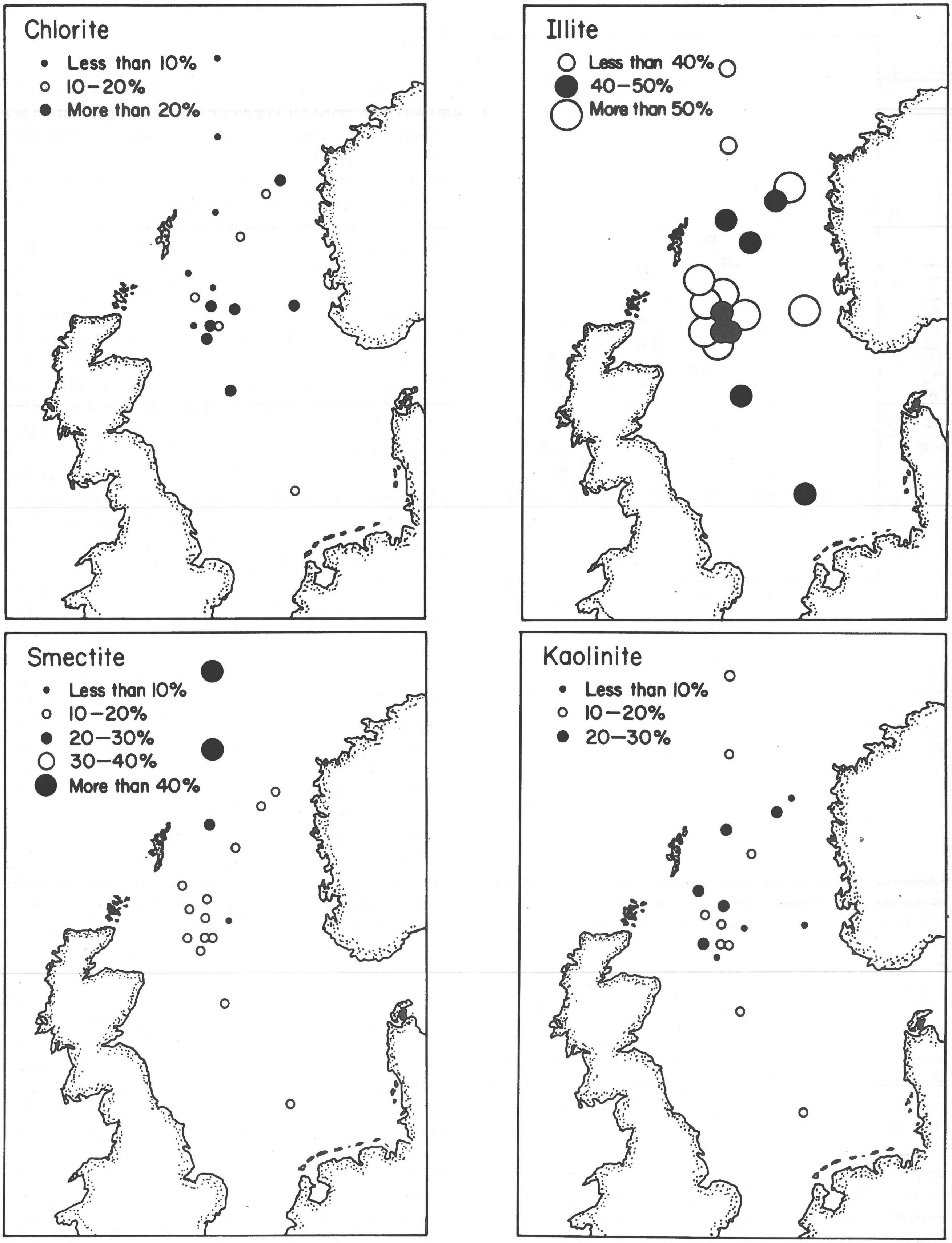

Fig. 6
Regional distributions of the four most abundant clay minerals in the surface sediments.

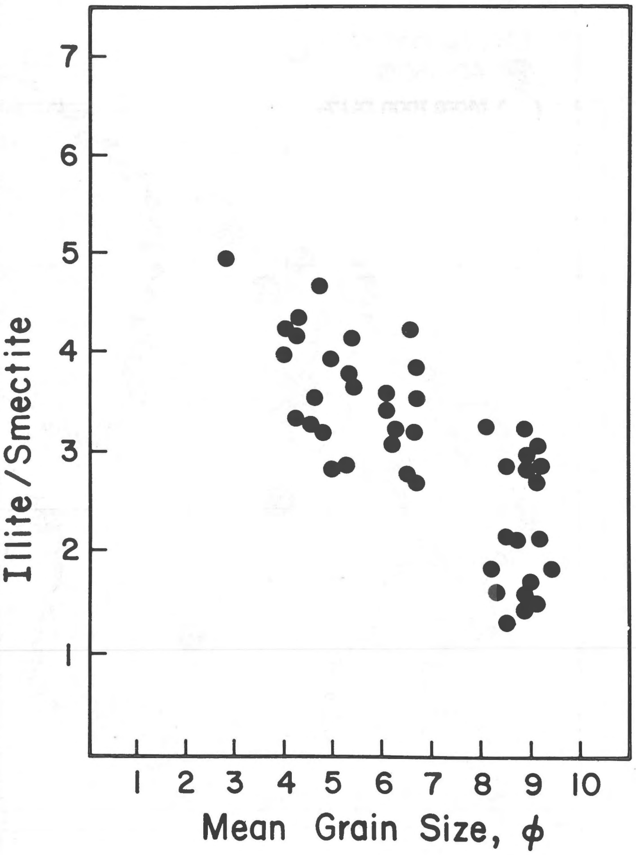

Fig. 7
Relationship between the mean grain size of the sediments and the relative abundances of illite and smectite, indicating that clay mineral segregation occurs in an open shelf environment far from river deltas.

However, storm waves could create bottom currents that erode the fine-grained materials from shallower areas of the sea floor and redistribute them into nearby depressions. Oscillatory motions caused by waves breaking on the continental shelf have been found to cause sediment resuspension in depths of at least 167 m (STERNBERG & LARSEN, 1975). Wave and tidal currents have been reported to control the distribution of mean grain size on shelf sediments southwest of England (CHANNON & HAMILTON, 1976) and elsewhere around the British Isles (e.g., STRIDE, 1963; BELDERSON, 1964; KENYON & STRIDE, 1970; MCCAVE, 1970), and are no doubt active today in the northern North Sea.

The cores having the finest mean grain size, 30BX, 50G and 51G, are all from locations within the Norwegian Trench at depths over 280 m. Here much of the clay-sized sediment may be derived from river runoff along the German coast, and carried northward into the Trench by surface currents (MCCAVE, 1973).

Sand Fraction

Microscopic analysis of the sand fraction (coarser than 62 μm) was performed for samples from the top and bottom few centimetres of each core. Relative abundances of biogenic and inorganic particles were estimated, and the biogenic fraction was further categorized into the abundances of benthic Foraminifera, planktonic Foraminifera and 'other' components. The data are tabulated in ELKINS (1977).

In general, deposits with the finer mean grain size contain a higher ratio of biogenic to inorganic components in the $>62\mu$m fraction. Within the biogenic fraction the percentage of benthonic Foraminifera usually exceeded the percentage of either planktonic Foraminifera or other invertebrates. The primary constituent of the 'other biogenic materials' is sponge spicules, attaining very high abundances in cores taken from the Norwegian Trench (up to 40% in core 30BX). Only a few cores, in particular core 70BX, had significantly higher amounts of planktonic than benthonic Foraminifera. Core 70BX was obtained from deeper water in a more pelagic environment than the other cores. Siliceous microfossils were rarely observed in the cores, except for the high amounts of sponge spicules in cores from the Norwegian Trench. Diatoms were observed in abundances less than 1% in cores 19BX, 22BX, 30BX, 50G, and 72BX, with their greatest abundance occurring in the top few centimetres of core 70BX (up to 4%). A few Radiolaria were observed only in core 70BX.

The biogenic composition is influenced by factors controlling the mean grain size of the sediment. The sandy sediments are composed almost entirely of benthonic Foraminifera, the silty sediments have larger abundances of planktonic Foraminifera species, and sediments with a mean size in the clay range exhibit a broader range of biogenic composition, ranging from 0% to 100% planktonic Foraminifera in their sand-sized fraction (Fig. 5). The predominance of benthonic Foraminifera in coarser sediments may result from more extensive reworking of these deposits, and the preferential dissolution of the less-resistant planktonic Foraminifera and siliceous microfossils.

Clay mineralogy

Figure 6 illustrates the regional distribution of clay minerals in surface sediments of the northern North Sea. Chlorite exhibits a wide range of values with somewhat lower percentages in samples from the northwest. Illite is the most abundant clay mineral in all samples except the two northernmost samples from the Norwegian Sea, in which smectite is the most abundant clay. Kaolinite concentrations range from 4 to 28% with the two lowest values in Norwegian Trough sediment, and the highest concentrations in the northwestern region of study. The distributions of chlorite and smectite subtly reflect the net southward flowing current that exists in the western sector of the gap between Norway and the Shetland Islands

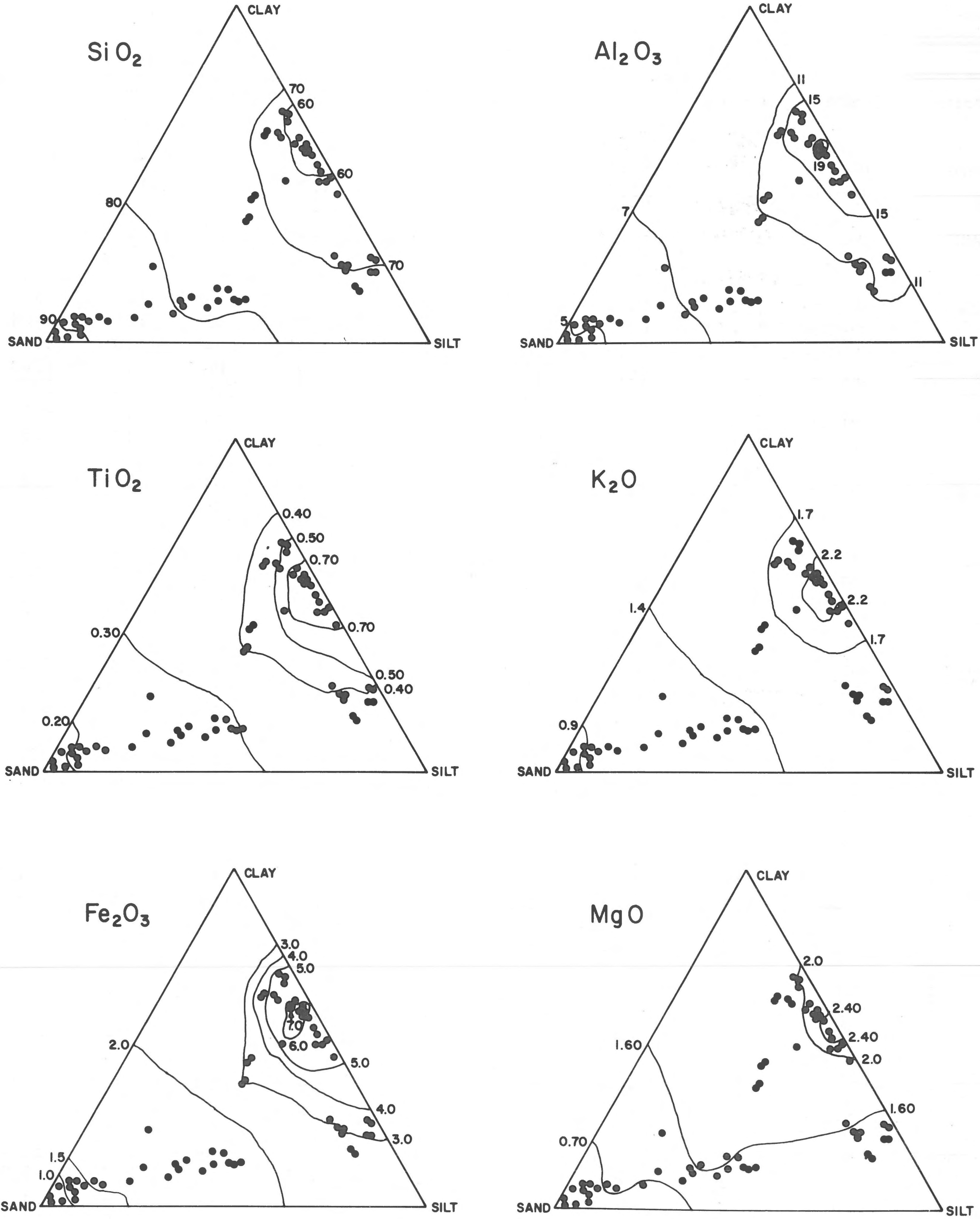

Fig. 8
Weight percent abundances of some of the major elements as a function of grain size.

Table II
Bulk chemistry.

Core	Depth	%Fe_2O_3	%SiO_2	%Al_2O_3	%TiO_2	%K_2O	%MnO	%MgO	%CaO
1BX	0-1	1.9	85.9	7.7	0.4	1.3	.19	0.3	2.1
	10-11	1.8	85.3	7.5	.3	1.2	.09	1.1	2.0
2BX	0-1	1.7	86.7	7.3	.3	1.0	.11	.3	2.3
	10-11	1.5	84.2	9.2	.2	1.3	.03	.7	1.9
3G	0-1	3.3	59.2	17.0	.5	1.2	.10	1.6	15.6
	10-11	3.1	63.7	13.2	.5	1.5	.06	1.6	14.3
	20-21	3.3	63.9	12.6	.5	1.4	.04	1.6	15.0
	30-31	3.9	66.2	12.8	.6	1.4	.09	2.0	12.0
	40-41	5.1	61.6	16.4	.7	1.4	.14	2.0	10.8
	50-51	5.2	66.3	13.4	.6	2.4	.13	2.4	8.8
	60-61	5.9	62.3	17.3	.7	2.2	.23	1.6	8.8
6BX	0-1	1.1	86.5	8.1	.2	1.1	.09	.7	2.0
	10-11	1.3	87.4	7.5	.3	1.0	.09	.7	2.0
19BX	0-1	2.4	70.6	11.7	.4	1.3	.04	1.1	11.3
	10-11	2.8	69.1	13.0	.5	1.3	.13	2.0	10.2
	20-21	2.3	71.6	10.3	.4	1.5	.01	1.6	11.6
	30-31	4.6	66.7	15.4	.7	1.9	.13	1.1	8.9
22BX	0-1	2.5	69.7	10.0	.4	1.4	.14	1.6	12.7
	10-11	2.1	74.5	11.7	.3	1.2	.16	.7	8.4
	20-21	1.9	77.7	7.7	.3	1.3	.04	1.1	9.0
30BX	0-1	7.0	61.2	17.3	.7	1.9	.61	1.6	8.4
	10-11	5.3	62.4	15.1	.6	2.1	.08	2.4	10.5
	20-21	5.8	62.0	18.3	.7	1.9	.16	1.6	8.0
	30-31	5.5	59.1	18.6	.7	2.2	.03	2.4	10.0
32BX	0-1	2.2	79.7	9.0	.4	1.1	.14	.7	6.1
	10-11	1.9	78.5	8.1	.3	1.3	.04	2.0	7.4
	20-21	2.2	79.5	8.1	.4	1.3	.16	.7	6.3
	30-31	2.3	75.6	8.8	.3	1.4	.13	2.0	8.5
44BX	0-1	2.1	72.9	12.4	.4	1.4	.13	1.1	8.2
	10-11	1.9	79.3	8.1	.3	1.5	.01	1.1	7.3
	20-21	2.0	77.1	8.5	.4	1.3	.21	1.6	8.6
48BX	0-1	.9	91.4	4.7	.0	.9	.13	.3	1.0
	10-11	1.2	90.4	4.7	.2	.8	.14	.7	1.9
50G	0-1	4.9	62.9	13.4	.5	1.7	.19	2.8	11.4
	10-11	5.3	57.4	16.9	.7	1.7	.25	2.0	15.2
	20-21	6.0	58.7	14.7	.5	1.9	.16	2.0	13.9
	30-31	6.1	56.8	18.8	.7	2.0	.25	2.0	11.5
	40-41	6.4	63.1	15.4	.6	2.5	.10	1.6	9.4
	50-51	5.5	63.2	15.4	.7	2.3	.20	1.6	10.6

Core	Depth	$\%Fe_2O_3$	$\%SiO_2$	$\%Al_2O_3$	$\%TiO_2$	$\%K_2O$	%MnO	%MgO	%CaO
51G	0-1	5.4	58.7	12.9	.5	1.7	.28	2.0	17.1
	10-11	4.8	55.4	13.6	.6	1.5	.18	2.4	19.6
	20-21	4.9	58.4	11.7	.5	1.6	.09	2.0	18.6
	30-31	4.4	55.5	12.9	.6	1.6	.34	2.4	20.3
	40-41	4.8	59.4	13.1	.5	1.9	.14	2.0	16.7
	50-51	4.5	57.3	16.1	.6	1.9	.17	2.0	16.3
	60-61	5.2	60.6	14.0	.6	2.2	.11	1.1	13.8
59BX	0-1	2.8	66.3	9.9	.6	1.4	.20	1.1	15.6
	10-11	3.2	68.4	9.7	.6	1.6	.12	1.0	13.7
	20-21	3.1	65.9	10.6	.6	1.5	.14	1.1	15.5
	30-31	3.9	64.6	12.9	.6	1.9	.13	2.4	11.6
66BX	0-1	1.6	83.4	6.9	.3	1.2	.15	.7	4.9
	10-11	2.0	82.6	7.6	.3	1.3	.14	.7	5.4
	20-21	1.8	81.9	7.8	.4	1.3	.19	.7	5.7
67BX	0-1	1.2	75.0	3.7	.1	1.0	.05	1.6	15.7
	10-11	1.3	70.6	6.5	.2	.9	.01	2.0	16.3
70BX	0-1	6.2	30.5	11.3	.7	.6	.34	3.3	41.8
	10-11	6.3	49.7	13.6	1.1	1.3	.32	2.8	22.7
	20-21	6.0	67.7	13.1	.7	2.4	.28	2.4	5.2
	30-31	5.8	61.3	18.8	.8	2.5	.31	1.6	6.0
	40-41	5.2	67.5	12.0	.5	2.4	.31	.7	7.8
72BX	0-1	2.0	81.6	8.1	.4	1.2	.14	2.0	4.5
	10-11	1.9	83.1	6.5	.2	1.4	.12	2.0	3.7
	20-21	3.6	71.9	12.2	.6	2.0	.19	1.6	6.5
	30-31	4.3	73.5	9.9	.5	2.1	.17	1.6	6.9
	40-41	3.6	74.0	12.4	.5	1.9	.08	1.6	5.8
76BX	0-1	1.1	90.4	3.0	.1	1.2	.07	1.1	2.4
	10-11	1.3	87.1	4.9	.2	1.2	.05	1.1	3.0

(BOHNECKE, 1922; HILL, 1973). No significant variations were noted in clay mineral abundances with depth in the cores except in those instances where mean grain size changed to a great degree. Illite is deposited preferentially with coarser sediments, and smectite with finer-grained sediments (Fig. 7). These data indicate that size-dependent segregation of clay minerals occurs in an open shelf environment just as it does in a deltaic environment (GIBBS, 1977). This dynamic control over the distribution of illite and smectite results in illite enrichment on topographic highs where silty and sandy sediment accumulates, and smectite enrichment in clayey deposits in protected topographic depressions.

Bulk chemical composition

Bulk chemical analyses were performed on all cores at 10 cm depth intervals. Results are presented in Table II. Most major elements analyzed are within the range of average values for typical sandstone, siltstone, and shale (PETTIJOHN, 1963; CLARK, 1924). Ca0 was found to be slightly higher in North Sea sediments than in those reported by PETTIJOHN (1963) and CLARKE (1924), with the average value for all samples being 9.62% Ca0. These higher values in North Sea sediments no doubt are due to the presence of Foraminifera and other calcareous shell debris. In comparison, analyses of calcareous lithic sandstones (CAYEUX, 1929) and carbonaceous shale (VON GAERTNER, 1955) have shown Ca0 abundances to be as high as 18.75% and 16.85% respectively.

Examination of chemical variation with depth in the core shows that little variation is present. Silica, alumina, and titanium oxide are particularly uniform with depth, once again reflecting a fairly constant sedimentary history for the last

5 000 to 7 000 years. Iron and manganese show a general trend of decreasing abundances from the surface down to 10 cm depth. This concentration gradient correlates with the brown oxidation layers visually observed in the upper centimetre of some of the cores that result from upward migration of iron and manganese toward the sea floor (BERNER, 1969).

The variation of regional chemical abundances in the northern North Sea and with depth in the cores also depends upon the mean grain size of the sample. Mean values for silica abundance are seen to decrease with decreasing grain size, while all other chemical components increase considerably in the finer-grained sediments (Fig. 8). The differences in composition reflect the enrichment of coarser-grained sediments in detrital quartz, and of the finer fraction in the clay minerals.

Potassium is a major constituent of illite, while iron and magnesium are more abundant in smectite and chlorite (DEGENS, 1965). Consequently sediments enriched in illite and depleted in smectite should have high K/Al and low Fe/Al and Mg/Al ratios. Such a relationship exists for potassium and iron (Fig. 9). The Mg/Al ratio, when plotted against both the illite/smectite and illite/chlorite ratios exhibits too much scatter to show any useful correlation, suggesting that magnesium content is influenced by factors other than clay mineralogy (e.g. carbonate content).

CONCLUSIONS

Throughout the northern North Sea it is evident that Late Pleistocene and Recent sediment type and distribution are closely related to the bathymetry, geologic history, and the present oceanographic conditions of the region.

With the onset of deglaciation thick (up to 15 m) sequences of silts and clays were deposited in deeper areas between adjacent rises and morainic banks. Sedimentation rates decreased considerably as sea level rose and the distance to subaerial source areas increased during the Holocene. During the last 5000 to 7000 years, sedimentation in this area has been on the order of 5 to 6 cm/1000 years in topographic depressions, and slower on elevated regions of the sea floor. Bottom currents due to tides and waves have caused some reworking and redistribution of the post-glacial sediments. The distribution and grain-size characteristics of Recent sediments appear to be primarily depth-controlled, with deeper sites, protected from strong bottom currents, accumulating poorly-sorted silts and clays.

Examination of the bulk chemistry and clay mineralogy of the near-surface sediments indicates a close correlation between chemical composition and mean grain size. Coarse-grained sediments are rich in detrital quartz and have higher Si/Al ratios than do fine-grained sediments, whose bulk chemistry is, to some extent, controlled by the clay mineralogy. Fine-grained sediments have higher smectite to illite ratios relative to coarse-grained deposits, and show correspondingly higher values of Fe/Al and lower values of K/Al. Coarse debris is primarily inorganic in sandy sediments, and is predominantly of biogenic origin in sediments with a finer mean grain size.

Size sorting of sediment by bottom currents has led to the observed relationships among grain size, depth of deposition, mineralogy and bulk chemistry. These results are probably characteristic of shallow-sea deposition in most high-latitude regions of the world, and may be recognizable in ancient continental-shelf marine deposits that are preserved in the geologic record.

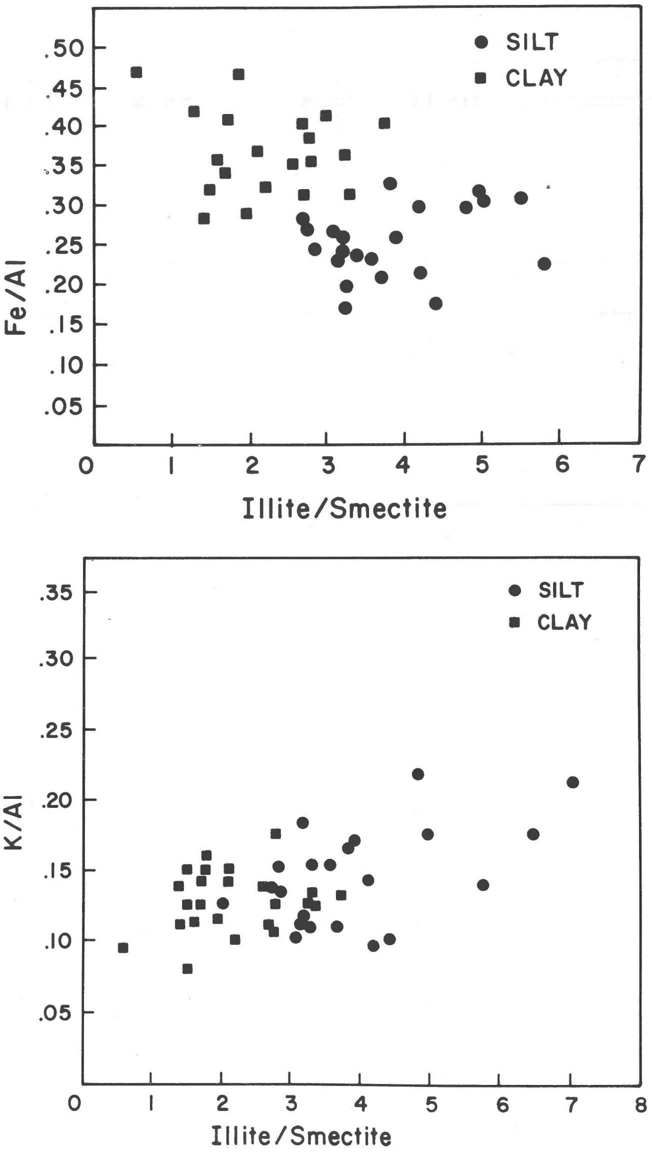

Fig. 9
The influence of clay mineralogy upon iron to aluminum and potassium to aluminum ratios in the sediments.

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