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Clay mineral associations in fine-grained surface sediments of the North Sea

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Abstract

With the help of about 500 samples of surface sediments from the North Sea crude maps of the distributions of the clay minerals illite, chlorite, smectite and kaolinite were constructed. Illite, with 51%, is the dominant clay mineral, followed by smectite (27%), chlorite (12%), and kaolinite (10%). There are well-distinguished areas of different concentrations of the individual clay mineral associations. Illite and chlorite show highest values in the north, kaolinite concentrations are high in a corridor a few hundred kilometres wide between the east coast of the UK and the Danish/south Norwegian coast. Smectite is high in the German Bight and in the southwestern North Sea. The distribution patterns of the clay mineral associations are mainly explained by late Quaternary history and by recent to sub-recent sedimentary processes. During the Pleistocene cold periods illite- and chlorite-rich sediments from the Fennoscandian Shield were transported by the great inland ice-masses in a southward direction. The present high sea-level erosion on the east coast of Great Britain provides the North Sea with kaolinite-rich fine-grained sediments. Smectites inherited from Elsterian deposits in the southeast corner and probably from sub-recent Elbe sediments are responsible for their higher values in the German Bight. The high values of smectite in the southwest may have originated from Cretaceous sediments eroded on the banks of the Strait of Dover. The present contribution of riverine suspended load to the North Sea appears to be low.

Keywords: North Sea; clay minerals; pathways; Pleistocene

1. Introduction

Despite the predominance of sands in the North Sea bottom (Jansen et al., 1979), small amounts of fine-grained particles occur in most places finely dispersed in the sand. Pure mud deposits are restricted to small areas, with the exception of the Norwegian trench and the Skagerrak. The distribution of fine-grained sediments in the North Sea is well described in Lüders (1939), McCave (1973) and Eisma (1973, 1981). The distribution of suspended load, the main source of the fine-grained sediments, is given by Eisma and Kalf (1987), McManus and Prandle (1997) and Van Raaphorst et al. (1998). Flocculation and particle settling of suspended matter is summarised by Eisma (1993). Johnson and Elkins (1979) described the mineral and chemical composition of Holocene deposits of the northern North Sea.

The pathways of the suspended matter are difficult to identify directly. A method from which very useful conclusions about the origin, pathways and

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deposition of fine-grained sediments can be drawn is the determination of the clay mineral composition along a grid of samples from surface sediments (Biscaye, 1965; Kolla et al., 1976; Chamley, 1989). The first study carried out in the southeastern corner of the North Sea (Irion et al., 1987) showed that clay mineral associations in surface sediments of this region are highly differentiated and the heterogeneity was expected to continue in the whole North Sea basin. In the present study we have analysed the clay mineral composition in the fine-grained fraction of the surface sediments (upper 20 cm) of the entire North Sea. The first study served to form a hypothesis that the distribution pattern of the different clay mineral associations in the fine-grained material of the North Sea may indicate the origins and pathways of the suspended matter. The fine-grained sediments are transported mostly as suspended load by currents. During the transport small amounts of particles are released to the bottom, where they may add to the existing coarse sediments. It is their presence that can serve as a tracer for the pathways of the suspended load.

In the water fine-grained material is present as suspended flocs in a size of up to 100 μm (Eisma and Kalf, 1987). Individual particles hardly exceed a 20-μm diameter, and about 50% of these particles belong to the <2-μm fraction (Kersten et al., 1991). Differential flocculation and settling rates of distinct clay mineral groups, which would highly influence the clay mineral distribution, are discussed by Whitehouse et al. (1960), and Gibbs (1977), but it seems that in nature these processes are not very effective (Hillier, 1995). According to Chamley (1989) there is a general tendency for smectite to remain suspended longer than other clay minerals. Wide areas of the North Sea bottom are covered with sands with generally small amounts of fine-grained particles, which allow a clay mineralogical analysis to be carried out. The sands of the North Sea are to a large extent a relict of the Pleistocene, but the surface itself is in the northern part covered by a several cm- to dm-thick veneer of fine-grained Holocene sands (Jansen, 1976). Holocene sands are also widespread in the south (Oele and Schüttenhelm, 1979). Besides the sandy areas, muddy sediments are also present in the Skagerrak, the Norwegian Channel, the Devil's Hole and the mud area of the inner German Bight (Eisma, 1981) where the <2-μm fraction reaches values up to 60%.

2. Samples

Two sets of sediment samples were used in the present study. One set comes from the North Sea bottom surface (mainly the upper 20 cm), the other from the Pleistocene sediment cores and coastal areas. The first set generally represents the present sedimentary environment of the North Sea. Altogether 500 surface samples have been investigated (Fig. 1). These samples were taken during various scientific programs and only a small number were collected for the present investigations (Zöllmer and Irion, 1996). Therefore the distribution of the samples over the area is somewhat heterogeneous. There is a dense grid of sampling stations in the German Bight but in the area off the Norwegian coast there are great distances between the stations (Fig. 2). The grain-size variation is very high (see Section 4, first paragraph).

The second set of sediment samples was collected from the east coast of Great Britain and from the lower sections of the Elbe, Weser, Ems, and Rhine rivers and their estuaries. From the Pleistocene, only Middle to Late Pleistocene sediments, starting with the Elsterian, are considered in this study (53 samples). The samples originate from cores taken under the 'Southern North Sea Project', and by the Geological Surveys of Schleswig Holstein and of Lower Saxony.

3. Methods

Different grain-sizes of the samples were obtained by means of settling tubes. According to Stokes' law the fractions of <2 μm, 2–6 μm, 6–20 μm of equivalent spherical diameter (e.s.d.) were separated. Fractions >20 μm were separated by sieves. From the <2-μm fraction (clay fraction), X-ray diffraction (XRD) diagrams were produced in order to determine the clay mineral distribution in the samples. The analyses were done by means of smear slides in which the clay minerals are oriented along their leaf-like surfaces. This orientation emphasises the

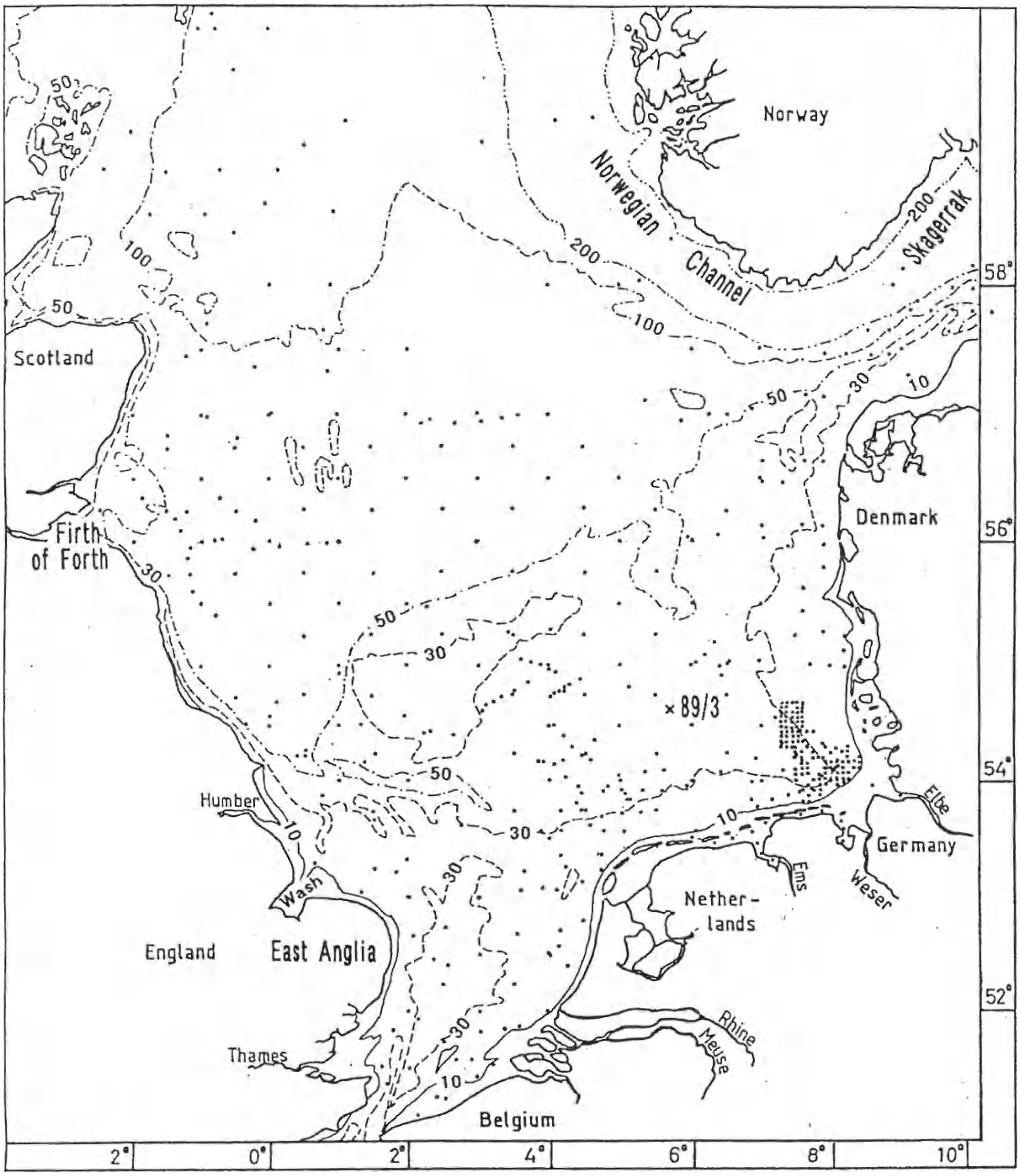

Fig. 1. Sampling stations for North Sea surface sediments.

lattice distances in the crystallographic c-direction which is the main characteristic of clay minerals. Since almost all samples are mixtures from various sources, only the four common main groups of clay minerals, smectite, illite, kaolinite and chlorite, could be distinguished but no clay minerals of rare occurrence. In order to obtain a standard condition for cation fixation and for a better recognition of the minerals the <2-μm fraction was treated with Mg-acetate, K-acetate and with vapour of ethylene glycol (EG) at 80°C. The X-ray analyses were done using a Philips PW 1729 diffractometer. The semi-quantitative analyses followed principally those used by Biscaye (1965). He weighted the peak areas in the XRD pattern with different factors. The peak area of smectite is multiplied by 1 and that of illite by 4. As

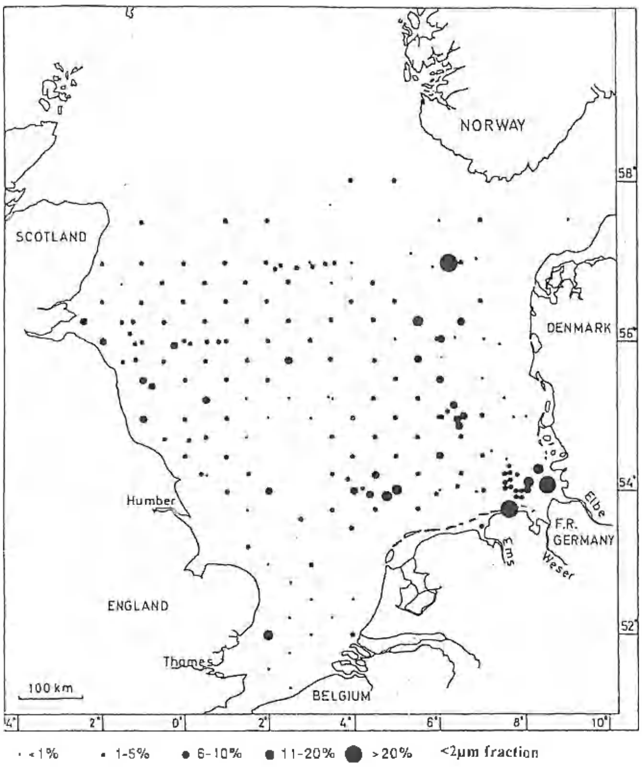

Fig. 2. The content of <2-µm fraction in 226 samples from North Sea bottom.

a follow-up of our own analyses of a test series of a chlorite-rich sample from Buntsandstein (Röt) of Helgoland and a pure kaolinite sample from an Amazonian river, we modified the kaolinite and chlorite factors of Biscaye (1965). We used the factor 1.7 for both minerals multiplied by a factor depending on the heights of the 002 kaolinite peak and the 004 chlorite peak (Zöllmer and Irion, 1996). Data for the four groups of clay minerals were taken together as 100%. In most of the samples, these four groups provide much more than 50% of the <2 µm fraction. The rest is formed predominantly by quartz, feldspar, calcite and some minerals with a minor distribution.

4. Results

The large variety in the grain-size distribution in the investigated North Sea surface sediments confirms the findings by Eisma (1981). In some samples, there are less than 0.1% of the <2-µm fraction, but in the inner German Bight, the <2-µm fraction contributes up to 60%. The average content of the <2-µm fraction is about 4% as calculated from 226 selected samples relatively uniformly distributed in the North Sea south of 58°N (Fig. 2).

Table 1
Statistic parameters of the clay mineral content of surface sediments of the North Sea

	North Sea surface samples			
	Average (%)	Std. dev. (%)	Min. (%)	Max. (%)
Smectite	27	8.6	5	53
Illite	51	5.9	34	67
Kaolinite	10	2.8	2	23
Chlorite	12	2.6	3	19

4.1. Distribution of clay minerals in the North Sea surface sediments

There is a large variation in the contents of the four different clay mineral groups of the North Sea surface sediments (Table 1). The distribution of the individual mineral groups is as follows.

4.1.1. Smectite

Most of the smectites of the North Sea sediments are characterised by high lattice charges. When treated with K^+-solution the basal spacing reduces to 10 Å. The smectite content in the analysed samples varies between 5% and 53% (Table 1). For differentiation, in Fig. 3 the following four categories have been selected: <20%, 20–30%, 30–40% and >40% smectite in the total clay mineral content in the <2-µm fraction. Smectite contents with less than 20% are found in the northwestern North Sea and along the east coast of Great Britain. Almost half (43%) of the samples belong to the category of 20–30% smectite. Sediments of this category are present in the central area and large parts of the southern North Sea. These sediments were found in the Skagerrak and in the Norwegian Channel as well. Smectite contents of 30–40% are distributed together with those of more than 40% along the coast of East Anglia and the southern and eastern North Sea coasts.

4.1.2. Illite

The illite distribution in the North Sea (Fig. 4) is characterised by relatively small differences vary-

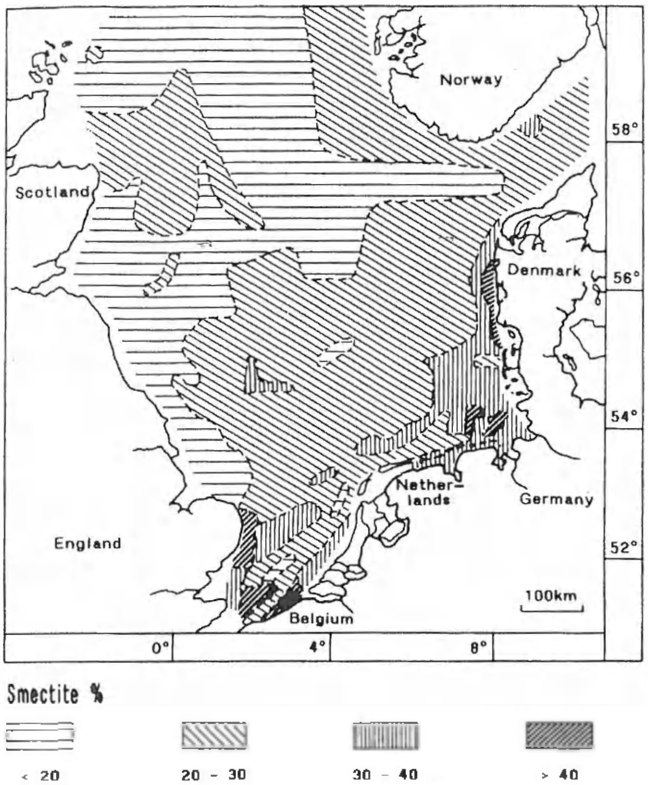

Fig. 3. Smectite percentage of the clay mineral content in the <2-μm fraction of North Sea surface sediments.

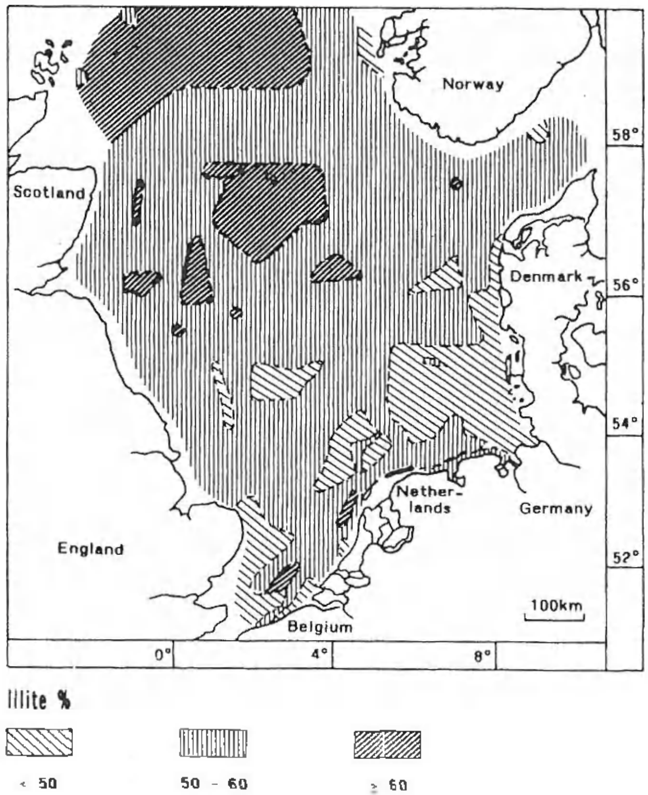

Fig. 4. Illite percentage of the clay mineral content in the <2-μm fraction of North Sea surface sediments.

ing between 34% and 67%. Therefore, only three categories were differentiated: those of <50%, of 50–60% and of >60%. Illite contents of <50% are found in the south and southeastern parts of the investigation area, whereas contents of >60% are concentrated in the very north and in some large areas between Scotland and the Skagerrak. Two areas of a high illite content are found south and north of the mouth of the river Rhine.

4.1.3. Kaolinite

Kaolinite content in the investigated samples ranges from 2% to 23% (Fig. 5). The concentrations were grouped as <10%, 10–12%, 13–15% and >15%. In spite of this small variation, a well-differentiated picture of the kaolinite distribution in North Sea sediments was obtained. Low content (<10%) was found in the northwestern part of the investigated area and along the southern and eastern North Sea coasts. The area in between is characterised by higher kaolinite contents of predominantly 10–12%. Highest values are found along the east coast of Great Britain and along a corridor running from southwest to northeast from East Anglia to the Skagerrak.

4.1.4. Chlorite

Chlorite contents range between 3 and 19%. The categories of <10%, 10–12%, 13–15%, and >15% are entered in the distribution map (Fig. 6). Low contents (<10%) were found only in the very south and in the German Bight, while further offshore northwards the contents were 10% to 12%, further increasing towards the east coast of Great Britain and in the northwestern half of the investigation area.

4.2. Coastal sediments

4.2.1. The east coast of Great Britain

In order to study the influence of coastal erosion, samples (61 in total) from outcrops (often cliffs), and from rivers and creeks, released into the North Sea between the Thames estuary and Scotland, have been analysed in detail. Between the Wash and Firth of Forth, the kaolinite content of Weichselian tillites and of older outcropping sediments (15 samples) is

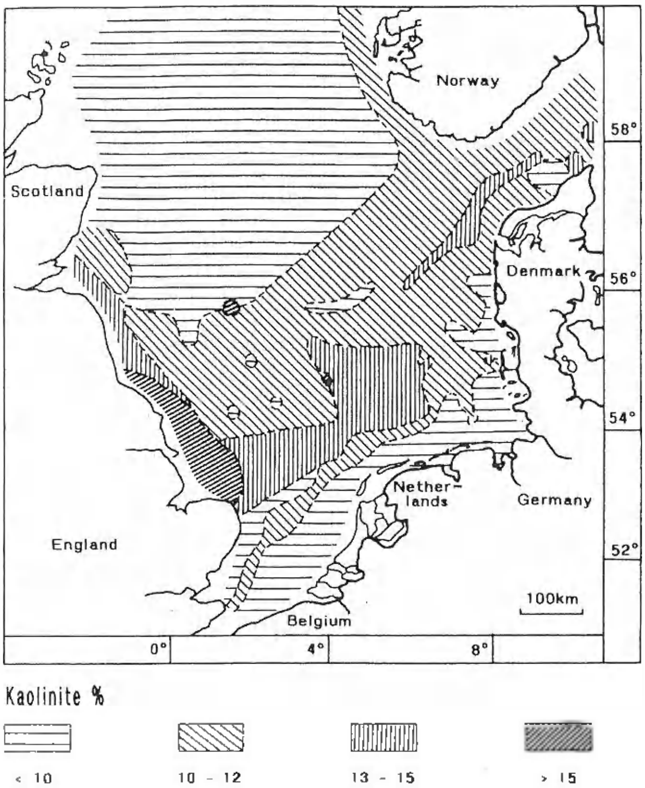

Fig. 5. Kaolinite percentage of the clay mineral content in the <2-μm fraction of North Sea surface sediments.

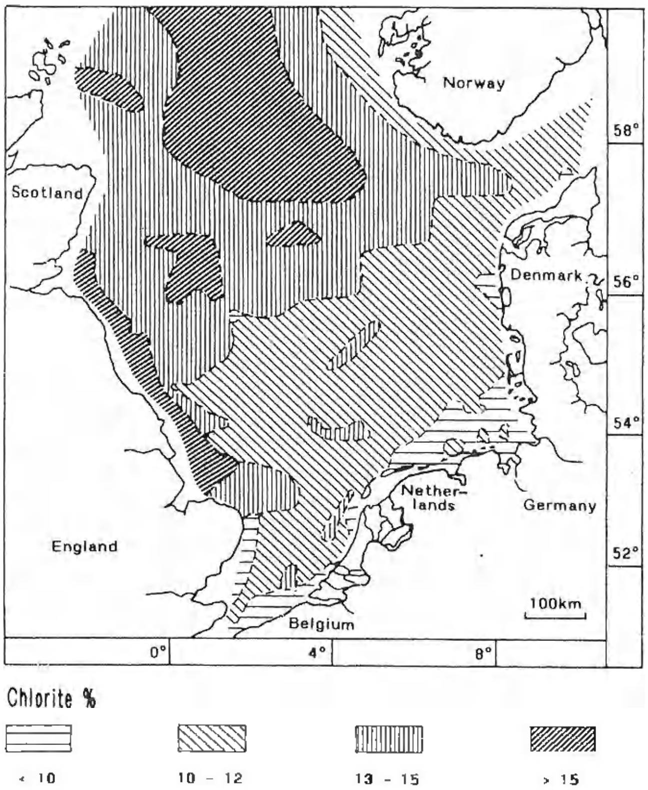

Fig. 6. Chlorite percentage of the clay mineral content in the <2-μm fraction of North Sea surface sediments.

29%; in the fluvial sediments, it is about 26%. These values are higher than the highest value of the North Sea surface sediments and more than 15% higher than the average value. The chlorite values are on average 14.8%, and, similarly to the kaolinite values, are to be classified as relatively high.

4.2.2. Rivers

Another potential source of sediments is the larger rivers entering the North Sea through estuaries on its south and southeastern coasts. Since estuarine processes are very complicated (Chamley, 1989; Eisma, 1993) it is difficult to estimate the input of river sediments to the sea. For rivers on the eastern coast of the USA, Meade (1969) showed that marine sediments can enter the estuaries in their entire length. Our analysis of clay mineral composition in bottom samples of the estuaries and the lower river sections of the Ems, Weser and Elbe rivers (Irion et al., 1987) shows the dominance of marine sediments in the estuaries of the Ems and Weser. This has been suggested also for the Elbe estuary by Müller and Förstner (1975), who analysed the heavy metal content of the estuarine sediments. Clay mineralogical studies of the landward section of the Elbe estuary by Ernst (1995) clearly show that marine and estuarine sediments enter the estuary as far as to the port of Hamburg, about 100 km away from its mouth. These studies suggest that large parts of the riverine sediments do not reach the North Sea, but there is no clear evidence about their fate. Estuaries formed during Flandrian transgression, over the last 6000 years, have been functioning as large sediment traps. Their capacity of sediment deposition is higher than the amount of sediments transported to the estuaries by the rivers during this period. Therefore the estuaries are predominantly regarded as net sedimentation areas.

4.2.3. Middle to Late Pleistocene deposits in the southeast corner of the North Sea

The ice masses of the Drenthe stage of the Saale glaciation were the last to reach the southern North Sea coast. During the transgressions of Eemian and Weichselian warm periods and during low sea-level stages there has been a far-reaching reworking and

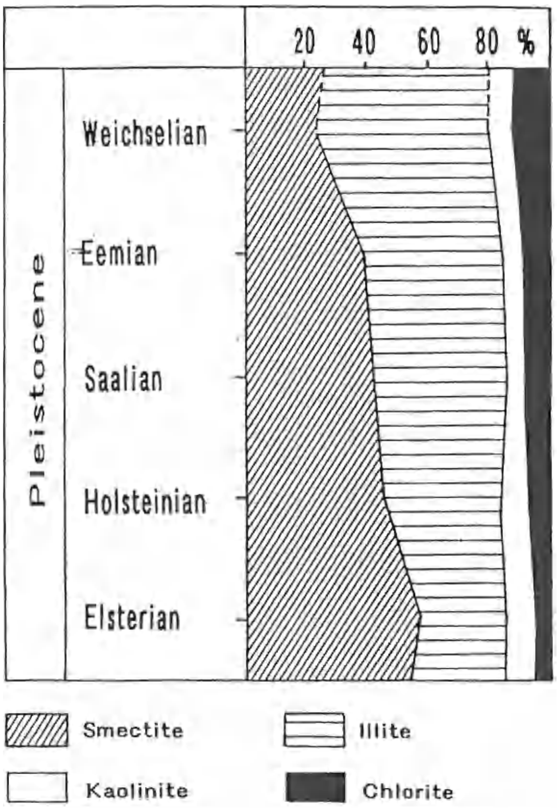

Fig. 7. Clay mineral content of the <2-μm fraction of Middle to Late Pleistocene sediments of northwestern Germany, with high content of smectite (56%) in the Elsterian, followed by decreasing contents in the Holsteinian, Saalian, Eemian, and Weichselian. In the same sequence the illite content is increasing from 29% to 57%, and chlorite from 6% to 12%, corresponding to their decreasing age.

depositioning of sediments in this area (e.g. Hoselmann and Streif, 1997) by which old glacial sediments, starting with the Lauenburger clay of Elstrian age, have been mixed with newly deposited material. This change is revealed by the clay mineral associations of sediments taken from the coastal plain south and east of the North Sea (12 profiles and samples from 15 locations of outcropping Pleistocene sediments) and by sediment cores taken during the North Sea Project (e.g. core 89/3, 5°45′E and 54°30′N). The results are summarised in Fig. 7. The Lauenburger clays are fine-grained sediments (about 30% clay fraction, 70% silt and a few percent fine sand), deposited in large lakes which developed in tunnel valleys of the Elsterian glaciation (Ehlers et al., 1984). The smectite content of the <2-μm fraction is constantly high. From the Elsterian to Weichselian, smectite content decreases from 56% in Elsterian, to 44% in Holsteinian, 41% in Saalian, 39% in Eemian and 23% in Weichselian time. In contrast, the illite content is increasing in this sequence from 29% to 57%, respectively. The composition of the Elsterian sediments is far from what would be expected from the glacial erosion of the Fennoscandian Shield (high illite and chlorite contents) where most of the glacial debris deposited in the North Sea area originates. The high smectite content may be explained by the fact that during the Elsterian the ice masses advanced for the first time into the southern North Sea basin. During this first advance a thick cover of strongly altered material probably formed a weathering crust in the warm climate of the Tertiary, and Tertiary secondary deposits may have been pushed away (Henning, 1976; Buchardt, 1978; Störr et al., 1978; Irion, 1983; Peuraniemi and Pulkkinen, 1993).

5. Discussion and conclusions

The clay mineralogical analyses of the surface sediments of the North Sea show a high heterogeneity in the distribution of the individual clay mineral groups of smectite, illite, kaolinite, and chlorite. The heterogeneity is mainly explained by the various sedimentological processes which occurred from the Middle Pleistocene to the present day.

Large ice masses carried illite- and chlorite-rich tillites during Pleistocene cold periods from the north into the North Sea basin. This material originated from the Fennoscandian Shield and was deposited in the entire basin during the first two great glaciations, the Elster and the Saale, whereas during the Weichsel only the northern part was covered by ice masses (Streif, 1990). Therefore the concentrations of illite and chlorite are higher in the north. The role of the sediment input from the North Atlantic is very difficult to assess. McManus and Prandle (1997) estimate its sediment delivery at 41.7×10^6 t y^{-1}. Chamley (1975) found high illite and chlorite contents in a sediment core from the North Atlantic. This is in agreement with the mineralogy of the northern North Sea, but Johnson and Elkins (1979) determined lower chlorite and higher smectite contents north of the Shetland Islands than in the area south of these islands. From these results it seems unlikely that the North Atlantic is an effective source of sediments for the North Sea. The same conclusions were drawn by Eisma (1973) and Eisma and Kalf (1987).

The composition of the mud in the Skagerrak and in the Norwegian Channel differs greatly from the other regions of the northern North Sea. Due to its great water depth this region acts as a sediment trap (Van Weering, 1981; Müller and Irion, 1984) and their lower chlorite and higher smectite and kaolinite values can be explained by sediment input from the south and from the Baltic Sea (Rosenquist, 1985)

On the west coast of the North Sea, the most striking phenomenon is the relatively high kaolinite content of the sediments. The kaolinite originates mainly from Weichselian tillites, formed from older sediments and from Tertiary soils. On the coast, there is an intensive cliff erosion (McCave, 1987) from which the kaolinite-rich material is delivered directly to the sea or, to a much lesser extent, may reach the sea through rivers or creeks draining these tillites. The cliff erosion takes place only during a high sea level. The distribution of kaolinite-rich sediments as shown above corresponds with the calculations of McManus and Prandle (1997), and with plumes shown by remote sensing (McManus and Prandle, 1997).

In the German Bight, smectite contributes high amounts to the sediments. This is partly explained by its origin in the Elsterian glaciation. The Elsterian was most probably the first glaciation covering large parts of the North Sea and adjacent regions. Hence, the Elsterian ice masses eroded the well-weathered surfaces and the secondary deposits formed during the tropical climate of the early Tertiary. The weathering products were clearly rich in smectite, as is the case in some tropical regions today, e.g. the southwestern Amazonian lowlands (Irion, 1984). As a consequence smectite is the main component of the <2-μm fraction of clays deposited in late Elsterian lakes (Lauenburger clay). This material was later mixed with illite- and chlorite-rich sediments from the north. In spite of that, the sediments in the southeastern corner of the North Sea remain fairly rich in smectite.

Our studies demonstrate that at present the suspended load of river contributes only small amounts of sediments to the German Bight (Irion et al., 1987). But older sediments of the Elbe, deposited when the sea level was lower, may still be very common and may be reworked into the surface sediments. At present, the sediment load of the Rhine river that reaches the sea is low (Salomons et al., 1975; Van Alphen, 1990; McManus and Prandle, 1997).

It is difficult to estimate the contribution of sediments transported from the Strait of Dover into the southern North Sea. The high smectite values are believed to be the result of the erosion of the smectite-rich Cretaceous formations of the Strait of Dover. Salomons et al. (1975) reached the same conclusion. Van Alphen (1990) estimated the amount of sediments to be 17×10^6 t y^{-1}, whereas McManus and Prandle (1997) calculated 44×10^6 t y^{-1} to be released from the Strait of Dover.

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