THE NORTH SEA AND NORTHEASTERN BERING SEA: A COMPARATIVE STUDY OF THE OCCURRENCE AND GEOMETRY OF SAND BODIES OF TWO SHALLOW EPICONTINENTAL SHELVES[1]

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ABSTRACT

Nio, S.D. & C.H. Nelson 1982 The North Sea and northeastern Bering Sea: a comparative study of the occurrence and geometry of sand bodies of two shallow epicontinental shelves.
In: C.H. Nelson & S.D. Nio (eds): The northeastern Bering shelf: new perspectives of epicontinental shelf processes and depositional products – Geol. Mijnbouw 61: 105-114.

The present-day shallow marine basins can be subdivided into marginal and epicontinental shelf areas. The occurrence, geometry and formation of large sand bodies in the southern bight of the North Sea and the Chirikov Basin in the northeastern Bering Sea are discussed here. The North Sea is mainly used as an example for reconstructing a sedimentation model. The large sand bodies which occur in the two basins consist of a lower sequence of sand banks and an upper sequence of stacked sand waves. The geometry and arrangement of the different lithotypes are not only controlled by the latest sea level rise, but also by the basin geometry. Peripheric basins, such as the southern bight of the North Sea show a concentric aggradational pattern; semi-peripheric basins, such as the Chirikov Basin, show an onlap pattern.
    Based on data from the North Sea and partly from the Chirikov Basin a hypothetical stratigraphic cross section is constructed which can be used for interpreting ancient analogues.

INTRODUCTION

Research on sedimentation in shallow seas has been widespread during the last decade. Part of this research focussed on marginal shelf systems, where nearshore and open ocean processes play an important role (see e.g. SWIFT ET AL., 1970; MILLIMAN ET AL., 1972; SWIFT ET AL., 1972; HOLLISTER, 1973; SCHLEE, 1973; SHERIDAN ET AL., 1974). Another subject of research is the study of sedimentation patterns in epicontinental constricted shelf regions, such as the North Sea (see e.g. NIO ET AL., 1981) and the northeastern Bering Sea (SHARMA, 1979; HOOD & CALDER, 1981; NELSON & NIO, 1982, this volume). Among the present-day shallow shelf seas and their sedimentary deposits two major types can be distinguished (SHAW, 1964; HECKEL, 1972):

1. Marginal shelf seas, adjacent to the open ocean and separated from this by active of passive continental margins.

In such seas open ocean processes have a free access.

2. Epicontinental shelf seas, which are bounded by a large landmass forming a nearly peripheric coastal boundary. Open oceanic processes are of less importance.

In the application of data from studies of modern shelf processes and the relevant sediments to fossil analogues no attention is being paid to the different character of the two above-mentioned types. However, clear differences exist, and in the analysis of fossil examples these should be made allowance for. Some important differences are:

a. The preservation potential of epicontinental shelf sequences will relatively be much higher. Active continental margin processes are likely to destroy large parts of the sequences built up in adjacent shelf areas.

b. Vertical and horizontal displacements of watermasses because of tidal action is rather limited in the open ocean and adjacent marginal shelf areas. In constricted epicontinental shelves, however, factors such as resonance of the basin, the presence of different amphidromic points may be of major importance and affect tidal ranges, character, and distribution of sedimentary facies.
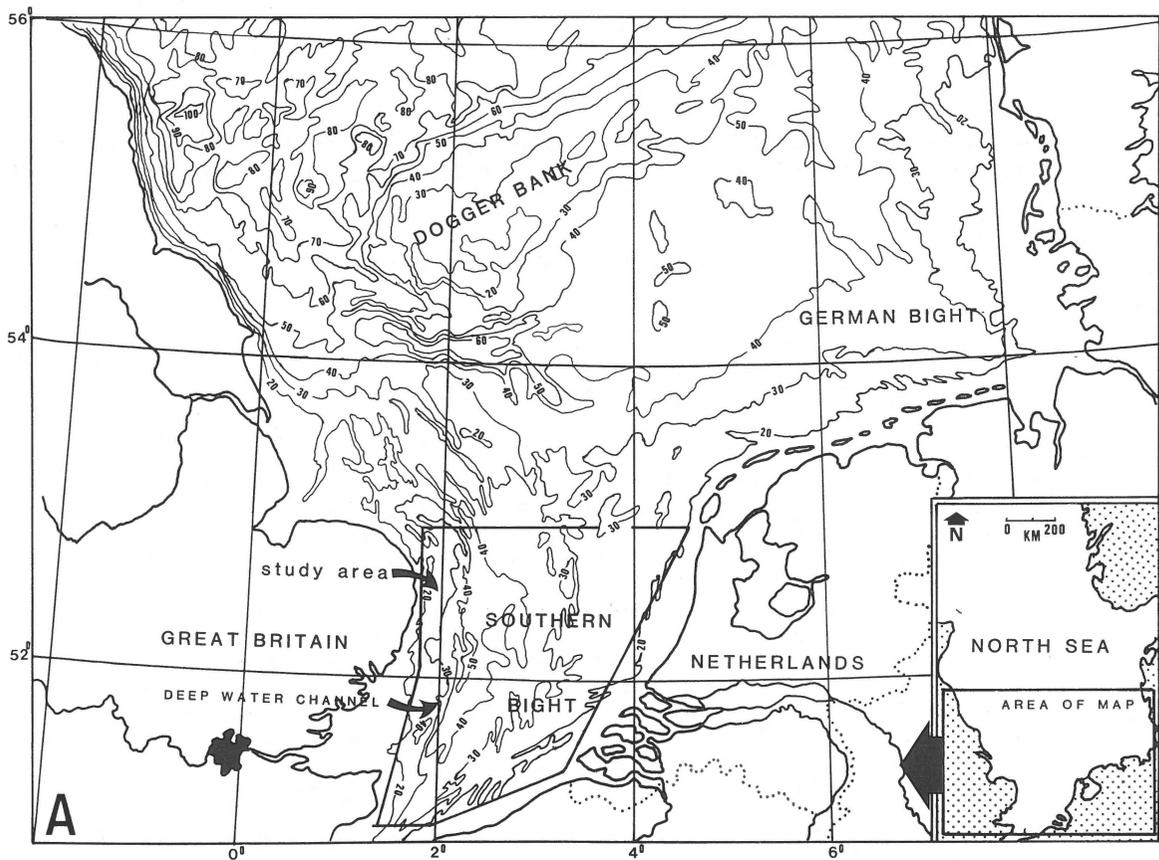
Fig. 1A
Bathymetry of the southern part of the North Sea and location of the study area (based upon Deutsches Hydrographisches Institut und Fischereikarte der Nordsee).

c. The sediment input in constricted epicontinental shelves through the coastal boundary is less dispersed, and is more likely to be trapped. Sediment bypassing may play a more important role in marginal shelves.

A decade of intensive research in the North Sea and recent work on the northeastern Bering shelf allow us to compare some striking aspects of the two basins, such as the distribution of very large sand bodies and their geometry. These sand bodies generally consist of a linear arrangement of large sand banks (see e.g. KENYON ET AL., 1981) and are often associated with larger and smaller sand waves. The presence of these sand bodies within the two basins and their formation are probably strongly related to a rise in sea level during the Late Pleistocene in the northeastern Bering shelf and during the Holocene in the North Sea, respectively. Present-day marine processes may cause some modifications or migration of these largescale bedforms. A large amount of data is available from the southern bight of the North Sea. It is because of this fact that the occurrence of large sand bodies within the southern bight of the North Sea will be discussed most extensively and compared with analoguous sand bodies in the Chirikov Basin of the northeastern Bering Sea. We do not deal extensively with present-day depositional processes, but will focus on the

geological significance of the occurrence and geometry of such sand bodies. To this end we shall discuss a hypothetical stratigraphic cross section.

SETTING OF THE TWO AREAS

This paper is confined to the study of large sand bodies in the southern bight of the North Sea and the area west of Seward Peninsula in the Chirikov basin (Fig. 1).

a. Geologic setting

The southern bight of the North Sea is apparently a region of 'palimpsests' sediments, which reflects mainly erosional events during the Late Pleistocene and both erosional and depositional events during the Holocene. The present-day distribution of sand is strongly related to the post-Pleistocene flooding of some 942.000 km^2 of the north-west European shelf (see BANNER, 1979). Within the Holocene sequence of the southern North Sea several transgressive periods can be recognized (JELGERSMA, 1961; HAGEMAN, 1969). The flooding of the southern bight started during the Preboreal some 10.000 years ago with the formation of the Lower Peat.
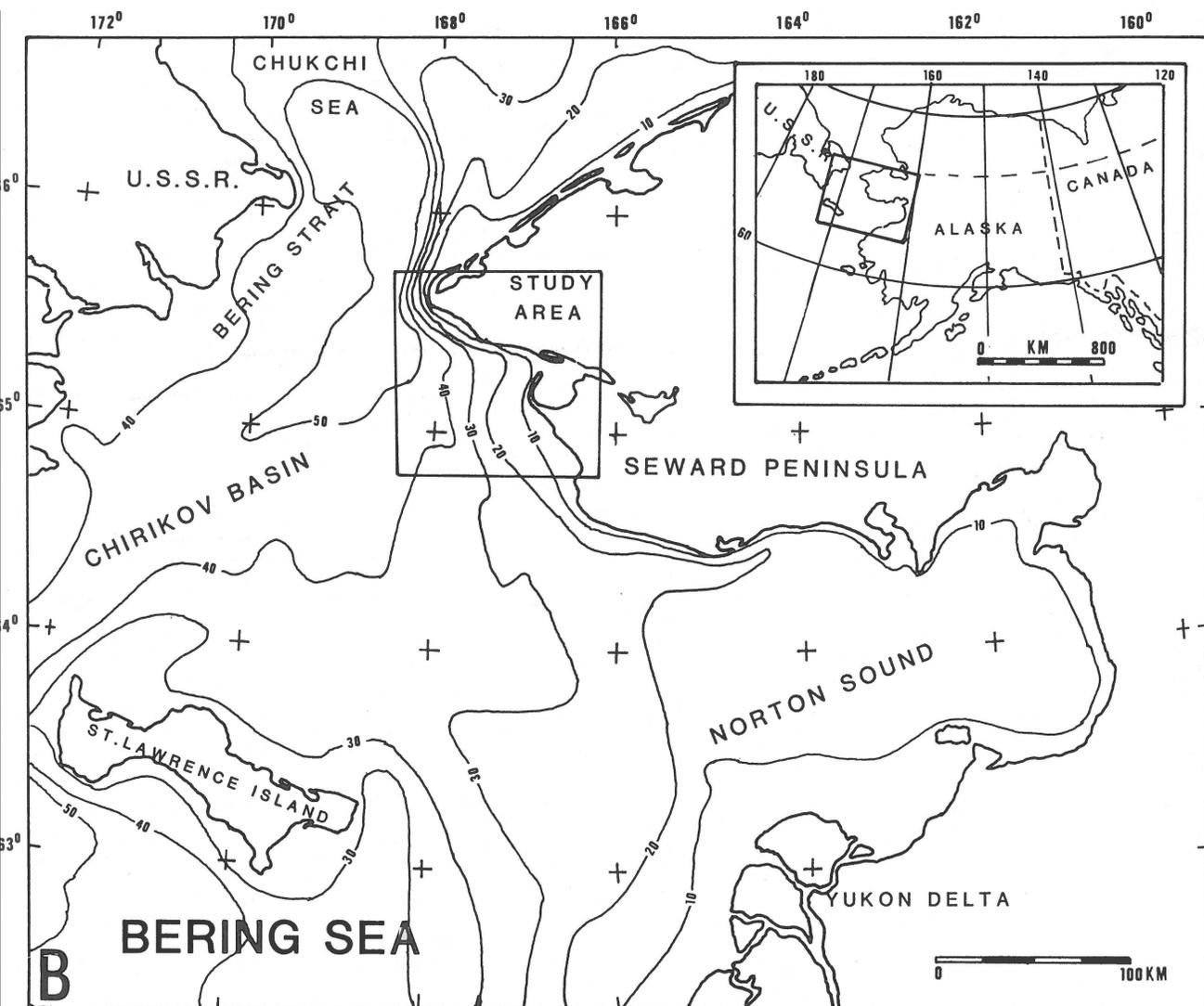
Fig. 1B
Bathymetric chart of the northeastern Bering shelf and location of the study area.

Continuous flooding of the area was responsible for the formation of extensive tidal flats in this part of the basin during the Boreal (8000-7000 B.P.; EISMA ET AL., 1981).

The most important sand bodies in the southern bight occur in the Calais deposits (formed between 7500 and 5000 years B.P.) and in the Dunkirk deposits (formed from 2000 years B.P. until now). The Calais sands are restricted to the coastal areas of the Netherlands and are mostly derived from older coastal barrier complexes (OELE, 1971; JELGERSMA ET AL., 1979).

Formation of the large sand banks, such as the Zeeland Ridges, the Sandettie, South Falls and North Hinder, probably took place during the Atlantic and Subatlantic (see e.g. LABAN & SCHÜTTENHELM, 1981). The continuous rise of sea level finally was responsible for the formation of the large sand waves (heights > 6 meters) and also for the degradation of these bedforms at a later stage (NIO, 1976). A thin veneer of several stacked sand wave sequences, which belongs to the

Dunkirk deposits, covers intermittently Pleistocene deposits. (see also OELE, 1971; CASTON 1979).

Most of the Quaternary sediments which unconformably overlie tectonically-deformed and truncated Tertiary sediments in the northeastern Bering Sea were deposited during the Late Pleistocene transgression (NELSON, 1982 this volume). The thin veneer of Late Pleistocene-Holocene sands intermittently covers the basal peat layer or older Tertiary rocks.

The dominant present-day source of sediment for the Chirikov Basin is the Yukon River. A larger part of the basin, however, consists of 'palimpsests' sediments comparable to those of the North Sea (NELSON, 1982 this volume).

b. Bathymetry

Depths within the southern bight of the North Sea are in general shallow and do not exceed 40 meters (Fig. 1A). An
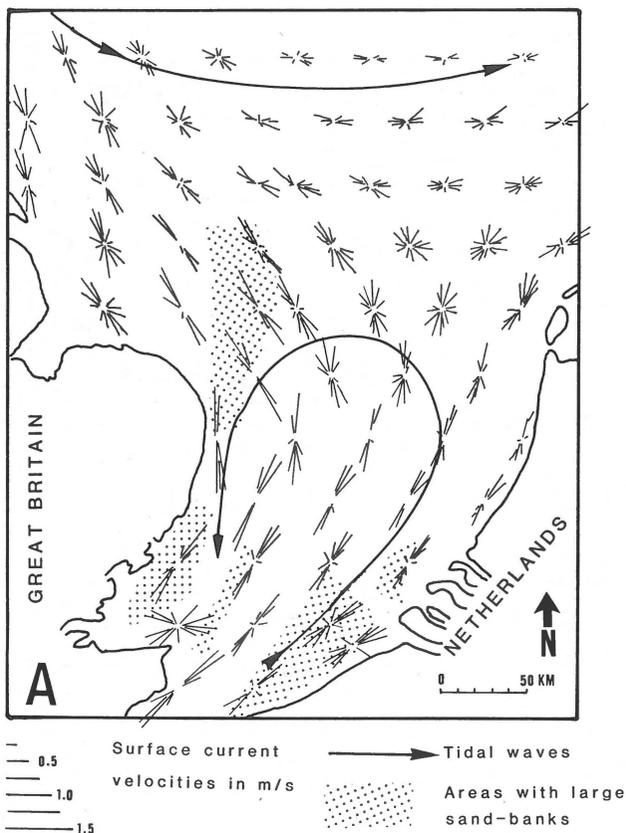
Fig. 2A
Path of the tidal waves in the southern bight of the North Sea with direction and tidal current velocities at the surface, measured at one hour intervals during one cycle (after Houbolt, 1968).

exception is the Deep Water Channel along the southwest coast of England where the depth exceeds 50 meters. The bathymetric conditions within the depocenter area vary between 0 and 40 meters. Depths increase gradually towards the north and reach 50 meters just south of the Dogger Bank.

In the Chirikov Basin similar bathymetric conditions exist around the area west of Seward Peninsula (Fig. 1B). Here also a gradual depth increase is observed from 10 meters near the western coast of Seward Peninsula to a depth of 50 meters in the middle of the Chirikov Basin. South of St Lawrence Island the shelf deepens to the Bering Sea basin; towards the north the basin narrows to 75 km in the Bering Strait, which connects it to the Chukchi Sea. Where the large sand bodies occur the depths vary between 20 and 40 meters.

c. Hydrodynamic conditions

The North Sea is a tidally influenced basin where a complex current pattern is produced by the interference of three tidal waves. The southern bight, however, is only influenced by two of these waves: one from the south which enters the North Sea through the English Channel and another which passes

along the Scottish coast and the Shetland Islands (Fig. 2A). The interference of these two tidal waves brings about a complex pattern of the net sand transport. Sand transport directions within the southern bight of the North Sea are to the NE and the SW (Fig. 2B), and the highly sinuous bed load parting runs more or less NW-SE across the basin (KENYON ET AL., 1981). Surface current velocities are in general moderate and do normally not exceed 80-100 cm/s. Current measurements during calm weather conditions at 0,5 meters above the sediment interface show values between 50-80 cm/s (TERWINDT, 1971). During storms, however, much higher velocities occur (MORTON, 1981). With an average grainsize distribution of 210-420 μ, this means that a net sand transport does occur during the peak velocities of the tide or during storm periods (TERWINDT, 1971; KENYON ET AL., 1981; MORTON, 1981). Another important feature is the amphidromic character of the tidal waves which makes a pure bipolarity of the tidal currents improbable. Due to this character the water masses are moving continuously, thus preventing the settling of mud.

Hydrodynamic conditions in the Chirikov Basin are completely different. Currents induced by atmospheric conditions seem to be more dominant than tidal currents. A steady northerly flow along the western coast of Seward Peninsula towards the Bering Strait is active throughout most of the year (Fig. 3). This flow is produced by a slope in sea level between the Pacific and Arctic basins (COACHMAN & AAGAARD, 1966; COACHMAN ET AL., 1975; FIELD ET AL., in prep.). The intensity of this northerly flow is strongly
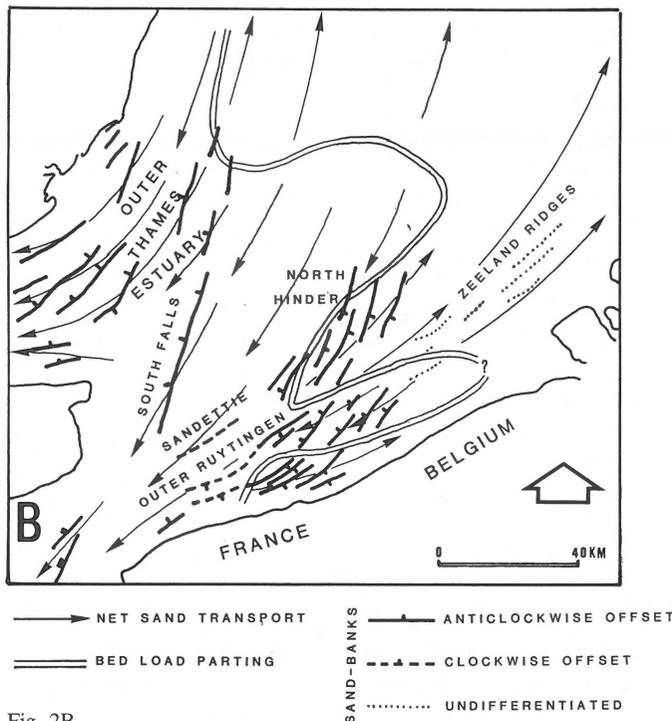

Fig. 2B
The distribution, orientation and net sand transport directions in the southern bight of the North Sea (after Johnson et al., 1981).
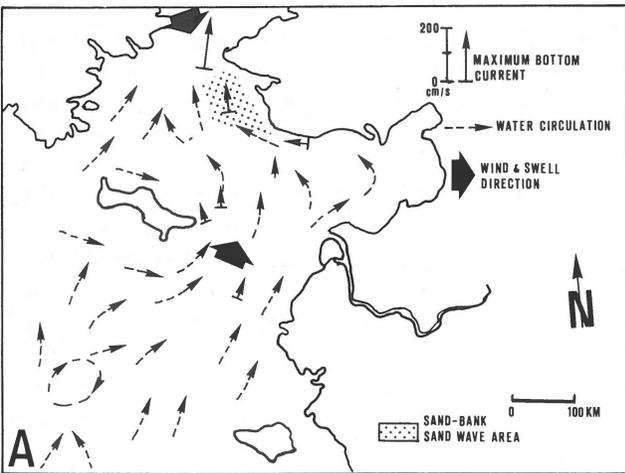
Fig. 3A
Schematic representation of circulation, maximum bottom current velocities and the influence of atmospheric pressure systems in the Norton Sound and Chirikov Basín (data compiled from Drake et al., 1980 and Field et al., in prep.).

influenced by the earlier mentioned atmospheric pressure systems and also by the winter ice cover. Winds from the north during winter storms for instance may temporarily diminish the velocity of the surface current and at times even retard the northward flow of water (COACHMAN & AAGAARD, 1966; FIELD ET AL., in prep.). Late summer storms on the contrary produce southern winds which will increase the northerly flow of surface water. Measured peak velocities during such periods range between 50-100 cm/s (MUENCH ET AL., 1978). Current measurements made at 1 meter above the sediment interface during a moderate storm in September 1977 for instance show a value of 30 cm/s (DRAKE ET AL., 1980).

Tidal currents may also influence the intensity of the northerly flow. In certain parts of the northeastern Bering shelf tidal currents are intense (PEARSON ET AL., 1980). The tidal action within the study area is in general weak as compared to the North Sea (see CACCHIONE & DRAKE, in press). Generally it appears that the modal as well as the maximum flow velocities are highest in the southern bight of the North Sea.
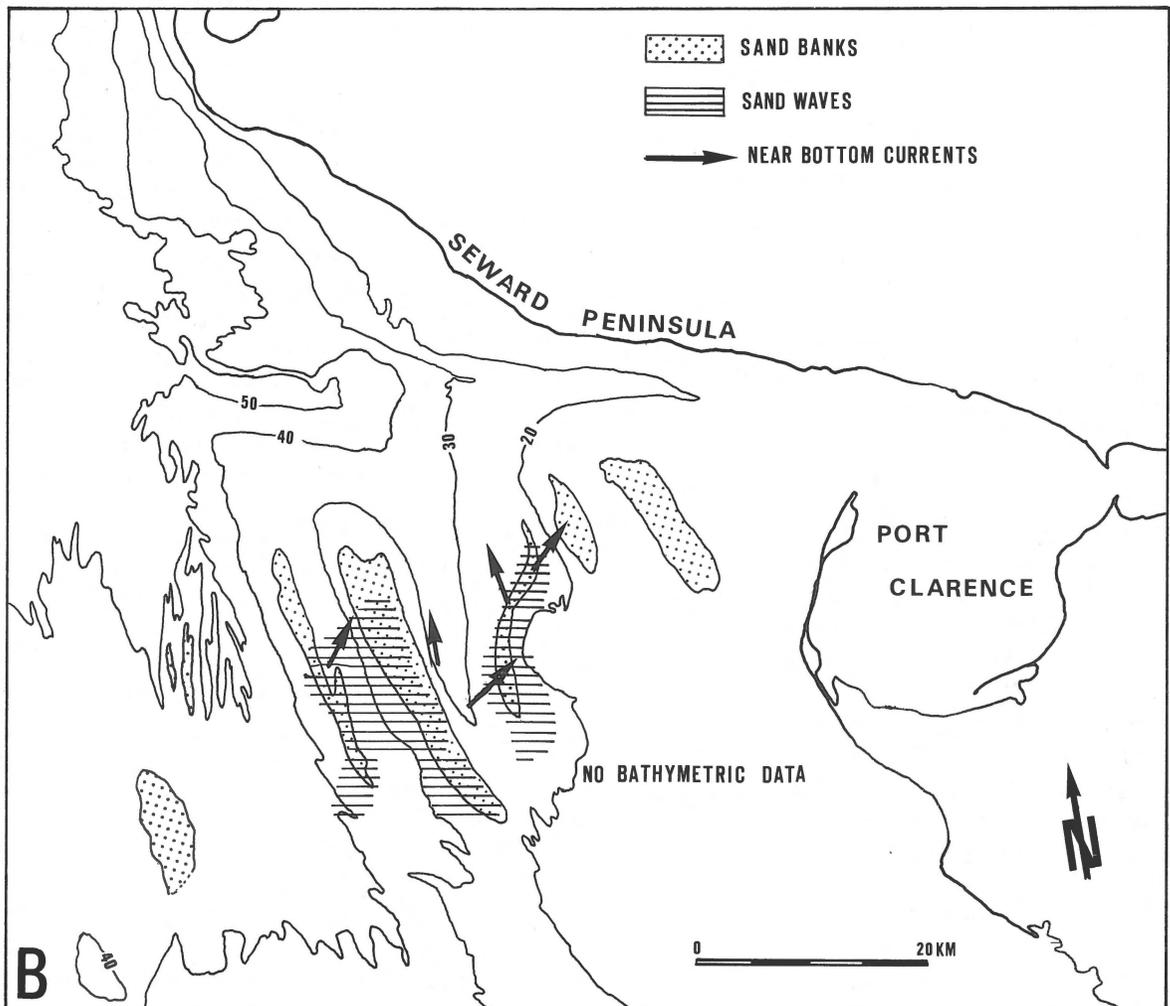

Fig. 3B
Location map of the sand banks and sand waves in the Chirikov Basin, northeastern Bering Sea.

THE SAND BODIES AND BEDFORM MORPHOLOGY

The sheet-like sand bodies consist of a complex upbuilding of two major bedforms. The classification of these bedforms is based on their dimensions, heights and wavelenghts.

1. The sand banks; these are by far the largest bedforms which occur in the two study areas. Formerly these bedforms were described as 'tidal current ridges' or 'sand ridges' (see e.g. HOUBOLT, 1968). The term 'sand banks' was used by e.g. CASTON (1972) and CASTON & STRIDE (1970). More recently KENYON ET AL., (1981) in his detailed studies of these features, formalized this term. In the respective study areas the dimension of these sand banks may reach up to 120 km in lenght and 30 km in width (KENYON ET AL., 1981). Furthermore one can distinguish two major types of tidal sand banks:
a. Sand banks with a V- or S-shaped crest, which seem to occur in the more shallow parts of the shelf or even in estuaries (CASTON & STRIDE, 1970; CASTON, 1972; KENYON ET AL., 1981). We will exclude this complex form of sand banks in our discussions.
b. Sand banks with more or less straight crests (KENYON ET AL., 1981).

Another important feature is the geometrical arrangement of these sand banks. KENYON ET AL. (1981) describe an anticlockwise or clockwise offset of the sand bank axis, which is ascribed to a different flow pattern.

Generally these sand banks are asymmetric and the steeper side is within the direction of the stronger flow (KENYON ET AL., (1981). Very little is known about the dip angles of the slopes of these banks. A reconstruction from SONIA records shows that the steeper slopes do not exceed an angle of 3° (Siegenthaler, pers. comm.).

2. The sand waves; these bedforms occur on the flanks as well as on the top of the sand banks. Furthermore they also occur within the depressions between two successive sand banks. Sand waves have been described extensively by many marine scientists (e.g. for the southern bight of the North Sea; VAN VEEN, 1938; STRIDE, 1963; HOUBOLT, 1968; MCCAVE, 1971; TERWINDT, 1971; CASTON & STRIDE, 1973 and more recently JOHNSON ET AL., 1981). Sand waves are more or less straight crested bedforms, whose wavelengths in general are at least 10 times as large as compared to their heights. Based on their heights one can distinguish three sizes of sand waves:
a. Large-scale sand waves which have heights larger than 6 meters and may reach heights of 15 meters.
b. Medium-scale sand waves whose heights range between 2 and 6 meters.
c. Small-scale sand waves which have heights less than 2 meters.

The tidal sand banks and especially the sand waves are concentrated in the lower part of the southern bight of the North Sea and show an intricate relationship. The orientation of the sand banks as well as the sand waves are more or less related to the regional current pattern. The sand bank axes are oblique to the regional flow (KENYON ET AL., 1981) and generally the crests of the asymmetric sand waves are transverse to the local tidal currents (STRIDE, 1970; TERWINDT, 1971). The distribution of the sand banks is restricted to the offshore region of western Belgium and southwestern Netherlands (Outer Ruytingen, North Hinder and the Zeeland Ridges) and within the Outer Thames Estuary (see Fig. 2B).

The occurrence of sand waves on the contrary is more widespread. An area with large sand waves with heights larger than 6 meters can be found north of the Zeeland Ridges and Hinder Banks (MCCAVE, 1971). This area appears as an oblong field with its axis more or less parallel to the axes of the sand banks. The size of the sand waves diminishes towards the north and only some patches are present in the offshore area of northern Netherlands.

A similar arrangement of sand banks and sand waves can be found in the Chirikov Basin off the south and southwestern coast of Seward Peninsula (Fig. 3B). The sand banks are 15-30 km long and 5 km wide (FIELD ET AL., in prep.). Their axes have a NNW orientation more or less parallel to the regional coastline. Measurements of the current directions show that the sand bank axes are oblique to the regional flow (Fig. 3B). The flanks and the adjacent troughs of the sand banks are covered by large and small sand waves.

Some important common features of the sand bodies in the two basins can be summarized as follows:
1. There is a lateral as well as a vertical superposition of large and small sand waves on the sand banks. Obviously the sand banks seem to have been formed at an earlier stage.
2. The axes of the sand banks are oblique to the regional flow. The crests of the sand waves, however, are transverse to the regional flow.
3. The arrangement of the sand bank axes is more or less parallel to the regional coastline.

GENESIS OF THE SAND BODIES AND ITS GEOLOGICAL IMPLICATIONS

The genesis of the sand banks as well as the sand waves was a matter of many discussions in the near past (e.g. STRIDE, 1963; HOUBOLT, 1968; TERWINDT 1971 and many others). Despite the large amount of unsolved problems and unknown features such as the internal structural organization of the sand banks and sand waves and the possible migration rates of these bedforms under present-day marine conditions, it is generally accepted that the sand banks and the large sand waves in the southern bight of the North Sea were formed at an early stage of the Holocene transgression (NIO, 1976; KENYON ET AL., 1981). Based on studies of modern and ancient analogues NIO

SAND WAVES

⊥ 1st generation
-⊥- 2nd generation
···⊥··· 3rd generation

NET SAND TRANSPORT

➡ initial system
▮ 2nd system
◁ 3rd system
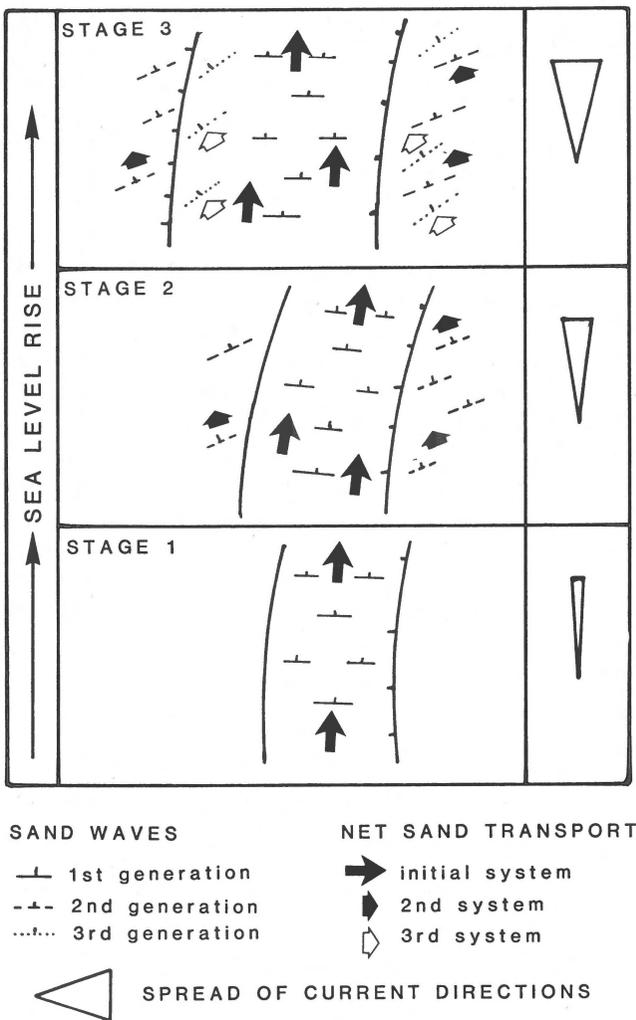
◁ SPREAD OF CURRENT DIRECTIONS

Fig. 4
A hypothetical reconstruction of the formation of sand banks and associated sand wave fields in a shallow epicontinental basin. The first generation sand waves are in general large; the second and third generations are medium- to small-scale sand waves. See text for further explanation.

(1976) proposed that the formation of these large bedforms is strongly related to marine transgressions.

The large sand waves were probably formed during the flooding of the extensive tidal flats during the Boreal and Atlantic between 8000 and 6000 years B.P. (NIO, 1976). Its initial formation probably took place in the large tidal channel systems of the flats. Also KENYON ET AL. (1981) described the existence of large numbers of sand banks which were probably formed at lower sealevels and are now considered to be moribund (see also LABAN & SCHÜTTENHELM, 1981).

A hypothetical scheme of the formation of sand banks and sand waves is given in figure 4. This reconstruction is mainly based on data from the southern bight of the North Sea. We are aware that still many questions and uncertainties exist.

STAGE 1: Initial flooding of extensive tidal flat areas, which were formed during the Preboreal and part of the Boreal some 8000-7000 years B.P. (EISMA ET AL., 1981). A continuous rise of the sea level caused a widening of the tidal channels. During this time large and wide tidal channels eventually developed into complete estuaria and existed together with large extensive shoals.

Intershoal channel processes and shoal processes similar to present-day conditions in the inshore tidal basins, interacted and this eventually resulted into the formation of large elongated levees (NIO ET AL., 1980). These levees have, similar to the sand banks, a steeper slope towards the channel axis and a more gentle slope towards the shoal. The lateral migration of the channels may produce an initial clockwise or anticlockwise offset. The offset of these submerged levees or sand banks and also its initial asymmetry are still influenced by present-day tidal processes (KENYON ET AL., 1981).

The aggradation of the sand banks probably occurred in several stages during the Holocene (LABAN & SCHÜTTENHELM, 1981). Also during this period large sand waves were formed in the large and wide tidal channels.

STAGE 2: The continuously rising sea-level drowned the previous system. The offset of the sand banks and especially the aggradation of the sand banks took place during this stage. At the same time smaller sand waves were formed at the flanks of these sand banks. The large sand waves in the now submerged tidal channels continued to grow.

STAGE 3: This stage represents the present-day conditions where some of the sand banks and sand waves still show a steady accretional pattern (JOHNSON ET AL., 1981; KENYON ET AL., 1981). A part of the large sand waves, moreover, shows a seasonal growth and migrational pattern. Others are decaying and are being modified by erosion (e.g. by storm waves and bioturbation; JOHNSON ET AL., 1981).

From the above discussion a distinct trend of development can be seen. The large bedforms, such as the sand banks and the large sand waves were formed during an early stage of sea-level rise; this is followed by a period where a consolidation and accretion of these bedforms occurred and finally a beginning of decay.

Another important aspect is the variability of current directions in relation to the sea level rise. During an early stage tidal currents were restricted to the channels and the elongated levees or intitial sand banks were probably parallel to the flow direction. With a higher sea level the tidal currents tend to have a wider spread and flow directions became oblique to the sand bank axes (c.f. HOUBOLT, 1968). Some preliminary studies of the sand waves off the Dutch coast show a similar variation. The crests of the large sand waves (heights more than 6 meters) are more or less perpendicular to the sand bank axes. These sand waves were formed in the large tidal channels during an early stage. Medium- and

small-scale sand waves, which are covering the flanks of the sand banks are oblique to the sand bank axes. These sand waves were formed during the second and third stage (see Fig. 4).

The formation of sand bodies in the Chirikov Basin can also be related to the Late Pleistocene transgression. It seems, however, that these sand bodies represent a later stage of development than those in the southern bight of the North Sea. Most of the sand banks are moribund and only the medium- and small-scale sand waves are in equilibrium with the present-day marine processes (FIELD ET AL., in prep.).

The presence of moribund sand banks and sand waves in the two basins offers good preservation possibilities in the geological record. The formation, distribution and arrangement of these sand bodies in the southern bight of the North Sea and in the Chirikov Basin show distinct similarities. In a hypothetical stratigraphic cross section, however, small differences in superposition might occur (Fig. 5). This is caused by the difference in geometry of the two basins. The southern bight of the North Sea is a nearly perfect peripheric basin; the Chirikov Basin on the contrary can be considered as a semiperipheric basin.

Figure 5 is a hypothetical stratigraphic cross section of a peripheric and semi-peripheric epicontinental basin and could serve as a model and base for further discussion. Three main units are differentiated:
Unit 1: A basal succession of tidal flat sediments, consisting of peat, clay and sand.
Unit 2: A lower sandy unit which is characterized by large scale low angle bedding. This sequence contains the sand bank complexes. The dip of the low angle bedding is generally

less than 3° and its lateral extent is several kilometers. The base of this unit is generally erosive.
Unit 3: An upper sandy unit which consist of a lateral and vertical succession of different sand wave generations. We assume that the internal structures consist of cosets of largescale crossbedding. This unit generally fills the local depressions and covers the former unit as a thin sheet.

A continuous sea level rise will diminish the net sand transport and sedimentation of fines will be dominant. Unit 3 will likely be covered by fine-grained muddy sediments in the final geological record. Observations on fossil sand wave complexes confirm this idea (NIO, 1976). The construction and upbuilding of the mega sequence is strongly influenced by a sea level rise. The arrangement of the different units within a peripheric basin is in general concentric (Fig. 5), which is the case for the southern bight of the North Sea.

In a semi-peripheric basin, however, an 'onlap' arrangement of the different units can be assumed. The last configuration can be applied to the Chirikov Basin in the northeastern Bering shelf.

CONCLUSIONS

Studies of large sand bodies in the southern bight of the North Sea and the Chirikov Basin in the northeastern Bering Sea show some similarities and also differences in their upbuilding and distribution pattern. The most important conclusions can be summarized as follows:

1. The large sand bodies in both basins consist of a succession of the following lithotypes:
a. A basal peat and tidal flat sequence, which mainly consists of a succession of peat layers and in the upper part an alternation of clay and sand beds.
b. A lower sandy sequence which mainly contains a lateral succession of different complexes of sand banks. This interval is characterized by a distinct low angle bedding.
c. An upper sandy sequence which covers the sand bank sequence like a veneer. The sequence consists of a lateral and vertical succession of different generations of sand waves.
2. The above-mentioned mega sequence has been formed during the transgressive periods of the Holocene (North Sea) and the Late Pleistocene (Chirikov Basin, northeastern Bering Sea). The different stages of sea level rise control the distribution of these large sand bodies within the basin with respect to depth. The lateral arrangement, however, depends on the basin geometry.
3. Peripheric epicontinental basins such as the southern bight of the North Sea show a concentric arrangement of the different lithotype units. Semi-peripheric basins like the Chirikov Basin, however, show an 'onlap' pattern of these units.
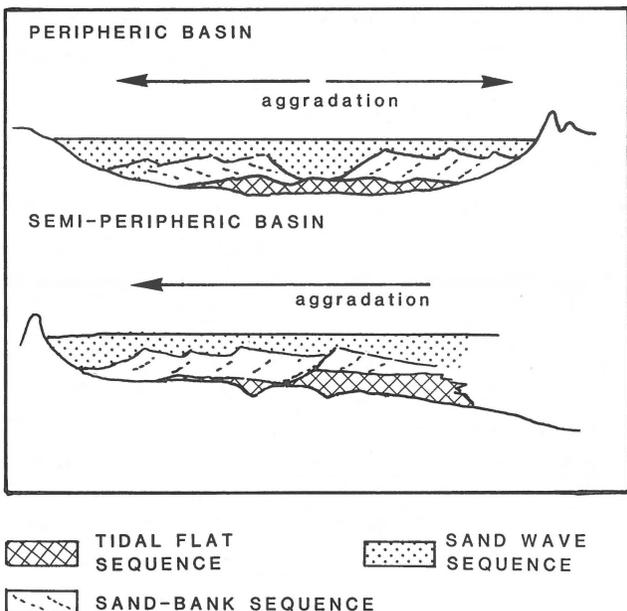

Fig. 5
A hypothetical stratigraphic cross section through a peripheric and a semi-peripheric epicontinental basin. See text for further explanation.

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