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Lithology and Subsidence in the North Sea

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Lithology and subsidence in the North Sea

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The North Sea sedimentary basin has developed on the northwestern margin of the European tectonic plate and contains an almost continuous record of epeirogenic marine and deltaic sedimentation from Carboniferous to Recent times. The subsidence required to accommodate the pile of sediment deposited, which in places exceeds 12 km, has been brought about at various times and in various places by differing geodynamical processes. As a result the types of sedimentary rocks deposited vary widely both in time and space, but the nature of the mechanism is reflected in the sedimentary type deposited.

The following broad generalizations can be made. The late Carboniferous was a period of deltaic sedimentation during which eustatic changes in sea level or local variations in subsidence rates are reflected in the typical Coal Measures swamp deposits. Late Carboniferous – early Permian times saw the silting up of this basin, and in an arid climate aeolian sands were deposited grading laterally to sabkha shales and evaporites. The Permian culminated in a series of widespread marine incursions during which repetitive evaporites were deposited.

Triassic times were marked by a period of major rifting and the deposition of thick sequences of continental clastics in the north, while widespread marine sedimentation persisted in southern areas. Jurassic times saw the re-establishment of marine to deltaic deposition in a series of basins possibly controlled in their distribution by the Triassic fault systems. Late Jurassic deposits were laid down in a sea whose bathymetry reflected the structure of the underlying horsts and grabens inherited from Triassic times, and towards the close of the Jurassic the bottom waters at least of this sea become increasingly stagnant. Sands deposited during the late Jurassic were deposited as near-shore marine bars, beach sands, and proximal and distal submarine fans.

Triassic to early Cretaceous deposition was concentrated in the areas now occupied by the main grabens of the North Sea, i.e. the Viking, Central and Moray – Witch Ground grabens. Subsequent deposition in late Cretaceous to Tertiary times took place in a more widely subsiding area, resulting in progressive onlap onto the surrounding basin margins. Deposition within this broadly subsiding and relatively unfaulted basin is characterized by chalky limestones in southern areas, giving way laterally to shales and minor sands to the north. During early Tertiary times a large delta was formed in the area beneath the present Moray Firth, and from this delta a supply of sand was fed into submarine fans to the northeast and southeast of the delta front.

Late Tertiary deposition is largely represented by a monotonous sequence of marine shales.

Introduction

The configuration and geological history of the North Sea Basin and adjacent areas has been well documented by various authors in the past few years, in particular P. A. Ziegler (1981), W. N. Ziegler (1975) and Kent (1980). Very detailed reports on various aspects of the North Sea with particular emphasis on the petroleum geology of the area have been published in the proceedings of the Institute of Petroleum's Bloomsbury Conference (Woodland (ed.) 1975), the Norwegian Petroleum Society's Mesozoic Northern North Sea Symposium (Finstad &

Selley (eds) 1977), and most recently the Institute of Petroleum's Lancaster Gate Conference (Illing & Hobson (eds) 1981).

As a result of these many papers, based as they are to a large extent on the vast amount of data held in the files of petroleum exploration companies and other institutions, the tectonic and lithostratigraphical framework of the North Sea is relatively well known. However, there are still quite large areas of the North Sea yet to be tested by the drill in which interpretation of the geology still depends on the imaginative interpretation of reconnaissance seismic data.

While the nature of the region's geological history is seemingly well understood the mechanisms that brought it about are less well known. An explanation of this mechanism is beyond the scope of this paper, which will attempt to highlight in a short, simplified form, as a starting point for the papers to follow, the relation that seems to exist between the types of subsidence that have occurred in the North Sea and the lithologies of the sediments that have filled the depressions created.

Structural setting

The North Sea Basin in its broadest sense is located on the northwestern margin of the Eurasian tectonic plate (figure 1). Before the break-up of the North Atlantic the area was bounded to the northeast by Fennoscandia, to the northwest by the Caledonides and to the

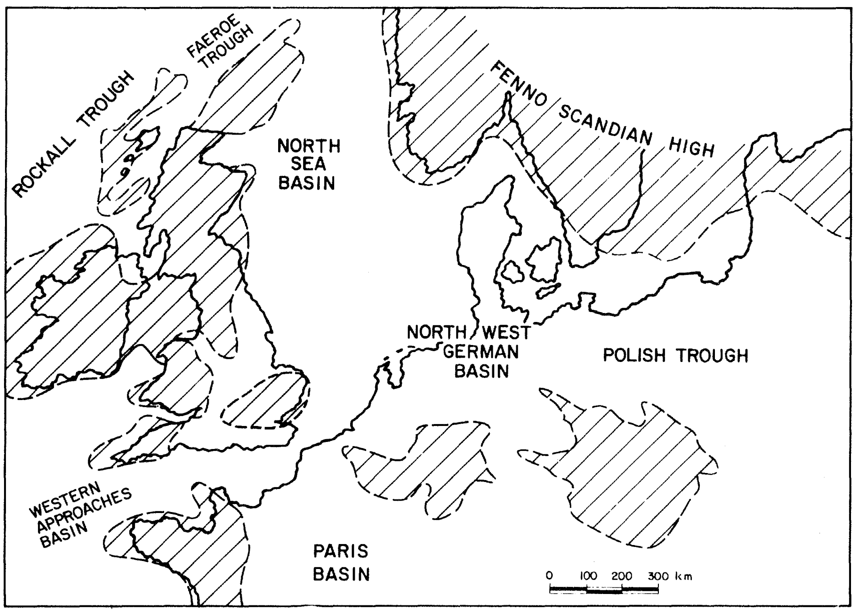

Figure 1. Location of the North Sea Basin showing the relative positions of major structural elements of northwest Europe.

south by various structural highs including the Brabant Massif, the Rhenish Massif and the Bohemian High. During the Carboniferous the area now underlying the southern North Sea subsided steadily in an epeirogenic downwarp. This relatively simple structural configuration appears to have persisted throughout the ensuing Permian period and to have created two east–west-oriented basins (figure 2).

During the Triassic, incipient opening of the North Atlantic was accompanied by the establishment within the northern North Sea region of a series of sharply defined rifts with a predominantly north–south orientation. Within the North Sea these comprise the Horn, Oslo, Central and Viking grabens (figure 2). Peripheral to this area a series of Triassic fault-controlled basins opened up to the northwest of Scotland (Steel 1977). These relatively narrow depocentres were thus established in a broad arc around the main southern North Sea Triassic basin, which continued the shallow synclinal pattern inherited from the Carboniferous to Permian periods.

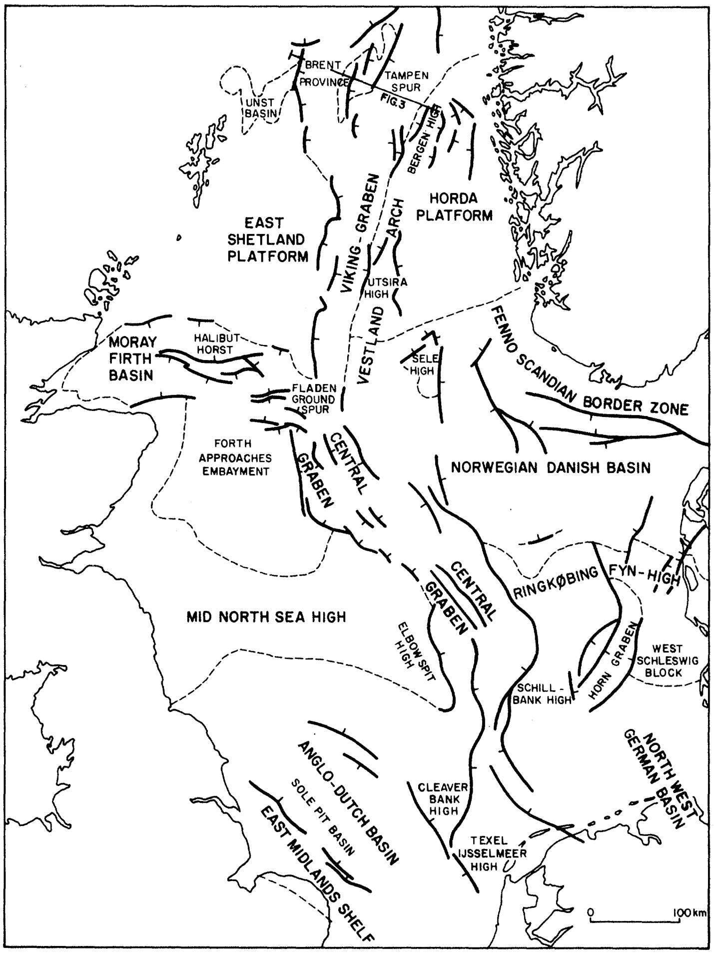

Figure 2. Tectonic elements map, North Sea, showing major fault trends and the location of the basin cross section.

In the Jurassic the rifting along the Viking, Central and Moray Firth grabens was firmly established and exerted a dominant control on the patterns of sedimentation in the area. Lower Jurassic sedimentation followed a similar pattern of the Triassic, i.e. a broad shallow synclinal area in the south contrasting with the narrow confined grabens existing to the north. A significant tectonic event occurred in the early Middle Jurassic when the area at the trilete junction of the North Sea grabens was domally uplifted, leading to the erosion of Lower Jurassic and some Triassic sediments (Ziegler 1981) and the outpouring of thick sequences of Jurassic volcanics (Howitt *et al.* 1975). The volcanism was concentrated in the area now underlying the Forties field, but volcanics are encountered as far west as the Piper field.

Subsidence continued during the Upper Jurassic and was concentrated along the old established rift system, but towards the end of the Jurassic, sea level changes had brought water levels sufficiently high to drown parts of the adjacent structural high areas.

Seismic sections across the northern part of the Viking Graben clearly show the nature of the horst and graben tectonics that have affected the region (figure 3). On the western side of the main graben the Jurassic sequence has been let down in a broad terrace that separates the western flank of the East Shetland Platform from the axial portion of the graben in which a very thick Cretaceous sequence is preserved. This terrace, the Brent Province, comprises at least three chains of horst blocks each containing a Triassic to Jurassic sequence which is tilted gently to the west with the bounding fault planes dipping steeply to the east. In contrast to what might have been expected, the more easterly chains, i.e. those closest to the axis of the main graben, are structurally the highest, reflecting perhaps earlier arching before rifting. Isopaching of the Lower, Middle and Upper Jurassic units within this Brent Province can be interpreted to show that the main Jurassic depocentre migrated westward with time.

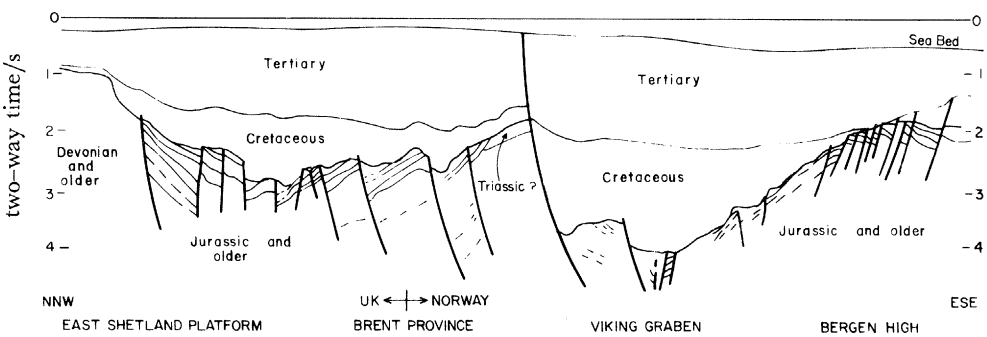

FIGURE 3. Schematic seismic profile of the northern North Sea (see figure 2 for location of section).

On the eastern flank of the Viking Graben, in Norwegian waters, the attitude of the pre-Cretaceous strata in the more centrally located fault blocks contrasts with that seen in the Brent Province. Here, the bounding faults dip steeply to the west and thus into the main graben, while the Jurassic strata within the blocks closest to the centre of the graben also dip westwards but at considerably smaller angle. The origin of this asymmetry in the Viking Graben is not fully understood, but it is tempting to speculate that the major subsidence along the edge of the Tampen Spur during the Cretaceous brought about a rotation of the Jurassic fault blocks on the eastern margin of the Viking Graben.

The Cretaceous was a period of widespread marine transgression, and the North Sea region is no exception. After filling in the irregularities still remaining on the Jurassic sea floor, Cretaceous deposition took place in a broad synclinal depression centred in the middle of the present North Sea. Few of the faults that controlled the Jurassic and earlier deposits were still active, and over a large part of the area the Cretaceous is unaffected by faulting. Salt tectonics in the southern North Sea locally had some effects on Cretaceous strata during their deposition.

The broad synclinal depositional trough established during the later Cretaceous continued throughout the Tertiary and is reflected in the present-day Tertiary isopachs. Seismic data clearly show that faulting, which had such important control of Triassic – Late Jurassic sedimentation, is not a feature of Late Cretaceous to Recent sedimentation and that subsidence since Early Cretaceous time has formed a broad synclinal flexure whose maximum points of subsidence have occurred in the areas overlying the older graben system.

Sclater & Christie (1980) published a very detailed analysis of the subsidence in the North Sea based on studies of well and seismic data from the Central Graben and incorporated in their study analysis of sediment backstripping, corrections for compaction, porosity–depth relations, thermal conductivities and palaeotemperatures. Their geological model for the post-Permian tectonic history of the Central Graben concluded, *inter alia*, that reinitiation of the Triassic graben system in the Middle Jurassic could have extended the underlying basement by 50–75 km. When the period of extension ended, thermal relaxation of the asthenosphere brought about general subsidence and the present-day synclinal downwarp was started. Seismic refraction studies in the Viking Graben and the Witch Ground Graben, together with gravity profiles (Donato & Tully 1981), suggest that crustal thinning has occurred beneath the main graben relative to the adjacent flanking areas.

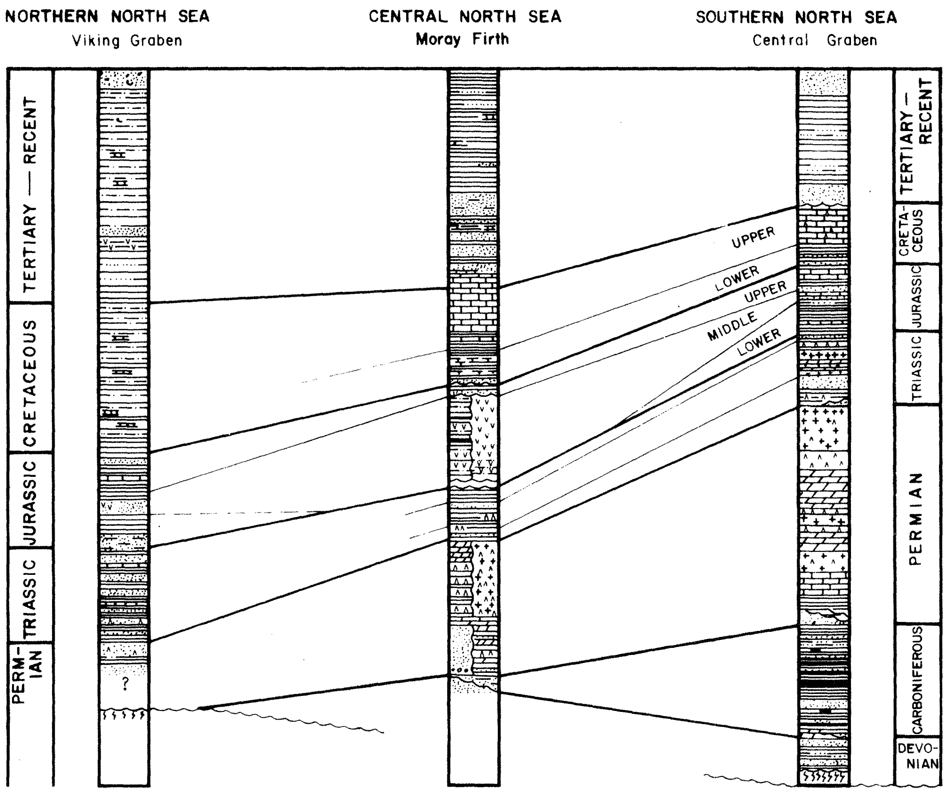

FIGURE 4. General stratigraphic summary of the North Sea Basin.

North sea lithologies

Carboniferous

The generalized stratigraphic columns for the North Sea are summarized in figure 4. It will suffice here to say that the main Carboniferous depocentre of the North Sea basin was located under the southern North Sea as a continuation of the Carboniferous basins of northwestern Europe and the English Midlands. Coal swamps were developed on delta plain sediments and it is these coals that were the source of the gas found in the overlying Rotliegendes (Eames 1975). Sedimentation obviously matched subsidence during this period, and probably minor fluctuations in sea levels were sufficient to allow periodic marine incursions.

Permian

Towards the end of the Carboniferous, more arid climatic conditions set in and the Permian sequence (figure 5) opens with the deposition of a thick sand–shale sequence best known from the southern North Sea and northwestern Europe. The sandstones of the Rotliegendes were largely deposited in an aeolian environment but locally have been reworked by subsequent marine transgression. In addition to the aeolian sands, the Rotliegendes contains sediments representing other typical desert facies such as wadis and sabkhas (van Veen 1975). The dune

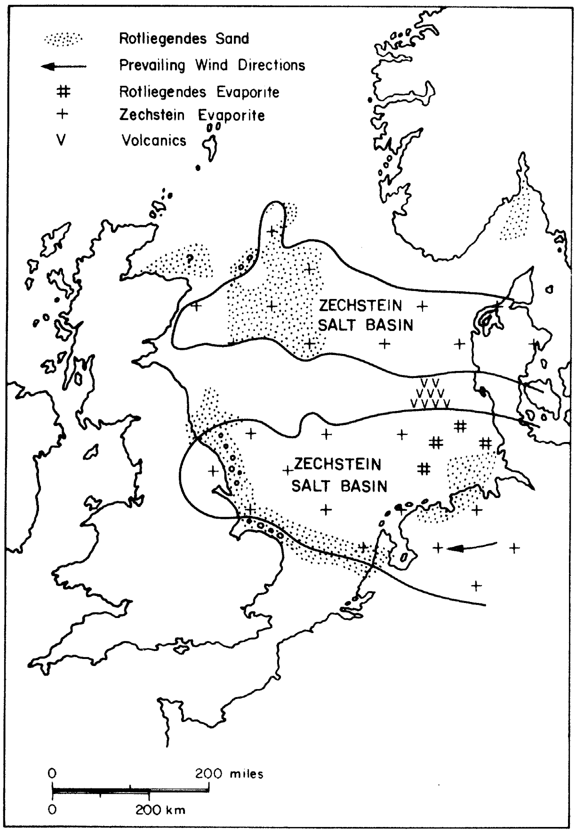

Figure 5. Map of Permian strata in the North Sea showing distribution of Rotliegendes sands and the Zechstein evaporitic basins.

sands, where preserved as such, show very good subaerial cross-bedding, and dipmeter studies of Rotliegendes wells have shown that the prevailing wind direction during the early Permian was from the east. An average of 300 m of sands were deposited along the southern margin of the Rotliegendes basin, while to the north of the aeolian sand belt, up to 1500 m of Rotliegendes was deposited in an evaporitic shaly facies adjacent to the Ringkobing–Fyn High. The concentration of coarse clastics along the southern flank of the basin and their virtual absence to the north indicates that the northern margin remained topographically subdued. Although the subsiding Rotliegendes basin appears to have been a relatively quiescent feature, some eruptive igneous activity did take place in the north Netherlands and German area.

Some coarse clastics of questionable Permian age have been recorded from beneath dated Zechstein strata in wells north of 56 °N, but there are insufficient well data to construct a

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satisfactory picture of Rotliegendes sedimentation in the more northerly Permian basin. The scant evidence indicates that aeolian sands similar to those of the southern basin were deposited (Jenkins & Twombley 1980).

Sedimentation later in the Permian produced a thick series of evaporites in two broad basins containing up to 2.5 km of sediments on either side of the Mid North Sea High. At times the high itself was submerged and was the locus of fringing carbonate sedimentation. Before the beginning of the Zechstein evaporitic cycles of sedimentation, the whole Permian basin was subjected to an anaerobic phase during which the Marl Slate or Kupferscheifer was deposited. Despite its thinness, often only 0.3–0.6 m thick, this laterally persistent marker unit can be found over a wide area of northwest Europe and the North Sea. It has a sharp boundary with the underlying sediments and in the north of England it can be seen to blanket the underlying Permian Yellow Sands even though they still preserve their original aeolian dune topography. These sands were probably not lithified before the deposition of the Marl Slate, which must have been deposited in an extremely quiet marine environment.

Taylor & Colter (1975) suggest that the first deposits of the Zechstein were laid down in a barred basin that was already well below contemporaneous world sea level before the invasion of sea waters. The interfingering and interbedding of the subsequent evaporitic and carbonate units of the Zechstein reflect the various stages of evaporite production on the margins of the basin as sea levels fluctuated and access to open waters opened and closed. The sediments thin both to the margin and to the basin centre, reflecting in one case a lack of space for deposition, and in the other a decrease in the amount of sedimentation because of increased water depth and lack of evaporation. Concentric to the basin, facies are uniform (Taylor & Colter 1975). This pattern and the uniformity of sedimentation within the Zechstein show that subsidence and sedimentation were balanced and that the basin subsided evenly across its entire area.

Triassic

The Triassic sediments of the North Sea (figure 6) mark the profound tectonic changes that accompanied the closing of the Palaeozoic in the region. In the southern North Sea sedimentation in the Triassic followed the broad synclinal downwarp pattern seen in the underlying Permo-Carboniferous and complete sequences of Triassic sediments, up to 2 km thick, were deposited and are locally preserved. Although subsequently affected by tectonism (halokinesis) and subdivided into several small basins, the pattern of sedimentation shows that the Triassic here comprised remarkably uniform sandstones, shales and evaporites. The whole sequence represents a broadly fining upward cycle (Brennand 1975). The distribution of evaporites in the basin shows a concentration towards the centre and is reminiscent of the pattern seen in the Rotliegendes.

In the central area of the North Sea only the Bunter Shale is preserved, since any younger sediments appear to have been stripped off during a period of Middle Jurassic erosion.

To the north of the southern North Sea basin a series of grabens were established during the Triassic. In contrast to the widely correlatable units of the gently flexured basin, the sedimentary infill of the Triassic grabens comprises very thick (up to 3.5 km) sequence of clastic sediments ranging from conglomerates to claystones (Brennand 1975). The Triassic basins described by Steel (1977) from northwest Scotland serve as a model for the totally unexposed North Sea grabens. In the Minch Basin, Steel showed that the basin fill consisted of thick fanglomerate wedges of sediment associated with fault scarps. As the fault scarps retreated – in this case

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westwards – up to 4 km of stratigraphical thickness of sediments were deposited. The basins were assymetrical half-grabens in which thick fanglomerates accumulated on the tectonically active side, while a thin condensed sequence was deposited on the opposite, flexured margin.

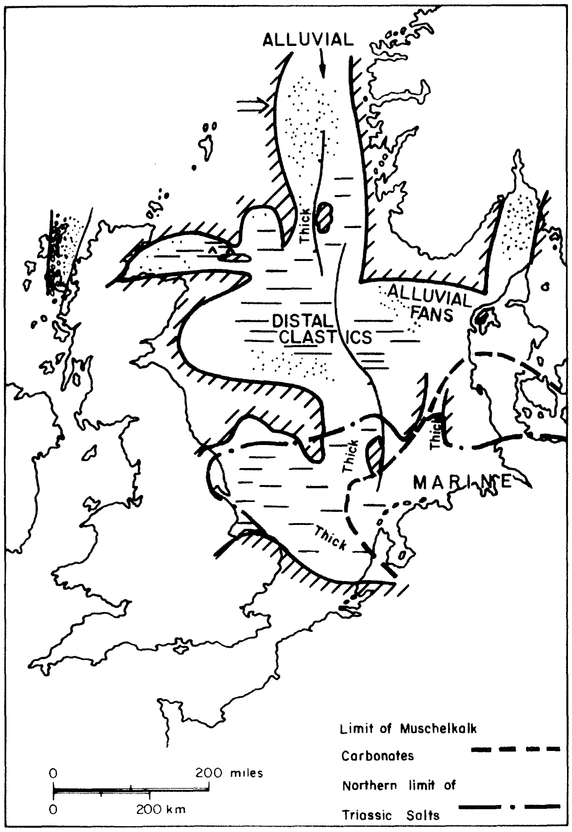

FIGURE 6. Distribution of Triassic strata in the North Sea and interpreted depositional environments.

Jurassic

Lower Jurassic deposition followed to some extent the pattern established during the Triassic, but part of the record has been lost in the central part of the North Sea through Middle Jurassic and later erosion (figure 7). In southern areas sedimentation continued in a quiet marine environment and locally gave rise to the formation of some 800 m of organic-rich shales in the Toarcian, which were subsequently to act as source rocks for small oil accumulations in the Netherlands (Bodenhausen & Ott 1981). In the northern North Sea, within the grabens formed earlier, the first Jurassic sandstones are conformable with and inseparable from the underlying Triassic.

The environment of deposition of the Statfjord Formation passed from continental alluvial to marginal marine as the graben continued to founder and as the seas encroached. The Dunlin Formation comprises prodeltaic mudstones deposited at the foot of the deltaic deposits of the Statfjord. The dominant source of sediments was still the active fault margins, but with the widening of the basin and the suppression of relief the overall clastic content is generally finer in a regional sense than in the Triassic section, and coarse fanglomerates are lacking.

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As noted earlier, the close of the early Jurassic appears to have been accompanied by a significant tectonic event in the central North Sea which brought about emergence and active volcanism in the area now occupied by the trilete junction of the North Sea graben system. Middle Jurassic sedimentation is concentrated in the Viking Graben, the Norwegian Danish Basin and the Moray Firth Basin (figure 8) where 600–800 m of sediments were deposited in

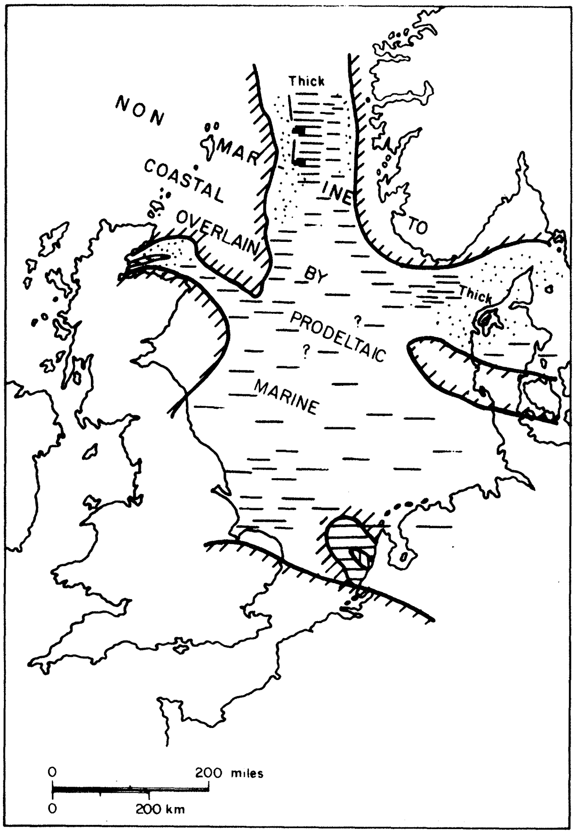

Figure 7. Reconstructed map of the distribution of Lower Jurassic strata in the North Sea and interpreted environments: Dunlin, Fjerritslev, Statfjord and Gassum Formations, and Lias Group.

each area. In all three areas marginal marine to deltaic environment dominated and sediments were once more confined to the faulted troughs. However, the margins no longer seem to have been the main source of sediment supply and there is evidence that much of the sand could have been derived – at least in the Viking Graben – from the central domal high described above. Middle Jurassic sands in the Brent area appear to have been derived in part from the south (Bowen 1975). Variations in thickness of the Middle Jurassic sands across the fault blocks of the Brent Province suggests that the seabed had some topography that affected their deposition, but the main depocentre had moved somewhat west of that of the Lower Jurassic.

The close of the Middle Jurassic was accompanied by a widespread marine incursion and a rapid deepening of the marine basin overlying the North Sea graben system. Within the Moray Firth embayment and the Central Graben the Upper Jurassic is marked by marginal marine sedimentation (figure 9), where about 800 m of coastal sands and shales were deposited in the proximal areas of the Moray Firth Basin. Elsewhere in the North Sea a wider variety of depositional régimes were established. In the areas bordering the Vestland Arch, sediments appear to be related to the marginal marine conditions, which were inherited from the Middle Jurassic and comprise offshore bars and various shallow water intratidal deposits. The Viking Graben itself was a deep-water basin filled mostly with the shales of the Heather and Kimmeridge Clay Formations. The seabed appears to have had significant relief and submarine highs were progressively overlapped by 500 m and more of late Jurassic sediments.

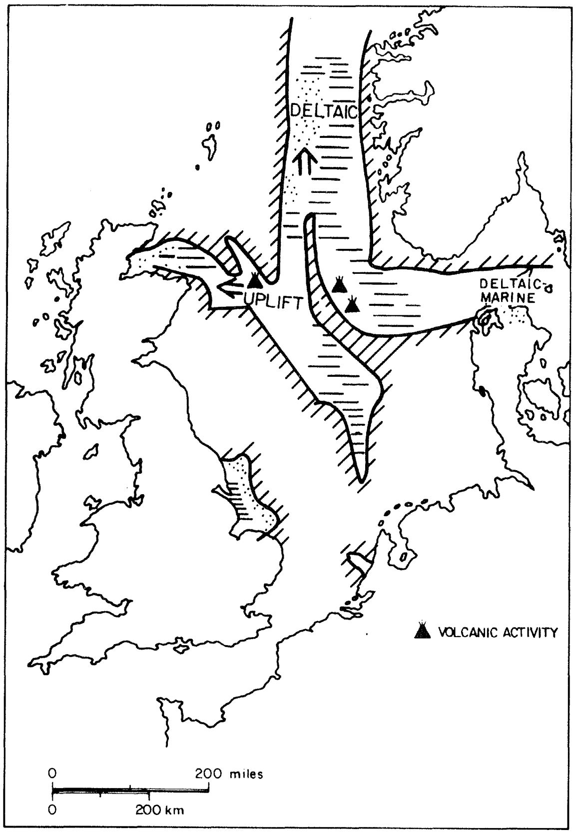

Figure 8. Middle Jurassic lithofacies map of the North Sea and interpreted depositional environments: Brent Group, West Sole Group, Haldager and Rattray Volcanics Formations.

Thicknesses, judged from seismic profiles, in the Upper Jurassic show that over 1 km was deposited in the Central Graben and in the axial portion of the Viking Graben. While the Upper Jurassic is predominantly a shale sequence, several commercially important sand units are developed in the Viking Graben. In the Magnus Field, Block 211/12, a sand unit within the Kimmeridge Clay formation, has been interpreted as a deep-water submarine fan derived from the East Shetland Platform to the west. With the considerable amount of core data available, De'ath & Schuyleman (1981) were able to show that the Magnus Sand represents the deposits of a middle fan environment and that Kimmeridge Clay was deposited contemporaneously in the outer fan régime. The inner fan deposits were subsequently eroded. The Magnus Sand can thus be interpreted as a sequence of submarine fan lobes derived from the East Shetland Platform, which lay some distance to the west.

The Brae Field, which also borders the East Shetland Platform and is located 280 km further south, where the Viking Graben was considerably narrower, is broadly contemporaneous with the Magnus Sand but presents an interesting contrast. The field is more closely associated with the edge of the graben and lateral changes within the Brae sand reservoir complex are more abrupt than in Magnus. Furthermore, a greater range of depositional environments is represented. The proximal, western portion of the complex is considered to be a subaerial fan delta that passes eastward into marine foresetted units (Harms *et al.* 1981). However, the subaerial origin of the Brae complex is not considered to be a unique explanation and a possible submarine origin not unlike that of Magnus is mentioned as a possibility by Harms *et al.* (1981).

FIGURE 9. Upper Jurassic lithofacies map of the North Sea and interpreted depositional environments: Kimmeridge Clay and Heather, Magnus, Brae and Piper Formations.

Cretaceous

The main period of faulting was completed by the beginning of the early Cretaceous. Some of the major bounding faults of the grabens persisted into and occasionally later than the Cretaceous but for the most part throughout the North Sea the Cretaceous was a time of prolonged synclinal basin subsidence with the maxima of subsidence located over the older graben system. The sedimentary environments blocked out in the late Jurassic persisted into the Cretaceous but water circulation and oxidation must have been more effective since the Cretaceous shales for the most part lack the high organic content of the Kimmeridge Clay formation.

Eustatic changes in sea level at the opening of the Cretaceous locally resulted in the spread of sedimentation beyond the limits of the earlier Jurassic. Despite evidence of periods of emergence in the North sea during the early Cretaceous, there is little development of sands associated with highs developed within the basin (figure 10). The greatest concentration of sands is in the Moray Firth embayment where a 1 km thick marginal marine to deltaic sequence exists that may pass laterally eastwards into pro-delta sands.

Some 0.8–1.0 km of the early Cretaceous deposits appear to have been laid down in a broadly synclinal depositional basin in which sandstones were concentrated along the basin edge but from which lobes of gravity-fed sand moved into the axial portions of the basin.

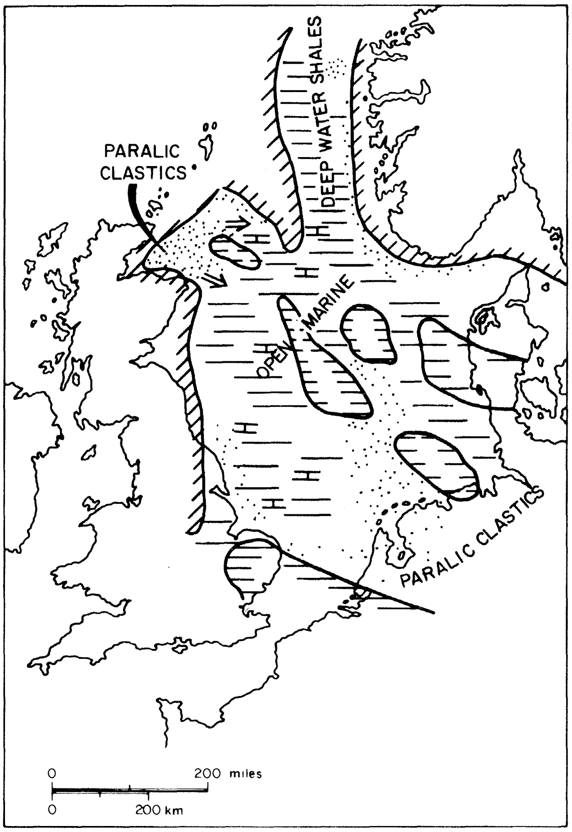

Figure 10. Lower Cretaceous lithofacies map of the North Sea and interpreted depositional environment: Valhall and Devils Hole Formations.

During the late Cretaceous (figure 11) widespread marine conditions were well established and resulted in the deposition of up to 1 km of chalky limestone in the central and southern North Sea. These pass laterally northwards into claystones and marls. Two very prominent troughs were created on either side of the Tampen Spur (figure 2) where very thick Cretaceous deposits (up to 2.5 km) are interpreted from seismic in the North Shetland Trough and the northern Viking Graben. Well evidence to date suggests that the Cretaceous in the northern areas is deficient in sand and it is difficult to explain the origin of the thick piles of monotonous claystones. The transition from chalky limestones in the south to claystones in the deeper waters to the north may be partly explained by subsidence in the northern areas taking the seabed below the carbonate compensation level.

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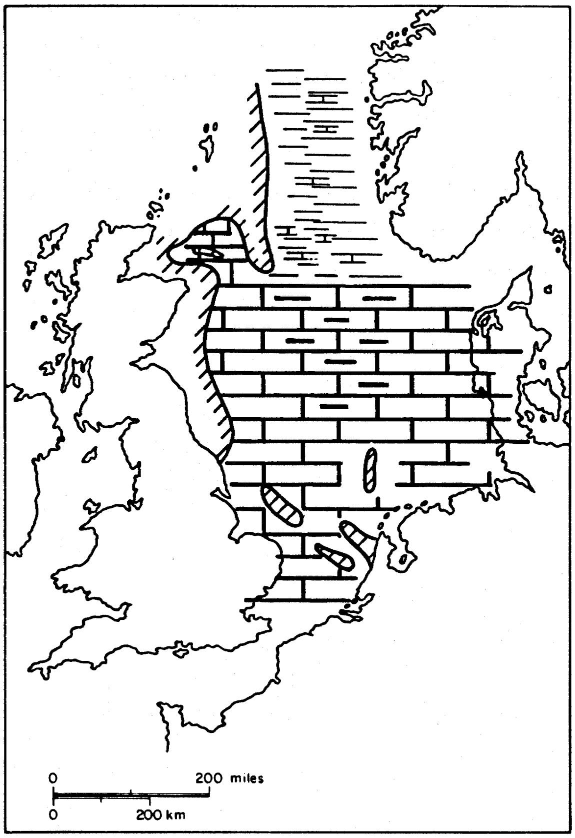

FIGURE 11. Upper Cretaceous – Danian lithofacies map of the North Sea: Shetland Group, Chalk Group, Ekofisk Formation.

Tertiary

During the Palaeogene, uplift of the area west of the northern North Sea Basin created a prominent easterly prograding in the Moray Firth delta (figure 12). This acted as a source of sediment supply to a series of deep-water turbiditic sands that were shed in a southeasterly direction into the axial portion of the North Sea Basin. Water depths ranged from near zero on the delta platform to several hundreds of metres in the axial portions (Parker 1975), and down these slopes a series of sand lobes were supplied with a constant supply of shallow-water sediments, including reworked marginal marine sands and terrestrial organic debris. These sands are best known from their occurrence in the Forties Field and adjacent areas.

A similar, but younger, sand sequence is to be found in the Frigg Field (Héritier *et al.* 1981) 250 km further north than Forties. Here an Eocene submarine fan was deposited on the sea floor of the central portion of the Viking Graben and the sands were derived from shelf sediments originally deposited on the edge of the Shetland Platform. In this aspect the two sand bodies differ, since there is no obvious delta build-up in the proximal portion of the Frigg complex. The Forties oil field is contained in a well defined anticlinal feature possibly caused by drape over the underlying Jurassic volcanic high. In contrast the relief at top sand level in Frigg, which gives the trapping mechanism, is very much an original bathymetric feature that has been subsequently enhanced by differential compaction of the surrounding marine shales (Héritier *et al.* 1981).

Since the Palaeocene the North Sea Tertiary basin has undergone a progressive subsidence in places of at least 2 km. The rate of subsidence is, however, subject to some controversy. According to Clarke (1973), evidence from well data suggests that the rate accelerated throughout the Tertiary, but Donato & Tully (1981) argue to the contrary that it decreased from Eocene to Miocene in the Viking Graben while in the Central Graben it remained constant. Sclater & Christie (1980) reached a similar conclusion to Clarke when plotting uncorrected data, but found on removing the effects of compaction that the rapid increase in deposition of the younger sediments was less pronounced.

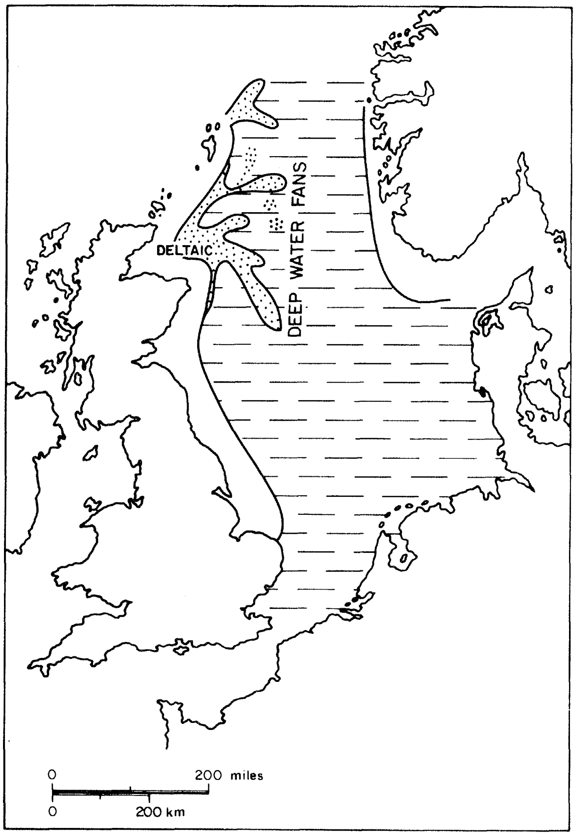

FIGURE 12. Palaeogene lithofacies of the North Sea and interpreted depositional environment of Forties and Frigg sands.

CONCLUSION

The North Sea Basin has subsided sufficiently since the pre-Carboniferous to accommodate a very thick, locally 12 km, sequence of sediments. The nature of the subsidence has varied in time and at differing places but essentially consisted of broad synclinal downwarping before the Triassic, a period of rifting in the Triassic to Jurassic, which may have been accompanied by a domal rise in the centre of the North Sea, and a final broad synclinal downwarp, which in effect has continued from late Jurassic to Recent. Within this structural régime the earlier synclinal phase was associated with deltaic clastics that gave way to an aeolian – evaporitic basin. There is some indication that initially the basin floor was substantially below existing worldwide sea levels.

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Rifting in more northerly areas initiated a period (Triassic) of continental fanglomerate deposition in narrow, steep-sided grabens. Widening of these grabens both by erosion and more widespread faulting allowed the deposition of less restricted sediments in deltaic to marine facies and culminated in the deposition of thick organic marine shales in a deep-sea basin of restricted circulation. Into this deep trough a system of submarine fans were able to build up a series of constructive sand lobes.

A second stage of synclinal downwarping (Upper Cretaceous and Tertiary) was associated initially with carbonate and shale deposition, but the basin morphology developed sufficient bathymetric relief to allow the formation of deltas and shelf-edge sands along its margins. These in turn were able to supply sediment to gravity-flow sand lobes in the axial portions of the basin.

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