# GEOLOGICAL PERSPECTIVES IN THE NORTH SEA AREA

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SORGENFREI, T.: Geological perspectives in the North Sea area. *Bull. geol. Soc. Denmark,* vol. 19, pp. 160–196. Copenhagen, september 11th, 1969.

The present publicly available knowledge of the geology and geophysics of the North Sea Basin is reviewed in order to demonstrate the great progress already achieved during the first six years of intensive offshore exploration for hydrocarbons.

Significant facts of the geology of the land areas bordering the North Sea have been compiled to a geological map. The map includes much simplified graphic logs of important boreholes and generalized formation columns for exposed areas. The sections are listed at the end of the paper together with references to the sources of information. The geological map is supplemented by other maps showing gravity anomalies, depths to the base of the Tertiary and the base of the Zechstein, and structural features respectively.

Light is thrown on the structural framework of the basin and the relations of structural development and sedimentation. With this starting point the regional stratigraphic and palaeogeographic aspects of the unknown areas are discussed. The geological systems are treated individually, and simple conclusions on regional features are drawn. A lithofacies study of the Lias illustrated by two maps demonstrate the state of dependence of Lower Jurassic sedimentation and regional structure.

Eventually the regional tectonics of the basin are discussed. It is believed that the distinct structural pattern formed by the dominance of specific types of salt structures in well defined areas is due to the effect of block faulting in the deep Precambrian basement. Both vertical and horizontal displacements are evidenced.

In the Skagerrak region the gravity anomalies suggest a westward extension of the Bohus Granite on the Swedish west coast and a southward extension of the Oslo Graben and its fill of Palaeozoic formations.

A valuable result of the current exploration activity of the oil industry in the North Sea, going on since 1962, is the steadily increasing amount of geological and geophysical data. This important scientific material, accumulating in the files of the oil industry, is gradually being released. A number of papers on the geology and the geophysical features of the North Sea have thus recently appeared.

It is now common knowledge that the exploration venture in the North Sea got its impetus from the discovery in 1959 of the giant gas field of Slochteren, near Groningen in the northern Netherlands. The Slochteren gas was found in a large uplift in a thick sandstone sequence of the Lower Permian Rotliegend formation which is capped by Upper Permian Zechstein salt. It is believed that the gas was formed by coalification of coal beds in the Carboniferous formations from where it migrated into the overlying Lower Permian sandstone (Patijn 1964).

The geological conditions at Slochteren have been determinative of North Sea exploration. The Rotliegend sandstone became the primary objective of the drilling programmes, and mapping of the top of the Rotliegend, or rather the base of the Zechstein, was the first challenge to the exploration seismologists. Possibilities of disentangling the geology of the North Sea on the basis of the exploration data have, therefore, largely been limited to the sequence above the base of the Permian.

However dominant the Rotliegend prospects might be as primary objectives, the secondary objectives of the Upper Permian Zechstein carbonate rocks and the sandstones and limestones of the Jurassic, the Lower Cretaceous, and the Tertiary ought also to be mentioned in this connection. Seismic mapping of reflection horizons in the sequence above the Rotliegend has accordingly been included in the exploration programmes (Cook 1965, Kent 1967a, Hornabrook 1967).

## Review of recent works on the geology and geophysics of the North Sea

The geophysical surveying of the North Sea started prior to the exploration activity. Colette (1958, 1960) published the first maps of regional Bouguer anomalies and offered a geological interpretation of the gravity features. On the basis of our present knowledge it is evident that Colette's maps reveal some of the major regional effects of the thick sedimentary sequence and the shallow Precambrian structures, as *e. g.* would appear from a comparison with the geological maps published by Heybroek *et al.* (1967, fig. 3, 6). Colette's conjectures regarding a SE branch of the Caledonian Chain and other interpretations seem, however, to be rather speculative. Supporting geological evidence is virtually meager.

In 1963, Bungenstock, Closs and Hinz gave a report on geophysical surveys in the southeastern part of the North Sea. Their geophysical maps clearly demonstrate the extension of the North German salt dome province over the southern part of the North Sea, thereby suggesting similar geological conditions in this part of the North Sea as on shore in northwestern Germany.

The first systematic geological mapping of the bottom of the North Sea was initiated by the University of Hull in 1963. In 1965, Donovan and Dingle were able to present a submarine geological map of a ca. 100 km wide near shore belt off NE England from 53°N to 55°25'N. The map shows the continuation of onshore formations and suggests regional and local structures off Flamborough Head of late or post Mesozoic age.

In 1966, O. B. Andersen published a gravity survey of the Skagerrak. O. B. Andersen gives no geological interpretation of the mapped area. It is remarkable how well the Bouguer anomalies match with those on shore in northern Jutland and southern Norway (Sorgenfrei & Buch 1964, Smithson 1963). In a general way, the Bouguer map of the Skagerrak suggests the continuation of the sedimentary cover of northern Jutland almost until the shores of Norway. An interesting feature is the local gravity maximum off Kristiansand at 7°53'E, 57°52'N which probably is caused by a volcanic plug. The potential plug may be of Permian or Tertiary age. The increase of thickness of the ash seams of the Lower Eocene of Denmark and northern Germany from S to N are suggestive of a source N of Jutland (S. A. Andersen 1935). It is therefore quite reasonable to assume that the gravity maximum off Kristiansand might indicate an Eocene volcano.

Geological and geophysical results brought about by the exploration activity have been dealt with by various authors.

The experience gained during geophysical surveys were commented on by Cook in 1965. From the evidence of previous gravity surveys and the general results of unpublished seismic work, Cook concludes that there are three sedimentary basins in the North Sea area: The Northwest German Zechstein Basin, the British North Sea Basin and the Norwegian North Sea Basin. The quality of seismic record sections is shown, and the operative problems of seismic mapping in the North Sea are discussed.

The two main reflectors in the British Basin are the base of the Upper Cretaceous and the Upper Magnesian Limestone in the middle part of the Upper Permian evaporite sequence which corresponds to the German Zechstein. The basal Permian has been difficult to map due to the deterioration of the reflections under rock salt areas. The effect of salt flowage and salt diapirs on the thickness of overlying Mesozoic and Tertiary formations is finally emphasized.

Three important papers on the geology of the North Sea were published by scientists of the oil industry in 1967. These are the papers by Kent on the geology of the southern North Sea Basin, by Heybroek, Haanstra and Erdman on the geology of the entire North Sea area, and by Hornabrook on seismic interpretation problems, particularly in the West Sole gas field.

The papers by Kent, and Heybroek *et al.* are instructive outlines of the geology of the North Sea based on a large amount of unpublished geophysical and geological data. Hornabrook's paper is a demonstration in detail of operative and interpretative implications in geophysical work in the North Sea.

Eventually four papers on the geology of the North Sea and adjacent waters presented at the 14th Inter-University Geological Congress in Great Britain and published in 1968 should be mentioned.

The most specific paper is the one by Donovan (1968) on the continental shelf around Britain. Illustrative outline maps with rather exact information on the geology of the sea floor south and east of Britain are given. Distinction is made between relatively safe mapping generalizations approaching facts and clearly conjectural additions.

Kent's paper on the geological problems in North Sea exploration is of a similar type, although of a more general nature. Conclusions and discussions are obviously based on the large amount of unreleased data emerging from the exploration activity of British Petroleum. The paper may be considered as a continuation of Kent's paper from 1967.

Hinz has made an interesting attempt to compile available information to a stratigraphical-palaeogeographical outline of the North Sea. By comparison with the paper by Heybroek *et al.* (1967) it is, however, obvious that the limitation of available data and lack of knowledge of the achievements of the oil industry made the conclusions less well founded. The many question marks on the maps should protect the reader from misuse of the most speculative generalizations.

In the case of the outline of Palaeozoic palaeogeography by Bartenstein question marks ought to have been spread a little more generously. However, if it is remembered that the maps are suggestions only, serving as illustrations of general ideas and possibilities, they are certainly useful.

Colette's paper on the subsidence of the North Sea area is speculative. Except for a seismic section, shot from the mouth of the Humber to Den Helder in North Holland, the factual data included in the discussion are the same as in his paper from 1960 on the gravity features. The idea that the regional gravity minimum between Scotland and Norway may evidence branching of the Caledonian Chain, and that the gravity minimum in the Moray Firth is due to a granite mass is maintained. In the writer's opinion it is more probable that the gravity minimum between Scotland and Norway outlines the subsided area of the Norwegian sedimentary basin. The Moray Firth minimum, on the other hand, may indicate a downfaulted block with Palaeozoic and Mesozoic sediments as *e.g.* suggested by the downfaulted Jurassic sediments of the Brora and Lossiemouth regions (Bailey and Weir 1932).

Colette emphasizes the point of view that the continental shelf is not the accidentally flooded margin of the continent, and that the North Sea is a "continental basin" different from the continental margin with regard to mechanism of subsidence. It is almost a truism that different processes probably are at work when different portions of the crust are subsiding.

However, it appears somewhat premature to establish types of subsidence before a sufficient number of subsiding areas have been studied in detail, and before their histories of subsidence have been carefully disentangled and compared.

## From hypotheses to geological knowledge

The geophysical mapping of the North Sea has been followed up by the drilling of a large number of wells during the last four years. However, the geological data from the great majority of the wells are not yet published. This is partly because relevant stratigraphic studies have not yet been terminated and partly for various economic reasons.

It is of course reasonable to expect that this situation may soon change, and that the geological data will be released successively. We shall then pass from our present stage of geological generalizations mainly on the basis of geophysical data into a period of geological analysis and synthesis. In this future stage, knowledge of the surface and subsurface geology of the land areas bordering the North Sea will be as important as the geological knowledge of the marine areas.

The following outline of the geological aspects of the North Sea area and the compiled information on significant well sections, geophysical data, etc. is an attempt to meet some of the requirements of future geological studies in the North Sea Basin.

## The structural framework of the North Sea Basin

The concept of the North Sea Basin (Nordseebecken) was introduced by Gripp in 1915 for the region covered by Oligocene and younger Tertiary formations in the North Sea area (Gripp 1915, pp. 46–47). In 1933, Gripp re-defined the North Sea Basin as the approximately triangular sedimentary basin limited by the high-lying edge of the Baltic Shield and the Russian Platform to the NE (now known as the Fennoscandian Border Zone), by the Caledonian belt of folding to the NW, and by the Central European Variscan Chain to the S (Gripp 1933, p. 126).

According to Gripp the Zechstein Sea was the earliest representative of a succession of seas covering the almost continuously subsiding area of the North Sea Basin.

Gripp's definition of the North Sea Basin in a wide sense is perfectly acceptable although it implies that, in addition to the North Sea, all of Denmark, southwestern Sweden, northern Poland, Northern Germany and Holland as well as eastern England are included in this regional basin. Gripp's definition of the North Sea Basin is practically identical with the much later definition given by Kent (1967, p. 3, 1968, p. 78).

The recent geophysical mapping of the North Sea and increased well control on and off shore has reached a stage in which it is possible to define new structural elements in the basin as shown by Kent (1967) and

Heybroek *et al.* (1967, p. 908). Two structural highs, the Ringkøbing-Fyn High and the Mid North Sea High, are dividing the basin into three subbasins: the German Basin to the SE, the British Basin to the SW and the Norwegian-Danish Basin to the N. The basins are interconnected with a N-S trending graben (Heybroek *et al.* 1967) which will be called the East Dogger Bank Graben in the following. It separates the two highs.

Other significant structural or palaeogeographical units are the Pennine Uplift in Britain, the London-Brabant Massif in the southwestern part of the North Sea Basin, and the Rhenish Massif in northwestern Germany (see map 4).

These units as well as the two highs, the central graben, and the three subbasins are of regional nature. They are all more or less complex features which include various local structures as is mentioned by von Gaertner (1960), Porth (1964), Thiadens (1964), Sorgenfrei (1951, 1966), and Anderson & Owen (1968).

## Tectogenesis and sedimentation

The structural history of NW Europe is relatively well known. There is general agreement regarding the main trends and directions of thrust of the Caledonian, Variscan and Alpine belts, and it is quite obvious that the structure of the North Sea Basin has in part been controlled by the geodynamics which gave rise to these belts of folding. Opinions deviate, however, regarding the significance of more speculative concepts like those of the concealed Caledonian trend (Wills 1951, Colette 1958, 1968, von Gaertner 1960, Znosko 1964, Sorgenfrei 1966, Kent 1968), the mechanism of structural development (Trusheim 1957, Richter-Bernburg and Schott 1959), and the dynamic evidence of the individual features and their patterns (Sorgenfrei 1951, 1966, Trusheim 1957, Richter-Bernburg & Schott 1959). All writers do, however, apparently assume that horizontal forces producing stresses and tensions as well as vertical adjustments due to gravity have been at work during the formation of the structural pattern of the North Sea area.

The forces have obviously acted on a system of crustal units of basement fault blocks and folded belts as well as on their covering sedimentary sequences.

The highs and massifs outlined above do probably mainly reflect shallow Precambrian, Caledonian or Variscan portions of the crust. The forces which were responsible for the formation of these structures did, undoubtedly, affect large regions. Approximately contemporaneous displacements of other units may, therefore, have occurred. It should, however, be emphasized that structural contemporaneity does not necessarily mean that the resulting structural features would be geographically contiguous. This is apparently believed by some adherents of the branching Caledonian Chain mentioned above.

The real crustal deformations may have included the rigid lithosphere and a potentially underlying, more ductile zone. In addition to the "eutectonic" forces acting upon the entire crust, the thick rock salt sequence of the Upper Permian represents a more or less independant tectogenetic factor which only affected the salt and the sedimentary sequence above the salt.

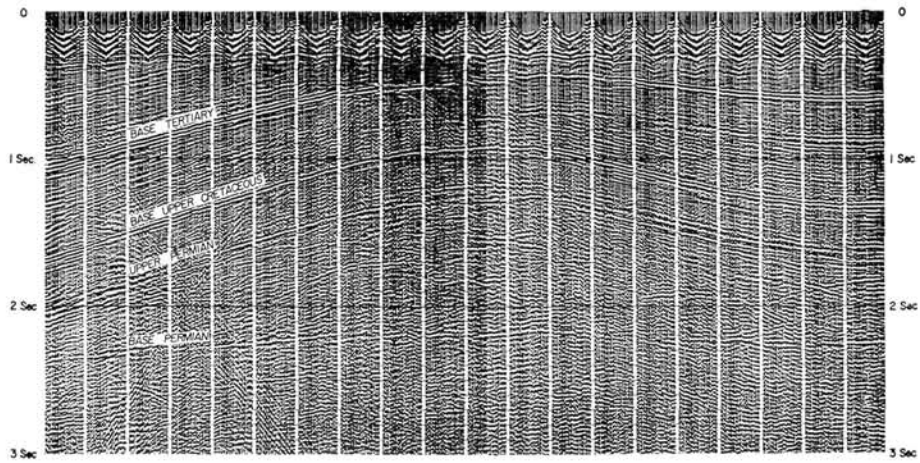



Fig. 1 a. Typical seismic record section over salt pillow in the North Sea. From E. E. Cook 1965.

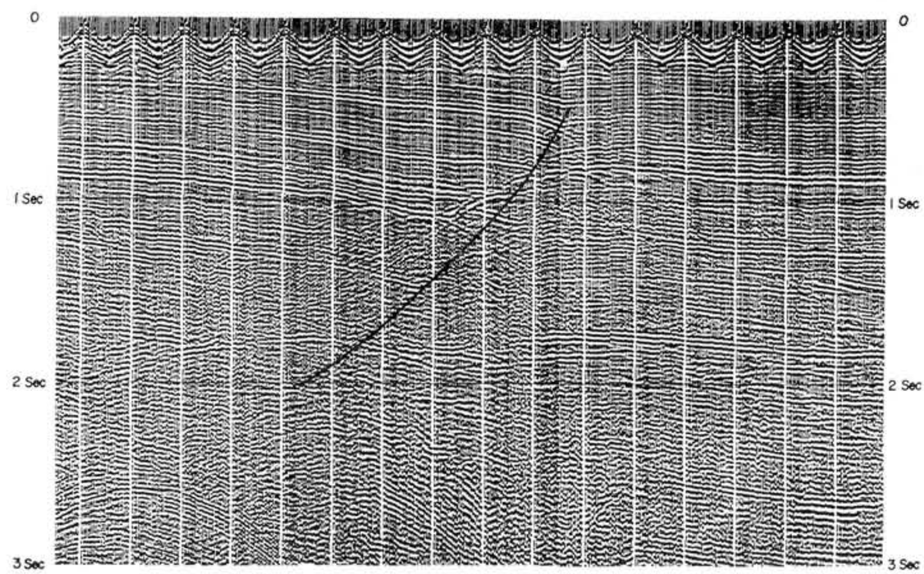



Fig. 1 b. Seismic record section over typical faulting adjacent to salt pillow in the North Sea. From E. E. Cook 1965.

The development of salt structures is well known through the classical works of Nettleton (1934, 1943, 1955) and the inspiring analysis of the salt structures of Northern Germany by Trusheim (1957). Trusheim coined the term halokinesis for salt tectonics in its restricted sense. The essential driving force in halokinesis is the buoyancy of the salt due to the deficit of mass of the rock salt as compared with the overlying, generally more dense, formations. Also the plasticity of the salt is important in this connection.

It should, moreover, be added that salt flowage, leading to the formation of genuine salt walls, plugs, and other diapiric salt structures, did apparently only occur under special conditions. The thickness of the bedded salt deposit should obviously exceed a certain minimum as should the load (*i.e.* the thickness) of the overlying rock column. Experience from the Danish salt basins suggests that the salt sequence involved should be more than ca. 1000 m thick and the overlying sediments more than 2000 m thick before doming might have been initiated. However, provided that such conditions were fulfilled salt flowage would, probably, generally not start until some outside force, as for instance real crustal movements, might initiate the process (Richter-Bernburg & Schott 1959).

The migration of the salt into the salt uplifts resulted in the subsidence of the areas of yield and, consequently, the formation of minor structural basins adjacent to the salt uplifts, which could receive new sediments. The important effect was the development of local maximum sedimentary thicknesses in these syn-halokinetic structural basins.

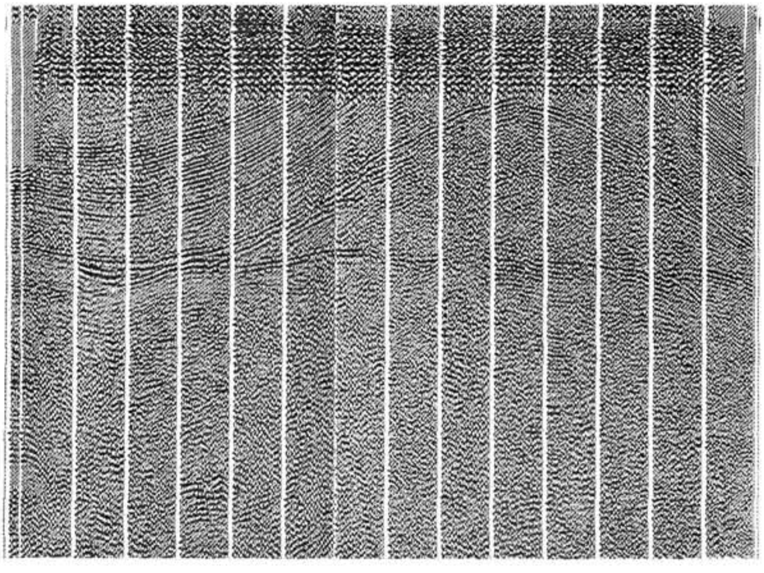


Fig. 2. West Sole Gas Field. Seismic record section across axis of 48/6 structure, line Z. From J. T. Hornabrook 1967.

The three typical seismic profiles through salt structures in the North Sea *fig. 1 a–b* and *2*, published by Cook (1965) and Hornabrook (1967), illustrate the principle of thickening of the formations away from the crest of the salt structures. The profiles show the depths measured in reflection time. *Fig. 3* indicates the calculated depths to important reflection horizons of the seismic profile on *fig. 2*.

The observations of the relationships between salt tectonics and the sedimentary fill in the structural basins bordering the salt uplifts may be generalized to a principle which is valid also for regional "eutectonic" structural development and sedimentation. An important condition for the formation of a thick sedimentary sequence is long lasting or strong subsidence of the basin area and a steady supply of sedimentary materials. Formation thickness is, accordingly, an approximate measure of subsidence.

If we, eventually, also keep the relations of lithofacies and structural development in mind, we may conclude that sedimentary sequences may hardly be understood without knowledge of the structural history and the geodynamics of the basins and their surroundings.

## Stratigraphic and palaeogeographic aspects

The distribution of exploratory wells drilled in the North Sea until the end of 1968 is shown on *map 1*, p. 170. Except for the generalized logs from the West Sole and Leman gas fields (Kent 1967, Davison 1968) the logs of this large number of wells are not yet publicly available. It is, therefore, not advisable to enter into far reaching and hazardous stratigraphic extrapolations from on shore knowledge at this moment. However, essential on shore data have been compiled on the geological map *(map 2, plate 1 a)*, which thus is a frame that may be filled in with future offshore well data. Very simplified graphic well logs and generalized columnar sections of exposed areas are shown on the map. The localities are listed in the *table* p. 189, including references to the sources of information.

General stratigraphic and palaeogeographic aspects will be discussed in the following on the basis of the geological map, the well data, and published geophysical evidence. The sedimentary basins, the tectonic control, and the volcanic activity will particularly be treated.

## The Precambrian

In Denmark, Precambrian rocks have been encountered at Frederikshavn in North Jutland and at Grindsted and Glamsbjerg in the area of the Ringkøbing-Fyn High. According to Noe-Nygaard (1963), the gneiss of Frederikshavn is related to the rocks of the adjacent Fennoscandian Shield, while no pronounced similarities have been demonstrated in the case of the metamorphic rocks of the Ringkøbing-Fyn High.

At Frederikshavn, the basement is covered by an arkose, presumably of Permo-Triassic age. The Precambrian of the Ringkøbing-Fyn High reaches

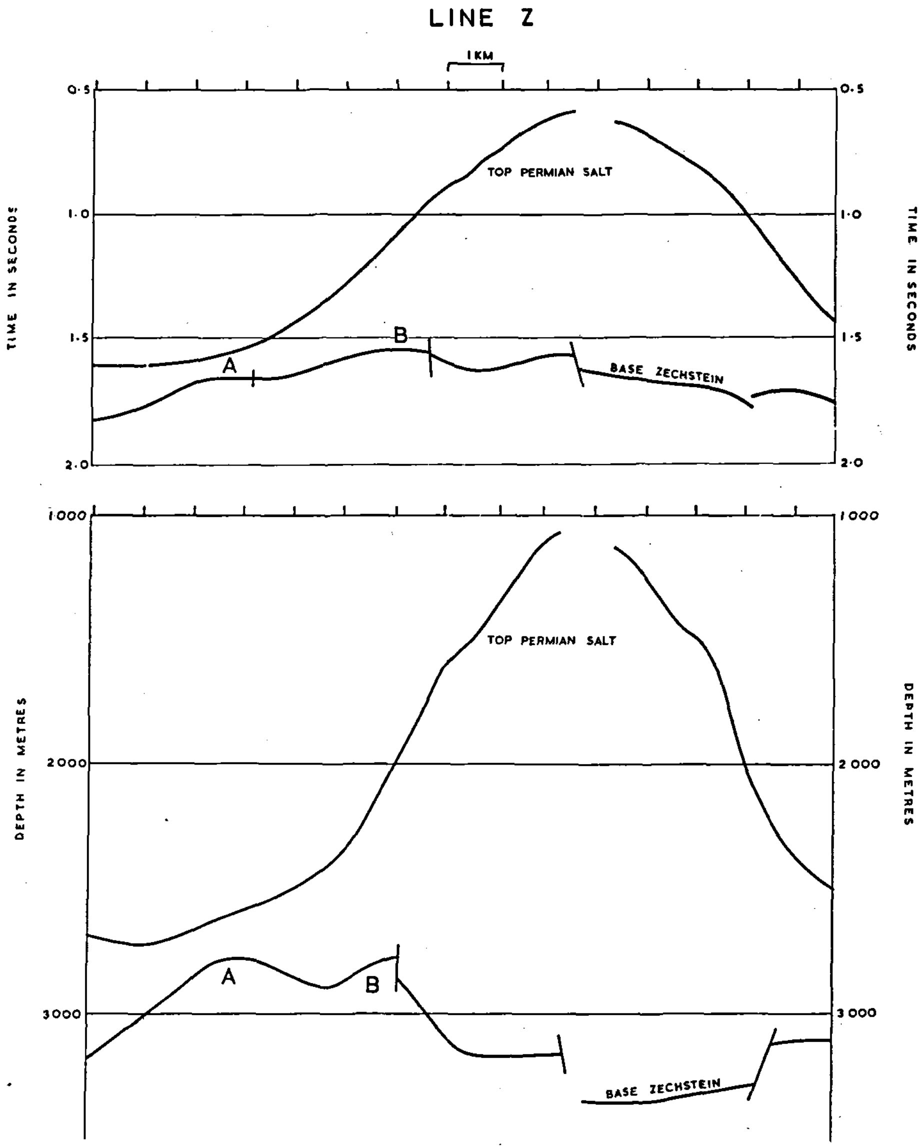



Fig. 3. West Sole Gas Field. Time and migrated depth section of seismic line Z shown in fig 2. From J. T. Hornabrook 1967.

maximum height at Glamsbjerg where the basement is overlain by a reduced, but possibly complete, Triassic sequence including Bunter, Muschelkalk and Keuper beds. A well developed Triassic sequence rests


NORTH SEA AREA. OUTLINE MAP WITH MAIN GAS FIELDS AND WELLS DRILLED UNTIL DECEMBER 1968

----- Continental shelf boundary
50 Water depth
• Well location
Gas field
0 50 100 150 200 Km

Fig. 4. Map 1.

upon the Precambrian at Grindsted. The stratigraphic conditions suggest that at least the eastern part of the Ringkøbing-Fyn High was exposed prior to the Triassic.

On the other side of the North Sea, the London-Brabrant Massif represents a crustal unit which to some extent may be comparable with the Ringkøbing-Fyn High. Shallow Precambrian rocks have been proved in the northwestern part at North Creake, East Anglia, at 742 m (2435'). The rock is a dark, greenish gray, somewhat sheared tuff of varying composition with traces of sub-basic fluidal lava (Phemister *in* Kent 1947). It is a finegrained, sericitic, chloritic rock with epidote which resembles the so-called Charnian rocks of the Charnwood Forest. The Charnian has been named after the Precambrian fossil *Charnia* (Rayner 1967).

Charnian rocks have also been encountered in a boring near Petersborough about midway between North Creake and Charnwood (Rayner 1947, p. 12). The three occurrences may indicate a Precambrian ridge extending from North Creake to the Pennine Uplift.

There is no evidence of uplifted Precambrian between the Precambrian region of Scotland and southern Norway. However, the gravity map *(map 3, plate 1 b)* shows two maxima, situated N of the Mid North Sea High, which might indicate shallow Precambrian. The gravity anomaly at 2°–3°E 56°–57°N might reflect a regional feature similar to the Ringkøbing-Fyn High, and the smaller maximum at 3°E and 57°40'N off Aberdeenshire could be a shallow fault block of Precambrian or Caledonian rocks.

The correlation of the Precambrian successions in the surroundings of the North Sea is of particular interest. An excellent outline of the problems involved is given by Anderson (1965) to whom reference is made for details. In general, the British rock types are distinctive by their low metamorphic grade and their metasedimentary character as compared with the rocks of relatively higher metamorphic grade of the Fennoscandian Shield.

The late Precambrian rocks of Britain are typical sediments, and the increase of thicknesses from E to W may evidence a late Precambrian geosynclinal region near the area where the Cambro-Silurian geosyncline later developed.

Outlines of the Precambrian of the countries bordering the North Sea are given by Barth & Reitan (1963), Noe-Nygaard (1963) and Anderson (1965).

## The Cambro-Silurian

Cambro-Silurian sequences are known from the Oslo region and the Hardanger Vidda in Norway, the eastern and southern flanks of the Ringkøbing-Fyn High in Denmark (Slagelse, Aabenraa, Hønning), northwestern Scotland, the Southern Uplands of Scotland, the Eakring area E of the southern Pennines and the northwestern flank of the London-Brabant Massif (Calvert, Twyford, Great Paxton) in England.

The Cambro-Silurian of the Oslo region has a maximum thickness of about 1400 m. Marine shales and limestones predominate. Otherwise the sequence includes occasional sandstone beds and conglomerates while volcanic rocks are absent. For biostratigraphic subdivision and other details reference is made to Henningsmoen (1960) and Störmer (1967).

The Hardanger Vidda Cambrian section consists of shales, sandstones, limestones and phyllites (Strand 1960). In Denmark, the Cambro-Silurian shales are underlain by quarzitic sandstones at Slagelse (Sorgenfrei & Buch 1964).

Cambrian deposits are rare in the eastern regions of Britain. Questionable Cambrian beds (ca. 84 m) consisting of igneous rocks, shales, siltstones, sandstones and quartzites were encountered at Eakring (Edwards 1967).

Knowledge of the Ordovician of the eastern part of Scotland is rather limited while the Ordovician sequence of the western Southern Uplands ranges among the most carefully studied sections. Lavas predominate towards the base of the sequence. Above follow thick marine shales, graywackes, mudstones, marginal conglomerates and subordinate limestones. The total thickness may locally approach 4500 m adjacent to contemporaneous faults (Rayner 1967).

In England, Ordovician marine shales have been reported from borings at Calvert St. in Buckinghamshire were about 290 m of a dipping sequence of Lower Ordovician marine shales were penetrated (Davies & Pringle 1913). Ordovician beds have also been encountered at Great Paxton in Huntingdonshire (Stubblefield & Bullerwell 1967). The Great Paxton bore was only drilled about 4.5 m into the dipping Lower Ordovician mudstones and siltstones without penetrating the formation.

Silurian beds are well exposed on the east coast of Scotland in the Pentland Hills inliers near Edinburgh. The folded sequence consists of marine mudstones, sandstones and conglomerates. It is estimated to be some thousand feet thick.

Farther south, in England, Silurian beds are present south of the Thames estuary between Canterbury and Gravesend (Smart, Sabine & Bullerwell 1964). The localities are situated on the southwestern flank of the London-Brabant Massif.

The situation of the known Cambro-Silurian occurrences, the facies conditions and the biostratigraphic relations suggest a more or less coherent marine region which extended from the Fennoscandian Shield over Denmark and the North Sea to Britain. This basin developed geosynclinal environments in western Norway, Scotland and parts of England. Epicontinental conditions may have prevailed in the remaining areas of the North Sea Basin. Cambro-Silurian beds may be absent on the basement highs and preserved in the deep parts of the subbasins.

## The Devonian

In the British Isles, the Devonian is represented by the well-known continental Old Red Sandstone facies, which is typically developed in Scotland, and the marine facies of the Hercynian geosyncline fringing Britain in Corn-

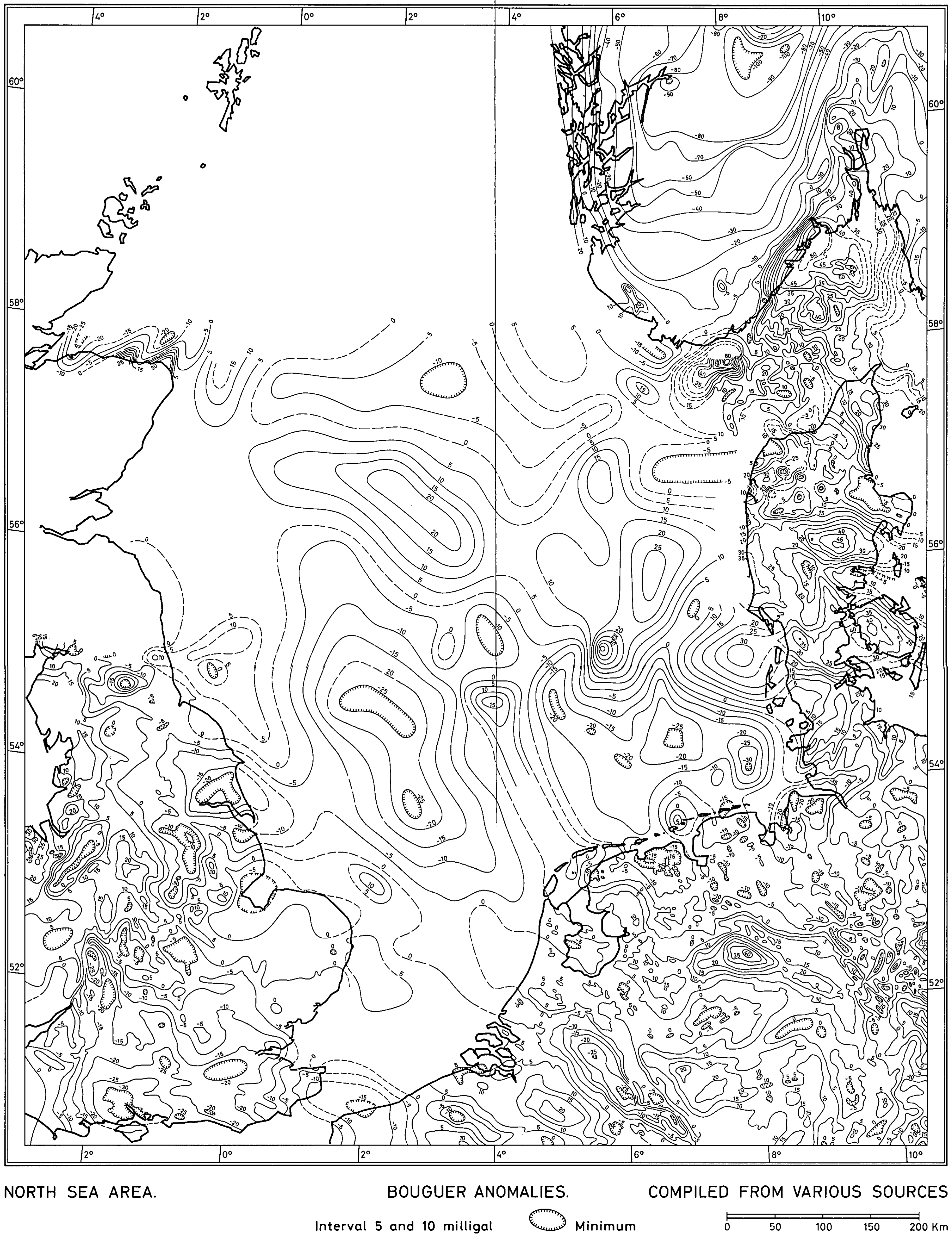

NORTH SEA AREA.
BOUGUER ANOMALIES.
COMPILED FROM VARIOUS SOURCES
Interval 5 and 10 milligal
Minimum
0 50 100 150 200 Km

Fig. 6. Map 3.

wall. However, only the Old Red Sandstone facies is found on the shore of the North Sea.

The detrital material which spread out from the Caledonian Mountain Chain accumulated to thick sequences of red beds in subsiding areas adjacent to the mountains as demonstrated by the Devonian deposits in the Orkney Islands, Caithness and the Midland Valley in Scotland. The Lower, Middle and Upper Old Red Sandstone, as defined by lithology and vertebrate fossils, may correlate reasonably well with the corresponding units of the tripartite marine Devonian in the countries south of the North Sea.

The most complete O.R.S. sequence is found in the Midland Valley adjacent to the Highland Boundary Fault at Stonehaven-Strathmore where the beds are exposed in the Mearn and Strathmore synclines (M. & A. G. MacGregor 1948, p. 18). The simple generalized section on *map 2* illustrates the great thickness of the series *(plate 1 a).*

The basal part, referred to the Downtonian, is 830 m thick. The bulk of the sequence consists of sandstones with some thin mudstones. About 12 m of volcanic conglomerates and tuffs occur in the middle part, and ca. 240 m of tuffs and tuffaceous sandstones terminate the Stonehaven Downtonian.

The overlying, very thick Lower O.R.S. consists of sandstones and conglomerates with intercalated dacite, andesite and basalt lavas as well as tuffs. The entire sequence is about 5500 m thick, and the main lava interval, situated somewhat above the middle of the section, approaches 800 m on the southern limb of the Mearn syncline close to the shore. It is thinning towards NW.

Middle and Upper O.R.S. is found in Caithness, the Orkney Islands and, probably, in the Shetland Islands. These occurrences represent remnants of a large Devonian basin, the Orcadian Lake, which extended over adjacent parts of the Atlantic and the North Sea. At Caithness the thickness is about 5900 m, at Hoy ca. 3000 m, and at Dunnet Head ca. 600 m. These impressive sequences consist of finegrained sandstones, mudstones, calcareous flagstones and some conglomerates including various fossiliferous horizons. In spite of the fact that they belong to the O.R.S., they are mainly of greyish colours. Yellowish and red colours do, however, also occur.

Tuffs and lavas are found at the base of the Upper O.R.S. in Hoy, but otherwise the Middle and Upper O.R.S. are devoid of volcanites of importance.

In going south from Scotland to Kent, the Devonian lavas and intrusives of the Cheviot are passed, but hence Devonian beds disappear or are deeply buried below younger deposits until the area of the London-Brabant Massif is approached. Several wells have encountered O.R.S. in the Cambridge, Oxford and the London-Canterbury regions (Smart *et al.* 1964, Rayner 1967, p. 162). Penetration is, however, limited.

Marine Devonian occurs in Cornwall, Belgium and Northern Germany. The Münsterland well represents the northernmost known locality of marine Devonian south of the North Sea. This well proved the presence of Middle and Upper Devonian. About 166 m of marine Middle Devonian, mainly consisting of limestone, was penetrated. The limestone was superposed by 283 m of Upper Devonian shallow water clastics, including sandstones and dolomitic beds.

The continental and marine Devonian may grade into one another in the southernmost part of the North Sea Basin. Originally, the apron of continental deposits extending from the Caledonian Mountains undoubtedly covered extensive areas of the western and northern areas of the North Sea Basin. They have partly been eroded during later periods. Chances are, however, that remnants are primarily preserved near the Caledonides, where maximum thicknesses developed, and in the deeper parts of the subbasins of the North Sea.

## The Carboniferous

In the British Isles, the Carboniferous system is widely distributed and exposed. British Carboniferous stratigraphy is, however, not always easy to disentangle due to the rapid variation of facies whereby correlation may be difficult. Generally, the following three main lithologic units may be identified:

| | |
|---|---|
| Upper Carboniferous | Coal Measures<br>Millstone Grit |
| Lower Carboniferous | Carboniferous Limestone |

The Carboniferous sediments were laid down in the same general areas as the Devonian. This suggests the persistence of the pattern of subsidence which developed in the area during Devonian time. However, the marine intercalations of the Carboniferous sequence evidence that large areas repeatedly submerged below the sea, while the freshwater deposits of shales and sandstones including numerous coal seams indicate swamp conditions during intervening periods. The much varied rock sequence with interbedded marine and freshwater beds and repetition of groups of beds also suggest rythmic subsidence in many areas.

The general vertical trend is from mainly marine sediments in the lower Carboniferous to dominantly freshwater and terrestrial sediments in the Upper Carboniferous. Limestones predominate in the marine intervals.

The principle of facies development as displayed stratigraphically is to some degree also valid horizontally. In southern England and Wales, the Lower Carboniferous is thus marine while in northern England and Scotland it includes freshwater intervals with coal seams.

The variation of formation thicknesses is pronounced. It is obviously due to the development of a number of local sedimentary basins.

Volcanic rocks play an important role in the Carboniferous of the Midland Valley of Scotland. Throughout the Carboniferous period, volcanoes were active in this region as evidenced by the lava sheets and tuff beds occurring in the succession of strata.

The generalized columnar sections given for Fife and Forth suggest that the thickest Carboniferous sequence of Scotland is found in this area. From

Scotland, the Carboniferous extends southwards practically along the entire east coast of Britain, maybe with the exception of the area of the London-Brabant Massif. The West Sole well has proved the presence of Carboniferous beds in the British subbasin in the North Sea.

In the Netherlands and Northern Germany, Upper and Lower Carboniferous have been encountered in several wells of which the more significant ones are shown on *map 2, plate 1 a.*

The Münsterland well encountered a very thin interval of Lower Carboniferous while the Upper Carboniferous was 3643 m thick, which is a remarkable development. The Dwingelo well, on the other hand, went through a rather reduced Upper Carboniferous sequence of Westphalian age resting on metamorphic rocks of intrusive types at 1267.5 m. Farther north a very thick Upper Carboniferous sequence may be present at Groothusen and in adjacent areas on and off shore. The two topmost Carboniferous divisions, the Westphalian D and the Stephanian, have been encountered at Groothusen (Trusheim 1959, Bartenstein 1968).

How far the Carboniferous extends from the Netherlands and Germany over the southern North Sea cannot be stated at present. The northernmost published occurrence is that of the E-1 well in the German offshore area N of Groningen. But no stratigraphic details have been published (*Erdöl und Kohle* 1966, p. 223).

Thrusheim (1959) and, following him, Bartenstein (1968) have suggested an extension of the Lower Carboniferous over the southwestern part of the North Sea. They also assume a wide belt of Upper Carboniferous deposits connecting the British and Dutch-German Upper Carboniferous regions. In addition to this main basin Bartenstein proposes a hypothetic trend of Carboniferous from the Carboniferous region of Eastern Germany over Denmark and the northern part of the North Sea to Scotland.

## The Permian

The formations of the NW European Permian basin have been thoroughly studied in Germany where the most varied and complete successions are found. The Permian covers also large parts of the Netherlands and Denmark, and it extends over Yorkshire, Lincolnshire and part of the Midland Plain in England. All these on-shore regions are parts of one basin, the Permian North Sea Basin, as shown on *map 4, plate 2.*

### *Lower Permian Rotliegendes*

The Rotliegendes has been less extensively studied than the Upper Permian Zechstein. It is, therefore, not possible to outline the sedimentary basin in detail. However, the margin of the Rotliegend basin may be approximately defined at the northern flank of the Variscan Mountain Chain in northwestern and central Germany, in the Netherlands, at the southern flank of the Ringkøbing-Fyn High in Denmark, and possibly at the London-Brabant Massif in the southern North Sea (Bartenstein 1968).

In regard to the origin of the Rotliegend, it is commonly agreed that the main part of the typical red beds have been deposited in a continental desert or playa basin. Rock salts and anhydrite, locally included in the sequence, is a proof of evaporite pans. The general sedimentary pattern is otherwise rather simple. Coarse clastics are found in the marginal belts. They consist of windblown sands. The central parts of the basin in Schleswig-Holstein and southwestern Denmark are dominated by shales, siltstones and claystones which include a rock salt sequence. The topmost part of the sequence in Holstein contains a marine microfauna which is related to the basal Upper Permian Zechstein fauna (Plumhoff 1966). It indicates the beginning of the marine stage later fully developed during early Zechstein.

In southeastern Denmark and East Germany, the sediments referred to the Rotliegend are underlain by extrusive rocks which are either late Carboniferous or early Permian (Knape 1963, Korich 1967). The Rødby No. 2 boring encountered 78 m of dacitic lavas without penetrating the volcanites (Sorgenfrei & Buch 1964). Volcanic rocks of probably the same age as at Rødby are rather abundant south of the Baltic. One of the most conspicuous occurrences in that of Grimmen, situated about 120 km SE of Rødby. A sequence of 983 m of volcanites was penetrated by the Grimmen well (Korich 1967), and Upper Carboniferous beds were encountered below the volcanites.

Volcanic rocks, presumably of Lower Permian age, are also known from southwestern Sweden and from Norway. The Swedish Konga diabases form a system of intrusive dykes trending NW-SE. In the Oslo region in Norway several groups of lava sheets are found. They rest upon a 20–50 m thick series of red and grey sandstones, red shales, and conglomerates of Lower Permian age (Holtedahl 1960). The total thickness of the more regional lava sheets may exceed 500 m.

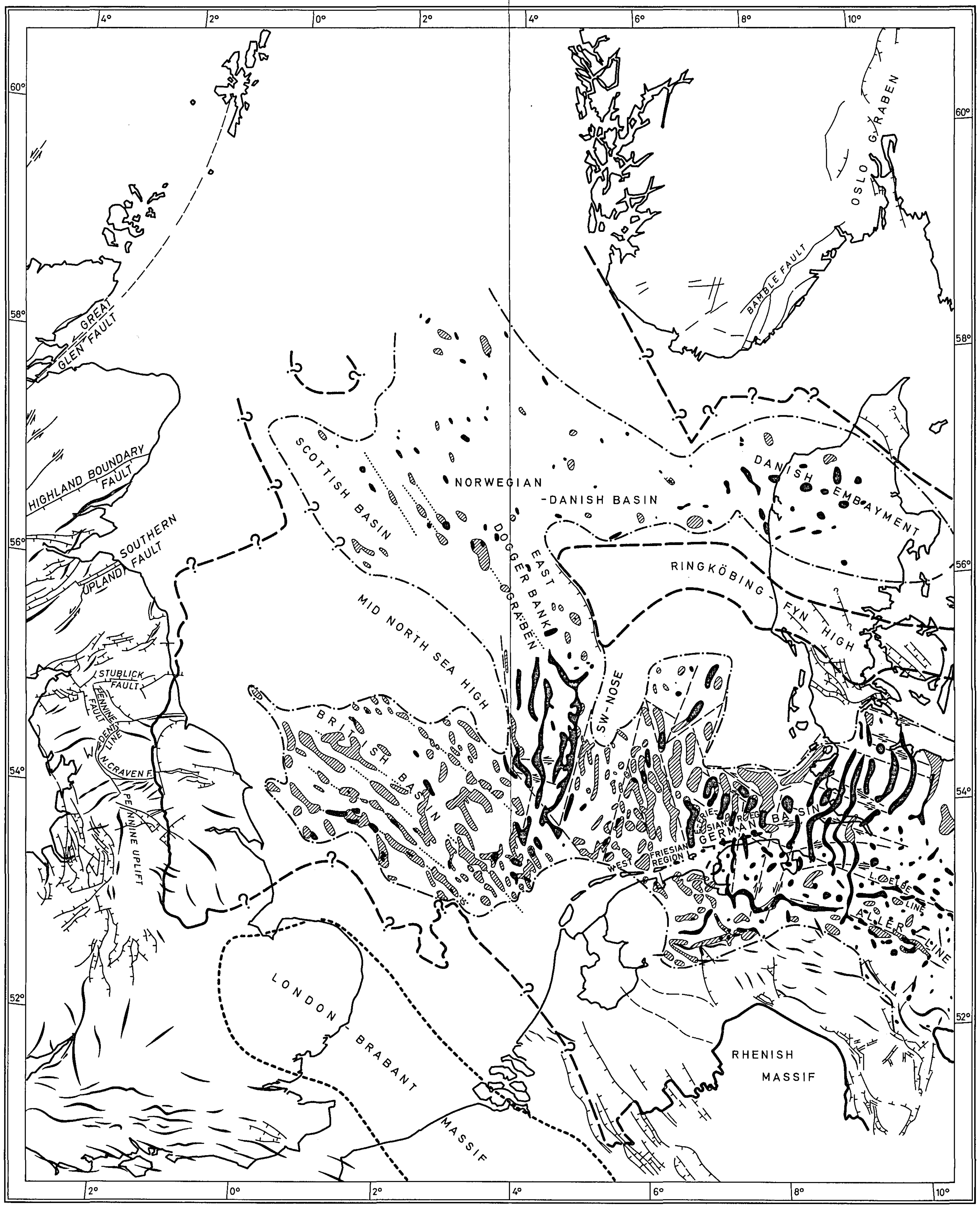
The volcanites of Norway, eastern Denmark, Sweden and Eastern Germany suggest a Lower Permian volcanic province at the eastern margin of the North Sea Basin.

Thickness figures for the Rotliegend sedimentary sequence are available from only few localities. The table below lists the approximate thicknesses in three boreholes and in the generalized sections established for Holstein and Groningen.

Thickness of the Rotliegend:

| | | |
|---|---|---|
| Holstein | >400 m | (Hecht *et al.* 1955) |
| Groothusen | 273 m | (Trusheim 1959) |
| Groningen | ca. 250 m | (Thiadens 1963) |
| West Sole | ca. 180 m | (Kent 1967) |
| Leman | ca. 250(–300?) m | (Davison 1968) |

As it was stated above, the Rotliegend sandstone now ranges among the most famous natural gas reservoirs. Patijn (1964) has explained the formation of the Slochteren gas by re-coalification of Carboniferous coal seams which subsided sufficiently in relation to the temperature gradient of the Earth's crust to attain temperatures above the level of maximum




NORTH SEA AREA. THE ZECHSTEIN BASIN AND THE MAIN POST-CALEDONIAN STRUCTURAL FEATURES

Boundary of the present extension of the Zechstein

Boundary of halokinesis

Potential boundary of London - Brabant Massif

Salt pillows (salt anticlines and interdomal features)

Salt piercements (salt walls and piercement domes)

Anticlines

UP DOWN Fault

Undefined faults

Wrench (tear) fault

Potential wrench fault

Structural trend

0 50 100 150 200 Km

Compiled by THEODOR SORGENFREI 1969

Fig. 7. Map 4.

coalification temperature during the Carboniferous. According to Patijn, re-coalification did occur under special conditions in particular regions in post-Carboniferous time. The statement is evidenced by coalification conditions in the Netherlands and Northwestern Germany. Another support of the coalification hypothesis is the $^{12}C$:$^{13}C$ ratio of the Rotliegend gas, which is different from that of hydrocarbons formed in marine environments but similar to the $^{12}C$:$^{13}C$ ratio of gas formed from decaying plants (Gaskell 1967).

The table below shows the composition of gasses in Rotliegend reservoirs. The low content of higher hydrocarbons is characteristic, and the relatively high amount of $N_2$ in the Slochteren gas is noticeable.

Composition of natural gas from Rotliegend reservoirs:

| | Groningen (Slochteren) (Visser *et al.* 1965) | Leman Davison 1968 | West Sole BP 48/6–1 (Gaskell 1967) |
|---|---|---|---|
| Methane ............ | 81.30 % | 95.50 % | 94.0 % |
| Ethane .............. | 2.84 – | 2.86 – | 3.0 – |
| Propane ............. | 0.40 – | 0.49 – | 0.5 – |
| Butanes ............. | 0.13 – | 0.17 – | 0.1 – |
| Pentanes ............ | 0.04 – | 0.05 – | 0.1 – |
| Hexanes ............. | 0.02 – | 0.02 – | |
| Heptanes ............ | < 0.01 – | 0.04 – | |
| Benzene ............. | 0.01 – | | |
| Toluene .............. | < 0.01 – | | |
| Carbondioxide ........ | 0.87 – | 0.04 – | |
| Oxygen .............. | 0.01 – | | |
| Nitrogen ............ | 14.32 – | 1.26 – | 1.0 – |
| Helium .............. | 0.04 – | 0.02 – | 0.03 – |
| Sulphur .............. | < 0.01 – | < 0.50 – | |
| Others .............. | | | 1.27 – |

*Upper Permian Zechstein*

The well known basal Zechstein which starts with the Zechstein conglomerate followed by the Kupferschiefer and the Zechsteinkalk shows that the North Sea Basin entered a marine stage in early Zechstein time. The Zechstein fauna and the basin configuration suggest connections with the ocean between Scotland and Norway (Sorgenfrei 1956). However, the North Sea Basin soon developed into a huge evaporite basin with various subbasins. Details will not be communicated in this connection since knowledge of the Zechstein is wide-spread, and literature on the subject is easily available. Reference should, however, be made to the summarizing papers by Richter-Bernburg (1953), Raymond (1953), Sorgenfrei (1956), Visser (1963) and Larsen (1964).

The regional features of the Northwest European Zechstein Basin the distribution of which is shown on *map 4, plate 2*, are the following:

The evaporites may be divided into 4 to 5 evaporite cycles. If completely developed, an evaporite cycle should include a normal succession of terrigenous sediments succeeded by limestone and/or dolomite, anhydrite, rock salt, and magnesium-potassium salts.

The limestone/dolomite and anhydrite intervals of the Zechstein attained maximum thicknesses at some distance from the Zechstein shore lines and around shoals. It means that these members of the cycles formed fringing reefs in the basin. The rock salt sequences, on the other hand, reached their greatest thicknesses in the central parts of the basin. They are very dominant in the two or three topmost evaporite cycles which may exceed 1000 m, and locally they have been most active as a tectonic factor by the formation of the spectacular salt structures of the North Sea Basin. This implies that the evaluation of the original thickness of the bedded salt deposits is rendered extremely difficult in areas of vivid salt flowage and doming.

Fringing limestone/dolomite and anhydrite reefs have been evidenced along the southern Margin of the basin in the Netherlands and in Germany, on the southern flank of the Ringkøbing-Fyn High, and along the western margin in Yorkshire. It is reasonable to expect reefs of this kind elsewhere in the Zechstein basin under near shore and shoal conditions.

The minimum area of distribution of the rock salt facies is of course indicated by the salt dome areas. Between these areas and the Zechstein shore line a belt of bedded salt or only slightly deformed rock salt formations may generally be found. It should, however, be kept in mind that the structural deformations of the crust below the Zechstein salt locally may have influenced salt flowage to a rather high degree in the salt dome areas and obscured the bedding of the evaporite sequence.

*Map 4* illustrates the areas of salt doming and the belts devoid of salt structures.

The most important dolomite/limestone intervals of the Zechstein are the Hauptdolomit at the base of the Stassfurt cycle and the Plattendolomit at the base of the Leine cycle in Northern Germany and the Netherlands. They correspond to the C 3 and B 3 dolomites of Denmark respectively. These dolomite intervals attract interest on account of their gas accumulations. The Hauptdolomit and Plattendolomit fields of Northern Germany and the Netherlands, which mainly contain methane, play a significant role in local energy economy, although they are of a much smaller scale than the Rotliegend fields of the Netherlands and the British offshore. A surprising result of exploration work in the German offshore and in southwestern Denmark is the demonstration of the high content of nitrogen in the Zechstein dolomites (Sorgenfrei & Buch 1964, *Erdöl und Kohle* 1964, p. 593, German B-1 well). Inexplicable as it is at present, the nitrogen gas has a destroying effect on exploration activity in the areas in which it has been encountered.

## The Mesozoic

Our knowledge of the Mesozoic sequence in the areas bordering the North Sea and the related structural framework enables us to draw some simple but rather important general conclusions regarding sedimentation and the distribution of the formations in the entire North Sea Basin.

The subsidence of the North Sea Basin that started in the Permian continued with local variations throughout the Mesozoic as evidenced by the well developed sedimentary sections. Regional structural uplifts like the Ringkøbing-Fyn High, the London-Brabant Massif, and possibly the Mid North Sea High were acting as separate units as reflected by their reduced and incomplete Mesozoic sequences. In addition new highs or blocks of retarded subsidence were outlined. This category of Mesozoic structures includes the North Holland Massif, the West Sleswick Block and the East Holstein Block on which Jurassic and Lower Cretaceous beds are absent or very thin.

Sedimentation of the Mesozoic deposits on top of the Zechstein salt would go on in a regular manner until the load of the sediments exceeded the limit of flowage of the underlying salt. Hence local salt uplifts with interjacent minor basins would start to form. Subsequently, the pattern of sedimentation and the thicknesses of the deposits were profoundly influenced by salt tectonics. The area of sedimentation was occasionally restricted to the structural basins between the salt domes and salt pillows. This situation occurred particularly during Middle and Upper Jurassic time.

Summing up: the history of the Mesozoic of the North Sea Basin is broadly speaking a report of the interaction of sedimentation, actual crustal movements and salt tectonics.

## The Triassic

This thoroughly studied system which is excellently exposed in Northern Germany comprises the continental, partly saline series of the Lower Triassic Bunter Sandstone, The Middle Triassic marine and saline series of the Muschelkalk, the continental-saline series of the Lower and Middle Keuper, and the marine and deltaic series of the Upper Keuper (Rhaetic).

The sedimentary cover developed in a rather uniform way during this initial part of the Mesozoic, and few if any salt tectonics complicated the picture. A complete Triassic sequence including all the main divisions mentioned is obviously present in the major part of the North Sea Basin south of the Ringkøbing-Fyn High and the Mid North Sea High (*cf.* Geiger & Hopping 1968). Part of the section may wedge out in marginal regions. This is, for instance, the case in the British onshore Triassic in which the Muschelkalk is missing.

Conditions north of the Ringkøbing-Fyn High may have been different as illustrated by the Gassum section (Sorgenfrei & Buch 1964). Two rock salt intervals are included in the Triassic at Gassum while no typical Muschelkalk facies has been recognized. It is possible that part of the section in which the rock salts occur is the substitute of the Muschelkalk. If this interpretation is accepted, it would imply saline lagunal environments north of the Ringkøbing-Fyn High during Muschelkalk time.

In dealing with palaeogeographic features of the Muschelkalk it should be noticed that connections with the ocean were obviously established towards SE and possibly not towards NW like in the beginning of Zechstein time. This is at least the generally accepted hypothesis. Drilling in the North Sea in the Norwegian Basin may already have contributed with new evidence on this interesting subject.

A related problem is the palaeogeographic configuration of the late Triassic Rhaetic basin. Rhaetic deposits occur in the Danish Embayment as well as in the German and British Basins. The marginal areas of the Danish Embayment are deltaic while the northwestern part is more marine. This circumstance and the faunal relations between the Rhaetic of the North Sea area and the Rhaetic of Britain and northern Ireland suggest connections with the Atlantic Ocean during Rhaetic time.

For further stratigraphic and lithologic details of the Triassic in the countries bordering the North Sea reference is made to the literature on the well sections listed on page 189 and to recent works by Boigk (1959, 1961 a-b), Haanstra (1963), Harsveldt (1963), Rusitzka (1967), and Geiger & Hopping (1968).

Formation thicknesses for the entire Triassic have been outlined for Denmark (Sorgenfrei 1965). North of the Ringkøbing-Fyn High in the area of the Danish Embayment the Triassic approaches 1800 m; minimum thickness on the high is 46 m, and maximum thickness on Danish territory south of the high is 1271 m. Farther south, in Holstein, thicknesses of the same order of magnitude as the maximum thicknesses in the Danish Embayment may be found. In going west to the British offshore we find a total thickness of 1413 m of Triassic beds in the Leman area, which up to now is a maximum figure for the British Basin. Onshore the Triassic is much thinner, particularly in the area of the London-Brabant Massif, which may have played a similar role as the Ringkøbing-Fyn High during Triassic time. In this connection also the Mid North Sea High attracts interest. So far, however, no information is available from this area.

In an attempt to generalize these barely sufficient observations, it would seem reasonable to assume a relatively thick Triassic sequence in the central parts of all three subbasins of the North Sea outside the salt diapirs and reduced sections on the regional highs.

## The Jurassic

The formations of the Jurassic are mainly marine in the onshore regions. In the generally adopted stratigraphic scheme of three divisions the Lower Jurassic or Lias is the most monotonous, particularly in the deep parts of the basin in which a very uniform and thick sequence of shales occurs. Sandstones and beds of limestone are intercalated in the shale in marginal areas.

The Middle Jurassic formations, which may be referred to as Dogger, are more varied, particularly in the British portion of the basin where limestones are rather conspicuous in the stratigraphic column. In Yorkshire, Denmark, and parts of Northern Germany deltaic sequences are characteristic of the Middle Jurassic. They include shales and sandstones of fluviatile, brackish and marine facies in various combinations. In the eastern and southern areas of the North Sea Basin, the extension of the Middle Jurassic is generally more restricted than that of the Lower Jurassic.

In comparison with the Lower and Middle Jurassic a rather different palaeogeographic situation developed during the Upper Jurassic or Malm. Evaporite intervals in the otherwise marine Upper Jurassic sequence of the Lower Saxonian Basin are proof of saline lagoonal conditions in the southern part of the North Sea Basin. Farther north and west, in the Danish Embayment and in eastern Britain, normal marine conditions are evidenced by the formations of the Oxfordian, Kimmeridgian and Portlandian stages.

The similarity of the development of the entire Jurassic sequence of Yorkshire and northern Denmark, which almost approaches identity, definitely indicates a permanent Jurassic subbasin in the northern region of the North Sea (Gregersen & Sorgenfrei 1951, Arkell 1956).

A further support of this assumption may be obtained by a study of the relations between Jurassic sedimentation and the regional and local structural features. In order to illustrate the possibilities of regional inferences from such studies, the maps of the generalized thicknesses and lithofacies of the Lower Jurassic Lias in the North Sea Basin have been compiled (*map 6* and *7, plate 3*). The data on the basis of which the maps have been drawn have been extracted from Arkell (1933), Brand & Hoffmann (1963), Dadlez (1964), Falcon & Kent (1960), Haanstra (1963), Kölbel (1967), Lees & Cox (1937), Lees & Tait (1946), and Sorgenfrei (1963).

The maps clearly demonstrate the interrelationships of structural and sedimentary patterns. The greatest thicknesses are found in the areas of the subbasins or adjacent to them and in the minor structural basins between pronounced salt walls and anticlines. It may hardly be questioned that the Lias extends beyond the shores over the offshore portions of the Danish Embayment, and the German and British Subbasins. The easy correlation of the biozones shows that the subbasins were undoubtedly connected.

In the Polish part of the basin, the sediments were deposited in freshwater, brackish water and, occasionally, marine environments. The environment of the Danish Embayment, on the other hand, was marine like the environment of Northwestern Germany and Britain. Connections with the Atlantic were probably established to the W in the British land area (Arkell 1933) and between Scotland and Norway.

The lithofacies features shown on the map generally indicate dominance of shale at the present limits of the Lias except for the Polish Basin and areas in Britain. It is possible that post-Liassic erosion of potential original near shore coarse clastics is responsible for the absence of a belt of bordering sand facies.

Now relating the extension of the deposits of the Dogger to the Lias, it is evident that the Dogger generally occurs in the same areas as the Lias. However, the Dogger is often restricted to the deep parts of more or less local structural basins as for instance demonstrated on the subsurface geological maps of northwestern Germany (Nodop 1961), northeastern Germany (Kölbel 1967), the Netherlands (Haanstra 1963), and Denmark (Sorgenfrei 1963). The situation in Britain is different since the extensions of the Lower and Middle Jurassic formations practically coincide.

The distribution of the Upper Jurassic Malm demonstrates changes in conditions of deposition and geographical configuration. Large areas of the flanks of the Ringkøbing-Fyn High in Denmark devoid of Malm deposits were apparently situated above sea level, and the axis of subsidence had shifted towards NE in the Danish Embayment. However, comparing the distribution of the Dogger and Malm in Denmark (Sorgenfrei 1963) and the Netherlands (Haanstra 1963) it is obvious that in these and other regions the Malm represents a period of relatively strong subsidence. Although the term "transgressive stage" is misleading in most cases it may be applied to describe the local stratigraphic situation of Upper Jurassic overlap in the generally subsided areas.

The anhydrite intervals of the Purbeck Basin in southern England and the evaporite sequence of the Upper Jurassic Lower Saxonian Basin in Germany is ample proof of lagoonal evaporite basins towards the end of the Jurassic.

In generalizing on-shore Jurassic geology it may be concluded that relatively complete sequences exist in the structurally deep parts of the North Sea Basin north of the two highs. The probability is that the Lias covers the largest areas, the Dogger a smaller area, and that the extent of the Malm comes in between. The general stratigraphy may be approximately the same as in Yorkshire and northern Jutland. The situation south of the highs may be more varied due to lagoonal conditions in the Upper Jurassic.

## The Cretaceous

### *The Lower Cretaceous*

In many ways the Lower Cretaceous reflects environment conditions, rate of subsidence, and basin features similar to those prevailing during the Upper Jurassic. The extrapolations suggested for the North Sea in the case of the Upper Jurassic may accordingly also apply to the Lower Cretaceous. For details regarding the palaeogeographic development reference is made to the palaeogeographic maps of the North Sea Basin compiled by Schott *et al.* (1967). Isopachs of the Danish on shore area show a maximum thickness adjacent to the Fennoscandian Border Zone.

### *The Upper Cretaceous*

The monotonous blanket of White Chalk extends almost over the entire North Sea Basin as shown on the map by Heybroek *et al.* (1967). In the southwestern part of the North Sea the Chalk is absent on local highs.

In Denmark, the maximum thickness of the Upper Cretaceous is found in the Danish Embayment adjacent to the Fennoscandinan Border Zone. In this vicinity the Lavø well encountered ca. 1929 m of White Chalk and limestone. For other parts of the basin thickness figures cannot be offered at present.

Above the White Chalk in Denmark follows the Danian, by definition the topmost member of the Upper Cretaceous chalk-limestone sequence. In all areas there is a pronounced unconformity on top of the Danian and an abrupt sedimentary change from the Cretaceous limestone facies to the shale facies of the Tertiary.

## The Tertiary

The contour map of the base of the Tertiary by Heybroek *et al.* (1967), here combined with the depth to the base of the Zechstein on fig. 8, suggests rather uniform subsidence of the North Sea area during the Tertiary. Subsidence of the central area may have exceeded 3000 m. This is remarkable considering the fact that the thickness of the Tertiary sequence approaches this figure. The thickness of the Tertiary may thus equal the thickness of the entire Upper Permian, Triassic, Jurassic and Cretaceous sequence in the same general area (*cf.* Heybroek *et al.* 1967, figs. 5–6).

In spite of the apparent uniformity of the contour map it is a fact that the onshore distribution of the various stratigraphic units, the variation of formation thicknesses, and the local structural pattern reveal rather diverse palaeogeographic and lithologic developments.

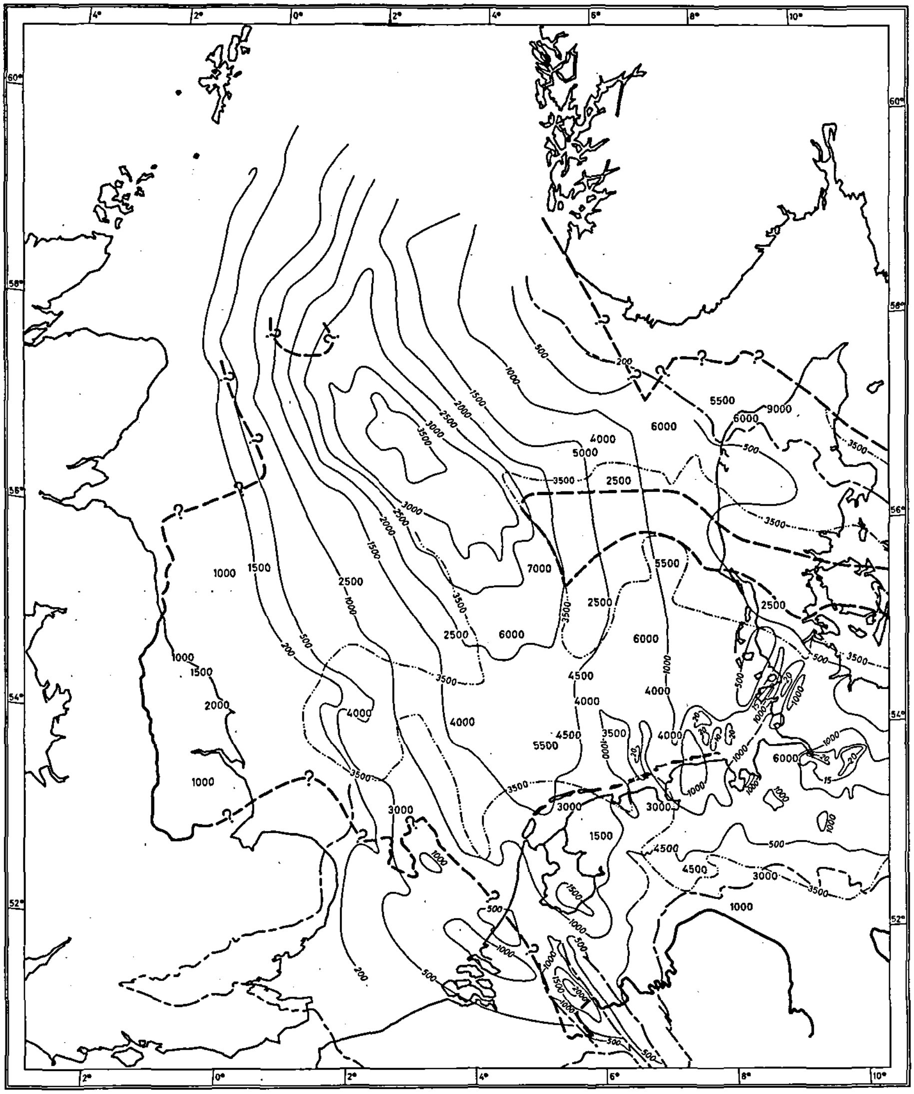
The Tertiary sequence of Denmark and Northern Germany falls naturally into two major divisions. In the lower marine division clayshales and clay are dominant. It includes the Paleocene, the Eocene, and the Lower and Middle Oligocene. The characteristics of the upper division, including the Upper Oligocene, the Miocene, and the Pliocene, are the occasional silt, sand, and gravel intervals, the shift from marine to non-marine facies and vice versa in the Miocene, and the occasional occurrence of lignite in the limnic-fluviatile intervals.

One significant stratigraphic aspect of the Eocene remains for consideration. The extremely pure and utterly finegrained clayshales and shales of the Danish and North German Eocene include a distinctive series of thin tuff seams. About 170 seams have been identified. The interval with these volcanic ash beds is the most excellent correlation horizon. It has been defined as the basal part of the Eocene in the continuous lower Tertiary sedimentary sequence of Denmark, starting with the basal conglomerate of the Paleocene and ending at the Middle-Upper Oligocene unconformity. The volcanic ash series represent the most exactly defined time stratigraphic interval of the Tertiary of the North Sea Basin. Its lower boundary marks the base of the Eocene and the top of the Paleocene.

Little will be added regarding the other land areas. Only Paleogene beds are found in Britain, and the Tertiary of the Netherlands resembles the Tertiary of Northwestern Germany. Data on the offshore have not yet been released. The occurrence of Lower Miocene reported from E of Scotland (Newton 1917, Anderson 1961) is to be noticed.

## The Pleistocene

The Problems of the Pleistocene are too complicated to be included in the present very sketchy outline. They merit special attention and studies which, however, could not be undertaken at the present time.



NORTH SEA AREA. CONTOUR MAP OF THE BASE OF THE TERTIARY SUPERPOSED ON OUTLINE MAP OF THE BASE OF THE UPPER PERMIAN ZECHSTEIN (Mainly according to HEYBROEK ET AL. 1967)

Contours: Metres below sea level

—500— (*italic*) Base Tertiary

-·-3500-·- 3000 (roman) Base Zechstein

Boundary of Tertiary

Boundary of Zechstein

0 50 100 150 200 Km

Fig. 8. Map 5.

## Regional structural Features

In addition to what has been said above regarding the structural framework and tectogenesis of the North Sea Basin, it remains to comment on some significant regional and local structural features.

The most conspicuous structures shown on the map compiled by Heybroek *et al.* (1967), here included in *map 4 (plate 2),* are the long piercement salt structures which were named salt walls by Trusheim (1960). This type of structure was originally recognized in Holstein and the Hamburg region in Northwestern Germany. The map demonstrates that salt walls have also developed in the East Dogger Bank Graben and elsewhere in the North Sea.

A second type of structure is represented by the elongate non-piercement salt anticlines which occasionally attain lengths comparable with the lengths of the salt walls.

The normal piercement domes may be classified as the third type of structure and the interdomal salt pillows which are more or less circular in outline may finally be referred to as the fourth type.

Trusheim (1957, 1960) has given a very inspiring account of the mechanism of the formation of these salt structures. He has demonstrated how they may have emerged as a natural consequence of the interplay of salt buoyancy and the varying pressure of the superstructure of overlying sediments. The analysis of the sedimentary fill in the basins between the salt structures of NW Germany disclosed excellent possibilities of reconstruction and dating of the stages of salt flowage.

With these few words and the recommendation to study Trusheim's works for details, we shall leave the interesting subject of halokinesis *per se* and proceed to the survey of the regional pattern of the salt structures.

A look at *map 4* reveals that the different types of salt structures are arranged in a characteristic pattern. It is admittedly true that the small scale map may conceal details that might destroy the impression of regularity. However, even a study of a large scale map like Nodop's map of Northern Germany (1963) which includes a magnitude of details does not change the picture of a mosaic of regional units of some sort.

We may start with the long salt walls which are typically developed in the Holstein-Hamburg region and in the southern portion of the East Dogger Bank Graben. The most easily perceptible feature of these walls is the approximate parallelism of their winding courses which is particularly obvious in the Holstein-Hamburg region. A remarkable circumstance is the correspondance of the sharp bends of the walls. Finally, the approximate strike which is about NNE-SSW in the Holstein-Hamburg region and almost N-S in the graben region is noticeable.

Two trends of shorter salt walls or elongate diapirs, the Lower Elbe Line and the Aller Line south of Hamburg (Richter-Bernburg and Schott 1959), stand opposed to the Holstein-Hamburg walls by their smaller size and their strike which is WNW-ESE. The two trends of the smaller salt walls are almost at right angles to the long salt walls of the Holstein-Hamburg region.

Returning to the salt walls of the East Dogger Bank Graben, it is significant that they display conformity of shape particularly to the south where the graben runs into the British Basin. Here the salt walls parallel the main NW-SE trend of the salt anticlines, say salt pillows, of the British Basin. This trend parallels the dominant NW-SE Charnian direction of the Midlands in England (Kent 1967) and the regional trend of the London-Brabant Massif.

It is rather easy to define a division line between the East Dogger Bank Graben and the British Basin from the southern tip of the Mid North Sea High towards SE. In the southeastern corner of the British Basin, the salt structures of the basin and the graben appear to cross.

The salt anticlines of the German Basin suggest three subregions: *1.* The continuation of the southwestern nose of the Ringkøbing-Fyn High, *2.* the West Frisian Region and *3.* the East Frisian Region.

The anticlines of the nose extension are relatively small, and the main trend is about NNE-SSW to N-S.

In the West Frisian Region the anticlines are longer and wider. The regional trend is NNW-SSE except for the flank of the Ringkøbing-Fyn High where two elongate salt diapirs are striking NNE-SSW.

The anticlines of the East Frisian Region are irregular. Some are large and most are relatively small. Adjacent to the extended central southern flank of the Ringkøbing-Fyn High the large anticlines bend and follow the margin of the flank. Several cases of mixed piercement and non-piercement structures are observed.

Turning north it appears that the structures of the Norwegian Basin are apparently generally small. Most of them are slightly elongate salt pillows. The regional trend is from NNW-SSE to NW-SE.

The majority of the features shown in the Danish Embayment are piercement structures. Two elongate features off the west coast of Jutland might be salt walls. Some salt pillows do also occur.

The structural pattern described is certainly not accidental. Opinions regarding the nature of the salt structures in Northern Germany, whether of halokinetic or combined "eutectonic" and halokinetic origin, differ. For details reference is made to the discussions by Trusheim (1957, 1960) and Richter-Bernburg & Schott (1959).

In 1951 the writer explained the salt walls of the Holstein-Hamburg region as a result of shearing movements in the Precambrian basement along NW-SE trending wrench faults (Sorgenfrei 1951, 1966). In accordance with this interpretation tension forces worked on the sedimentary sequence, due to the wrench faulting in the basement, and long tension rifts were formed in the sedimentary cover at about right angles to the trend of the basement faults. The weakness zones of the rifts facilitated the formation of the diapiric salt walls.

The NW-SE striking features north and south of the salt walls were, on the other hand, explained by the action of components of horizontal stress.

The hypothesis of tension rift diapirism is illustrated by the diagram *fig. 11*.

At this stage, it is reasonable to examine how far we may go in an at-

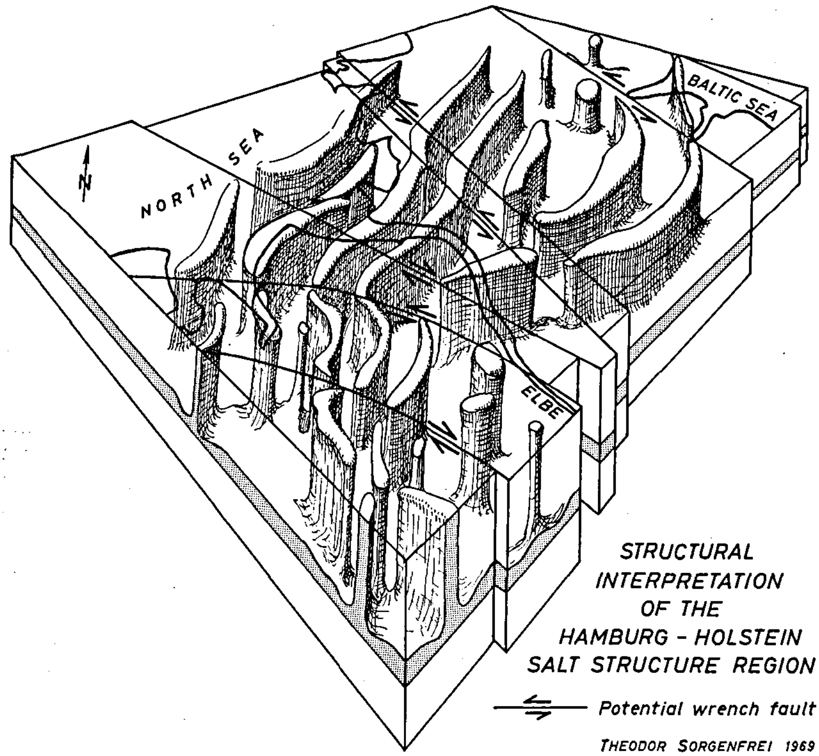



Fig. 11.

tempt to define regional structural units in the subbasins of the North Sea.

The distributional pattern of the salt structures may conveniently be ascribed to the different positions and depths of basement blocks carrying the Zechstein salt and overlying sediments. It is assumed that these blocks moved differently both vertically and horizontally. Deeply subsided blocks with thick Permian salt and a thick post-Permian cover became the site of piercement structures while anticlines may evidence shallower blocks with a thinner sequence above the salt. In other cases horizontal stress or shearing stress may have been wholly or partly responsible for the salt anticlines.

The location of the round piercement domes and salt pillows is less easily explainable. The possibility is that some of these features may be due to pure halokinesis, while others may be of complex halokinetic and tectonic origin.

It has been attempted to delimit major regional units on *map 4* by suggesting a number of faults. Possible directions of differential horizontal movements along the faults have furthermore been indicated. The hypothetical nature of this interpretation should, of course, be kept in mind. However, in spite of ample evidence of structural complexity in the North Sea Basin it is undoubtedly safe to conclude that regional units do exist. It is hoped that the present interpretation of the actual situation is a reasonable approximation at this time.

The dating of the salt movements on the individual blocks is of considerable interest. Little can be said about this problem at present.

In the case of the salt walls of Holstein, Richter-Bernburg & Schott (1959) state that the walls developed during post-Dogger and pre-Lower Cretaceous time. Salt movement was later resumed during pre-Miocene and Pleistocene time. Kent (1967) discussed the movements of the salt in the British Basin. He concluded that movement had begun by Keuper time and continued from then onwards during the Jurassic, the Cretaceous and the Tertiary. Kent also mentions strong faulting offshore and emphasized the Charnian trend of the salt structures.

Some of the conspicuous structural features on and off shore outside the subbasins have been indicated on *map 4*. They have been compiled from various sources (Tectonic Map of Great Britain and Northern Ireland 1966, Anderson & Owen 1968, Holtedahl *et al.* 1960, Porth 1967, Pannekoek 1956, Sorgenfrei 1949, 1966, and others). The writer has refrained from a chronological subdivision of the features in this connection. The intention is only to show the main trends in one picture in order to spur imagination.

After these comments on the pattern of salt structures it only remains to draw attention to the geological evidence of the gravity anomalies of the Skagerrak shown on *map 3, plate 1 b*.

There is an obvious agreement between the on and off shore anomalies. The continuation of the Oslo Graben trend of maxima out into the northern part of the Skagerrak is easily recognizable. It suggests similar geological conditions in this part of the Skagerrak as in the Oslo Graben (*cf.* Grønhaug 1962). Conditions change E of the Norwegian Channel. A large minimum extends from the Swedish coast to Skagen in Denmark. The lowest gravity values are found over the Bohus Granite in Sweden (Lind 1967). From this we may infer that the granite extends over a large submarine area which may touch the northernmost tip of Jutland.

The gravity highs and lows in the central and western parts of the Norwegian Channel match very well with the anomalies in northern Jutland. The main regional trend appears to be NW-SE to NNW-SSE. It is therefore, as already stated above, a reasonable conclusion that the distribution of formations and the types of structure in this part of the Skagerrak are the same as in Vendsyssel. We may expect a cover of late Palaeozoic and a rather complete Mesozoic section over the Palaeozoic sequence of the southern part of the Oslo Graben extension. Faulted structures may prevail in the northernmost areas while Zechstein salt may have modified the structures of the Jammerbugt and adjacent offshore areas.

The gravity map displays many other details which may be correlated with geological features. It is, however, beyond the scope of the present outline to enter into this very interesting subject.

Plate 3

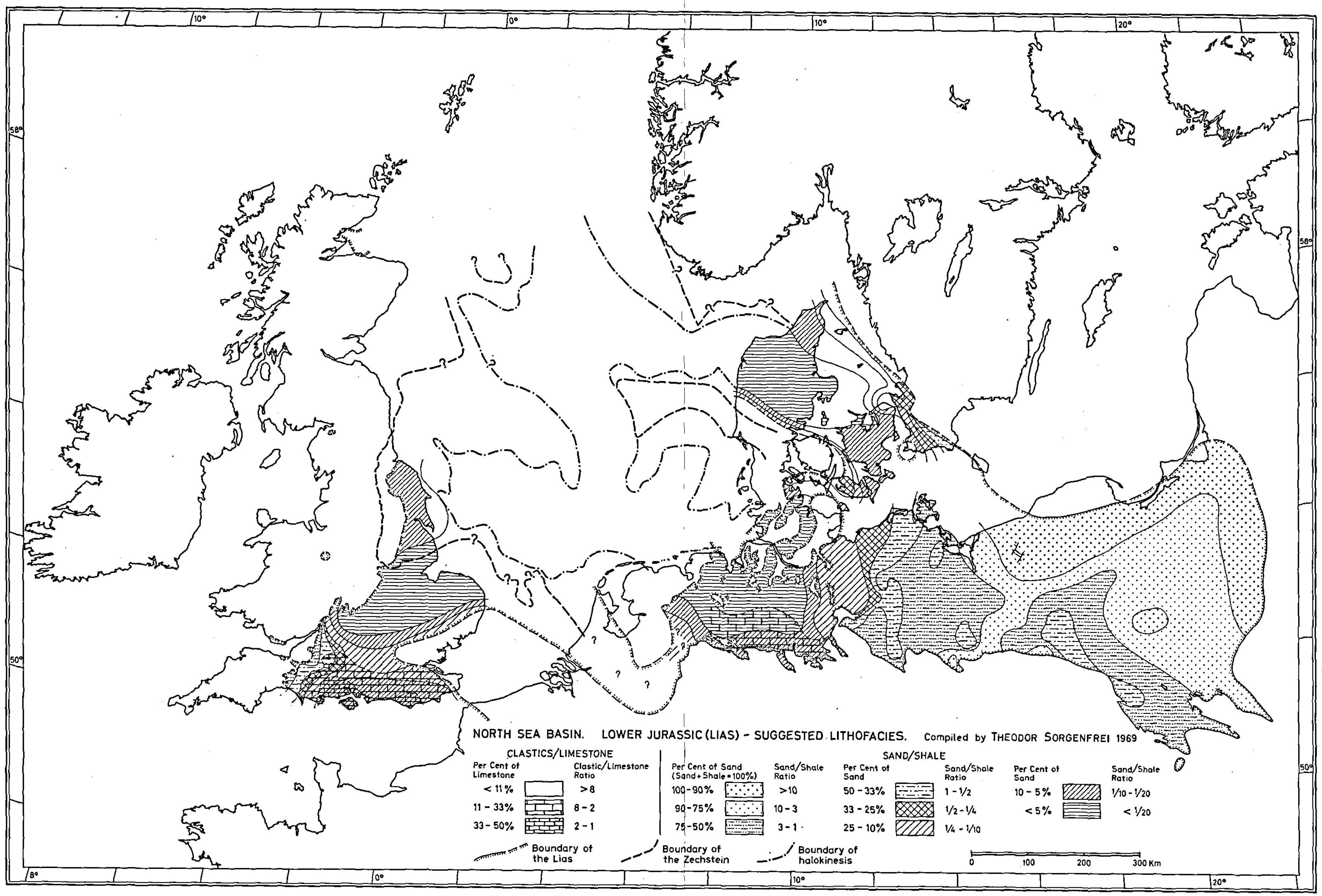



Fig. 9. Map 6.

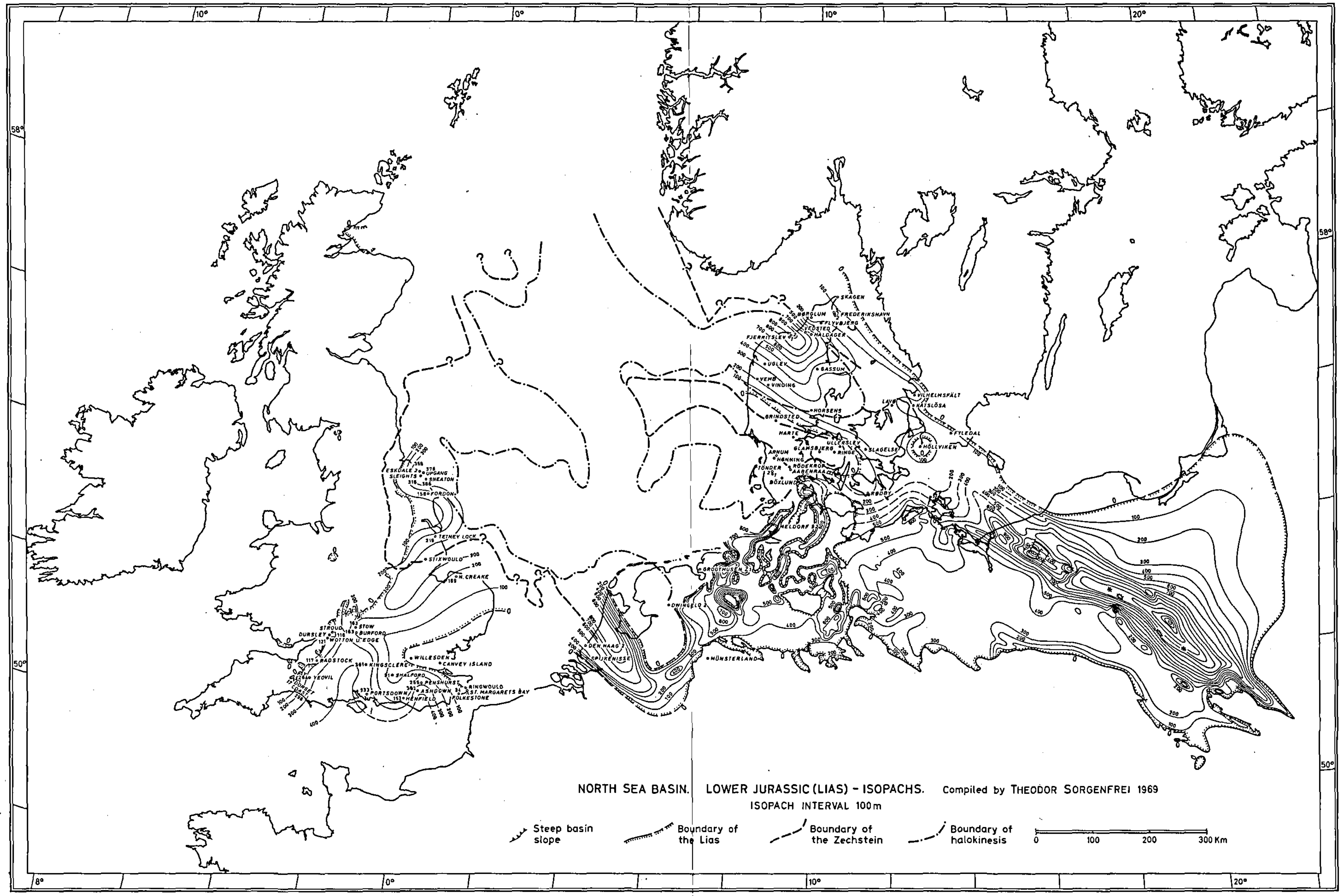

NORTH SEA BASIN. LOWER JURASSIC (LIAS) - ISOPACHS. Compiled by THEODOR SORGENFREI 1969
ISOPACH INTERVAL 100 m
Steep basin slope
Boundary of the Lias
Boundary of the Zechstein
Boundary of halokinesis
0 100 200 300 Km
10°
0°
20°
58°
50°

Fig. 10. Map 7.

*Acknowledgements*

I wish to acknowledge the assistance given me in the preparation of this paper by the following:

Dr. Ernest E. Cook, Houston, Dr. J. T. Hornabrook, London, Professor Dr. H. Kölbel, Berlin, Dr. Carl H. Savit, Houston, Sir James Stubblefield, D. Sc., F.R.S., London, the Elsevier Publishing Company, and the N.V. Nederlandse Aardolie Maatschappij.

Finally I should like to express my gratitude to three members of my own staff: Mrs Kirsten Ros who took care of the manuscript, and Miss Inger Petersen and Mrs Gurli Svensson who were responsible for the drafts-work.

## Boreholes and generalized sections of *map 2* with references

| | |
|---|---|
| Aabenraa 1 | Sorgenfrei & Buch 1964, p. 28 |
| Alnwick | Eastwood 1946, p. 36 |
| Böxlund 1 | Hecht, Helms & Kehrer 1955, p. 721 |
| Brora | Baily & Weir 1032, p. 432 |
| Caithness | Phemister 1048, p. 64 |
| Canvey Island | Smart, Sabine, Bullerwell, Melville & Croft 1964, p. 1 |
| Cleveland Hills | Fowler, 1944, p. 194 |
| Cousland | Falcon & Kent 1960, pl. III |
| Den Haag 2 | Haanstra 1963, encl. 4a–4b |
| Dunnet Head | Phemister 1948, p. 72 |
| Durham | Eastwood 1946, p. 49 |
| Dwingelo 2 | Haanstra 1963, encl. 5; Thiadens 1963, p. 14, encl. 9E |
| Eakring 146 | Edwards 1967, p. 15, 17, 275 |
| Fife | Craig *et al.* (Francis) 1965, p. 309–379 |
| Fjerritslev 2 | Sorgenfrei & Buch 1964, p. 37 |
| Fordon 1 | Falcon & Kent 1960, p. 30, t. III |
| Forth off shore 1–2 | Ewing & Francis 1960, p. 1–68 |
| Frederikshavn 1 | Sorgenfrei & Buch 1964, p. 40 |
| Gassum 1 | Sorgenfrei & Buch 1964, p. 45 |
| Grindsted 1 | Sorgenfrei & Buch 1964, p. 48 |
| Groothusen Z 1 | Trusheim 1959, p. 273 |
| Hardanger Vidda | Holtedahl *et al.* (Strand) 1960, p. 153 |
| Hayton 1 | Falcon & Kent 1960, p. 30, t. III |
| Hönning 1 | Sorgenfrei & Buch 1964, p. 54 |
| Hoy | Craig *et al.* (Waterson) 1965, p. 299 |
| Kirkleatham 1 | Falcon & Kent 1960, p. 30, t. III |
| Leman 49/26–1 | Davison 1968, p. 26; Geiger & Hopping 1968, p. 17, fig. 9 |
| Lossiemouth | Berridge & Ivimey-Cook 1967, p. 155 |
| Meldorf 92 | Hecht, Helms & Kehrer 1955, p. 722 |
| Münsterland 1 | Richwien, Schuster, Teichmüller, Wolburg & Kelch 1963, p. 357; Hedemann & Teichmüller 1966 |
| North Creake | Kent 1947, p. 2 |
| Oslo Region | Holtedahl *et al.* (Henningsmoen, Oftedahl) 1960, p. 133, 301, 310 |
| Ringwould | Bisson, Lamb & Calver 1967, p. 111, 134 |
| Robin Hoods Bay | Falcon & Kent 1960, p. 30, t. III |

| | |
|---|---|
| St. Margarets Bay | Bisson, Lamb & Calver 1967, p. 105, 123 |
| Salsburgh 1a | Falcon & Kent 1960, pl. III, t. V |
| Shalford | Falcon & Kent 1960, p. 47 |
| Sleights | Raymond 1953, p. 285, 295 |
| Spijkenisse | Haanstra 1963, encl. 5 |
| Spital 1 | Lees & Taitt 1946, t. I |
| Stixwould 1 | Lees & Taitt 1946, t. 1 |
| Stonehaven-Strathmore | MacGregor, M. & A. G. 1948, p. 15–21; Craig *et al.* (Waterson) 1965, p. 274 |
| Vemb 1 | Sorgenfrei & Buch 1964, p. 87 |
| Vedsted 1 | Sorgenfrei & Buch 1964, p. 85 |
| Vinding 1 | Sorgenfrei & Buch 1964, p. 89 |
| West Sole, BP 48/6–1 | Kent 1967, p. 10–11 |

# Dansk sammendrag

Den livlige efterforskningsaktivitet, som foregår i Nordsøen siden fundet af det store Slochteren gasfelt ved Groningen i 1959, har resulteret i et omfattende geofysisk og geologisk materiale, som nu gradvis offentliggøres. Foreløbig foreligger der kun en række oversigtsarbejder og enkelte tekniske publikationer, spredt i lokale tidsskrifter og internationale kongresberetninger. Den tilbundsgående videnskabelige bearbejdelse af lagserierne i de mange boringer vil derimod uden tvivl tage meget lang tid.

I indledningen til det foreliggende arbejde omtales de vigtigste afhandlinger og artikler om Nordsøens geologiske forhold. Derefter gøres der rede for de geologiske hovedtræk, således som de tager sig ud for os i dag.

Nordsøen er en del af Nordsøbassinet, et aflejringsområde, som af Gripp i 1915 og 1933 blev defineret som det regionale sænkningsområde mellem den kaledoniske Foldekæde, den Fennoskandiske Randzone og den Variskiske Foldekæde. Nordsøbassinet omfatter således ikke alene selve Nordsøen, men store dele af England, næsten hele Holland, Nordtyskland, Danmark, Sydvestskåne, de danske farvande og det nordøstlige Polen.

De seneste geologiske publikationer om selve Nordsøen viser, at man i store træk navnlig kan danne sig et billede af strukturforholdene. To højdeområder, Ringkøbing-Fyn Højderyggen, der fra Jylland strækker sig mod vest, og den Centrale Nordsøhøjderyg, der udgår fra den engelske østkyst, deler Nordsøen i tre strukturelle bassiner. Mod sydvest ligger det britiske bassin, mod sydøst det tyske bassin og mod nord det dansk-norske bassin. Disse bassiner er især kendetegnet ved deres saltstrukturer. Mellem de to højderygge ligger Øst Dogger Banke gravsænkningen.

Boringerne Glamsbjerg nr. 1 og Grindsted nr. 1 har vist, at grundfjeldet ligger højt i alt fald i den østlige del af Ringkøbing-Fyn højderyggen. Fra den centrale Nordsøhøjderyg foreligger ingen oplysninger om grundfjeldets beliggenhed.

Til belysning af de øvrige geologiske forhold er der udarbejdet et geologisk kort, hvorpå forenklede boreprofiler og generaliserede lagserier fra landområderne er vist. Ud fra forholdene på land og strukturforholdene i Nordsøen opridses en række perspektiver for formationsfordelingen, idet de enkelte geologiske systemer gennemgås hver for sig. Mulighederne for at opstille prognoser for formationsudbredelsen under permsaltet er meget begrænsede. Forholdene på og omkring Ringkøbing-Fyn højderyggen og på et andet regionalt højdeområde, London-Brabant massivet, giver dog visse antydninger. Det er sandsynligt, at kambrosiluriske lag er bevarede i de dybere dele af bassinerne, og at de oprindeligt har dækket en betydelig del af Nordsøbassinet.

De kontinentale devonaflejringer findes sandsynligvis under størstedelen af den vestlige Nordsø, idet de har en stor udbredelse både i Skotland og England. Om marine devonaflejringer foreligger derimod endnu ingen vidnesbyrd.

De karbone aflejringer er blevet påvist i det engelske bassin. Ud fra forholdene på land må man vente, at sedimentationen i karbontid er foregået i flere mindre aflejringsområder, om hvis beliggenhed det er vanskeligt at gisne. På forhånd kan man imidlertid gå ud fra, at der er størst mulighed for, at karbonaflejringer er bevaret uden for højdeområderne.

Øvre perms udbredelse er overordentlig godt kendt takket være den geofysiske kortlægning og saltstrukturernes optræden. Anderledes stiller det sig med nedre perm, som i virkeligheden er ligeså vanskelig at kortlægge geofysisk som alle andre formationer under permsaltet. Sandsynligheden taler for, at der findes rotliegend aflejringer i størstedelen af det britiske og det tyske bassin. Fra det nordlige bassin foreligger endnu ingen oplysninger.

De mesozoiske lags udbredelse er stærkt afhængig af både de regionale »eutektoniske« strukturforhold og af saltstrukturernes udvikling. Triasaflejringerne har formodentlig oprindelig dannet et forholdsvis tykt og sammenhængende sedimentdække over praktisk taget hele Nordsøbassinet, mens juraaflejringerne og de nedrekretaciske aflejringer stort set er begrænset til områderne uden for højderyggene. Det tyske bassin blev endvidere opdelt i mindre strukturelle bassiner som følge af salttektonik i løbet af juratiden, og andre steder reduceredes aflejringsområderne i samme tidsrum på grund af eutektoniske ændringer. Dette gælder således både for det danske sænkningsområde og for det hollandske landområde.

For at illustrere sedimentationens afhængighed af den strukturelle situation er der udarbejdet et tykkelseskort og et lithofacieskort for liasaflejringerne.

I løbet af øvre kridt var praktisk taget hele Nordsøbassinet marint aflejringsområde.

Det nye med hensyn til tertiæret er påvisningen af en betydelig sænkning af hele Nordsøen med tyngdepunktet i det centrale område. Der er i løbet af tertiæret og kvartæret i midten af Nordsøen aflejret en sedimentserie, hvis tykkelse er af samme størrelsesorden som den samlede underliggende lagserie fra basis af øvre perm til toppen af øvre kridt.

Afsluttende behandles strukturforholdene i det tyske, det britiske og det dansk-norske bassin. De forskellige saltstrukturtyper optræder i et karakteristisk mønster, som sættes i forbindelse med størrre strukturelle enheder i dybere dele af jordskorpen. Saltstrukturernes form og forløb antages at stå i nøje relation især til horisontale forskydninger i jordskorpen. Men også vertikale bevægelser i jordskorpen samt forholdet mellem den oprindelige tykkelse af saltet og tykkelsen af de overliggende lag har været afgørende for saltstrukturernes udformning.

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*April 18th, 1969.*

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