North Sea Troughs and Plate Tectonics

A. J. WHITEMAN, G. REES, D. NAYLOR & R. M. PEGRUM

Whiteman, A. J., Rees, G., Naylor, D. & Pegrum, R. M. 1975: North Sea troughs and plate tectonics. *Norges geol. Unders. 316*, 137–161.

Interlinked roughly trilete-shaped predominantly sub-Upper Cretaceous trough systems extending north-south for more than 1200 km are described for the North Sea Basin and the Northeast Atlantic. Palimpsest tectonic controls are rejected as a major explanation of their development and an explanation in terms of lithospheric plate development is offered. The trilete trough patterns are seen as failed arms, superficial manifestations and consequences of plume or hot spot generated crestal uplifts initiated mainly in Late Carboniferous and Early Permian times over an area extending from Hatton and Rockall Banks in the west to the Skagerrak in the east. The Tertiary and Late Cretaceous broad basinal development of the North Sea Basin is seen as an inner continental margin development of the Bott and Watt type related to Cenozoic spreading of the North Atlantic arc development of the Cenozoic continental margin. The Mainz trilete system may be part of the overall pattern but data are inconclusive. Close relationships exist between trough and trap formation, geothermal history and the generation, maturation and accumulation of hydrocarbons. The role of mantle plumes – hot spot activity in the formation of the rift network is discussed.

A. J. Whiteman, Petroleum Exploration Studies, Department of Geology, University of Aberdeen, Aberdeen, Scotland

G. Rees, D. Naylor & R. M. Pegrum, Exploration Consultants Ltd., 31/33 Grosvenor Hill, London W1X 9HG, England

Introduction

If publicly available data on the Mesozoic structure, isopachs and facies distributions for the North Sea are plotted together with similar data from the adjoining land and sea areas, a highly distinctive and striking pattern emerges (Fig. 1). The pattern is necessarily generalised as only part of the information concerning bounding and internal structures, thickness variations, etc. is available in the public sector. Nevertheless, long linear troughs, some of which are over 50 km wide and over 300 km long, infilled by thick wedges of sediment of up to 10 km thick and ranging in age from Permian to Cretaceous, can be delineated. The Mesozoic troughs are separated by horsts and platforms upon which the sedimentary sequences are much thinner.

The trough and platform systems extend from Hatton Bank in the west to Poland in the east; and from the Pre-Alps in the south to the Lofoten Islands in the north (Figs. 1 and 2).

The trough margins are either faulted or monoclinal flexures, or combinations thereof. The interlinked trough system in the North Sea area roughly follows the median line between offshore U.K. and Norway and extends from the continental margin northeast of the Shetland–Orkney platform at approximately 63°N to the Broad Fourteens Trough in the Dutch offshore waters. This trough appears to continue into the West Netherlands–North Rhine

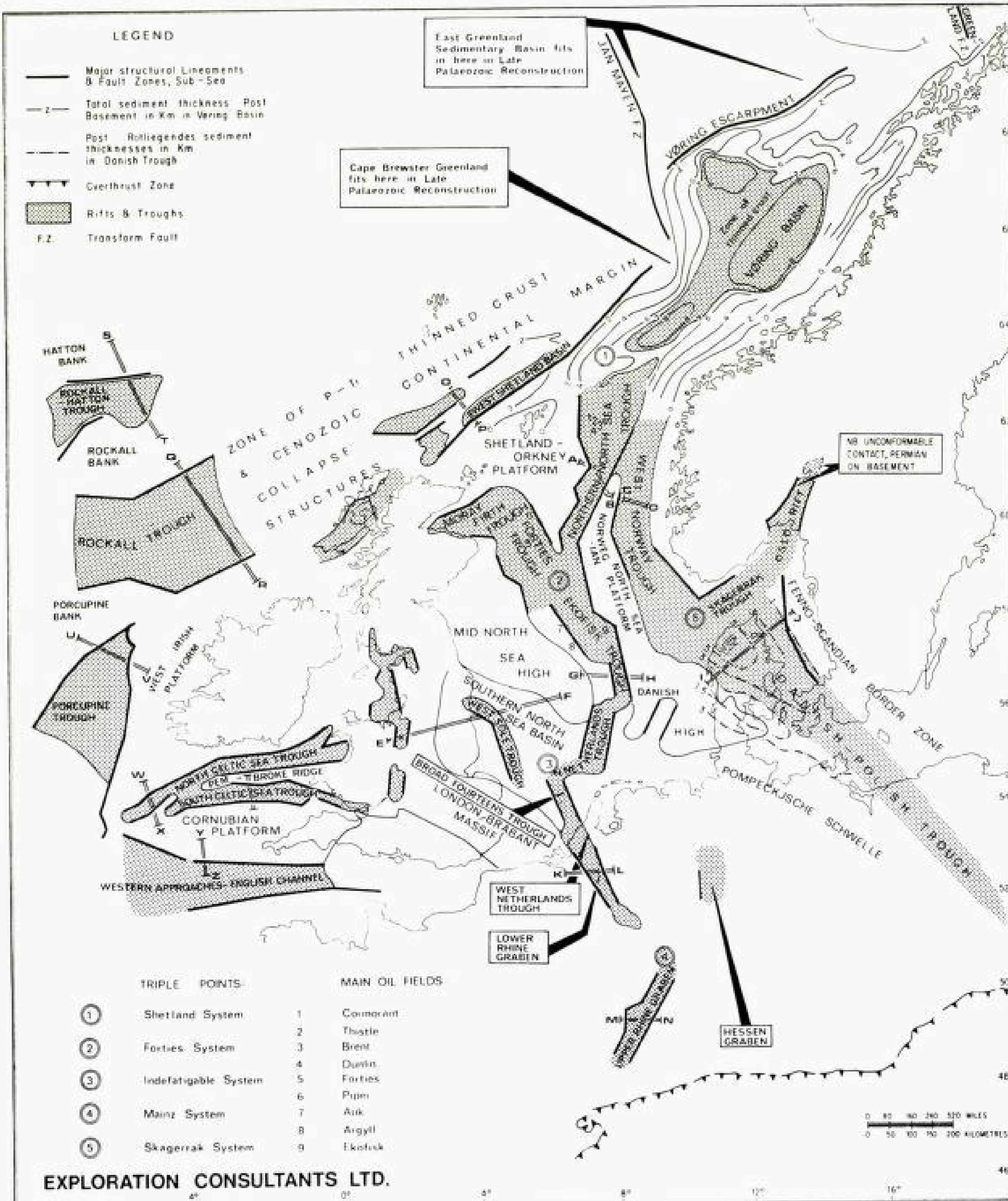


Fig. 1. General map showing troughs and platforms. North Sea and adjacent areas.

Trough which in its turn may be linked with the Upper Rhine and Hessen grabens. The latter apparently converge in the Mainz district.

A trough system extending from the continental margin between Shetland and Norway into the Netherlands is almost 1200 km long and constitutes a first order structural feature on the geological map of Europe (Fig. 1). Including the Upper Rhine and Hessen grabens as an integral part of the trough system, this structural entity is over 1800 km long.

The Mesozoic trough systems are extremely important economically because in the northern North Sea the large oil and gas fields appear to be genetically related to the formation and sedimentary history of these troughs.

Another trough system of similar size, exhibiting a marked asymmetrical trilete shape in plan, is present between southern Norway, Scania, Denmark, Germany and Poland. It consists of the West Norway, Oslo–Skagerrak and Danish–Polish troughs. The latter extends from the Skagerrak into East Germany and Poland and is more than 1000 km long (USSR International Tectonic Map of Europe 1 : 2,500,000 scale). In northern Denmark it contains more than 9 km of post-Palaeozoic sediments.

West of the British Isles there is a further system of sedimentary platforms and troughs approximately defined by the major elements of sea floor topography. These include the Hatton Bank, Rockall–Hatton Trough, Rockall Bank, Rockall Trough, West Irish Platform, Porcupine Bank, Porcupine Trough and the Southwest Irish Platform. Sea floor spreading and continental margin evolution (consequent on spreading) has clearly been involved in the formation of these and adjacent features. Further north McQuillin & Binns (1973) have shown that the structural history of the Sea of the Hebrides is consistent with the idea that the Sea of the Hebrides and the Inner and Outer Hebrides Troughs evolved as the Northeastern Atlantic opened.

In addition a linear fault-bounded basin occurs in the Celtic Sea south of Ireland and north of the Cornubian Platform (Fig. 1). A northern arm extends into the Cardigan Bay area and a southern arm into the Bristol Channel between the Pembroke Ridge and the Cornubian Platform. Both troughs are fault-bounded beneath the Cenozoic and contain thick Mesozoic sequences beneath a thinner Cenozoic and Upper Cretaceous cover (Pegrum & Rees 1973) (Fig. 2).

The Vøring and Stadt basins (Sellevoll & Sundvor 1973; Talwani & Eldholm 1972; Exploration Consultants Limited Report 1972) situated north of 62°N mainly on the Norwegian Continental Margin (although much broader apparently, if we are to judge from various generalized isopach patterns available, than the other troughs mentioned above), may also belong to this northwest European trough system (Fig. 1) and are associated with crustal thinning (Hinz 1972).

To date, the greater part of the commercial oil and gas found in N.W. European shelf has been associated with the fault-bounded troughs described above. A common origin, similarities of basin architecture and sedimentary development, etc., may well point to favourable prospecting conditions existing in other troughs and on the flanks of other platforms.

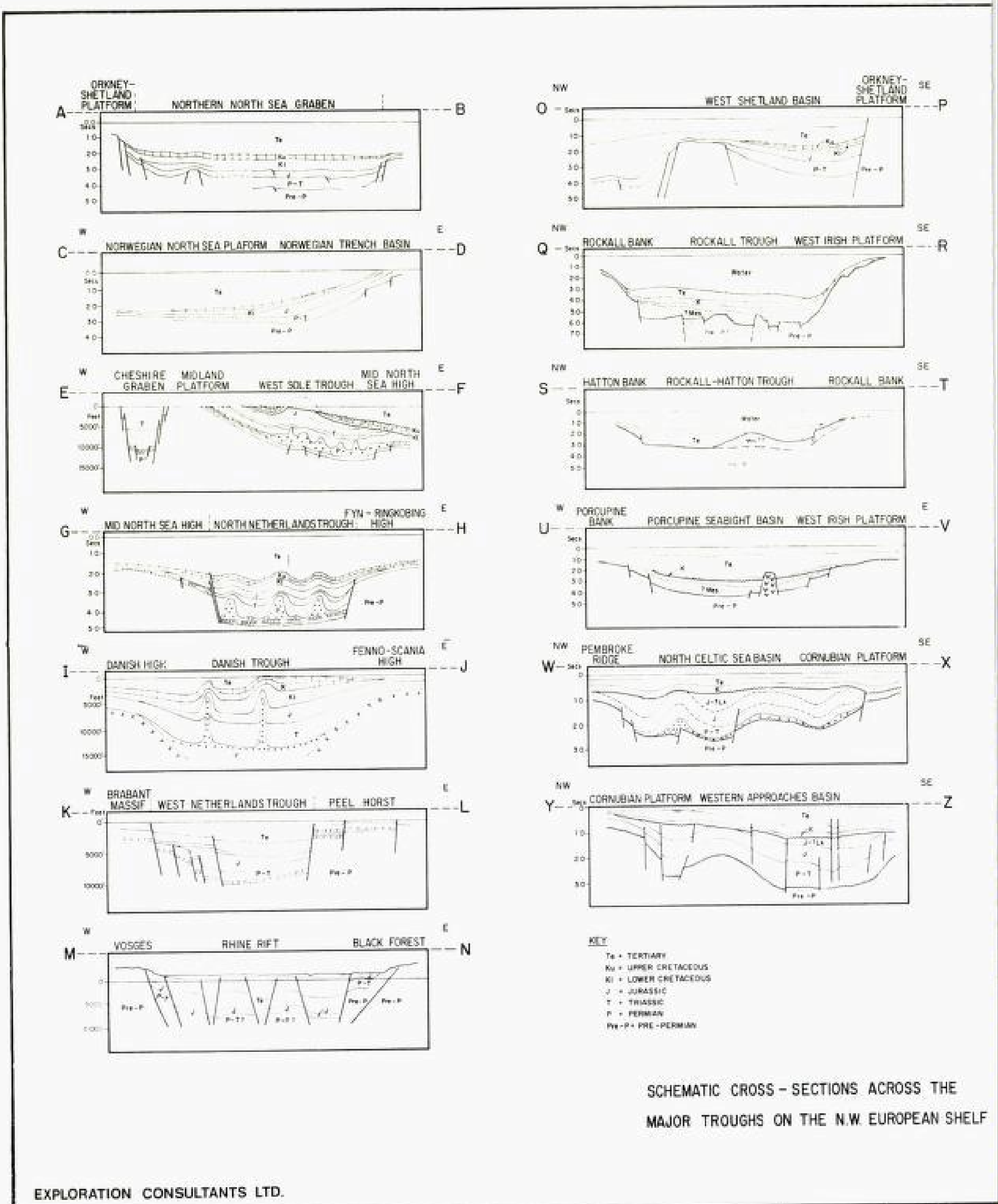


Fig. 2. Geological interpretations based on seismic profiles, North Sea and adjacent areas.

Origin of the Northwest European and Northeast Atlantic trough-platform systems

All these troughs are believed to have deep-seated controls and a common origin, 1) because of the shape, size and structure of the pre-Cenozoic North Sea Troughs and their close association with the Rhine and Oslo rifts, which are known to be underlain by thin crust. (Mueller et al. 1969; I. Ramberg 1972) and 2) because similarly shaped troughs (some complete and some now fragmented and modified) are closely associated with oceanic and thinned crust generated in Triassic time (Bott & Watts 1970 & 1971) or earlier in the troughs are developed over zones of new oceanic crust as in the case of the Hebrides, Orkney and Shetland.

Certain features can be recognized in trough-platform development: *either* the troughs are developed over zones of new oceanic crust as in the case of the Rockall–Hatton and the Rockall troughs (Fig. 2); *or* they evolved over zones of thinned crust (Figs. 2 & 3) as in the Oslo section of the Skagerrak system. They are 'failed arms' in the terminology developed by Burke & Whiteman (1973) and Burke & Dewey (1973).

The sections (Fig. 2) show that sedimentation must have proceeded contemporaneously with crustal development involving: either (i) thinning, spreading and then cessation of spreading, or (ii) crustal thinning, no spreading and failure. The sections also show that the sediment-filled troughs under discussion may be thought of as the near surface expression of deep-seated crustal structures which developed at different rates through Mesozoic time. Troughs then may be used to identify crustally thinned zones.

The majority of the troughs were formed as the Late Palaeozoic Laurasian super-continent began to break up and some of the trilete patterns of the North Sea and Skagerrak (Centres 1, 2 and 5, Fig. 1) may have originated in plume-generated crestal uplifts (Burke & Whiteman 1973) initiated in Late Carboniferous and Early Permian times. The Indefatigable and Mainz systems (3 and 4, Fig. 1) appear to have developed later. The Mainz system (4, Fig. 1) involving the Rhine and Hessen rifts developed much later in the Late Mesozoic and Cenozoic but nevertheless it may be considered as a trilete break-up feature affecting the western part of the Eurasian continent under which plume systems and plume-derived phenomena may have been active in some places as late as Recent (Burke et al. 1973). Troughs forming part of the Indefatigable system may have originated in the Triassic and have been superimposed on Permian basins whose architecture had been blocked out by Hercynian earth movements.

According to crestal uplift hypotheses (Burke & Whiteman 1973, Burke & Dewey 1973) the early stages of continental break-up (as in Mesozoic and Cenozoic Africa) are marked by the development of plume-generated crestal uplifts formed as large quantities of magma are generated near the lithosphere–asthenosphere boundary. During this process rift arms form as tensional structures and meet in triple junctions (rrr – rift, rift, rift) on the crestal uplift; the pattern probably being a least work configuration. Further evolution (without large-scale crustal melting; Burke & Whiteman 1973) involves the intrusion of axial dykes in the r-branches throughout the lithospheric break. The Gregory Rift has just reached this stage. Once dyke intrusion has started then continental rupture can begin as the system develops both longitudinally and laterally, connecting up adjacent plume centres and establishing new ones.

Spreading results only if the movements can be accommodated in the world-wide plate system. If this occurs then the rrr's pass into the RRR's or other combinations of spreading and transform systems as described by McKenzie & Morgan (1969).

A system may then proceed by gravity drive with the plates moving away from the topographically high ridges (Hales 1969, and others) or by the plates being 'pulled down' or subducted by the leading edge (Jacoby 1970).

In some rrr systems dykes are intruded but spreading only takes place on two arms e.g. (Benue Depression, Gulf of Guinea and South Atlantic in pre-Santonian times; Burke et al. 1971) or the system spreads on one arm, transforms on another and the third arm fails (Northern Red Sea, Gulf of Aqaba – Dead Sea and Gulf of Suez). The failed arm becomes a major depocentre infilled with clastics derived from the shoulders of the rift, and from within the rift depression itself, and with physicochemical sediments formed within the rift. Sediments may accumulate to thicknesses around 10 km and depositional conditions frequently approach optimum for the generation, maturation, migration and accumulation of hydrocarbons. Hence failed arms are of considerable interest to the oil industry (e.g. Benue Depression, Niger Delta, Gulf of Suez, North Sea, Barents Sea.) Examples of rrr development occur in many parts of the world and Burke & Dewey (1973) deal with the evolution of 45 selected triple junctions.

It is also conceivable that some (rrr) trilete systems do not reach the lithospheric dyke injection phase in all three arms and that therefore all three arms fail. This could be brought about by rapid plate movements immediately after formation, so carrying the upper crustal part of the structure 'off plume'. Failed rift arms generated in this manner would not remain static but develop into first order depocentres, as would single failed arms which evolve at different rates and in different ways, as the thermal energy derived from the plume system is dissipated.

The trilete structural and depositional pattern which is proposed herein for the North Sea and adjacent areas (Fig. 1 and Table 1) appears to be accountable in terms of the plate development, crestal uplift hypothesis, and the waning history of failed arms. Alternative hypotheses are 1) continental margin development (Bott & Dean 1972) and 2) palimpsest tectonics: in which old lineations find expression in successively younger sediments.

Table 1. Five trilete trough systems postulated for North Sea and adjacent areas

1. The Shetland System consisting of:
   1.1. Northern North Sea or Viking Trough.
   1.2. The Rockall Trough–Faeroes–Shetland Channel.
   1.3. Vøring and Stadt Basins.
2. The Forties System consisting of:
   2.1. The Moray Firth–Forties Troughs.
   2.2. The Ekofisk Trough.
   2.3. The Northern North Sea Graben.
3. The Indefatigable System consisting of:
   3.1. West Netherland and Broad Fourteens Trough.
   3.2. The English Sub-Basin and the West Sole Trough.
   3.3. The North Netherlands Trough.
4. The Mainz System consisting of:
   4.1. The Upper Rhine Graben.
   4.2. Hessen Graben.
   4.3. North Rhine Graben, West Netherlands Trough and Broad Fourteens Trough.
5. The Skagerrak System consisting of:
   5. The highly asymmetrical Oslo Rift and Skagerrak Basin.
   5.2. The Danish–Polish Trough.
   5.3. The West Norway Trough.

(See Fig. 1 for locations).

The Skagerrak trough system

Soon after the Asturian and Saalian climactic phases of the Hercynian orogeny had ended, the Laurasian super-continent began to break apart. It is proposed that a rrr crestal uplift (a potential RRR triple junction) developed under what is now the Skagerrak–Oslo rift trough, the Danish–Polish trough and the fault- and monocline-bounded West Norway Trough (Fig. 1).

In the Oslo Rift, crustal thinning (Ramberg 1972) took place in Late Carboniferous and Early Permian times when a variety of highly complex high-level igneous intrusives were emplaced and lavas were erupted (Oftedahl, *in* Holtedahl 1960).

Rapid easterly plate movement carried the crestal uplift rrr system off the plume energy source so initiating a waning pattern of sedimentary, igneous and structural development. In the Skagerrak area the waning phase lasted through Mesozoic and part of Cenozoic time with igneous activity apparently restricted mainly to the Permian in the Oslo rift. Some igneous activity may have been recorded in Rødby –1 area in Denmark (Sorgenfrei 1969).

Distension tectonics, consequent on thinning of the crust (clearly demonstrable in the Oslo area) resulted in faulting which operated during deposition of sediments and igneous intrusion. Faults cut the youngest Permian lavas and subsidence in the Oslo Rift may have continued well into the Mesozoic and perhaps into the Tertiary. Igneous and sedimentary rocks of these ages are not now known onshore in the rift, but they may well have been intruded and deposited and subsequently eroded since they are present in the Skagerrak section of the rift arm. The present-day Oslo Rift may be regarded as the partially stripped-out section of a southwesterly pitching irregularly floored rift depression.

The Danish Trough, outlined by Mesozoic isopachs (Sorgenfrei 1969; Voigt 1963; Schott 1969) and locally containing as much as 9 km of post-Rotliegendes sediments, is situated between the Danish High and the Basement Complex of the Fennoscandian Border Zone (Fig. 1). Its long linear form may be due to the trough being underlain by thin crust, and subsidence being controlled by crustal thinning tectonics. Because of the great thickness of sediment overlying the 'Basement' and because of the complexities of halokinesis, this trough does not show the same gravity pattern as the Oslo Rift and the Skagerrak Trough, where there are compounded effects of thinned crust, igneous intrusions of Permian and Tertiary age, troughs with thick sediments and platforms with thin sediments.

Marked subsidence took place in the Danish Trough in Permian times. The scale of Rotliegendes (early Permian) subsidence is not known but the Zechstein is thick enough for the salt to have been mobilized. Whether the trough is fault- or monocline-bounded, or both, has never been stated publicly except for northern Jutland (Sorgenfrei 1969). The linearity of the Zechstein boundaries plotted by Heybroek et al. (1967) point to strong, structural, probably fault but possibly monoclinal controls. The Danish trough continued to subside in Triassic and Jurassic times but by Early Cretaceous times subsidence had been greatly reduced and in Tertiary times was comparatively small.

The Polish section of the trough which extends in a southeasterly direction from Høllviken is more than 800 km long and was active from Permo–Triassic, through Jurassic into Cretaceous times. Again the amount of subsidence during the Cenozoic appears to have been much less than in the earlier Mesozoic (Voigt 1963).

Preliminary seismic evidence acquired by the oil industry indicates that thick Permian and Mesozoic sediments occur in the West Norway Trough, which is fault-bounded on the east and probably fault- and monoclinally-bounded on the west (Figs. 1 & 2). It is suggested that subsidence here was controlled by 'necking' associated with the development of the third arm of a Skagerrak rrr system. Like the Oslo Rift this could have been initiated in Late Carboniferous times.

Considering the West Norway, Danish and the Skagerrak–Oslo troughs together, and assuming that plume activity may have needed approximately 30 million years to run from inception to the emplacement of shallow igneous intrusions and surface vulcanicity (in the Cameroon Zone onshore plumes have been operating for more than 30 million years, while in the East African Gregory Rift vulcanicity started 30 million years ago in the Miocene), then plume activity and crustal thinning must have started in Carboniferous time. Surface volcanic activity appeared in the Oslo section in Early Permian times and apparently subsidence started in the Permian, continued through the Triassic, Jurassic and Early Cretaceous, tailing off in the Late Cretaceous and Tertiary in the Skagerrak section of the trough.

The median North Sea trough systems

As three possible systems may be involved in the North Sea area their developments are necessarily more difficult to decipher than the Skagerrak system. Also much wider issues are involved at the Atlantic and Alpine ends of the trough systems and the present data need integrating with the existing knowledge of these areas. Most of the data are derived from the offshore subsurface and only a limited amount are available in the public domain. This is turn prevents us from accurately drawing in our trough and platform boundaries.

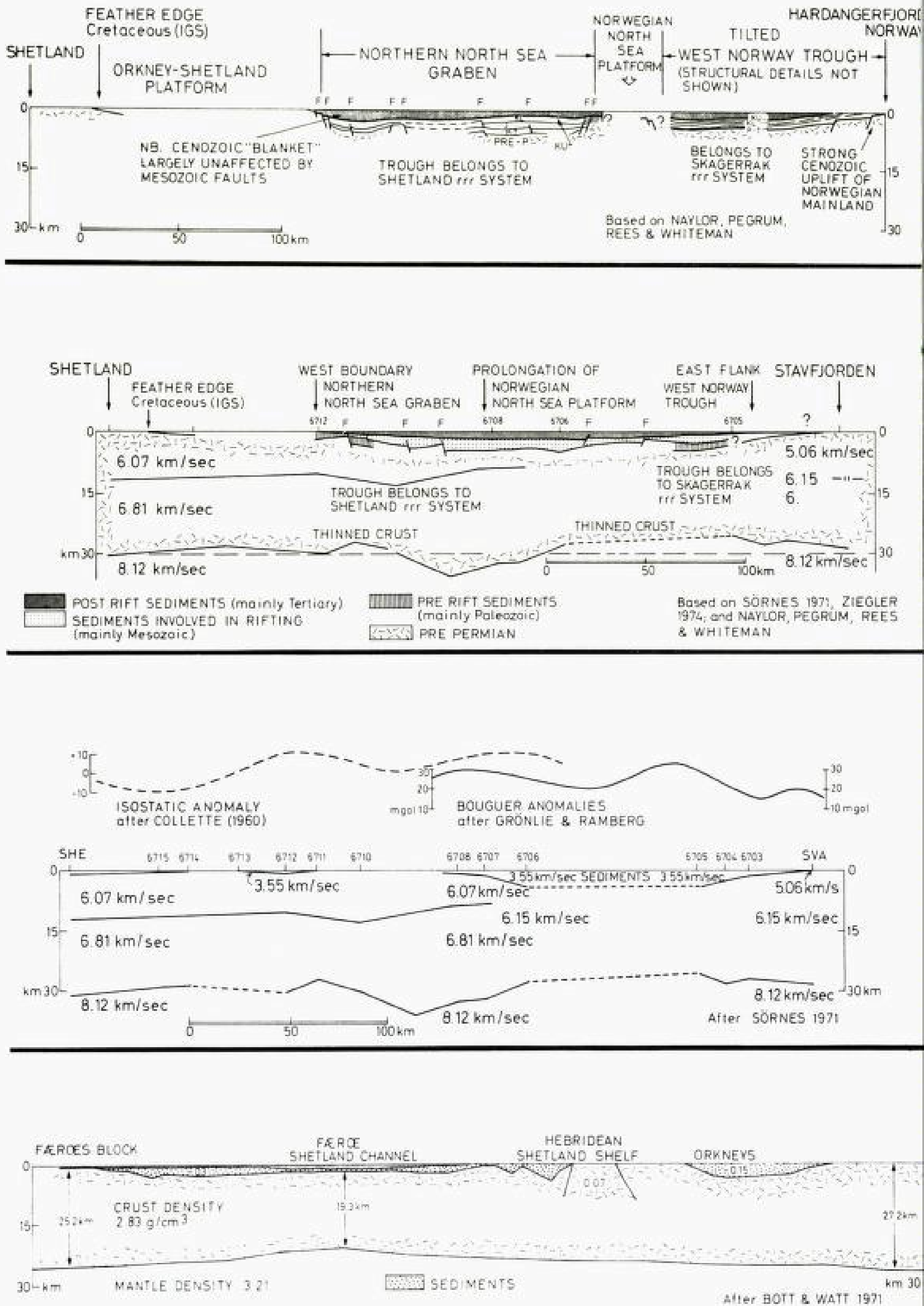
NORTHERN NORTH SEA GRABEN – VIKING GRABEN

The northern limit of this trough has still to be defined. It appears to extend to the Faeroes–Shetland section of the continental slope lying south and west of the Jan Mayen Fracture Zone (Fig. 1). Whether the structure continues into the Cape Brewster–Scoresby Sound area in Greenland, which in a Late Palaeozoic–Early Mesozoic reassembly lies in juxtaposition to the northern North Sea is not clear. It is unlikely in our view. Much of the area between the continental margins of Norway and Shetland and Greenland, and between the Jan Mayen and Iceland–Faeroes fracture zones consists of 'new' crust.

The spreading history of the Norwegian Sea (Johnson & Heezen 1967; Talwani & Eldholm 1972) clearly indicates that the Northern North Sea pre-Late Cretaceous Trough was formed before the 'dormant' or 'dead' spreading ridges which occupy the southeastern Norwegian Sea. These were actively spreading from 42 to 60 m.y.a. (Anomalies 18–24) and are not connected with the formation of the Northern North Sea Trough. Indeed at this time (Early Eocene) the North Sea Basin overall was steadily subsiding under a thick sequence of marine sediments while interconnected uplift was taking place around the margins of the basin in Britain, Norway and elsewhere. The marine transgression which started in the Late Cretaceous with the widespread deposition of the Chalk blanket continued into the Tertiary and the basin development clearly shown by isopachs (Heybroek et al. 1967; Pegrum 1970) is believed to be related to the rapid opening of the North Atlantic and regional adjustment of the newly developed continental margins of which the North Sea is a part.

Other dimensions of the Northern North Sea trough have been described publicly only in very general terms (Armstrong 1972; Hinde 1972; Pegrum 1970; Dunn et al. 1973). The structure may have a width of 150 km in the north but narrows considerably in the south, where it merges with the Forties Troughs and the Ekofisk Trough.

A shallow seismic profile across the northern end of the trough extends from the Northern Shetland shelf to the Norwegian coast off the mouth of Hardanger Fjord (Talwani & Eldholm 1972). The Tertiary appears to be greater than 1.5 km thick on their maps. Other published isopachs (Dunn et al. 1973) indicate thicknesses of between 6000 and 8000 ft. (1.82–2.43 km)


FEATHER EDGE
Cretaceous (IGS)
SHETLAND
ORKNEY-SHETLAND PLATFORM
NORTHERN NORTH SEA GRABEN
NORWEGIAN NORTH SEA PLATFORM
TILTED WEST NORWAY TROUGH
(STRUCTURAL DETAILS NOT SHOWN)
HARDANGERFJORD NORWAY
NB. CENOZOIC "BLANKET" LARGELY UNAFFECTED BY MESOZOIC FAULTS
TROUGH BELONGS TO SHETLAND rrr SYSTEM
PRE-P
BELONGS TO SKAGERRAK rrr SYSTEM
STRONG CENOZOIC UPLIFT OF NORWEGIAN MAINLAND
Based on NAYLOR, PEGRUM, REES & WHITEMAN
SHETLAND
FEATHER EDGE
Cretaceous (IGS)
WEST BOUNDARY NORTHERN NORTH SEA GRABEN
PROLONGATION OF NORWEGIAN NORTH SEA PLATFORM
EAST FLANK WEST NORWAY TROUGH
STAVFJORDEN
6.07 km/sec
6.81 km/sec
8.12 km/sec
TROUGH BELONGS TO SHETLAND rrr SYSTEM
TROUGH BELONGS TO SKAGERRAK rrr SYSTEM
THINNED CRUST
5.06 km/sec
6.15
POST RIFT SEDIMENTS (mainly Tertiary)
SEDIMENTS INVOLVED IN RIFTING (mainly Mesozoic)
PRE RIFT SEDIMENTS (mainly Paleozoic)
PRE PERMIAN
Based on SÖRNES 1971, ZIEGLER 1974; and NAYLOR, PEGRUM, REES & WHITEMAN
ISOSTATIC ANOMALY after COLLETTE (1960)
BOUGUER ANOMALIES after GRÖNLIE & RAMBERG
SHE
SVA
3.55 km/sec
3.55 km/sec SEDIMENTS
6.07 km/sec
6.15 km/sec
5.06 km/s
6.81 km/sec
8.12 km/sec
After SÖRNES 1971
FÆROES BLOCK
FÆROE SHETLAND CHANNEL
HEBRIDEAN SHETLAND SHELF
ORKNEYS
CRUST DENSITY 2.83 g/cm3
MANTLE DENSITY 3.21
SEDIMENTS
After BOTT & WATT 1971

for the Cenozoic. The broad regional relationships of the Northern North Sea Graben, the Norwegian North Sea Platform and the West Norway Trough and related crustal thinning are shown in Fig. 3, which is based on data from Fig. 2 (this account); Zeigler (in press) and Sørnes (1971).

The lowermost Tertiary is partly fault-bounded on the west against the Orkney–Shetland platform but the higher Tertiary rocks overlap and rest non-conformably on the crystalline and metamorphic Basement complex and the Devonian (O.R.S. facies). The eastern boundary of the Northern North Sea Trough is also faulted along the western margin of the Norwegian North Sea Platform (Figs. 1, 2 & 3). The 'graben' is some 500 km long, extending from the Faeroes–Shetland 'Escarpment' in the region of 67°N, to the trilete junction with Forties Embayment and the Ekofisk Trough (Fig. 1), which may be a failed rrr triple junction.

The floor of the graben is block-faulted, schematically shown in profile (Fig. 1) and the trough is thought to contain a thick sequence of Permo–Triassic, Jurassic and Cretaceous rocks which have been proven to be highly prospective for oil and gas.

Within the Northern North Sea Trough the structure is much more complex than we are able to show, and there may be several Mesozoic unconformities present, including the important Late Jurassic (Kimmerian) phase of epeirogenic uplift and unconformity. This phase of widespread uplift has been documented further south in the Southern North Sea (Heybroek et al. 1967; Kent & Walmsley 1970; Pegrum 1970). The total post-Palaeozoic sediments in this trough must exceed 6 km in thickness, of which the Cenozoic may account for 1.5 km and the Mesozoic 4.5 km.

Regarding the structural history of the Northern North Sea Trough the following observations can be made: 1) Bott & Watt (1971) believe that the Rockall Trough was formed by ocean floor spreading in Permo–Triassic times; 2) It has been suggested that a zone of thinned crust underlies the Shetland–Faeroes Channel (Fig. 1); 3) We postulate that this zone of crust thinned in Permo-Triassic time (now considerably modified by continental margin adjustments of the type described by Pegrum & Rees 1973; Bott & Watts 1971; Hall & Smythe 1973; McQuillin & Binns 1973) and may have extended north-eastwards to meet the Northern North Sea Trough. It seems that there was a Late Carboniferous–Permian–Triassic Northern North Sea Trough which formed part of a Shetland rrr triple junction (Fig. 1), of which the third arm lies under the Vøring Basin and the (?) deeper but smaller Stadt Basin. Such a trough system could have provided the Southern North Sea–German–Dutch–British Rotliegendes and Zechstein basins with the connection to the open Permian ocean to the north.

Again the lack of available data (Sellevoll & Sundvor 1973; ECL Report 1972; Talwani & Eldholm 1972) prevents us from saying very much about

Fig. 3. Geological, seismic and gravity cross-sections, Northern North Sea and Faeroes–Orkney, showing crustal thinning and relationship to trough development.

the structural history of the Vøring and Stadt basins, but the shape of the basins, the presence of salt diapirs, and the fact that the basins have developed on continental crust may point to some unusual deep-seated structural control (Fig. 1). Hinz (1973 has recently postulated that the crust is thin under the Vøring Basin.

In conclusion, then, we think that there is a possibility that a trilete trough system may have existed between Norway and Scotland and Greenland in Late Carboniferous and Early Permian times and that the Northern North Sea graben began to develop as long ago as the Late Carboniferous.

THE FORTIES-MORAY FIRTH TROUGHS

The westward and landward end of the Moray Firth Trough was described by Dunham (1972). The northern and southern boundaries are, in part, fault-bounded, enclosing a trough containing Devonian, Permo–Triassic, Jurassic, Lower and Upper Cretaceous sediments (Fig. 1). Permo–Triassic and Jurassic rocks crop out on the margins of the Moray Firth Basin and are extensively faulted, whereas the Permo–Triassic at the south end of the Midland Valley is unaffected by faults which clearly pre-date these rocks.

A trough with locally thick Mesozoic sediments extends from the Ekofisk Trough into the Forties and Moray Firth Troughs and contains the Forties, Montrose and Piper fields. The Permo–Triassic rocks in 'red bed facies' and Jurassic and Lower Cretaceous rocks in marine and deltaic facies are over 1.5 km thick in this trough. In the Forties Field area, the trough is more than 105 km wide but it narrows considerably at its western end due to the south-easterly downthrow of the Great Glen Fault (Fig. 1). Howitt & Aston (in press) have described extensive Forties–Piper area basalts from trough intersection.

EKOFISK TROUGH

The Moray Firth Trough merges with the Ekofisk Trough (2, Fig. 1), which is the least documented of the North Sea troughs. Its eastern margin is possibly fault-bounded beneath the Cenozoic and constitutes the western boundary of the Norwegian North Sea Platform (Figs. 1 & 2), the narrow northward extension of the Fyn–Ringkøbing High or Danish High (Hinde 1972; Dunn et al. 1972).

The western boundary is also fault-bounded (en échelon) with the main fault zone lying to the east of the Shell Auk 30/16 Field. The Auk field has a Zechstein reservoir (Armstrong 1972) and may be located on the upthrow side of the fault zone. The Hamilton Argyll Field in Block 30/24 is situated along strike with a Lower Permian reservoir. This suggests that the western margin of the trough is locally a Mesozoic platform or ridge extending north-westwards from the Mid–North Sea High in a similar manner to the Norwegian North Sea Platform, which is an extension of the Danish High (Fig. 1).

Beneath the thick Cenozoic cover (up to 3.5 km according to Armstrong 1972) there are thick Triassic and Jurassic sediments often updomed by halokinetic Zechstein salt structures, The Cod, Ekofisk, Torfield and Josephine discoveries are located within the trough. At its northern end (Fig. 1) it is about 60 km wide between the Mid–North Sea High and the Danish High.

Again, the trilete trough pattern formed by the Moray Firth, Northern North Sea and Ekofisk troughs may have had its origin in a Late Carboniferous –Early Permian crestal uplift. We would, on the other hand, be dealing with the chance interlocking of faults, the trends of which were determined by structures generated along Charnian, Caledonian and Hercynian lines (palimpsest tectonics). Many more data are needed to resolve the question; although we strongly favour the trilete explanation, especially because of the existence of a large Jurassic (Late) volcanic basalt pile (Howitt & Aston, in press).

NORTH NETHERLANDS TROUGH

The Ekofisk Trough connects with the North Netherlands Trough, (Figs. 1 & 2) a fault-bounded structure situated beneath Cenozoic and Upper Cretaceous strata; bounded on the east by the Danish High (Fyn–Ringkøbing High) and on the west by the Northumbrian Arch–Mid–North Sea High. The trough links with the Broad Fourteens Trough along the western margin of the Texel or Mid–Netherlands ridge but as with the link with the West Sole Trough, relationships are difficult to decipher because of a complex fault pattern, strong halokinesis and lack of detail.

The North Netherlands Trough is infilled with sediments of Permian Triassic, Jurassic and Lower Cretaceous age. Upper Cretaceous and Cenozoic sediments extend well beyond the graben and bury the flanking platform highs. Clearly there was marked differential subsidence in the Mesozoic brought about by the so-called 'rim trough' mechanics (Voigt 1963). This was followed by broad regional subsidence in Late Cretaceous and Early Cenozoic times. The trough contains large sub-linear, north-south trending Zechstein salt walls and internal block faults. Halokinetic structures here clearly deform the Tertiary sediments (Fig. 2). Locally the northern part of the North Netherland Trough is called the West Danish Trough and is noted for its thick Jurassic sequence.

Several kilometres of pre-Late Cretaceous sediments must have accumulated in the North Netherlands Trough, which was probably initiated in Late Carboniferous and Early Permian times and formed part of the link (1 & 2, Fig. 1) between the northern Permian ocean and the English and German Permian Basins. Such a link has been sketched or is implied in maps produced by Wills (1951), Heybroek et al. (1967) and Pegrum (1970). This trough system remained a main connecting seaway with the open ocean throughout Triassic, Jurassic and early Cretaceous times, frequently marked by deeper water sediments.

WEST SOLE TROUGH

A broad east-west trending basin known generally as the Southern North Sea Basin is outlined by Mesozoic isopachs and lies between the Mid-North Sea High to the north, the Pennine High on the west and the London–Brabant

Massif or Platform to the southwest (Heybroek et al. 1967; Kent & Walmsley 1970; Pegrum 1970) (Fig. 1). In the deeper part of this basin there are more than 2–3 km of Mesozoic sediment.

The West Sole Trough lies in the eastern half of this basin and is situated en échelon with the Broad Fourteens Trough described below. These two troughs are separated by an area which was uplifted in Late Jurassic times (Late Kimmerian epeirogenic movements). The Viking and Indefatigable gas fields are located on this uplift. The West Sole Trough extends onshore into Yorkshire and Durham and across the Southern North Sea (Fig. 1). The trough is a 'half graben' flanked to the southwest by the East Midland and London–Brabant Platforms. Its north-eastern margin is ill-defined.

The interpretations of the structure and stratigraphy of the West Sole Trough are difficult because of the complications produced by strong halokinetic deformation of the Zechstein salt. The trough is infilled by Triassic, Jurassic and probably Lower Cretaceous sediments and its axial zone has been deeply eroded consequent on Late Cretaceous uplift (inversion). Data illustrating the regional structure of the trough have not yet been published but the Hewett, West Sole, Leman and the Viking–Indefatigable gas fields associated with it have been described (Kent & Walmsley 1970).

Again we believe that the trilete pattern (3, Fig. 1) is highly suggestive of deep structural control but many more data are required to prove the point.

From published data it is not clear to what degree the margins of the Permian English sub-Basin and German Basin are fault- and monoclinally controlled. The data which have been released indicate that the basin framework was strongly controlled by Hercynian structures. Certainly the limits of the Rotliegendes sandy facies and the porous Zechstein facies show a strong WNW–ESE Hercynian trend, and palimpsest tectonics probably provides the best explanation of basin architecture for the English and German Permian Basins. Available isopach evidence certainly does not show a trilete pattern in the Permian.

If our ideas are accepted then the Indefatigable system must be younger (Triassic–Jurassic–Early Cretaceous) than the Shetland and Forties systems where the stratigraphy points to a Late Carboniferous and Permian existence of the troughs.

BROAD FOURTEENS TROUGH–WEST NETHERLANDS TROUGH–LOWER RHINE GRABEN

The Broad Fourteens Trough is a fault-bounded linear structure flanked to the southwest by the London–Brabant Platform and to the northeast by the Mid-Netherlands or Texel Ridge (Fig. 1). Considerable subsidence took place in Late Jurassic and Early Cretaceous times with almost 2 km of sediments accumulating in the trough. Sediments of this age are either thin or absent on the flanks. The northwestern end of the trough is structurally complicated because the Zechstein salt is halokinetically deformed. Again, published data on this basin are lacking.

A schematic section across the West Netherlands Trough (Fig. 2) indicates that the majority of the faults associated with the structure are clearly of pre-Tertiary age but that others affect the Tertiary. The existence of Tertiary faults taken together with the development of the Rhine Delta complex indicates that the trough is still actively subsiding. Subsidence appears to have taken place more rapidly in parts of the Jurassic, Lower Cretaceous and Tertiary, all of which are considerably thicker in the trough than on the flanks (Haanstra 1963).

The West Netherlands Trough is continuous with the Lower or North Rhine graben. Together they are more than 350 km long and both have had similar sedimentary histories.

DEVELOPMENTS OF SOUTHERN NORTH SEA TROUGHS

From the sparse published information on the Southern North Sea a preliminary systematic account of trough development can be presented, but a detailed explanation of the origin of the pattern certainly cannot be made at this time.

Permian isopach and facies patterns point to important Hercynian control of the Rotliegendes and Zechstein basin frameworks. Rotliegendes isopachs (Dunn et al. 1973) show elongate eastward trends swinging to south of east in south Denmark and northwest Germany. The 1000 ft isopach shows a marked linearity, which may reflect some structural control.

A well-defined north-south trending trough bounded by the 1000 ft isopach extends into the Broad Fourteens area towards the West Netherlands graben, again perhaps indicating some degree of structural control.

The area enclosed by the 1000 ft isopach (Dunn et al. 1973) broadens eastwards and encloses the area of deposition of the Haselgebirge (halite) facies of North Germany. This facies exceeds 1 km in thickness.

Permian volcanics occur on the northern and southern sides of this trough, east of Groningen and beneath eastern Denmark, at Rødby, for instance, and are believed to be present on the margins of the Northern North Sea Trough, but hitherto the structural setting of these volcanics has not been discussed in relation to the Permian break-up of the Northwest European plate.

It is only in the northern part of the Rotliegendes and Zechstein depositional basins that there is any obvious indication of structural control of sedimentation (Heybroek et al. 1967; Sorgenfrei 1969; Pegrum & Rees 1973). Here the zero isopach in the Norwegian, Danish and German sectors clearly defines a trough centred on the North Netherlands Trough which was later filled with thick Triassic, Jurassic and Cretaceous rocks. The Rotliegendes thicknesses are less than 150 m and the trough opens northwards into the Northern North Sea.

Dunn et al. (1973) did not present Zechstein isopachs and the only reliable information available has been supplied by Heybroek et al. (1967), who gave general spot depths for these base of the Zechstein and the 3.5 km structure contour on the base of the Zechstein. The English and German basins are clearly defined by this contour.

The limits of the Zechstein shelf carbonate and anhydritic facies show some degree of structural control in the West Netherlands Trough, but the Zechstein facies boundary transgresses the limits the Broad Fourteens and West Sole troughs, which are mainly Kimmerian and Laramide features, i.e. Late Jurassic and Late Cretaceous.

There are strong linear Zechstein salt piercement structures and pillows in the North Netherlands Trough, which links with the Ekofisk Trough.

Two different sets of isopachs are available for the Triassic rocks of the Netherlands (Haanstra 1973; Dunn et al. 1973). Haanstra shows a thin Triassic in the Netherlands thickening northeastwards and ranging from 250 to 500 metres. Marked thickening also occurs along the German–Dutch frontier where strata of this age are from 500 to 1300 m thick. Dunn et al. (1973) do not show this embayment near the Dutch–German border, but show a 5000 ft thick sandy Trias in the West Netherlands–Broad Fourteens troughs. Similarly, the Sole Pit Trough is defined by a 4000 ft. isopach. The North Netherlands Trough (Central North Sea Trough of Dunn et al.) is shown as containing more than 8000 ft of Triassic sediments. The axis is generally coincident with the Zechstein trough.

By Jurassic time more than 1 km of sediments had accumulated in the West Netherlands–Broad Fourteens troughs, and the North Netherlands Trough is shown as a major depocentre with more than 4000 ft of sediments (Dunn et al. 1973). The Jurassic sediments are predominantly marine and mark the first *major* marine incursion into the area since Early Carboniferous times. Sedimentation was complex and was strongly influenced by structure. Thick sediments were deposited in the Northern North Sea, the Ekofisk and the North Netherlands troughs at this time. Markedly differential movements took place. Sole Pit Trough (Heybroek et al. 1967; Kent & Walmsley 1970) developed between the London–Brabant Massif and the Mid-North Sea High; and the West Netherlands and Broad Fourteens troughs between the London–Brabant Massif and the Mid-Netherlands Ridge. The North Netherlands Trough (Heybroek et al. 1967) developed between the Danish (Fyn–Ringkøbing) and Mid-North Sea highs (Fig. 1). The Groningen structure (Stauble & Milius 1971) and probably the Leman and Viking–Indefatigable structures (Kent & Walmsley 1971) were probably formed at this time.

Widespread erosion followed the strongly differential epeirogenic Late Jurassic movements, and over large areas the Jurassic was stripped off and erosion extended deep into the Triassic and locally as deep as Zechstein (Brunstrom & Walmsley 1969; Kent & Walmsley 1970; Pegrum 1970). Voigt (1963) has described the effects of these movements on land.

A very significant feature is the area extending from the eastern margin of the Mid-North Sea High into the Northern North Sea, in which the Upper Cretaceous directly overlies Zechstein carbonates. This area is believed to be an asymmetrical fault-controlled block, which Dunn et al. (1973) suggest was emergent for much of the Upper Mesozoic and/or suffered deep Kimmerian erosion. This ridge flanks the deep Ekofisk trough and could be regarded as one of the horst blocks bordering the Ekofisk graben, which has been buried only by Tertiary subsidence and sedimentation.

Some of the troughs continued to subside during the Early Cretaceous and all appear to have been affected by epeirogenic movements during the Late Cretaceous and Early Tertiary (Laramide) phase (Voigt 1973). As elsewhere in the North Sea the Tertiary was a period of overall subsidence (Pegrum 1970; Heybroek et al. 1973) with minor transgressive and regressive phases recognizable (Brouwer 1963).

Upper Rhine Graben and Hessen Graben

As mentioned above, the West Netherlands Trough continues into the Lower or North Rhine graben and meets with the Hessen and Upper Rhine grabens in the Mainz area (Cloos 1939). The Upper Rhine Rift, which breaks across the Odenwald, Schwarzwald and Vosges, is the best known of these structures (H. Cloos 1939; Illies 1962; Picard 1968, Mueller et al. 1969; Sittler 1969).

The Upper Rhine graben is more than 300 km long and extends from the folded Jura Mountains to the Mainz area. It is generally in excess of 40 km wide and trends north-northeast into the Mannheim region, where it becomes more or less north-south. The average throw on the eastern side of the northern section of the graben is 4 km and in the Heidelberg area it is perhaps as much as 5 km (Andres & Schad 1959). On the western border the throw is estimated at 2–3 km.

The initial movement of the principle Upper Rhine graben faults may have started in the early Mesozoic and probably resulted in the deposition of distinctive Jurassic facies in the trough (Bruderer & Louis 1958). However, others (e.g., Sittler 1969) maintain that the deposition of the Mesozoic sediments was not controlled in any way by the Rhine graben. Liassic isopachs do not show a correlation with graben structure, for example. Generally speaking total thickness decreases regionally southwards (Sittler 1969).

The Cretaceous is not present in the graben (Bruderer & Louis 1958; Sittler 1969) and Middle Eocene deposition was restricted to small lacustrine basins. The trough deepened in Late Eocene and Oligocene times. Early Oligocene (Lattorfian) subsidence was greatest in the south and 1,500–2,000 metres of saliferous marls were laid down in the Mulhouse potash Basin. About 500 m of Pechelbronn oil-bearing marls accumulated in the north.

In Rupelian times (Middle Oligocene) thick grey marls were laid down in an arm of the sea which extended from the North Sea, and in Late Oligocene and Miocene times the trough subsided mainly in the north. The sea gradually withdrew in this direction. Some 2,000 metres of marine, brackish to fresh water formations accumulated and are overlain by 300 metres of Quaternary alluvium.

Younger volcanism is concentrated mainly away from the rift in the Eifel, Laaken, Neuweld, Siebergebirge and Westerwald areas, as it is in some other rift areas. The Kaiserstuhl is the main centre of volcanism in the southern part of the Upper Rhine graben and was active some 20 million years ago.

Opinions vary concerning the deep structure and mode of formation of the Mainz system, especially concerning the Upper Rhine arm. A 'rift cushion' with a compressional velocity of 7.6–7.7 km/sec. is 'considered to be the driving mechanism of the rift process' (Mueller et. al. 1969). Exactly how this operated is not made clear, especially as the rift cushion has a thickness of 15 km and an east-west extension of 200 km and the rift is asymmetrical with respect to the anomalous zone. The fault-bounded zone is nearly everywhere only 50 km wide. Whatever the detailed geophysical interpretation, it appears that some crustal thinning and modification have taken place and the Upper Rhine graben has resulted from crustal thinning tectonics. The date of initiation of the structure is less clear from the geological evidence.

Also, there are fundamental differences between the deep structure of this graben system and the Northern North Sea graben resulting from age differences and patterns of development (Fig. 3). The Northern North Sea graben is an old (initiated in Late Carboniferous and Permian) failed arm, whereas the Rhine graben appears to be in the early uplift stage of the sequence proposed by Burke & Whiteman (1973), having been initiated in the Late Mesozoic & Early Cenozoic. There is, however, possible evidence of a Permian age for some of the bounding faults.

The gravity pattern is also not readily explainable. Unlike the Oslo Rift, it is underlain by negative anomalies which appear to be basin-located; the main gravity low being situated near the eastern side of the rift, west of the Odenwald, where the sedimentary rocks are thickest.

The northeastern arm of the Mainz triple trough is the Hessen graben, which is more than 200 km long. The Vogelsberg shield volcano separates the Frankfurt section of rift from the Kassel section. Immediately north-northeast of the Vogelsberg the fault belt is narrow and is only 30 km wide (*International Geological Map of Europe* 1:1.5,000,000 Ed 1972) but widens markedly towards Hamelin, and east of the Teutoburgerwald it is more than 80 km wide.

Considering the three arms of the Mainz structure it appears that separation of the French and German blocks has not taken place and that axial dykes have not been intruded. Crustal modification and thinning have taken place, however, and the long narrow isopach patterns and the faulted and monoclinal margins of the troughs point to crustal thinning controls.

Regional uplift associated with the Mainz structure has been considerable (Cloos 1939; *International Geological Map of Europe* 1972). This is evident from the dispositions of the erosional boundaries of various Mesozoic formations. The uplift and trilete rift pattern was tersely described by Cloos (1939) as the result of 'Hebung, Spaltung und Vulkanismus'. Burke & Dewey (1973) believed that it is plume generated.

West Britain grabenal system

A system of grabens is developed on the continental shelves around the western shores of the British Isles. Whereas the linear troughs of the Western Approaches and Celtic Sea bear striking resemblance to those of the North Sea, the troughs along the Atlantic margin are less obviously part of an interconnected grabenal system. The evolution of the Late Mesozoic–Cainozoic continental margin has clearly influenced this latter group of troughs.

WEST SHETLAND BASINS

Reconnaisance geophysics conducted by the Institute of Geological Sciences and by several universities in the late 1960's revealed a series of elongate SW–NW trending basins on the continental shelf west of Scotland and the Orkney–Shetland islands. These basins — the West Shetland Basins — are filled with low velocity sediments which contrast strongly with the adjacent basement rocks. Bott & Watts (1970, A & B) outlined four main sedimentary troughs separated by areas of shallow basement. A marked north-easterly trending feature — the West Shetland Platform — forms a gravity high and is interpreted as one of the basement highs. Magnetic anomalies and sparker profiles confirm that basement metamorphic rocks crop out on the sea floor in this area. To the west of this feature are several sedimentary basins characterized by gravity lows. Two of these basins, D & E of Bott & Watts (1970), have been confirmed by gravity, magnetic and sparker records. Basin E may be 5.2 to 7.7 km deep, assuming a density contrast of 0.4 to 0.5 g/cm^3 while Basin D may be 3.4 to 5.0 km deep using the same density contrast. Seismic profiles across Basin E (Fig. 2) show landward-dipping sediments unconformably overlain by seaward-dipping strata which thicken to at least 1500 ft on the continental slope. The sediments occupying the deeper part of Basin E and lying beneath the unconformity are likely to be Mesozoic in age. Also, it is worthwhile noting that the Faeroes–Shetland Channel is underlain by thinned crust (Fig. 3).

The faults outlined by Feir (1971) from a reconnaisance reflection seismic programme show a remarkable agreement with the margins of the basins outlined by Bott & Watts (1970 & 1971). The faults bounding Basins C, D and E are thought to have displacements in the order of 3000–5000 m. In general, the more prominent faults downthrow to the west but there are a number of lesser faults downthrowing to the east.

Corroboration of the presence of Mesozoic rocks in these basins is provided by samples dredged from the sea floor just north of the Minch and by the likelihood of the 13,000 ft Stornoway Formation being Permo–Triassic in age, rather than Torridonian (Steel 1971 and in press).

ROCKALL PLATEAU AND TROUGHS

The structure of Rockall Plateau has been discussed by Roberts (1971), Scrutton & Roberts (1971) and Scrutton (1972). There is a general agreement that the Rockall plateau is a fragment of continental crust, laterally displaced from N.W. Europe by the mechanism of sea-floor spreading. Reflection and refraction seismic work conducted by Scrutton & Roberts (1971) established velocities of 3.8 km–6.36 km/sec, compatible with that of continental crust. Only a thin veneer of sediment is indicated on Rockall and Hatton Banks but the reflection profiles reveal a thick sequence of layered sediments in the Rockall and Rockall–Hatton Troughs. Subdued magnetic lineations in the Trough indicate spreading which appears to have occurred during the Lower Cretaceous. The trough was certainly in existence in Mid to Late Cretaceous times and crustal thinning and spreading may have begun much earlier — in the Jurassic or Triassic.

At least 10,000 feet of sediments are present in the Rockall Trough (Scrutton 1972). Refraction profiles in the Hatton–Rockall Basin show 1700–2350 feet of relatively unconsolidated sediments (5600 ft/s to 7880 ft/s), which can be correlated with Middle–Upper Tertiary sediments of the Joides Borehole No. 116. The underlying 4000–5000 feet of strata with a velocity of 9450 ft/s corresponds to the Eocene/Paleocene of the Joides 116 and 117 sites (Laughton 1972) and an even deeper layer some 10,000 ft thick has a velocity of 14,500–15,000 ft/s. The latter interval, which could be sedimentary or volcanic lavas, rests on a high velocity 22,000 ft/s layer that can be correlated with the crust beneath Rockall Bank.

To summarize, both Hatton and Rockall Banks have a shallow acoustic basement of continental crust, and are covered by a relatively thin veneer of Upper Tertiary sediments. Rockall Bank has a number of fault-bounded sedimentary basins with up to 1 sec of Lower Tertiary strata. Rockall Trough has a much thicker sedimentary sequence and may have been initiated as a graben in the early Mesozoic infilled in part with Triassic. A later marine incursion in the Upper Late Mesozoic was related to the spreading of the trough. At the same time there may have been an abortive attempt at opening the Rockall–Hatton Basin, resulting in crustal sag. Although there is considerable crustal thinning there is no indication of oceanic crustal material (Roberts 1971).

PORCUPINE BASIN

Porcupine Banks and Sea-bight have attracted considerable attention in recent years. (Gray & Stacey (1970), on the basis of some 500 km of seaborne gravity and magnetic work, suggest that later displacement of the Porcupine Bank relative to the main continental mass of Ireland has resulted in crustal thinning.

Porcupine Bank is a large shallow water area on the continental margin of western Ireland about 250 km from the mainland. The Bank is separated from the Irish shelf by a north-south trending trough, the Porcupine Sea-bight. Porcupine Bank is characterized by NE–SW Caledonoid magnetic lineations and the recovery of metamorphic and ancient igneous rocks (Stride et al. 1969) indicate shallow Caledonian basement. The Slyne Ridge linking Porcupine Bank to the mainland probably has the same structure. Gray et al. (1971), from seismic reflection and refraction and magnetic data, conclude that the Sea-Bight basin contains about 5 km of sedimentary section. From the refraction data they define six velocity layers. Layer 5 (5.1 km/sec) may represent Older Paleozoic or metamorphic rocks and the underlying and deepest recognizable Layer 6 (7.7 km/sec) an intermediate layer of the earth's crust. Layer 4 (4.4 km/sec) probably represents Permo–Triassic to Lower Cretaceous strata and the overlying layers (Layers 1–3) successively younger rocks.

At the northern end of the Sea-Bight Trough the sedimentary fill is affected by folding and marginal faulting (Bailey et al. 1970). The faults propagate from acoustic basement, show an upward diminution in throw and fail to affect the younger reflectors. They show displacement down into the axis of the trough.

A sediment-filled trough, the Slyne Trough, forms a north-eastward shallower arm of the Sea-Bight Trough, cutting across the east-west trending Slyne Ridge. The relationship of the Slyne Trough to the shelf margin basins farther north is not known.

WORCESTER GRABEN, CHESHIRE AND IRISH SEA BASINS

A complex of connected rift valleys formed on the west side of the Pennine axis in England during Lower Permian times. This development has been documented by Wills (1956), who refers (p. 107) to a 'large-scale rift valley trending from the present Irish Sea and West Lancashire . . . south southeastwards to Worcester and Gloucester'. The inferred great thickness of Permo–Triassic strata has recently been confirmed by the drilling of the Prees–1 well in the Cheshire graben. The well spudded on an outlier of Lias and is the deepest boring, to date, in Britain. A considerable portion of the 12,500 feet penetrated was most likely in beds of Permo–Triassic age.

The Cheshire–Worcester graben system continues northwards into the Irish Sea and may be part of the Solway–Stranraer–Minches grabenal systems. To the south, Permian sediments occur in the graben only as far south as Worcester. During the Triassic, however, sedimentation extended further south, probably as the topographic expression of the grabenal structure became more marked.

WESTERN APPROACHES–CELTIC SEA BASINS

The Western Approaches and Celtic Sea margin has been the subject of several studies following the pioneering work of Bullard & Gaskell (1941), Hill & King (1954) and Hill & Vine (1965). Again there appear to be a number of linear basins or grabens with sedimentary fill of probably Upper Paleozoic (Day et al. 1956) to Lower Cretaceous age. Upper Cretaceous and Tertiary sediments blanket the older rocks with marked unconformity, transgressing both basin and platform areas. In the Western Approaches basin sediments of post-Carboniferous age may be up to 10,000 feet thick (Day 1959). This basin extends eastwards into the Channel and is confined to the north by the Cornubian Massif and to the south by the Brittany Massif. North of the Cornubian Massif a further deep linear basin — the Celtic Sea Basin — extends north-eastwards from near the shelf edge south of the Irish mainland.

It maintains a rough parallelism to the southern coast of Ireland, and bifurcates around the Pembroke Ridge. One arm passes northwards through St. George's Channel into Cardigan Bay, the other into the Bristol Channel between Wales and Cornubia.

It seems probable from the evidence of Blundell et al. (1971) and from the Mochras Borehole (Woodland 1971) that the Cardigan Bay Basin fill ranges in age from Permo–Trias to Quaternary, although Upper Cretaceous (Chalk) strata are notably absent.

It seems reasonable to conclude from this evidence and from a consideration of the geology of Portuguese and Newfoundland coastlines, given their proximity in the pre-drift stage, that Permo–Trias and Jurassic rocks fill the grabenal basins of the Celtic Sea.

Conclusions

We believe that most of the trilete structural trough pattern for the North Sea and adjacent areas (Fig. 1) was initiated in Late Carboniferous and Early Permian times. This could have been due to relative movement of the lithospheric plate with respect to the asthenosphere, so enabling plume-generated crestal uplifts to develop in the area extending from Rockall Bank to the Skagerrak, as happened in Miocene and later times for Africa (Burke & Wilson 1972; Burke & Whiteman 1973).

Rapid plate movement then carried the crestal uplifts off plume and so prevented the rrr systems from developing by lithospheric dyke injection into RRR spreading systems. On this hypothesis the Skagerrak and Forties trough systems, separated by approximately 300 km, may have developed over the same plume system due to the rapid plate movement (5 & 2, Fig. 1). Trilete trough system 1 may also have been formed over a plume system, which because of plate movement gave rise to volcanic activity in the Faeroes and which is now the Icelandic Plume.

Trough systems 1, 2 & 5 (Fig. 1) and the Rockall–Hatton and Rockall Troughs began to develop as major depocentres in Early Mesozoic time with individual arms (troughs) showing different rates and patterns of sedimentation and structural development (Figs. 2 and 3). In general, the North Sea troughs became infilled in Permo–Triassic times with predominantly continental arid sequences with evaporites, and with marine-paralic sequences in Jurassic and Lower Cretaceous times.

A large intracratonic salt basin (the architecture of which was strongly Hercynian dominated) was established in the southern North Sea in Permian times extending from England to Poland and it is not clear whether the Indefatigable trough system (3, Fig. 1) was initiated in Permian or Triassic times. A later Mesozoic history is decipherable from the published data for this trough.

During Jurassic and Early Cretaceous times several stages of active block faulting associated with the North Sea central graben system have been defined.

These movements may have occurred because of adjustment beneath the continental margin consequent on new crust being generated in the Atlantic. Marine incursions entered the area from the spreading Atlantic and from the Tethyan ocean. Most of the North Sea troughs had become inactive by Late Cretaceous time but some differential activity persisted into the Paleocene.

The Rhine and Hessen grabens developed in Late Mesozoic and Early Tertiary times and may be considered part of the fragmentation sequence. The West Netherland Trough appears to be currently actively subsiding (Rhine Delta Complex) and the Rhine graben may also still be active.

During most of the Cenozoic time much of the North Sea generally subsided. This was coupled with uplift of the adjacent land masses of Norway, Scotland, England, Wales, etc.

There is a close relationship between oil field distribution and the trough system, especially in the Northern North Sea area (Naylor et al. 1974).

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