The Geological Evolution of the North Sea Area in the Tectonic Framework of North Western Europe

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Ziegler, P. A. 1975: The geological evolution of the North Sea area in the tectonic framework of North-Western Europe. *Norges geol. Unders. 316*, 1-27.

The development history of the North Sea area can be subdivided into five stages: 1) Caledonian geosynclinal stage (Cambrian-Silurian) 2) Variscan geosynclinal stage (Devonian-Carboniferous 3) Permo-Triassic intracratonic stage 4) Jurassic-Cretaceous taphrogenic rifting stage 5) Tertiary post-rifting intracratonic stage.

The Jurassic-Cretaceous North Sea central rift system is related to the rifting processes in the Arctic North Atlantic. During the Tertiary this sector of the Atlantic entered the drifting stage. At the same time the North Sea rift system became inactive, leading to regional subsidence. Emplacement of the late Tertiary Rhône-Rhine rift system postdates the central North Sea rift.

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Introduction

From Cambrian to Recent the North Sea area underwent a complex geological evolution during which it formed part of different tectonic provinces and sedimentary basins.

From the viewpoint of basin development we distinguish the following stages in the evolution of the North Sea area:

1. Caledonian geosynclinal stage (Cambrian-Silurian)
2. Variscan geosynclinal stage (Devonian-Carboniferous)
3. Permo-Triassic intracratonic stage
4. Taphrogenic rifting stage (Jurassic-Cretaceous)
5. Post-rifting intracratonic stage (Tertiary)

The superposition of these basins in various combinations in the different areas controls the hydrocarbon potential of the respective sectors of the North Sea.

The geological history of the North Sea area can only be fully understood when viewed against the broad background of the tectonic evolution of NW Europe. The aim of this paper is therefore to retrace with the aid of a sequence of paleogeographic maps in a kaleidoscopic fashion the main development stages of the North Sea within the framework of NW Europe.

Geological information obtained during the recent exploration efforts in the North Sea is integrated with data available from the onshore areas. For the latter the author has drawn heavily on the voluminous compilation of literature dealing with the paleogeographic evolution of Europe. The paleogeographic maps cover a large area and span large time intervals, necessitating much generalisation and simplification. These maps have not been palinspatically corrected; facies provinces are therefore distorted and crowded to various degrees in areas that have been subjected to compression during orogeneic periods. It is hoped that despite these shortcomings the maps convey a ready outline of the main development stages of NW Europe in general and of the North Sea in particular. It should be noted here that a common legend to the paleogeographic maps is presented at the end of the paper, as Fig. 19.

Thanks are due to SIPM, to ESSO Europe and to the Dansk Undergrunds Consortium for releasing this paper for publication. The help and constructive criticism of many of my colleagues are herewith acknowledged.

Caledonian geosynclinal stage

The late Silurian paleogeographic setting (Fig. 1) as summarised by Walter (1972) provides a good starting point for our discussion of the evolution of the North Sea area. This setting precedes the Caledonian orogeny but is eugeosyncline and geanticline. Denmark, Sweden and the Baltic formed part

During this time NW Europe formed part of the Appalachian-Caledonian geosyncline and of the eastward adjacent shelf areas. Ireland, northern England, the northern North Sea and Norway were occupied by the Caledonian eugeosyncline and geanticline. Denmark, Sweden and the Baltic formed part of the Caledonian miogeosynclinal realm. For the Silurian, Walter (1972) postulates emergent areas for southern Norway and parts of the southern North Sea and adjacent Germany. For lack of adequate exposures the paleogeographic framework of Central Europe during this period cannot be fully reconstructed. Although sediments of the Caledonian geosynclinal stage have not yet been reached by the drill in the North Sea their potential significance should not be underestimated since this sequence contains the Cambrian Alum shales, an excellent source rock exposed in southern Sweden (Schlatter 1969).

Variscan geosynclinal stage (Devonian to Carboniferous)

The Caledonian orogeny resulted in the fusion of the North American-Greenland and the North-West European continental masses (Wilson 1966) with the Caledonian fold belt crossing the northern North Sea. In Central Europe the Caledonian orogeny caused an accentuation of the Alemanic-Bohemian geanticline and with this a sharper definition of the Variscan geosyncline.

A speculative connection between the Caledonids of Norway and those of southern Poland along a trend paralleling the Tornquist line (Shurawlew 1965, Fig. 2) has been postulated by von Gaertner (1960) and Znosko (1964) but was later questioned by Franke (1964, 1968). For lack of a sufficiently complete sedimentary record in Denmark this problem cannot be solved at this time. The Tornquist line that marks the boundary between the stable Fenno-Sarmatian platform and the more mobile Western European areas can be recognised as a major structural feature during much of the post-Caledonian history of NW Europe.

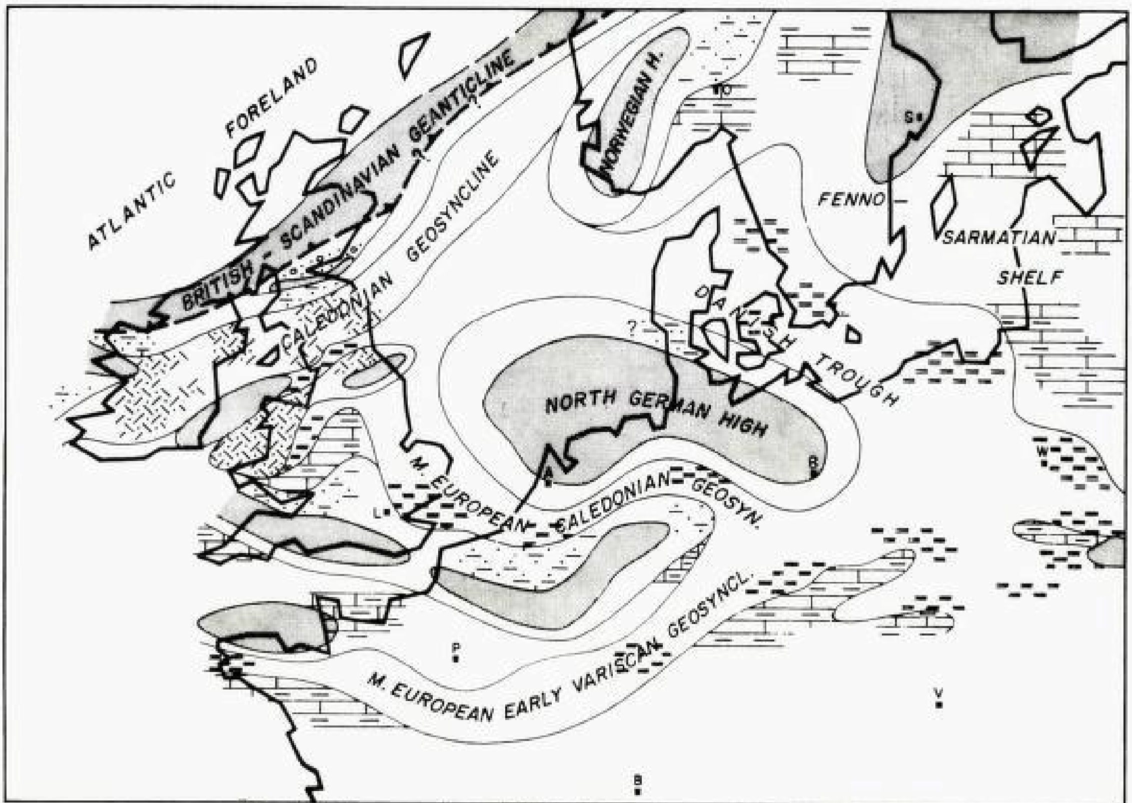


Fig. 1. Paleogeography of NW Europe during the Silurian (Wenlockian) mainly after Walter (1972).

As a result of the Caledonian orogeny the tectonic framework of the North Sea area obtained a new polarity (Fig. 2): the picture was now dominated by the Variscan geosyncline in the south while the Caledonian mountain ranges to the north were rapidly degraded. Late to post-orogenic uplift, associated with a partial collapse of the Caledonian mountain system, resulted in the deposition of the thick, in part lacustrine and bituminous series of the Devonian Old Red sandstone in intramontane basins such as the Orcadian and the Caledonian Cuvette (Bennison & Wright 1972, Allen et al. 1967). A connection between these basins and the scattered outcrops of Old Red sandstone on the Norwegian coast (Nilsen 1973) cannot be ruled out. Old Red equivalent sandstones occur also in the Baltic (Pajchlowa 1970) and have been encountered in a few boreholes in the central North Sea. Marine ingressions from the Variscan geosyncline, which was flanked to the north by a wide, in part reef-bearing, carbonate shelf, reached as far as the central North Sea. Control points are still too sparse to reconstruct details of the Devonian paleogeographic framework of much of NW Europe. However, the London–Brabant massif appears for the first time as a major stable block, a role which it continued to play during much of the subsequent development of the North Sea area.

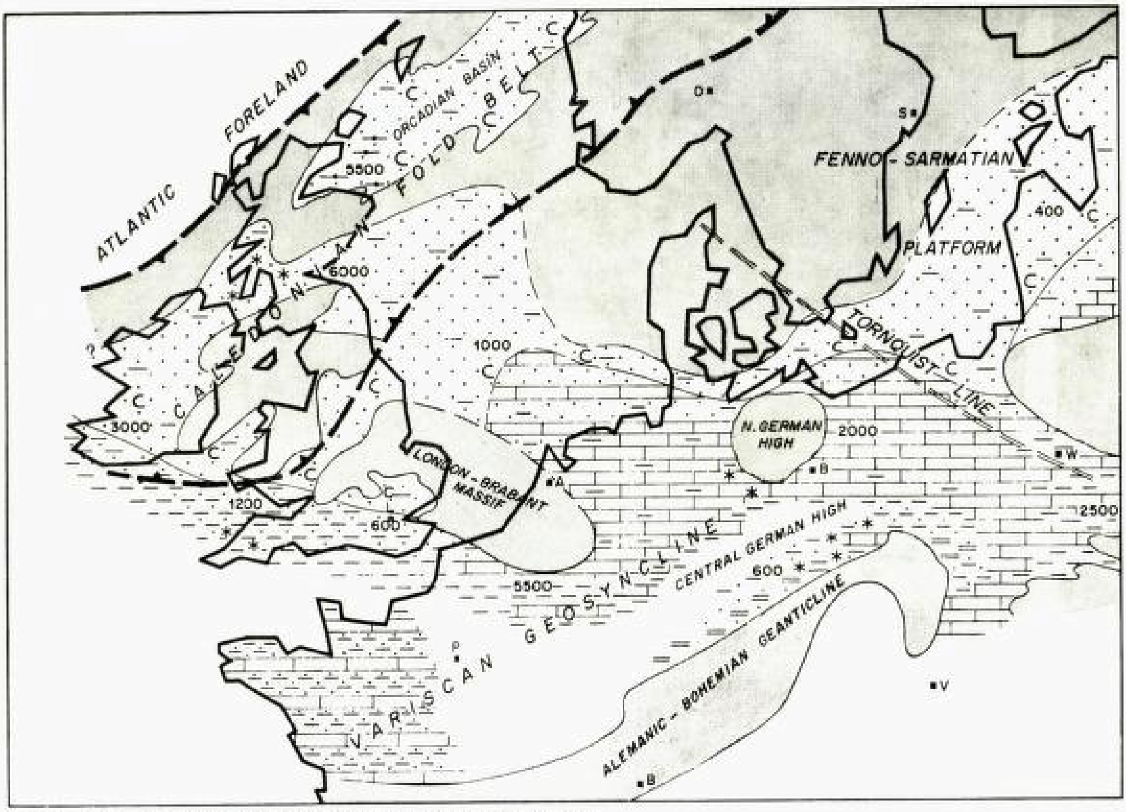


Fig. 2. Paleogeography of NW Europe during the Devonian.

The late Devonian–early Carboniferous Bretonic orogeny resulted in a consolidation of the Alemanic–Bohemian geanticline and in the emergence of the Armorican–central German highs. During the *Lower Carboniferous* (Fig. 3) these highs formed the source of the thick, flysch-like Culm series that were deposited in the Variscan foredeep. During the Visean its distal northern parts were occupied by a wide carbonate shelf which extended from the Irish Waulsortian reef platform to Poland. Marine ingressions reached far to the north into the progressively degraded Caledonian chains. Visean coal-bearing sequences were locally deposited in the central North Sea and northern England. Of special interest is the thick, essentially non-marine Oil Shale sequence in the Scottish Midland valley (MacGregor 1948; Bennison & Wright 1972). Based on the sparse control available, the northern and eastern parts of the North Sea appear to have formed part of a large, positive area during much of the Lower Carboniferous.

At the turn from the Lower to the Upper Carboniferous the Sudetic orogeny led to a further consolidation of the Variscan mountain system with deposition continuing in intramontane successor basins. During the *Upper Carboniferous* deposition of the marine Culm series was restricted to a narrow trough flanking the rising Variscan mountain chains. During the Namurian, marine ingressions

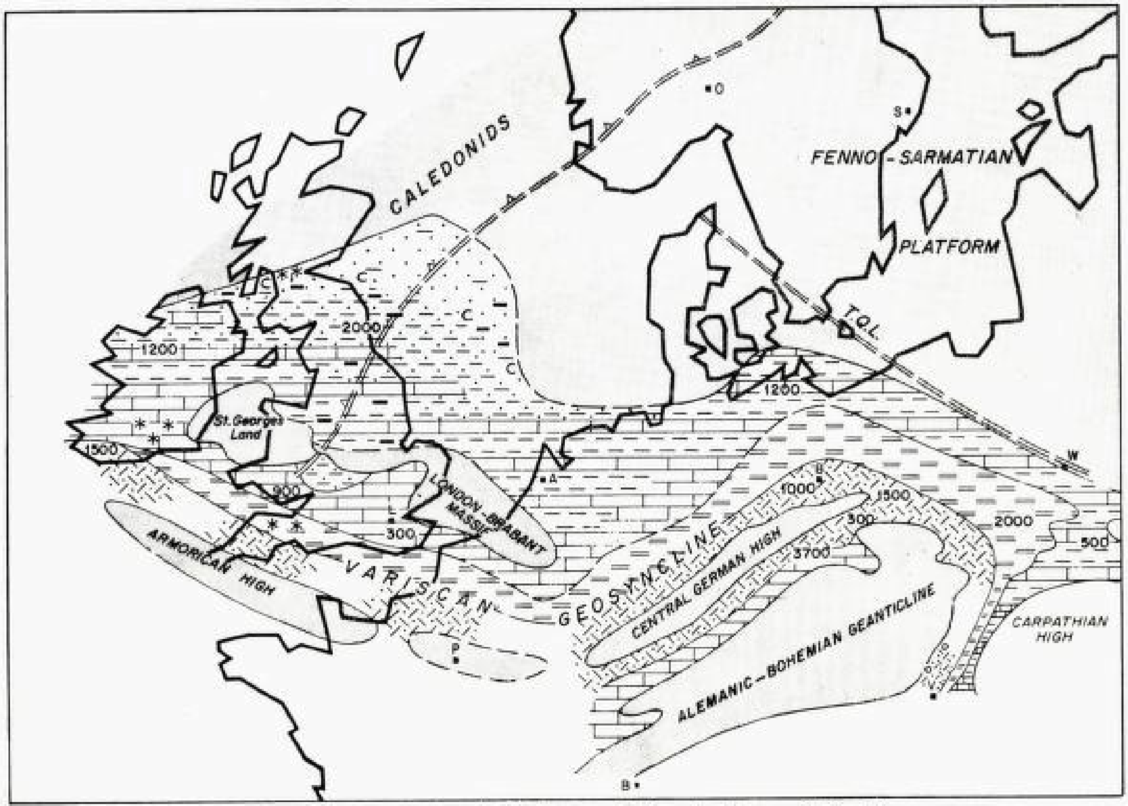


Fig. 3. Paleogeography of NW Europe during the Lower Carboniferous.

originating from the Variscan foredeep inundated much of the Baltic and north German shelf but also reached northern England and Scotland (Yordale and Limestone Coal Group).

Fig. 4 depicts the paleogeographic set-up of NW Europe during the Westphalian. Paralic conditions prevailed in much of the Variscan foredeep and the northward adjacent shelf areas, leading to the deposition of very thick coal-bearing sequences. These are of particular economic interest, especially since they constitute the source rocks for the gas found in the southern North Sea and the adjacent Netherlands and German onshore area (Patijn 1964). These Upper Carboniferous coal-bearing sequences do not appear to extend into the central and north-eastern North Sea.

Permo-Triassic intracratonic stage

The late Carboniferous Asturian and the early Permian Saalian orogenic phases (Variscan orogeny) resulted in décollement folding of the Variscan foredeep and a final consolidation of the Variscan chains with the north European craton. The Permian tectonic framework (Figs. 5 and 6) is characterised by the formation of large post-orogenic intracratonic basins with deposition

Fig. 4. Paleogeography of NW Europe during the Upper Carboniferous (Westphalian).

of red beds and evaporites. During the Triassic a new megatectonic setting came into being as a set of narrow rifts and grabens. This tectonic phase can be related to the collapse and subsidence of the Variscan domain resulting in the establishment of the Tethis and the emplacement of the Arctic–North Atlantic rift system. The Permo–Triassic period is marked by the change from the predominantly compressive Variscan tectonic setting to a period of extension and collapse, the full polarity of which only became evident during the Jurassic and Lower Cretaceous.

During the *Permian* the Variscan fold belt was subjected to post-orogenic uplift leading to its partial collapse and the establishment of continental intramontane basins (Falke 1972) very reminiscent of the post-Caledonian Old Red intramontane basins. This process was accompanied by volcanic extrusions. Similarly, the undeformed Variscan foreland was initially subject to uplift, tilting and erosion, followed by differential subsidence along normal faults, which was accompanied by the widespread effusion of the Lower Permian volcanics. Progressive subsidence led to the establishment of the Upper Permian Rotliegend basins (Fig. 5). The mid-North Sea–Fyn–Grindsted high appeared as the major positive element separating the less well known northern Permian basin from the southern Permian basin.

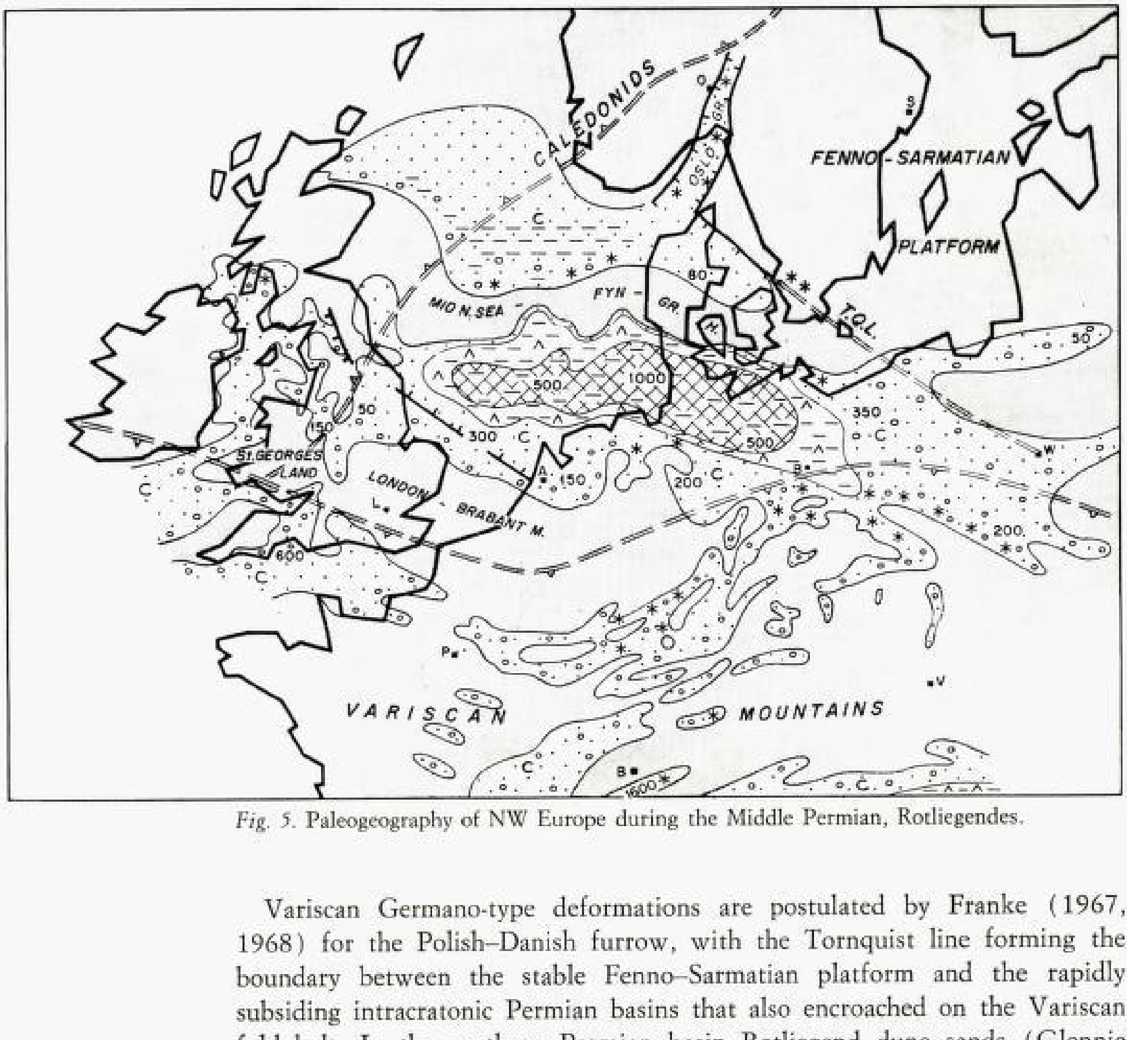
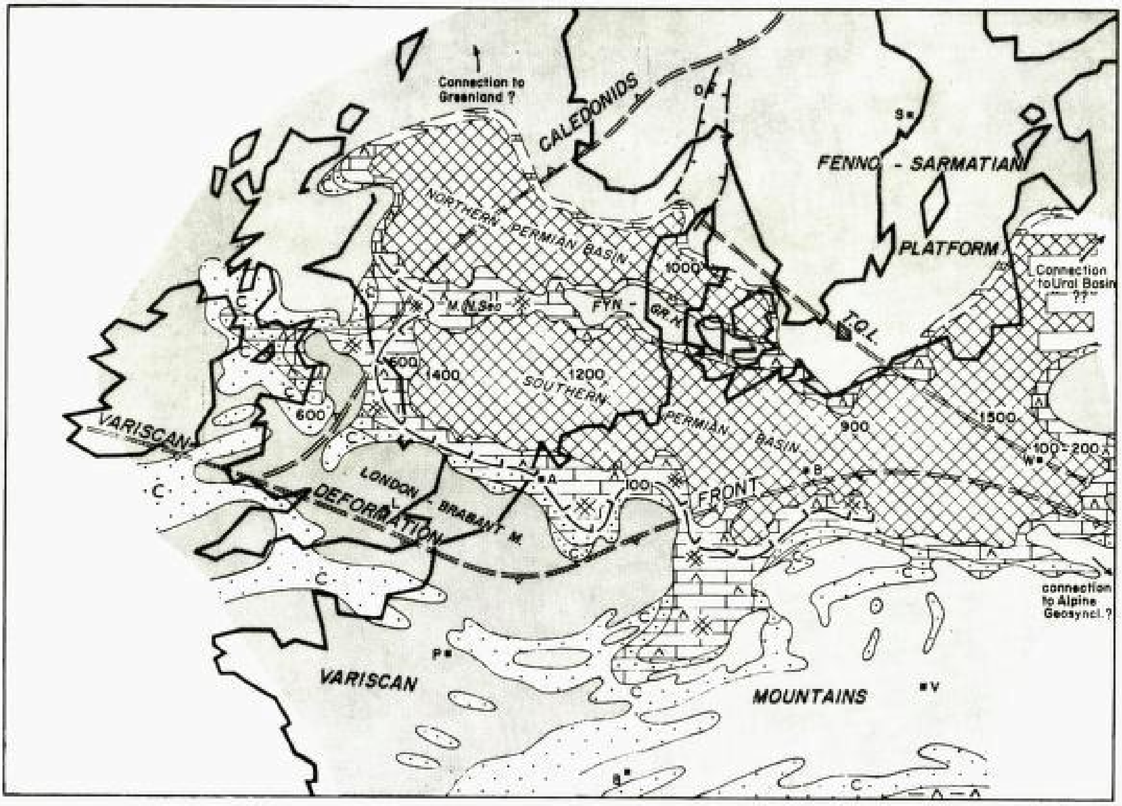


Fig. 5. Paleogeography of NW Europe during the Middle Permian, Rotliegendes.

Variscan Germano-type deformations are postulated by Franke (1967, 1968) for the Polish–Danish furrow, with the Tornquist line forming the boundary between the stable Fenno–Sarmatian platform and the rapidly subsiding intracratonic Permian basins that also encroached on the Variscan fold belt. In the southern Permian basin Rotliegend dune sands (Glennie 1972) are the primary gas reservoir in the southern North Sea and the adjacent Netherlands and German onshore areas. These sands grade northward into Sebka shales and evaporites. The latter gave rise during the Mesozoic to salt diapirism in the German Bight and the adjacent onshore areas.

The configuration of the northern Permian basin is less well known, and for want of sufficient well data no reliable facies pattern can as yet be drawn up. A significant element of the northern Permian basin is the volcanic Oslo graben (Wurm 1973).

Continued subsidence of the arid Rotliegend basins, possibly below sea-level, resulted finally in the catastrophic ingression of the Zechstein seas, the origin of which is still open to speculation (Fig. 6). No concrete evidence has been obtained to date for a connection between the northern Permian basin through the northern North Sea to the marine Permian series of Greenland (Maync 1961) and Spitsbergen (Harland 1961), nor has the possible connection via



Limit Zechstein 2 – Salt

Fig. 6. Paleogeography of NW Europe during the Upper Permian, Zechstein.

the Moravian Gate to the marine Permian of the eastern Alpine geosyncline been established. The least likely link to Permian seas is via the Russian platform to the Ural foredeep and in a roundabout way to Spitsbergen. However, the clearly marine character of the Z–1 and Z–2 carbonates (Füchtbauer 1962) as well as the large amount of evaporites contained in both the southern and northern Permian basins leaves little doubt that these basins had at least a narrow connection to the open seas. The deposition of thin shelf carbonate and sulphate sequences was restricted to the margins of the Zechstein basins. These were offset by thick, basin-filling halite sequences that reached thicknesses in excess of 1000 m.

Zechstein carbonates form a significant gas and oil reservoir in onshore areas but play a subordinate role in North Sea hydrocarbon prospects. Diapirism of the Zechstein salts, both in the southern and northern Permian basins, strongly influenced post-Triassic sedimentation.

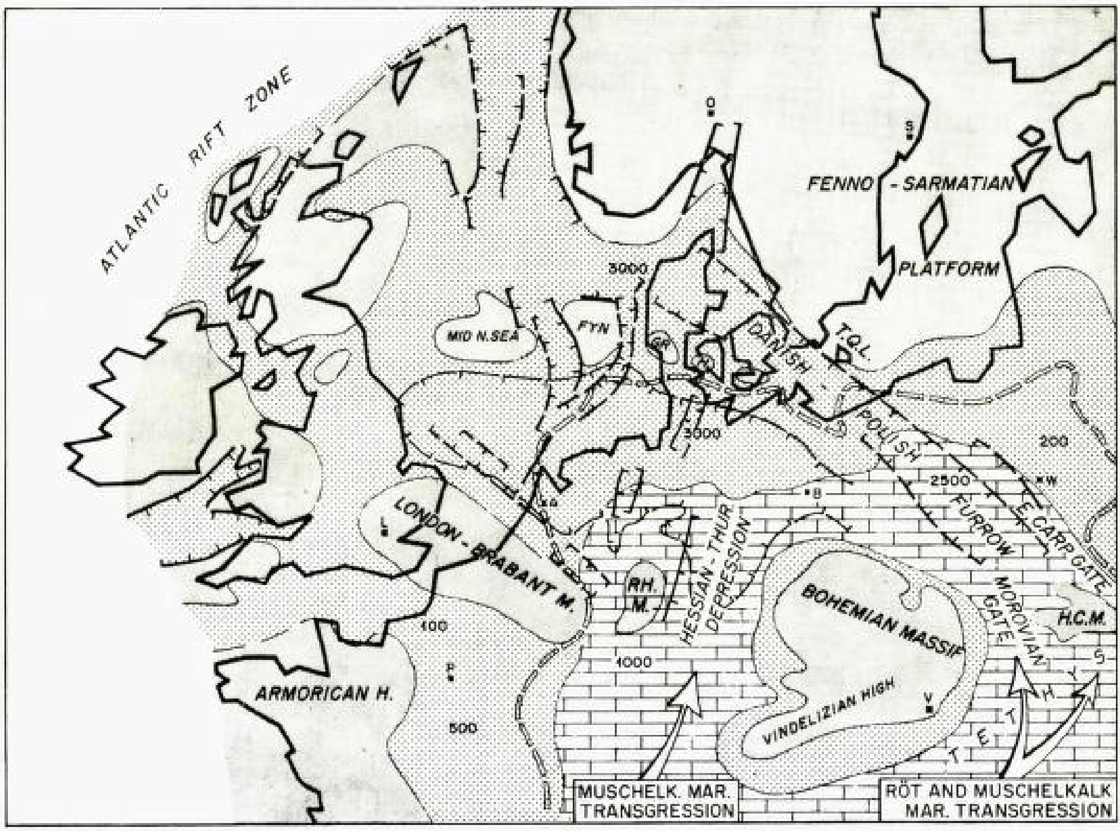
The *Triassic* period meant for much of the North Sea area a return to a continental depositional regime. The Permian structural pattern still dominated the paleogeography of northern Europe. However, the emplacement of new graben systems resulted in significant modifications (Fig. 7). These grabens probably formed in conjunction with early movements along the Arctic North Atlantic rifting zone (Hallam 1971).

It is likely that the Central Graben system of the North Sea was established during the Triassic; however, at this time it had not yet developed into a dominant structural feature. Similar rapidly subsiding Triassic grabens in the North Sea area are the Horn and Glückstadt grabens in the Danish offshore and northern Germany, respectively, and the Danish–Polish furrow which is bounded to the east by the Tornquist line. Similar grabens developed in the Celtic Sea and the Western Approaches and along the Atlantic seaboard of Scotland and Ireland. Normal to the northern margin of the Brabant–Rhenian massif the Emsland and Weser depressions formed during the Bunter. Their flanking highs were actively uplifted and subjected to erosion, as illustrated by the Hardegsen unconformity (Wolburg 1961, 1962). Progressive downwarping and widening of the northern and southern Permo–Triassic basin resulted in the gradual burial of the mid-North Sea–Fyn–Grindsted High. Further degradation of the Variscan mountains and progressive subsidence of the intramontane basins brought about a link-up between the north European basin and the Tethian basin (Boselli & Hsü 1973). During the Röt time marine incursions reached the southern North Sea via the Moravian Gate (Polish furrow).

The Muschelkalk transgression entered into the North European basin through the Hessian Depression as well as the Moravian Gate (Tokarski 1965). During the Triassic no marine connections existed between the North Sea and the marine areas of north-eastern Greenland (Birkelund 1973) and Spitsbergen (Parker 1967; Defrentin–Lefranc 1969; Harland 1973; Cod & Smith 1973).

In these parts of the North European basin, where thick Zechstein salt deposits coincided with Triassic depôt centres, halokinetic movements were triggered during late Triassic times. These movements continued to influence at least on a local scale the depositional pattern of the Jurassic, Cretaceous and Tertiary.

In the future Alpine geosynclinal domain the erosion and collapse of the Variscan mountain system led to the deposition of the thick, graben-bound Permian Verrucano that is frequently associated with volcanic extrusion (Trümpy 1965, 1972). Permian marine series are known from the southern Alpine facies realm only (Rau & Tongiorgi 1972). During the Triassic these graben systems were enlarged, leading to a general marine transgression and the deposition of thick, carbonate sequences in the Eastern and Southern Alpine facies realm (Trümpy 1971). From this incipient Alpine geosyncline (Tethis basin), marine transgressions reached northward into the Alpine foreland.



Distribution solid Muschelkalk carbonates
Northern limit of Muschelkalk carbonates
200 Thicknesses total Triassic in metres
Maximum distribution of Triassic deposits
Edge of Rötsalt

Fig. 7. Paleogeography of NW Europe during the Triassic.

Taphrogenic rifting stage (Jurassic-Cretaceous)

The late Triassic topography of NW Europe was characterised by an extremely low relief (Trümpy 1971). The Early Kimmerian (Rhaetian) movements marked the transition from the Triassic depositional framework to the Jurassic sedimentary pattern (Rusitzka 1967, 1968). With the Liassic transgression, marine conditions returned to large parts of NW Europe. Marine ingressions into the North Sea area originated chiefly from the newly established North Atlantic Seaway (Hallam 1971) through the northern North Sea, but also from the Tethis via the Paris basin and southern England, via the Hessian–Thuringian depression and in the Toarcian also through the Moravian Gate (Köbel 1968).

Fig. 8 presents an outline of the Jurassic framework of NW Europe, indicating areas of maximum total Jurassic subsidence. A comparison of the approximate depositional edges of the Liassic, Dogger and Malm conveys

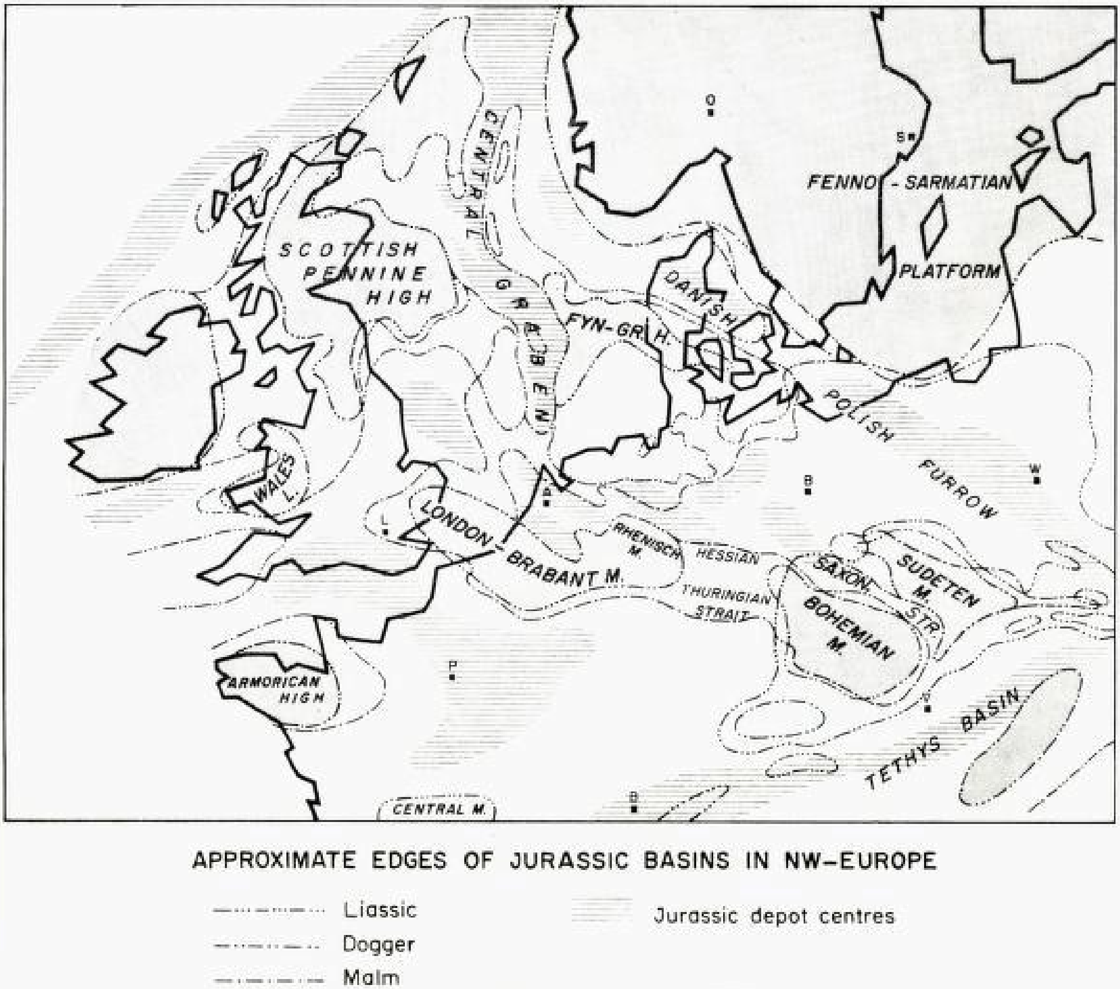


Fig. 8. Approximate edges of Jurassic basins in NW Europe.

an impression of the paleogeographic changes that occurred in the general North Sea area during the Jurassic. Main features of the Jurassic paleogeography are:

a. Opening up of the Arctic North Atlantic seaway during the Pliensbachian and its continued widening during the Middle and Upper Jurassic (Hallam 1971); the North Atlantic remained, however, in a pre-drifting stage.
b. The establishment of the North Sea Central Graben system as the dominant rift system. The Horn and Glückstadt grabens became largely inactive. The Danish–Polish furrow continued, however, to subside rapidly.
c. Flanking the London–Brabant–Rhenish–Ardennes massif as well as the Bohemian massif, marginal troughs (so-called 'Randtröge', Vogt 1962) developed. During the Dogger and Malm the narrow Silesian strait transected the Bohemian massif in a NW–SE direction.

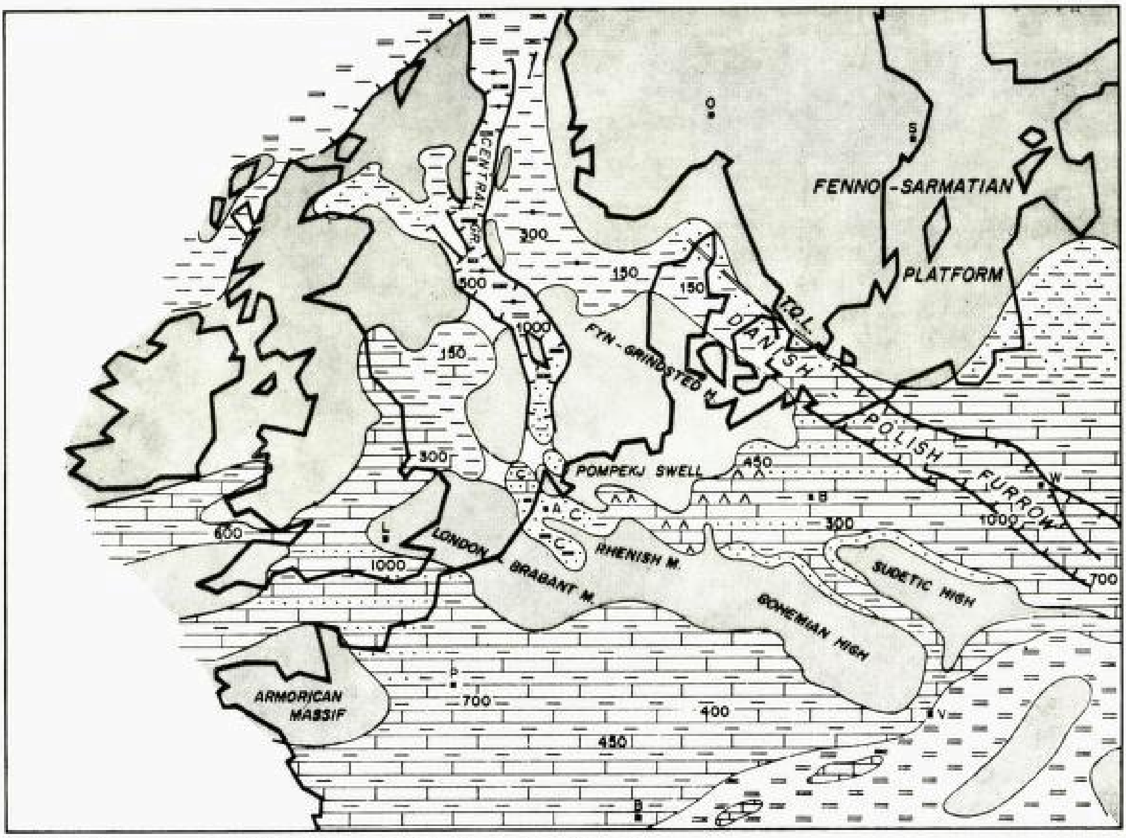


Fig. 9. Paleogeography of NW Europe during the Upper Jurassic.

d. The Alpine geosyncline reached a 'Mediterranean paraoceanic' pre-orogenic stage during the Jurassic with eugeosynclinal (oceanic) troughs separated by more stable platform areas (Trümpy 1971). Subsidence of large areas along flexures and normal faults is documented from the northern margin of the geosyncline and is indicative of an extensional stress setting (Trümpy 1960; Köbel 1968).

The overall impression gained is the one of NW Europe being subjected as a whole to extensional stresses. This led to its partial fragmentation whereby the North Sea central rift and the Polish furrow represent the major fracture zones in the Alpine foreland (Fig. 9). The North Sea Central Graben system should be considered as an offshoot of the Arctic North Atlantic rift system. The Variscan massifs appear to have prevented a southward extension of the North Sea graben system. Instead a series of en échelon tensional depressions developed mainly along their northern margin. Emplacement of these marginal troughs probably followed pre-existing fault patterns and was possibly in response to deep-seated transform movements between the Danish–North German segment (North) and the Central European–English segment (South). The Tornquist line formed the boundary between the stable Fenno–Sarmatian

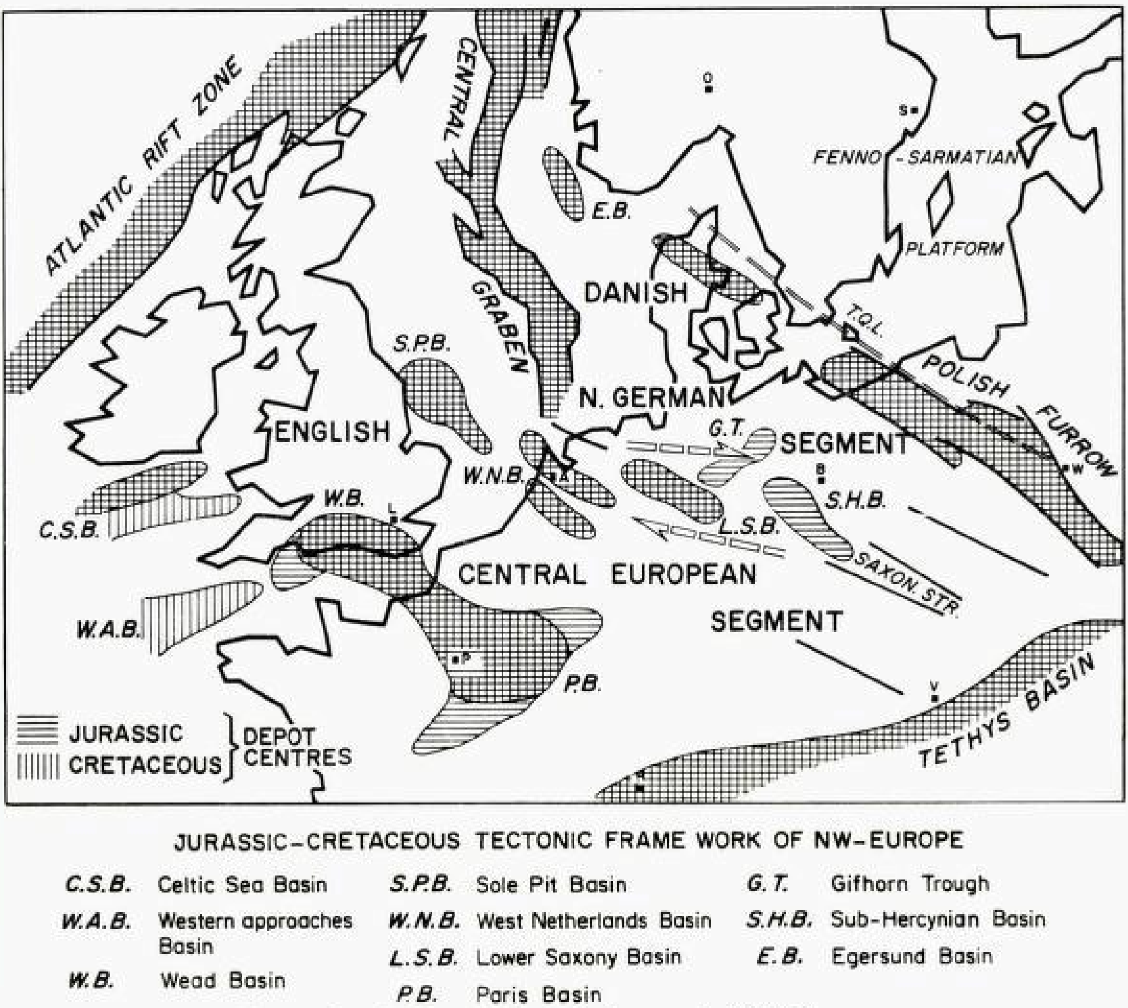


Fig. 10. Jurassic–Cretaceous tectonic framework of NW Europe.

platform to the east and the metastable blocks to the west, the southern boundary of which was formed by the Alpine geosyncline.

The Jurassic record of the North Sea is not yet well enough known to develop a comprehensive story of the evolution of its Central Graben system at this stage. Halokinesis as well as several stages of downfaulting and differential subsidence of the fragmented graben floor, coupled with uplifting of the rift margins, make the deciphering of events rather difficult. In the northern North Sea there is clear evidence of continuous differential subsidence of the graben floor since the Triassic and well into the Jurassic. A major rifting phase locally corresponding to an angular unconformity within the Dogger is documented from the central North Sea. In the southern and northern North Sea this phase is expressed by regressive–transgressive clastic cycles often in concordance with the underlying marine Liassic sequences.

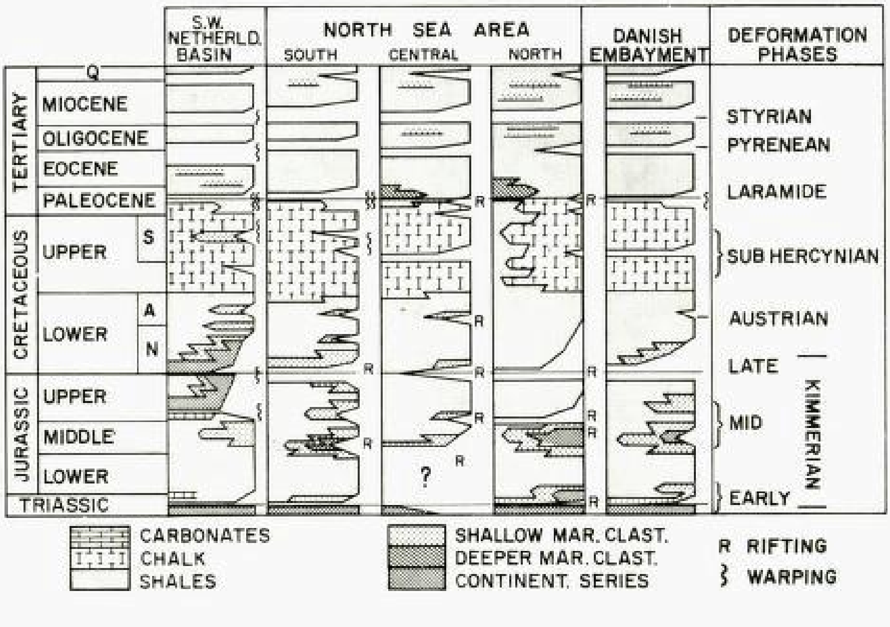


Fig. 11. Stratigraphic diagram of the North Sea area.

A second phase of rifting, this time better documented in both the southern and northern North Sea, occurred during the transition from the Middle to the Upper Jurassic. In the North Sea Central Graben the Upper Jurassic is often represented by organic deeper-water shales which indicate that the raft system had developed into a submarine trough (Fig. 10). At the Jurassic–Cretaceous boundary a further major rifting phase occurred throughout the Central Graben (late Kimmerian phase). All of these three main phases are recognisable through much of the North Sea area either as unconformities, disconformities or regressive–transgressive cycles (Fig. 11). Only in the deepest part of the Central Graben, a veritable taphrogeosyncline (term used in the sense of Trümpy 1960), do more or less continuous Upper Jurassic–Lower Cretaceous sequences occur. During the successive periods of downfaulting of the graben floor the graben margins were uplifted and subjected to erosion, thus conforming to the rift model drawn up by Illes (1970). Erosion on the highs flanking the Central Graben cut down, e.g. in the Central North Sea, as deep as the Zechstein and locally even into the Devonian.

Drilling in the Central Graben has as yet yielded only sparse evidence of rift-volcanism during the Jurassic and Lower Cretaceous. In the marginal troughs flanking the Variscan massifs the above-described rifting phases can roughly be recognised as either regressive–transgressive cycles or as unconformities associated with minor warping of the basin floors followed by rapid subsidence (Fig. 12).

Warping and temporary uplifting of the basin floors may have been due to

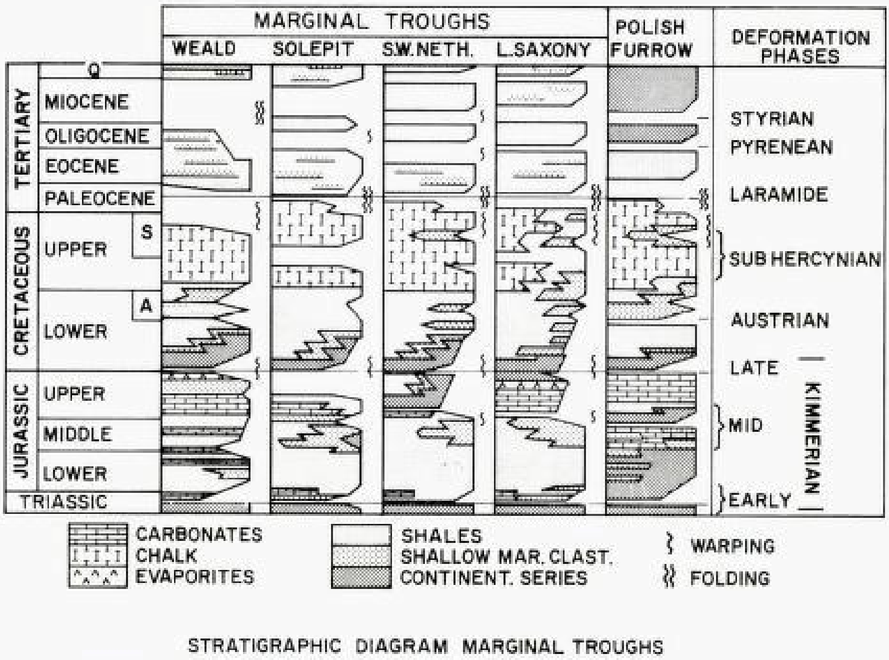


Fig. 12. Stratigraphic diagram of the marginal troughs.

slight jarring of these basins in response to the postulated deep-seated transform movements between the North German–Danish segment and the Central European–English segment (Fig. 9).

Phases similar to those recognised in the North Sea Central Graben are also evident in the Danish–Polish furrow where the Dogger phase corresponds to a marine transgression, the Callovian–Oxfordian phase to an unconformity, and the Late Kimmerian phase to a basin-wide unconformity (Fig. 12). The above-postulated regional tectonic model is in good agreement with the occurrence of similar, largely extensional phases in the Alpine geosyncline that resulted in an accentuation of positive platforms and negative areas. Of particular interest are the early mid-Jurassic phase (Trümpy 1960), which is recognised, e.g., in the Briançonnais as an erosional phase associated with the shedding of breccias in the Sub–Briançonnais, and the Oxfordian phase that is documented by, e.g., the Brèche du Télégraphe in the Sub–Briançonnais (see also Gwinner 1971; Fig. 13). In the Alpine geosyncline the stress pattern changed during the Lower Cretaceous from essentially extensional to a compression (Trümpy 1965). The occurrence of Neocomian flysch in the Penninic facies realm of the eastern Alps is thought to be linked to early compressive movements resulting in the rising of the Penninic Geanticline (Gwinner 1971, Wunderlich 1967).

The extrusion of ophiolites in the Swiss Alps is dated as Lower Cretaceous. These extrusives are considered by some authors as being contemporaneous with early folding phases (Trümpy 1958, 1965). The gradual change of the

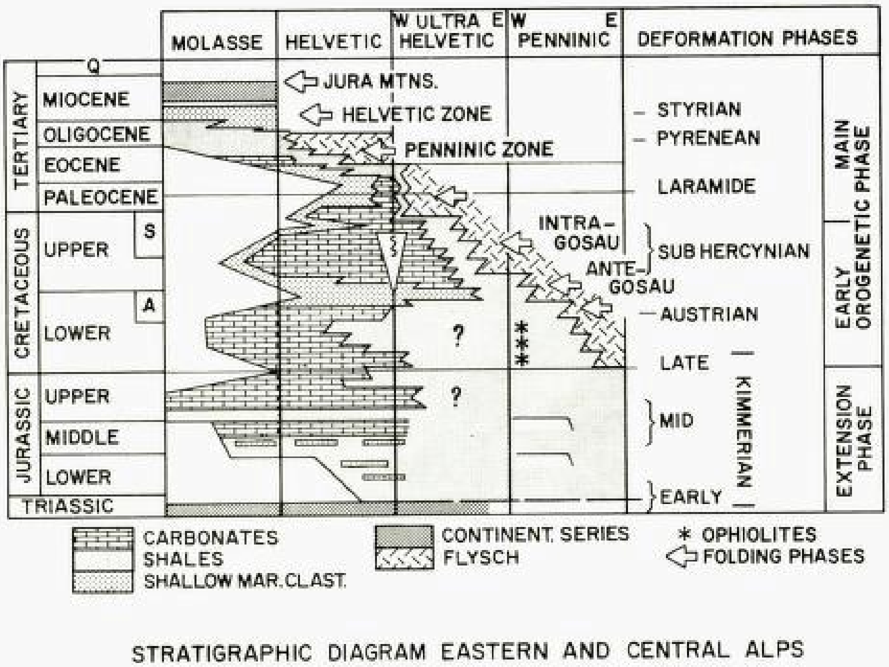


Fig. 13. Stratigraphic diagram of the eastern central Alps.

stress pattern during the Lower Cretaceous, however, remained restricted to the Alpine Geosyncline. In the North Sea area and in central Europe the Jurassic setting that was accentuated by the Late Kimmerian tectonic phase persisted through much of the Cretaceous period (Fig. 14). In the North Sea Central Graben only minor rifting movements can be recognised during the Lower and Upper Cretaceous; the Graben itself, however, continued to subside rapidly.

The last phase of rifting accompanied by uplifting of the graben margins and rapid subsidence of the Graben itself occurred during the Paleocene (Laramide phase; Fig. 11). In the North Sea the gradual abatement of rifting movements during the Cretaceous was accompanied by widespread transgressions resulting in the inundation of the uplifted flanks of the central rift during the Upper Cretaceous. The Upper Cretaceous development of the North Sea area is thus transitional between the Jurassic–Lower Cretaceous taphrogenic stage and the Tertiary post-rifting stage.

During the Late Kimmerian phase the Variscan massifs were once more consolidated into a continuous barrier reaching from southern England to Poland (Fig. 14). In the marginal troughs this phase is recognised as an unconformity accompanied by minor warping, followed by rapid subsidence of the respective basins and by the deposition of thick clastics. During the Lower Cretaceous a gradual transgression over the northward adjacent highs can be observed. The effects of the Albian–Aptian Austrian phase that are readily recognisable in the marginal troughs are only vaguely reflected in the

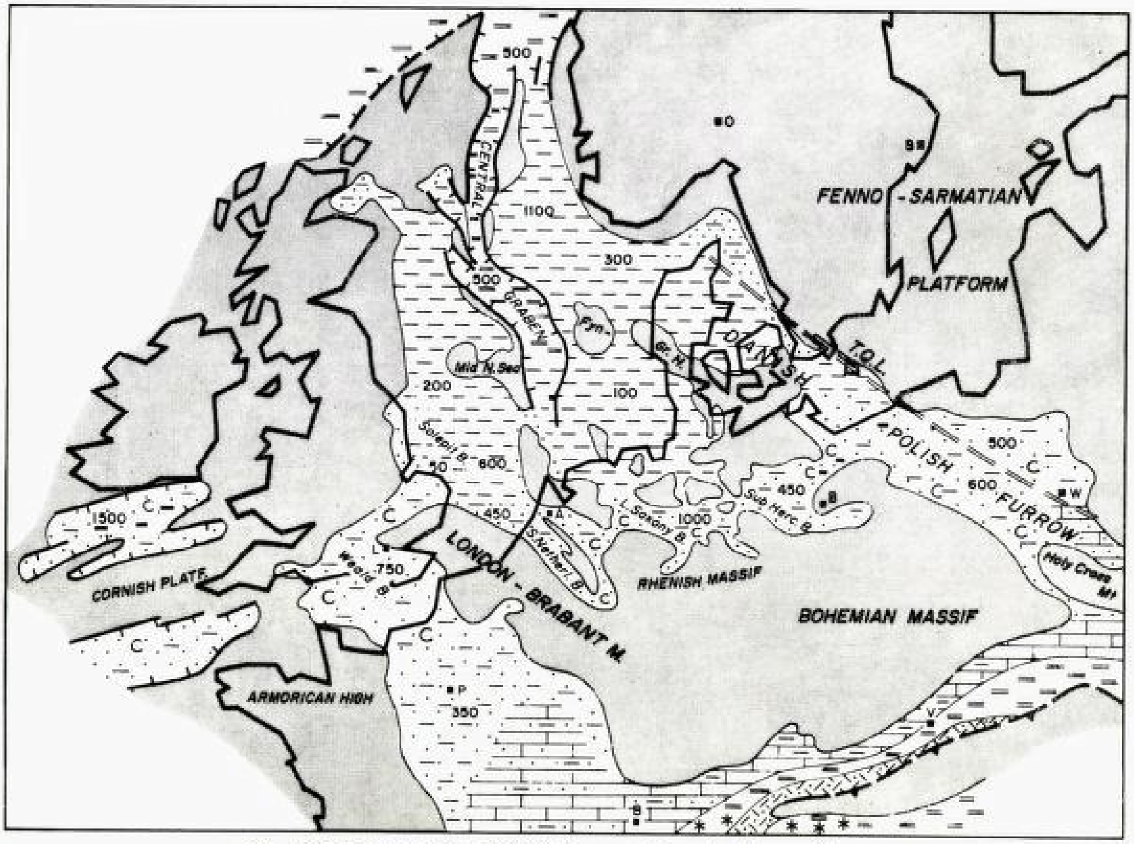
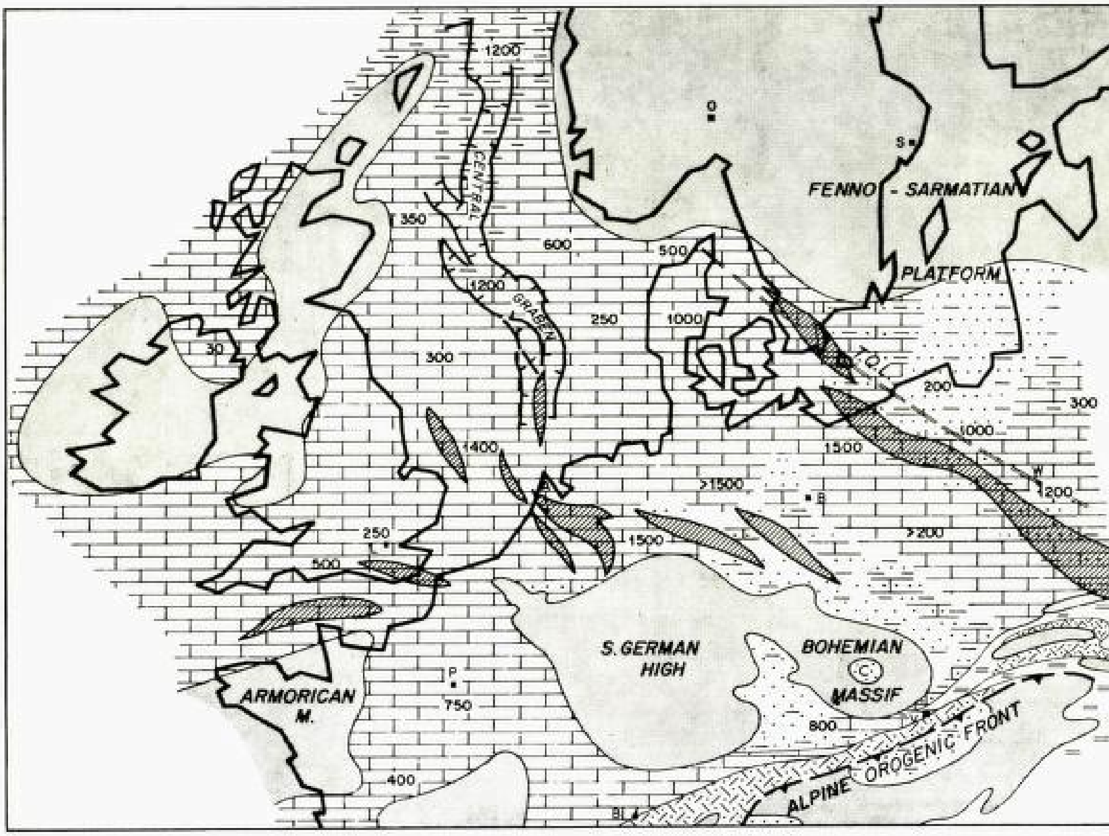


Fig. 14. Paleogeography of NW Europe during the Lower Cretaceous.

North Sea Central Graben, but are clearly evident in the Polish furrow Figs. 11, 12). As in the North Sea area the Upper Cretaceous transgression is very widespread in central Europe (Fig. 15). First inversion movements (term used in the sense of Voigt 1962) occurred in the marginal troughs as well as in the Polish Lowland during the Senonian (Subhercynian phase), leading to the uplifting of the axial zones of the basins and the development of secondary depôt centres flanking the uplifted basin centres (Voigt 1962; Heybroek 1964; Pozaryski 1960). Large-scale inversion involving also the southern part of the North Sea Central Graben took place during the Maastrichtian to Upper Paleocene, resulting in uplifting of the basin fill either along steep reverse or normal faults and/or by regional warping above the erosional level. These inversion movements are time-correlative with the last phase of downfaulting of the central and northern parts of the North Sea Central Graben and are thus not compatible with the above-developed tectonic model. However, in the Alpine geosynclinal realm compressive movements became dominant during the Upper Cretaceous with flysch deposition spreading in the Maastrichtian from the Penninic into the Ultrahelvetic facies domain (Fig. 13). It is hypothesized that the forces causing these Late Cretaceous–Early Tertiary Alpine



Inversion Axes

Fig. 15. Paleogeography of NW Europe during the Late Cretaceous.

orogenic movements had reached the dimensions to exert a compressive stress on the Alpine foreland causing the inversion of the marginal troughs that acted like shear-pins in the otherwise rigid platforms. However, once inverted these basin became largely inactive.

Only minor inversion movements are recognised in the marginal troughs flanking the Variscan Massifs during the post-Laramide, main Alpine orogenic phases with the exceptions of, e.g., the Weald Basin (Gallois & Edmunds 1965), which was mainly deformed during the Miocene and in which only mild warping occurred during the Laramide phase (Fig. 12).

An explanation for the contemporaneity of rifting movements in the North Sea and possibly in the North Atlantic and compressive, orogenic movements in the Alpine geosyncline has to be sought on an even larger scale than is considered in the present paper.

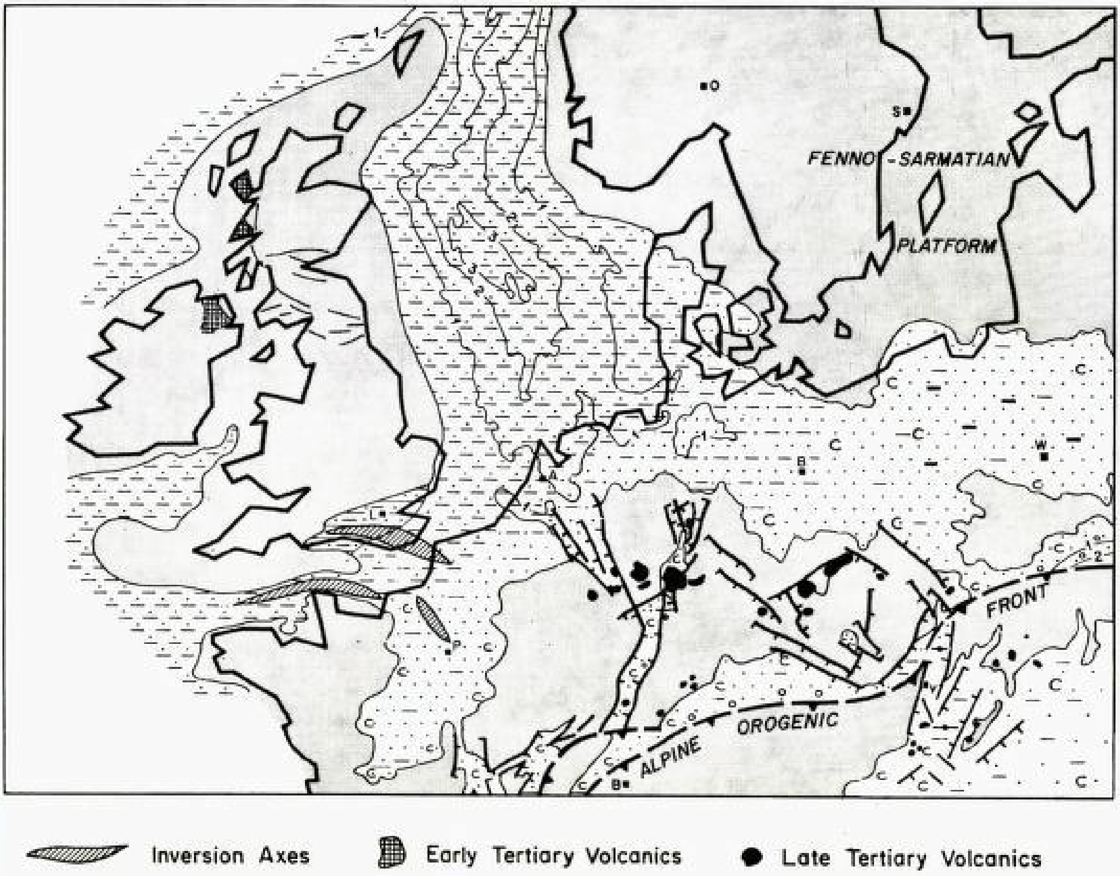


Fig. 16. Paleogeography of NW Europe during the Tertiary.

Post-rifting intracratonic stage (Tertiary)

The taphrogenic stage of the North Sea, that lasted possibly since the Triassic but definitely since the Jurassic, came to a close in the Late Paleocene. Final parting of the European and the North American–Greenland plate may have been effectuated during the Late Paleocene or Eocene (Pitman & Talwani 1972), thus initiating the drifting stage in the Arctic North Atlantic. Late Paleocene to Eocene flood basalts extruding during the final rifting and early drifting phase are known from Scotland (Rayner 1967; Richey 1961; Mitchell & Reen 1973) as well from Greenland (Brooks 1973). With the Arctic North Atlantic entering the drifting stage during the Late Eocene (Pitman & Talwani 1972), extensional stresses apparently ceased to influence NW Europe.

The North Sea area was dominated by regional subsidence resulting in a symmetrical saucer-shaped intracratonic basin, the axis of which coincides with the now inactive central rift valley. Maximum Tertiary thicknesses of up to 3.5 km (Dunn et al. 1973; Heybroek et al. 1967) occur in the central parts of the North Sea.

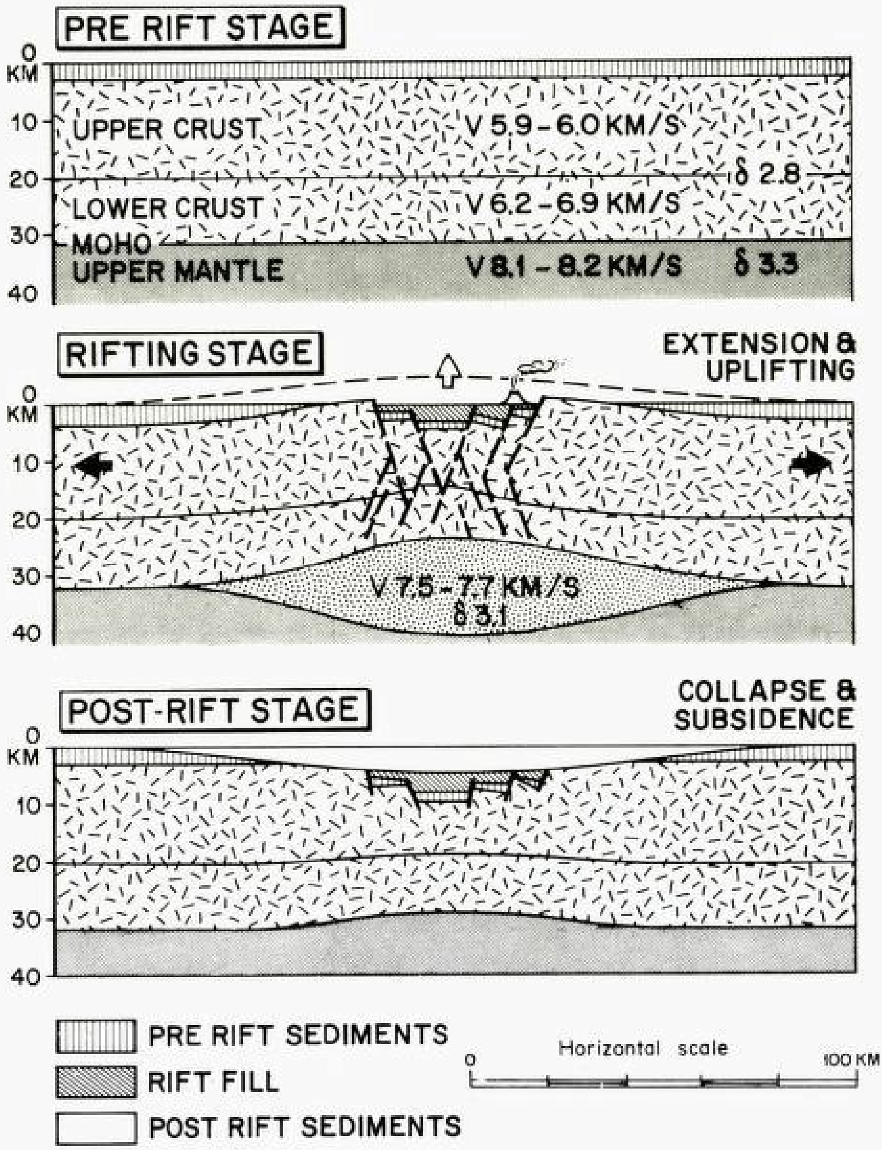


Fig. 17. Conceptual model of rift development.

ATTEMPT AT A GEODYNAMIC INTERPRETATION

The Tertiary subsidence pattern of the North Sea basin can be explained by the conceptual rift model as summarised in Fig .17.

The *'Pre-rifting' Stage* (Fig. 17a) represents a standard continental crust in isostatic equilibrium. The 'Rifting Stage' model (Fig. 17b) was fashioned according to the refraction data obtained by Ansorge et al. (1970) and Ahorner et al. (1972) for the Rhine Graben area and incorporating the more theoretical considerations of Illies (1970) and Laubscher (1970).

The most significant element in the 'rifting stage' model is the rift cushion

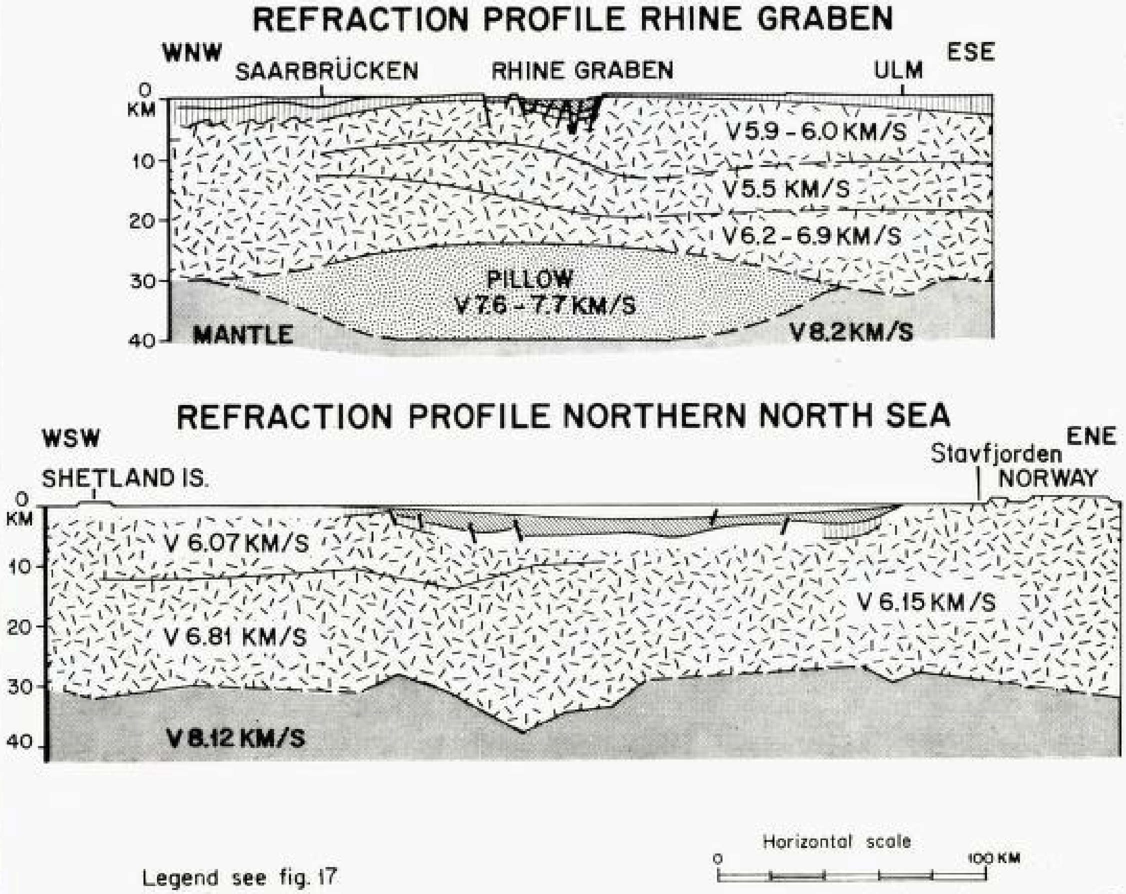


Fig. 18. Comparison of a refraction profile across the Rhine Graben and one across the northern North Sea.

that has a p-velocity of 7.5–7.9 km/sec and a density of 3.1 (Meissner et al. 1970). Similar rift cushions have been observed in, e.g., the Baikal graben (Artemiev & Artyushkow 1971) and the Red Sea rift (Drake & Girdler 1964). These cushions centre under the central rift valley and pinch out laterally under the uplifted flanks of the rift.

In Fig. 17b an unbroken rift dome (stippled line) is reconstructed. Artemiev & Artyushkow (1971) estimate the crustal extension resulting from uplifting of a correspondent 200 km wide and 3–4 km high rift dome to amount to some 200 m only. Laubscher (1970) estimates the extension across the Rhine Graben rift, which has similar dimensions, to be in the order of 5 km. This indicates that the uplifting of a rift area is probably only a subsidiary cause of the Central Graben development, but that the primary cause of the rifting is regional extension (see also Osmaston 1971).

It is hypothesized that intracontinental rifts such as the North Sea Graben or the Rhine Graben are initiated as the result of regional extensional stresses and that progressive rifting results in 'necking' of the crust, causing decompression of the mantle and the formation of a rift cushion through fractional distillation from the mantle. This, however, is only possible if a temporary decoupling between the crust and the mantle is assumed (Artemiev & Artyushkow 1971). Osmaston (1971) postulates as an alternate a model with coupling between the crust and the mantle and fracturing extending into the mantle.

Emplacement of the low density rift cushion causes uplifting of the rift zone and, with this, secondary subsidence of the central rift valley. This is furthermore thought to be linked to the initiation of the rift volcanisms. This stage was reached in the North Sea rift in the Middle to Upper Jurassic and lasted through much of the Lower Cretaceous.

The *'Post-rifting' model* (Fig. 17c) is largely based on the present-day configuration of the northern North Sea as depicted by the regional cross-section from the Shetland Islands to the Norwegian shore (Fig. 18). This section combines the deep refraction data obtained by Sørnes (1971) and reflection seismic results for the shallower sedimentary layers. In the line of the section unfortunately no information is available on the position of the central rift. valley floor. The 'post-rifting' stage is characterised by the absence of the rift cushion under the former rift zone and by the presence of thick post-rifting sediments, deposited in a symmetrical saucer-shaped basin, the deepest parts of which coincide with the former rift valley.

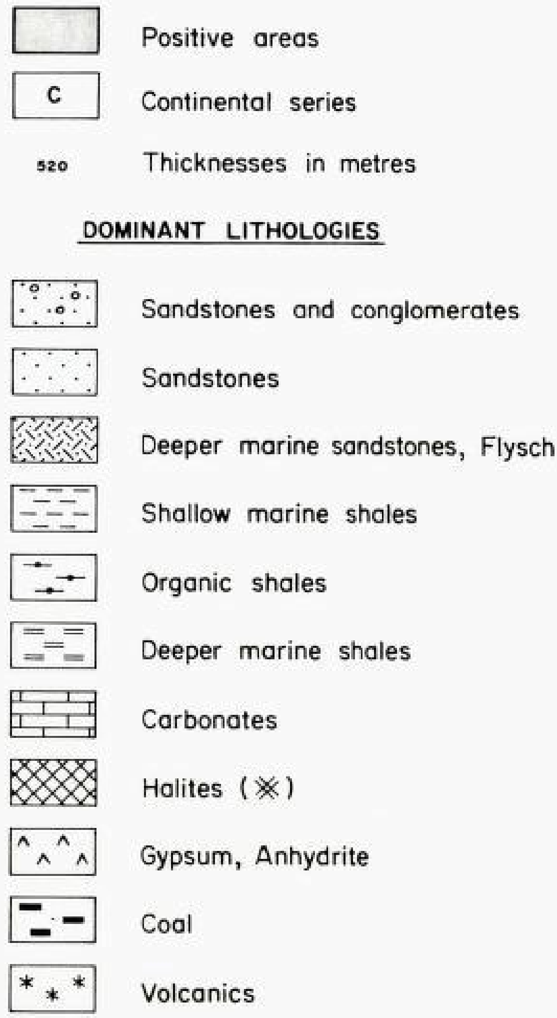
The subsidence of the rift zone is explained by the gradual resorption of the low density rift cushion by the mantle. This is in keeping with Osmaston (1971), who considers by the formation of a rift cushion a 'reversible thermal effect upon the uppermost mantle material'. It is further speculated that the rift cushions can only exist as such during the active rifting stage during which rifting movements result in progressive decompression of the mantle.

Once rifting movements cease the resorption of the rift cushion proceeds, resulting in a gradual ascending of the Moho and a corresponding subsidence of the rift dome. In view of the 'necking' of the crust and erosion on the rift margins, a large saucer-shaped basin develops, the width of which corresponds roughly to the width of the original rift dome. However, insufficient refraction data are available from the North Sea to date to fully verify the above hypothesis.

During the Tertiary, central Europe was dominated by the Alpine orogeny, the main phases of which are summarised by Fig. 13. In the North Sea regional disconformities correlate roughly to these main orogenic phases that are reflected in the marginal troughs by minor inversion movements. A notable exception is the Weald basin that underwent major inversion during the Miocene.

During the Eocene the Rhône–Rhine Graben system was emplaced in the Alpine foreland (Illies 1970). Its further development during the Oligocene and Upper Tertiary is largely concomitant with the Alpine folding phases. Other graben systems developed during the Tertiary in the Panonic basin with the Vienna basin practically crossing the Alpine orogenic front. Uplifting and

Fig. 19. Legend to the paleogeographic maps.



fracturing of the Variscan massifs led to widespread volcanism during the Mio–Pleiocene (Knetsch 1963). The northernmost branch of the Rhône–Rhine Graben system is the Rur Graben that reaches the southern Netherlands (Heybroek 1974). There is no evidence of a Late Tertiary reactivation of the North Sea central rift system. In view of the age disparity between the Rhône–Rhine Graben system, which is in an active rifting stage, and the North Sea central rift system, which is in a post-rifting stage, the two should not be considered as part of one megafracture system dissecting western Europe. However tempting such a speculation may be, their apparent continuity is largely fortuitous.

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