NORTH-WESTERN EUROPE: TECTONICS AND BASIN DEVELOPMENT

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ABSTRACT

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This paper discusses the geologic evolution of North-Western Europe from Late Silurian to Cainozoïc times on the base of 13 palaeogeographic and 6 palaeotectonic maps. Furthermore a pre-Permian and a pre-Tertiary subcrop map as well as an isopach map of Upper Permian to Cainozoic sediments is presented.

This synthesis is based to a large extent on geophysical and subsurface data acquired by the oil industry during its exploration efforts in the various on-shore and offshore sedimentary basins of North-Western Europe.

A more comprehensive summary is given at the end of the paper.

INTRODUCTION

During the last two decades a tremendous amount of new data has become available on the geology of North-Western Europe. A large proportion of this new geological and geophysical information has been gathered by the petroleum industry in the course of its search for oil and gas in the various sedimentary basins of Europe. This applies particularly to the shelf areas which hitherto had remained geological 'terra incognita'. With this new information in hand, many blanks in the puzzle of European geology can now be filled in. Thus a much better understanding of the geological history of Europe can be obtained. Nevertheless, the tectonic complexity and stratigraphic diversity of North-Western Europe can only be fully appreciated when seen in its plate-tectonic framework.

This paper aims at outlining the geological evolution of North-Western Europe from Upper Palaeozoic to recent times. Geological information obtained by the petroleum industry during its exploration efforts in the various basins of North-Western Europe is integrated with data from outcropping areas as well as the geology of the North Atlantic.

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LATE CALEDONIAN TECTONIC FRAMEWORK

Considering a Late Palaeozoic plate assembly North-Western Europe covers the T-junction between the Arctic-North Atlantic Caledonides and the Appalachian - Mauretanides -

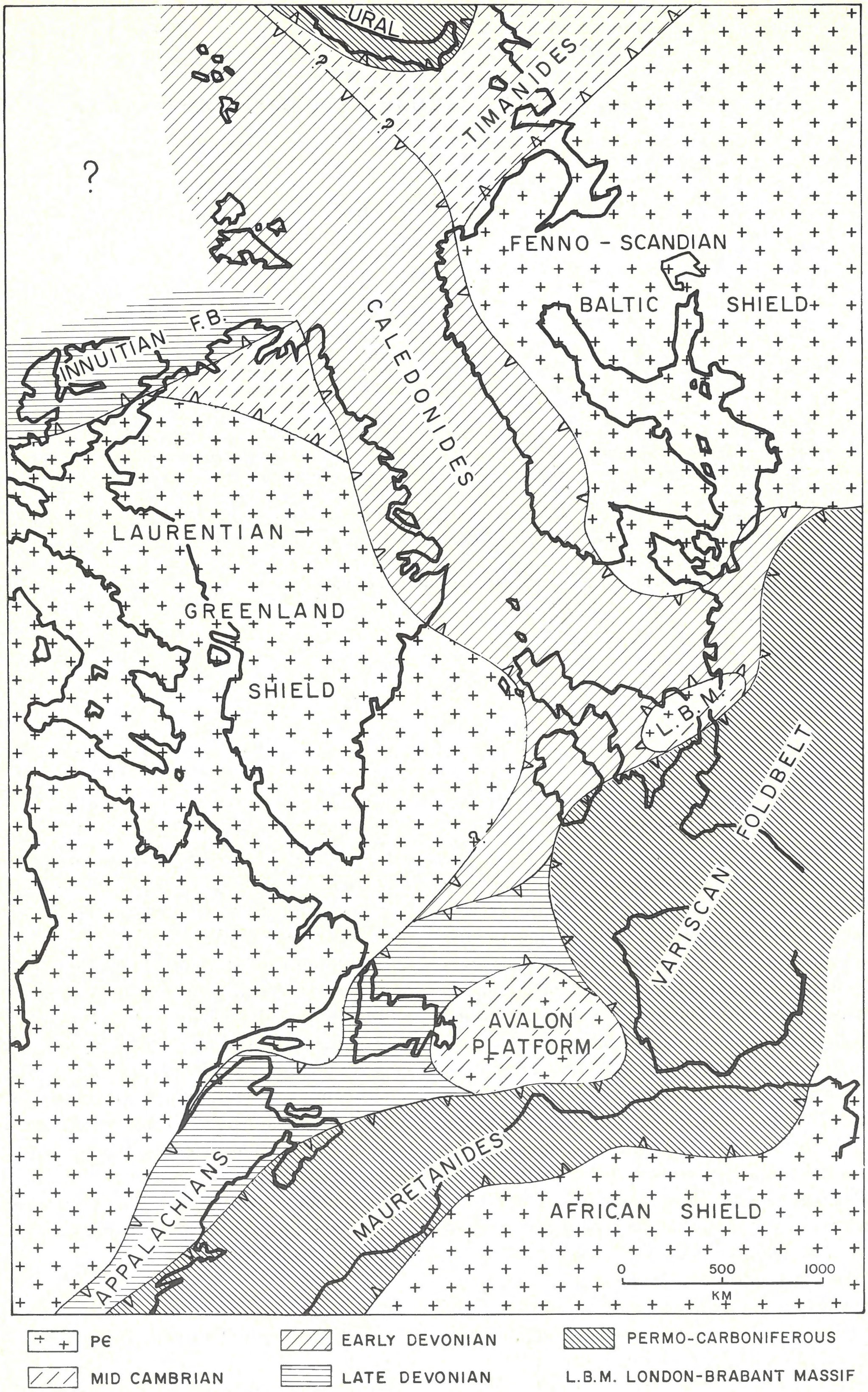

Fig. 1
Spatial relationship of Palaeozoic orogenic belts in the North Arctic-Atlantic realm (continental fit after Le Pichon, 1977).

Table I
Isotopic age determination on basement rocks from wells drilled in the North Sea area.

United Kingdom	
Shell 210/4-1	co-ord. 61°50′28.8″N/00°38′26.1″E Biotite Gneiss 435 ± 2 my* overlain by Permian red beds
Shell/Esso 211/21-1	co-ord. 61°11′11″N/01°05′54.1″E Muscovite-Biotite Gneiss ± 425 my overlain by Triassic red beds
Shell/Esso 30/16-5	co-ord. 56°23′11.8″N/02′°10′45.6″E Phyllitic Slate 418 ± 23 my* overlain by mid-Devonian carbonates
Norway	
Petronord 3/7-1	co-ord. 56°27′43.5″N/04°00′07.8″E Gneiss 425 ± 3* and 407 ± 2 my* overlain by Upper Cretaceous carbonates
Esso 16/2-1	co-ord. 58°53′35.2″N/02°21′25″E Biotite Micro-Granite ± 435 my* with complex overprinting between 400-390 my* overlain by Aptian-Albian marls
Esso 25/11-1	co-ord. 59°10′53″N/02°24′49″E Augen Gneiss 441 ± 2 my* overlain by red beds (Devonian-Triassic?)
Esso 8/3-1	co-ord. 57°59′13″N/03°14′13″E Schist 411 ± 4 my overlain by Zechstein shales and salts
Denmark	
DUC[1]) P-1x	co-ord. 56°02′04.4″N/03°46′10″E Albite-Epidot-Hornblende Schist. 428 ± 4* and 410 ± 5 my* overlain by Carboniferous red beds
Germany	
GNSC[2]) B-4-1	co-ord. 55°46′49.1″N/04°07′27.5″E Chlorite Schist 441 ± 6 my overlain by Old Red Sandstone
GNSC[2]) Q-1	co-ord. 54°51′02″N/05°56′07″E Muscovite Schist 408 ± 8 my overlain by mid-Devonian O.R. Sst.
Deutsche Schachtbau/ Preussag/Elverath Flensburg Z-1	co-ord. 54°43′42″N/09°24′03.7″E Folded Chlorite Metapelite 430 ± 11 my* 393 – 448 my* overlain by Rotliegendes
DEAG/Wintershall Westerland Z-1	co-ord. 55°02′30″N/08°24′30″E Folded Metapelite 445 ± 2 my* overlain by Rotliegendes
Netherlands	
Mobil A/17-1	co-ord. 55°01′11.4″N/03°39′24.4″E Granite 340 ± 7 my* (date of altered biotite) overlain by unmetamorphosed Old Red Sandstone

* dating by fractional Argon release method quoted ages are based on significant Argon release plateau rates
– other age determinations are based on conventional whole rock K/Ar analyses
– all ages quoted are based on the Geological Society of London Constants

1. Danish Underground Consortium
2. German North Sea Consortium

Variscan fold belt (Fig. 1). The Arctic - North Atlantic Caledonides were consolidated during the Late Silurian to Early Devonian Caledonian orogeny. This resulted in the suturing of the North American-Greenland and the Fennoscandian-Russian plates. This 'Northern Continent', which is also referred to as 'Laurasia', formed the foreland of the Variscan-Mauretanides-Appalachian fold belt which was consolidated during Late Carboniferous to Early Permian times. However, also in the domaine of the future Variscan fold belt can the effects of a Caledonian deformation phase be recognized. In geanticlinal areas ('island arcs') this is reflected by metamorphic and intrusive events (SCHMIDT, 1976; DORNSIEPEN, 1977; JÄGER, 1977). Yet in 'inter-arc' basins, sedimentation continued with little or no interruption from the Silurian into the Devonian. Most of these basins were apparently underlain by a presumably thinned continental crust, the consolidation age of which ranges from early Caledonian (450-500 Ma) to Cadomian and older (570 + Ma) (JÄGER, 1977, 1978). During the past two decades, results of wells drilled in the North Sea, in northern Germany and in Poland have materially contributed towards clarifying the Caledonian tectonic framework of North-Western Europe (Fig. 2) (KREBS, 1978; ZIEGLER, 1978).

Isotopic age determinations on metamorphic and intrusive rocks encountered in wells drilled in the North Sea area (Table I) indicate that the Caledonides of Scotland and Norway linked up across the northern North Sea but also that a branch of this fold belt extended from southern Norway through the central North Sea to northern Germany. From there it extended eastwards to Rügen and northern Poland where subsurface data again give evidence of Late Silurian to Early

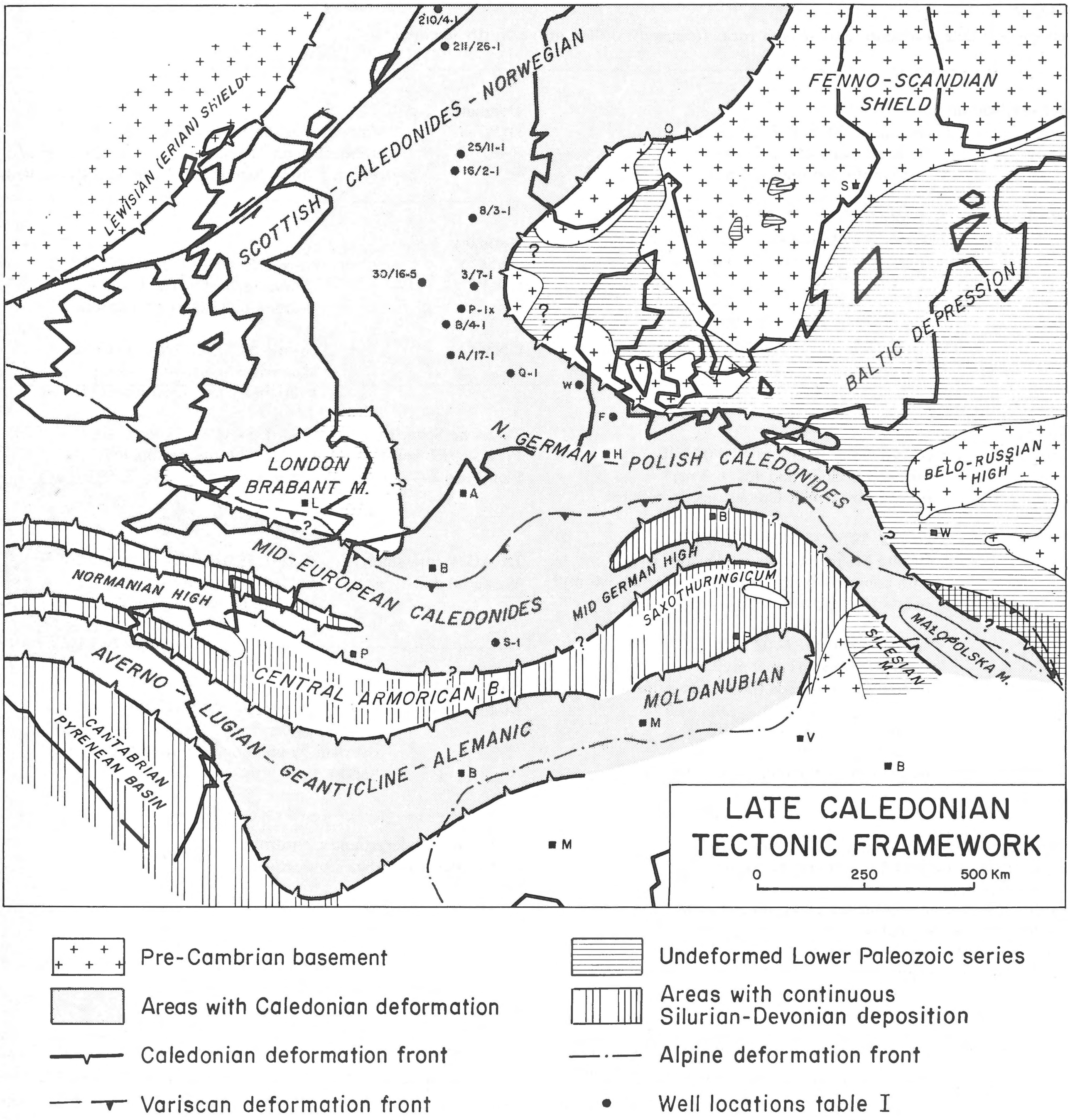

Fig. 2
Late Caledonian framework of NW Europe.

Devonian folding (GLUSCHKO ET AL., 1975, 1976; POZARYSKI & KOTANSKI, 1978). The boundary between this 'North German - Polish Caledonian' fold belt and its north-eastern undeformed foreland is as yet ill-defined. The Ringkøbing-Fyn-Møn High is formed by Precambrian basement rocks (690-870 Ma) which are in part overlain by undeformed Lower Palaeozoic sediments (LARSEN, 1971). Seismic and limited drilling data show that the thick Lower Palaeozoic sediments occurring in the Skagerrak, in the Kattegat, in Jutland, Sjaelland and the Bornholm area also remained unfolded during the Caledonian diastrophism.

From northern Poland the deformation front of the North German-Polish Caledonides extended probably south-eastwards through the area of the Western Holy Cross Mountains and under the Carpathian Mountain front (ZNOSKO, 1974; WJALOW & MEDWEDEW, 1977).

In the Polish sector of the Caledonides, several stable intramontane blocks are recognized. In northern Poland the Bialogard (Szczecinek) block separates the Koszalin-Chojnice and the Rügen-Pila Trough, both of which were affected by the Caledonian diastrophism (POZARYSKI & BROCHWISZ-LEWINSKI, 1978; POZARYSKI & KOTANSKI, 1978). In southern Poland the Upper Silesian massif, with its Precambrian basement and partial Lower Palaeozoic cover, is separated from the Cadomian Malopolska Massif by the Krakow Trough which underwent intense late Caledonian deformation. The Sudetic area, in which narrow bundles of Caledonian folds separate areas of continuous Silurian-Devonian deposition (OBERC, 1977), marks the transition between the Polish Caledonides and the system of island arcs and inter-arc-basins that occupied during the Late Silurian and Early Devonian the domaine of the future Variscan fold belt. Main elements of this complex geosynclinal system were the Central Armorican-Saxothuringian and the Cantabrian-Pyrenean successor basins which were separated by the Averno-Lugian-Alemanic-Moldanubian geanticline. The latter was only moderately affected by the Caledonian orogenic event (ZWART, 1978).

The North German-Polish Caledonides are likely to link up through the southern North Sea with a Caledonian fold belt extending along the southern margins of the London-Brabant Massif from Cornwall via the Boulonnais to the Ardennes (WATERLOT, 1974; KLEIN, 1977). This fold belt is referred to as the 'Mid-European Caledonides' (MICHOT, 1976; KREBS, 1978).

The Precambrian basement of the London Platform (700 Ma and older) is overlain by undeformed Lower Palaeozoic sediments. The Brabant Massif consists of folded and metamorphozed Cambrian(?) series that are unconformably overlain by non-metamorphic Siluro-Ordovician sediments that were in part deformed during the Caledonian orogeny (LEGRAND, 1968). In the light of this the London-Brabant Massif can be regarded as an intramontane stable platform (Zwischenmassif, Microcontinent) that was surrounded on all sides by Caledonian fold belts. Whether the purely geophysically defined East Elbe Massif in northern Germany should be interpreted in a similar way is an open question (GLUSKO ET AL., 1976).

In the Mid-European Caledonides the degree of deformation increases southwards. Caledonian metamorphism is documented from the Lizard Group in southern Cornwall (MILLER & GREEN, 1961), from the southern parts of the Brabant Massif and from the Stavelot Massif (MICHOT ET AL., 1972).

The Saar-1 deep test bottomed in a late Caledonian albite granite (381 ± 24 Ma) that is overlain by unmetamorphozed Middle Devonian carbonates (LENZ & MÜLLER, 1976). This control point is interpreted to be located within the internid parts of the Mid-European Caledonides, which probably extended westwards into the Normanian High and eastwards into the Mid-German High ('Mitteldeutsche Kristallin Schwelle': BRINKMANN, 1948; NEUMANN, 1966; WATZNAUER ET AL., 1976). In the latter, evidence for a late Caledonian orogenic and/or thermal event is documented for the Spessart (KREUZER ET AL., 1973) and the Thuringian Forest (NEUMANN, 1972).

In its eastern parts the Mid-German High separates such areas of continuous Silurian-Devonian sedimentation as the Harz to its north and the Saxothuringicum to its south. Thus in its eastern parts the Mid-German High may have played the role of a geanticlinal zone ('island arc') along the margins of which underthrusting may have taken place during the late Caledonian diatrophism.

From the above it follows that the south-eastern parts of the North German lowlands are likely to cover a transition zone between the consolidated North German-Polish Caledonides and the Variscan geosynclinal domain. This hypothesis, however, is difficult to verify as in critical areas Lower Palaeozoic series are deeply buried under very thick younger sediments.

Thick Lower Palaeozoic series that were deposited on the continental shelf that now forms the foreland of the Norwegian and North German-Polish Caledonides are preserved in the Baltic depression, in grabens along the Fennoscandian border zone and also as small outcrops on the Fennoscandian shield. It is likely that Cambro-Silurian shelf sediments originally covered most of the Fennoscandian shield.

Only a narrow strip of the Erian shield which formed the western foreland of the Scottish-Norwegian Caledonides is preserved on the shelves of the Shetland Islands and the Hebrides. The Rockall bank and probably also the Faeroe plateau are underlain by a Precambrian basement.

It should, however, be realized that the present-day juxtaposition of the northern and the southern Scottish Highlands post-dates the Caledonian orogeny and is the result of Devonian transcurrent movements along the Great Glen fault.

NORTH ATLANTIC DEVONIAN TRANSLATION

Following the late Caledonian diastrophism movements between the North American-Greenland and the Fennoscandian-Baltic plate changed over from a head-on collision to sinistral translation of major proportions (HARLAND & GAYER, 1972; HARLAND, 1973).

Palaeomagnetic data from the northern Appalachians and the British Isles indicate that Devonian lateral displacements between these two plates amounted to some 1000 to 2600 km (MORRIS, 1976). The bulk of this translation took place during the Middle Devonian and is thus coeval with the Acadian orogeny of the Appalachians and the Ellersmerian orogenic pulse of the Innuitian fold belt (Canadian Arctic Islands and northern Greenland). These two fold belts were apparently linked by a complex wrench-fault system subparalleling the axis of the Arctic-North Atlantic Caledonides and the Appalachians. A major element of this fault system is the Great Glen fault of Scotland for which palaeomagnetic data indicate a Devonian sinistral displacement of 200-300 km (STORED-

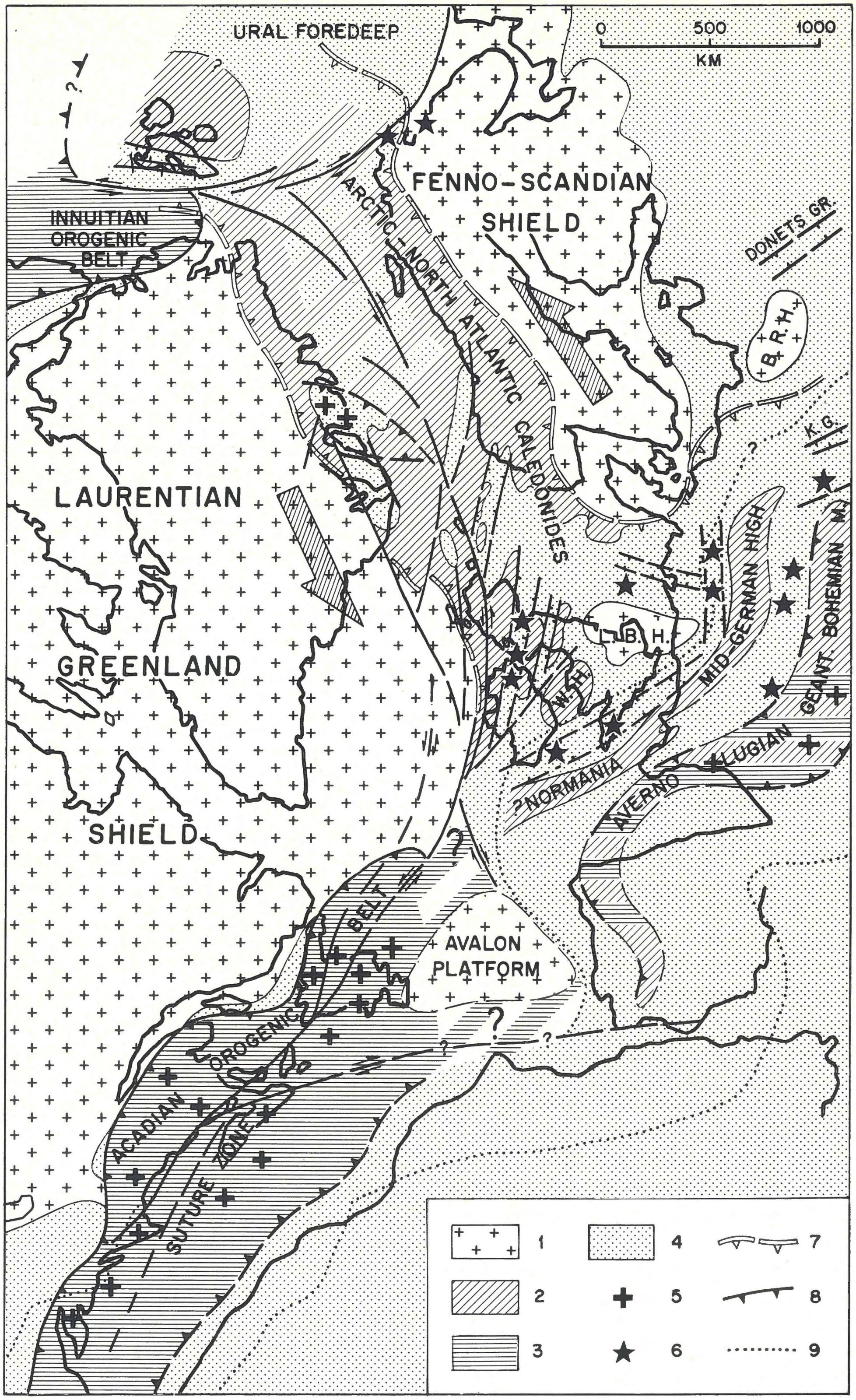

Fig. 3
Arctic-North Atlantic Late Devonian tectonic framework.
1: pre-Caledonian stable elements; 2: Caledonain foldbelts; 3: Devonian foldbelts; 4: Devonian sedimentary basins; 5: Devonian granites; 6: Devonian volcanics; 7: Caledonian deformation front; 8: Devonian deformation front; 9: Permo-Carboniferous Variscan deformation front.
BRH: Belo-Russian High; LBH: London-Brabant High; WH: Welsh High; KG: Krakow Graben.

VEDT, 1973). Major Devonian lateral movements may have also taken place along the Cabot (Lubec-Hampden) Fault and related fault systems of New Brunswick and Newfoundland (HAWORTH, 1974; MORRIS, 1976). However, much of this postulated North Atlantic wrench-fault system is not accessible to observation. Thus the fault pattern shown on Fig. 3 should be regarded as schematic at best.

Stratigraphic evidence from Eastern Greenland (HALLER, 1970) and Svalbard (HARLAND, 1973) indicates that by Early Carboniferous times transcurrent movements had ceased in the Arctic-North Atlantic area and had given way to purely extensional tectonics. Thus it must be assumed that by Early Carboniferous times a stable plate assembly as shown in figure 3 was achieved in areas north of the Late Carboniferous Variscan deformation front. South of the Variscan front this sketch map has not been palinspastically corrected for post-Devonian crustal shortening and therefore gives a distorted picture for these areas. Despite this shortcoming it provides a conceptual overview of the main Devonian tectonic elements in the North Atlantic realm.

It is of interest to notice that the Acadian fold belt does not appear to extend directly into the Variscan geosynclinal domain where traces of a mid-Devonian orogenic pulse can be discerned only in the Averno-Lugian (BERNARD-GRIFFITHS ET AL., 1977) and the Alemanic-Bohemian geanticline. Overall tensional tectonics dominated the Devonian and Early Carboniferous development of North-Western Europe. However, also in the Canadian Maritime Provinces a number of post-Acadian tensional successor basins started to subside during the Late Devonian and Early Carboniferous (HOWIE & BARSS, 1975; POOL, 1976). In the Arctic and Norwegian-Greenland Sea a tensional setting persisted throughout late Palaeozoic times. In contrast, the largely tensional Devonian and Early Carboniferous development of the northern Variscan domain came to a close with the onset of the Variscan orogeny during the late Early Carboniferous.

DEVONIAN AND CARBONIFEROUS RIFTING IN THE NORTHERN BRITISH ISLES

In the domain of the Arctic-North Atlantic Caledonides strong post-orogenic uplifting coupled with transcurrent faulting led during the Devonian to the rapid subsidence of the intramontane Old Red 'Molasse' basins of Ireland, Scotland, Western Norway, Eastern Greenland and Svalbard (Fig. 4). Faults bounding these basins form an intricate part of the Devonian North Atlantic transcurrent systems and its secondary tensional and compressive features (Fig. 3).

In the North Sea area, subsidence of the Midland Valley Graben, and the Orcadian and Northumberland basins started during the Early Devonian. This was accompanied by the extrusion of calc-alkaline volcanics and the widespread intrusion of Lower Devonian post-orogenic granites in the Scottish Highlands and the Southern Upland Massifs (LEEDER, 1974; FRANCIS, 1978). Continental and in part lacustrine series reaching aggregate thickness of 6 to 8 km were deposited in the fault-bounded Old Red basins of the British Isles and Western Norway. Syndepositional wrench faulting resulted in local folding (STEEL, 1976). A main folding phase affecting the Old Red basins of Ireland and the U.K. marks the boundary between the lower and the middle Old Red and is approximately dated as Middle Devonian (WILLS, 1950). This corresponds to the peak of transcurrent movements along the North Atlantic wrench systems and the Acadian orogeny.

During the Carboniferous, the Midland Valley, the Northumberland-Solvay Basin and the Dublin Trough continued to subside rapidly (Fig. 5). This was paralleled by a predominantly alkaline rift volcanism that contrasts with their Devonian calc-alkaline volcanism (FRANCIS, 1968, 1978; LEEDER, 1976). Thus a purely extensional setting has to be assumed for the Carboniferous development of these graben-shaped basins.

North Sea drilling data indicate that the Old Red basins of Scotland linked up with the scattered occurrences of Old Red series on the Norwegian west coast and that Devonian series are widely distributed in the central North Sea. The Carboniferous Midland Valley and Northumberland Basin extend into the central parts of the North Sea where they apparently loose their identity. A further, albeit smaller, Carboniferous basin is recognized in the outer Moray Firth area. It is likely that most of the major SW-NE striking faults in the northern North Sea were emplaced during the Devonian and Early Carboniferous.

DEVELOPMENT OF THE VARISCAN FOREDEEP BASIN

During Devonian times a large sedimentary basin developed under a tensional setting in the area of the rapidly degraded Mid-European and North German-Polish Caledonides. This basin, referred to here as the 'Cornwall-Rhenish Basin', was limited in the south by the Normanian - Mid German High (Fig. 4). In the west this basin merged with the Devonian troughs of Ireland, to the north it linked up through the central North Sea with the Old Red basins of Scotland, and to the east it extended into the Baltic and through Poland to the Devonian Donets Graben. Flanked by the Wales-London-Brabant High to the north, the Cornwall-Rhenish Basin started to subside rapidly during the Early Devonian.

A marine transgression originating presumably from such areas of continuous Silurian-Devonian marine deposition in the east as the Harz and southern Poland and possibly similar areas to the west, invaded this basin during the Gedinnian and Siegenian. Continued subsidence of the Cornwall-Rhenish Basin was accompanied by tensional tectonics as documented by MATTHEWS (1977) for Cornwall and South Devonshire, by BENDER ET AL. (1977) for the Rheinische Schiefergebirge and by ALBERTI ET AL. (1977) for the Harz.

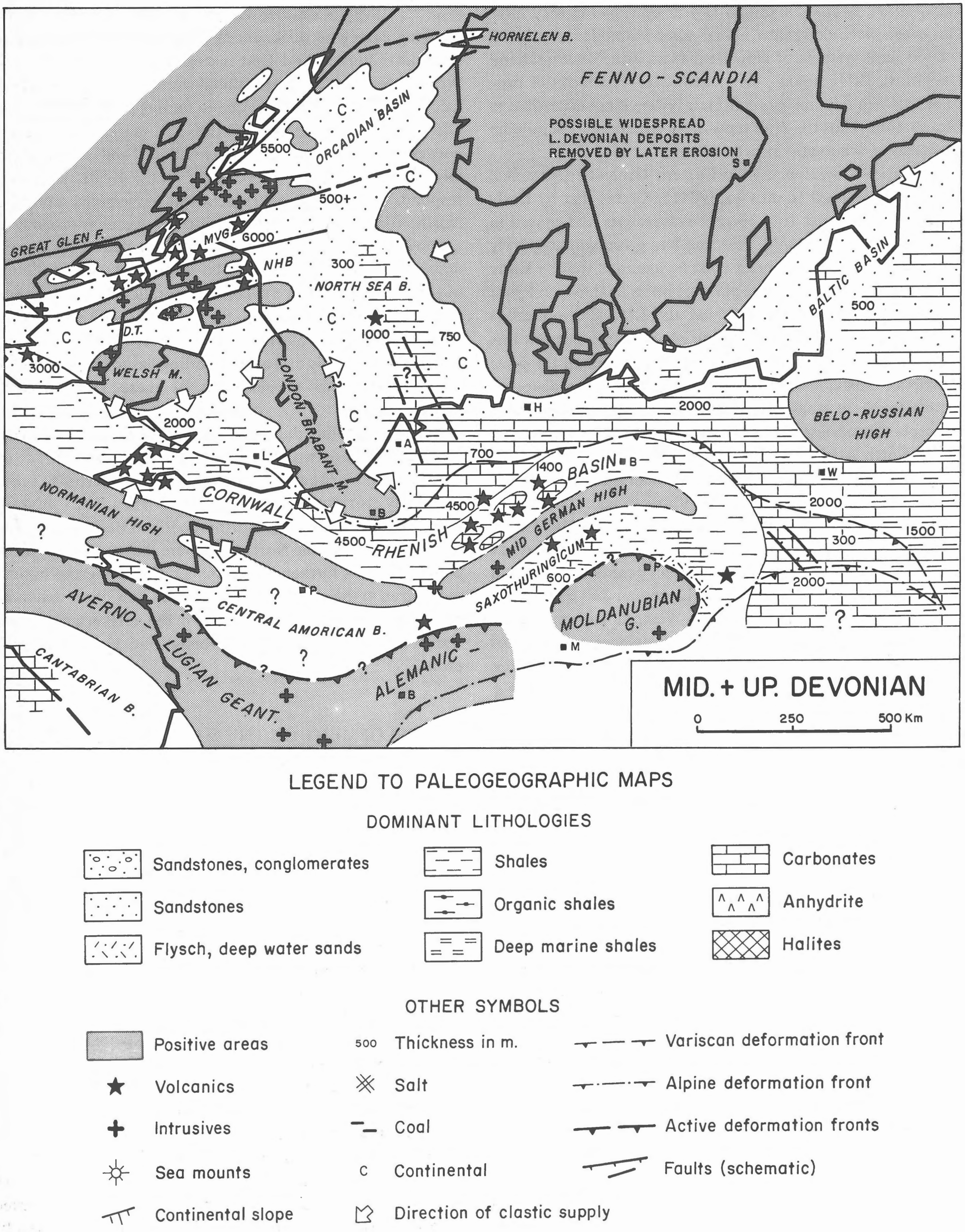

Fig. 4
Middle and Upper Devonian palaeogeography. The legend is to be used for the other palaeogeographic maps, too.

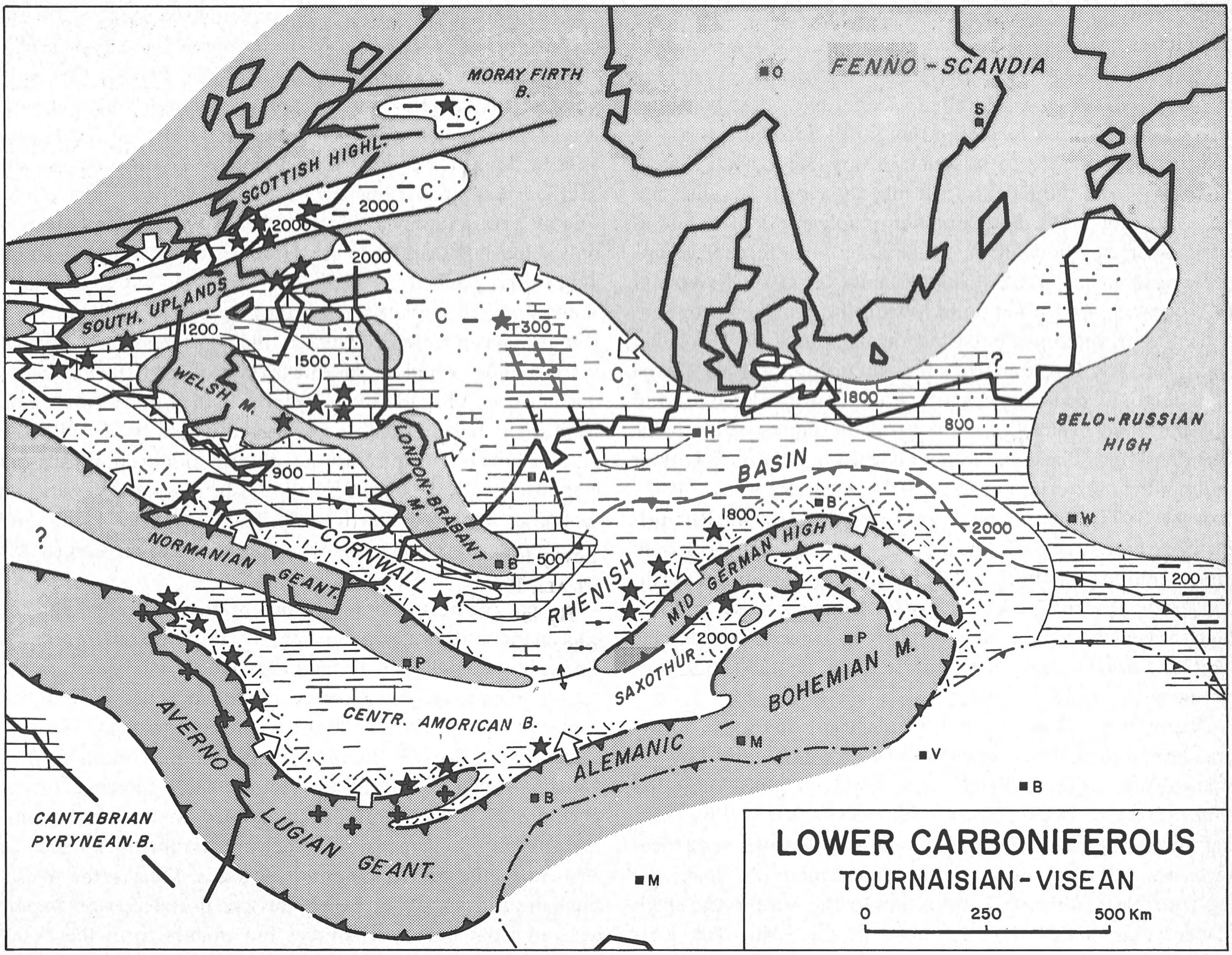

Fig. 5
Lower Carboniferous palaeogeography.

During the Early and Middle Devonian clastics were shed into this basin from the Old Red Continent to the north; shallow-water sands accumulated in shelf areas where they were in part trapped in local sub-basins; in the southern deeper parts of the basin, Lower and Middle Devonian series are represented by such thick black shale sequences, as the Hunsrück and the Wissenbach Schiefer respectively. Increased tectonic activities during the Middle Devonian resulted in block faulting of the basin floor and the accentuation of a number of fault-bounded sub-basins and intervening swells (PAPROTH, 1976). In Southern England (MIDDLETON, 1960), in the Sauerland, the Lahn-Dill and Kellerwald areas of the Rheinische Schiefergebirge (LEHMANN, 1972; HERMANN & WEDEPOHL, 1970) and in the Harz (ALBERTI ET AL., 1977) this was accompanied during the early Givetian by a strong, in part submarine, spilite-keratophyr volcanism (JUTEAU & ROCCI, 1974; FLICK, 1977, 1978). Such bimodal (mafic-felsic) alkaline volcanic suites are characteristic for intracratonic rifts (MARTIN & PIWINSKI, 1972). This volcanism therefore emphasizes the intracratonic tensional nature of the Cornwall-Rhenish Basin which may be regarded as a complex rift (SAWKINS, 1978) that formed part of the Devonian North Atlantic fault system. However, the actual geometry of the Cornwall-Rhenish rift is difficult to unravel as it became strongly deformed during the Late Carboniferous Variscan diastrophism. Unfortunately a palinspastic reconstruction of the Variscan externides is still lacking. Furthermore a possible extension of the Cornwall-Rhenish rift system into the North-German and Polish lowlands is masked by thick Late Palaeozoic and Mesozoic series. The bimodal chemism of the Devonian volcanics in the Cornwall-Rhenish Basin indicates that rifting had not proceeded to the point of crustal separation.

In NW-Europe the Middle Devonian tensional phase went parallel with a regional marine transgression that reached far to the north, thus shutting off much of the clastic supply to the deeper parts of the Cornwall-Rhenish Basin. During the Givetian, large reef-fringed carbonate platforms were established in shelf areas and on local highs (KREBS, 1974). From these shelf areas a relatively narrow and possibly fault-controlled sea arm extended into the central North Sea area where Middle Devonian carbonates transgress on Caledonian metamorphics (Fig. 4). Although Upper Devonian volcanics have been recorded locally in the North Sea there is as yet insufficient evidence to postulate a possible graben system extending from the Rhenish rift into the North Sea. Despite this it is noteworthy that a number of volcanic centres and in part also facies lines in the Rheinische Schiefergebirge apparently align in NW-SE striking trends (KREBS, 1968; DVORAK, 1973; BOTTKE, 1978) that point toward the central North Sea.

Extension tectonics persisted throughout Late Devonian and into Early Carboniferous times. During the Late Devonian tectonic disturbances triggered density currents and slumping and even olistostromes on the flanks of the Mid-German High. These mass flows consist mainly of reworked sedimentary material (SCHWAB, 1974; LUTZENS ET AL., 1975; STOPPEL, 1977). In the axial parts of the Cornwall-Rhenish Basin carbonate deposition continued on local highs with only minor amounts of clastics reaching the basin from the north. Calcareous turbidites were derived from shelf areas, local highs as well as from the apparently reef-fringed Normanian - North German High. Volcanic activity abated somewhat during the Late Devonian.

During Early Carboniferous (Dinantian) times, the northern shelf of the Cornwall-Rhenish Basin was occupied by the Waulsortian reef and 'Kohlenkalk' platform which extended from Ireland to Poland (SCHMIDT & FRANKE, 1975) (Fig. 5). In the southern parts of the basin, carbonate deposition on local highs was gradually drowned out by continued subsidence. At the transition from the Tournaisian to the Visean the thick 'Deckdiabas' series were extruded in the Lahn-Dill, Kellerwald and the Harz areas (BENDER ET AL., 1977; ALBERTI ET AL., 1977; HERMANN & WEDEPOHL, 1970). These tholeiitic basalts display a clearly continental affinity. The Early Carboniferous peak of volcanic activity is interpreted as an indication for a last major rifting phase affecting the southern parts of the Rhenish basin. An alkaline Early Carboniferous volcanism is also reported from Cornwall and South Devonshire (FRANCIS, 1970).

The Early Carboniferous volcanism in the Cornwall-Rhenish Basin correlates with the onset of the alkaline volcanism in the Midland Valley, the Northumberland-Solvay Basin and the Dublin Trough (FRANCIS, 1978; LEEDER, 1974) and may therefore be related to the onset of regional extension in the Arctic-North Atlantic realm.

During late Late Devonian to Early Carboniferous times the relief of the Mid-German High was gradually accentuated as illustrated by an increasing influx of clastic material derived from southern sources into the Rhenish Trough. Culm graywackes make their first appearance in Moravia during the Tournaisian (DVORAK, 1975). However, in the remainder of the Cornwall-Rhenish Basin wholesale deposition of the synorogenic Culm flysch only started during the upper Visean (FRANKE ET AL., 1978). This is interpreted as marking the onset of the Variscan orogeny and the start of underthrusting along the margins of the Normanian-Mid-German High (KREBS, 1968). With this the Cornwall-Rhenish Basin became strongly polarized to the south and assumed the geometry of a classical foredeep. Absence of late Visean Culm flysch in the Ardennes and the Saar area indicates that at this time the Normanian-Mid German geanticline had not yet developed into a continuous emergent high (PIRLET, 1976; MICHOT, 1976). This was only achieved during the early Namurian by which time Culm deposition reached its peak. By this time the Kohlenkalk shelves that occupied the northern parts of the Cornwall-Rhenish Basin were drowned by the transgressive Namurian marine shales which reach thicknesses of over 2000 m in the northern Netherlands and Germany. In the central North Sea, Namurian shales grade northwards into red beds. With the gradual advance of the Variscan deformation front during the Namurian and Westphalian, the basin axis of the Variscan foredeep migrated northwards (TEICHMÜLLER, 1973) and newly folded-up sediments were subjected to erosion (BLESS ET AL., 1977).

By late Namurian times, sedimentation exceeded subsidence in the southern, proximal parts of the Variscan Foredeep. This is illustrated by the basin-wide change of the depositional regime from a deeper-water flysch type to a shallow-water to continental molasse type (PAPROTH & TEICHMÜLLER, 1961).

During the Westphalian continental paralic conditions prevailed throughout the basin (Fig. 6); these, however, were periodically interrupted by short-lived marine incursions. Westphalian coal measures reach maximum thicknesses of 3500 m in the North German lowlands. During the Westphalian clastics supplied to the Variscan Foredeep were in part derived from northern sources but mainly from the rising Variscan mountains to the south (BLESS ET AL., 1977).

THE VARISCAN OROGENY

From the above it follows that the Caledonian and the Variscan orogenic cycle are separated in the Variscan foredeep basin by a period of extension tectonics that lasted from Early Devonian until Early Carboniferous times. During this period the intracratonic Cornwall-Rhenish Basin came into existence whereby rift tectonics played a significant role. By late Early Carboniferous times this basin was incorporated into the Variscan orogenic system and developed into a strongly asymmetric foredeep. During the Late Carboniferous Asturic orogenic pulse the southern parts of this foredeep were scooped out by decollement thrusting; they now form the Variscan externides. In the Variscan foredeep basin the Variscan orogenic cycle thus spans the period from the late Visean to the late Westphalian.

In the southern parts of the Variscan geosynclinal system a distinction between a Caledonian and a Variscan orogenic cycle is less obvious. Continuous Silurian-Devonian sedimentation characterizes the Central Armorican-Saxothurin-

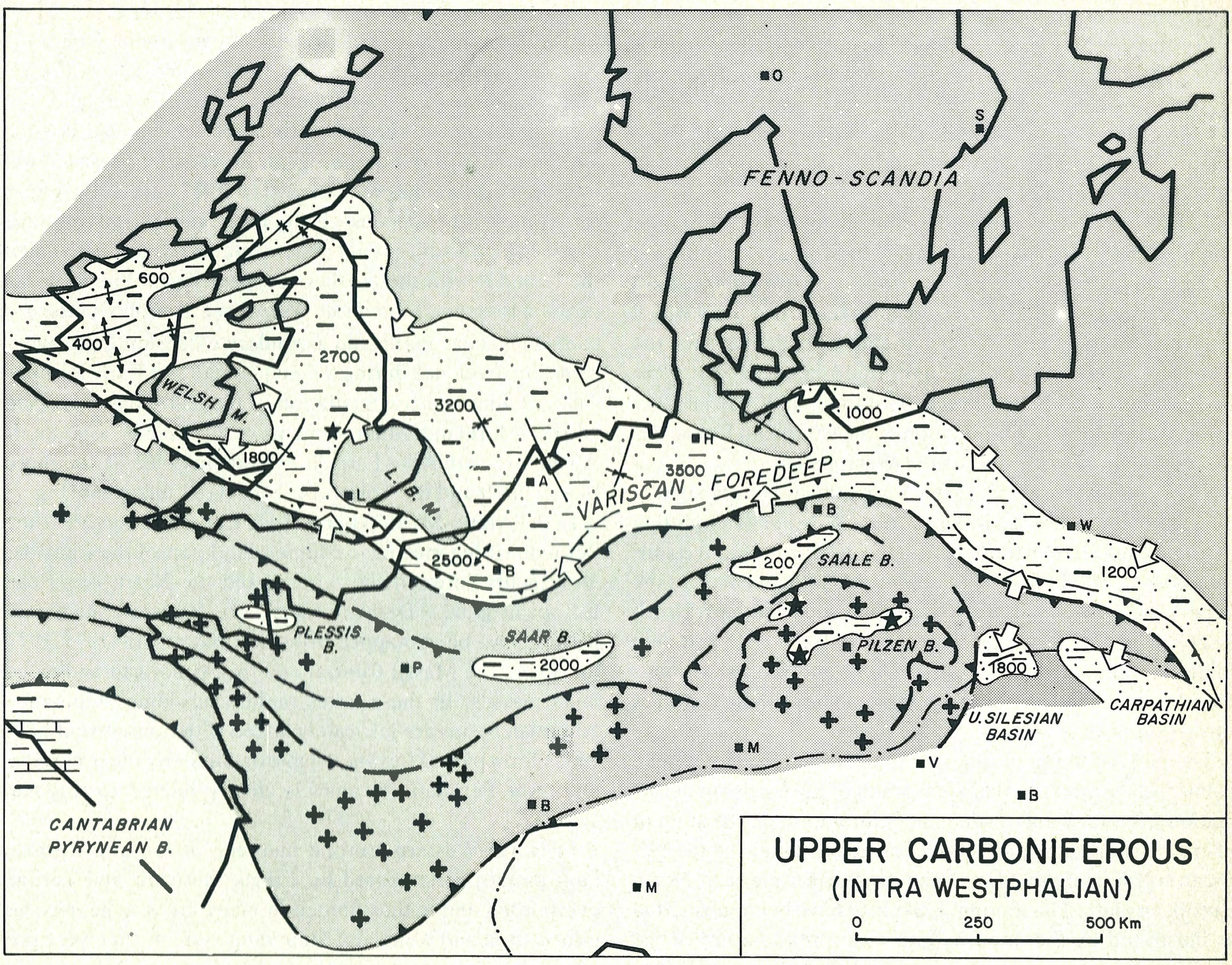

Fig. 6
Upper Carboniferous palaeogeography.

gian as well as the Cantabrian-Pyrenean Basin. Devonian extension tectonics are reported from the latter by BECKER ET AL. (1977).

The occurrence of Devonian and Early Carboniferous spilite-keratophyr volcanic suites in the northern Vosges and in eastern Thuringia (JUTEAU & ROCCI, 1965, 1966; WATZNAUER ET AL., 1976; KREBS, 1977; BEBIEN ET AL., 1977) indicates that during these times extension tectonics also played a role in the Saxothuringian Basin.

Furthermore Devonian extension tectonics led in Moravia to the subsidence of a number of NW-SE oriented troughs; this was accompanied by a bimodal rift volcanism (DVORAK, 1973, 1976). At the same time the NW-SE oriented Krakow Trough subsided in southern Poland. Also the Donets Graben may be considered as forming part of this complex rift system that developed during the Devonian in the Variscan geosynclinal realm and in its northern foreland.

On the other hand in the Averno-Lugian-Alemanic-Moldanubian geanticline a Caledonian thermal event was followed by an Acadian one (AUTRAN & GUILLOT, 1977). The late Devonian-early Carboniferous Bretonic phase strongly affected the Averno-Lugian-Moldanubic Arc causing folding, metamorphism and granitization as well as the onset of Culm deposition along the northern margins of the Armorican Massif; the Massif Central (CHENEVOY, 1974; COGNÉ, 1974, 1976; HAMET & ALLÈGRE, 1976) and the Bohemian Massif (DVORAK, 1978) at a time when the development of the Cornwall-Rhenish Basin, the future Variscan Foredeep, was still governed by extension tectonics (KREBS, 1968). With the late Visean Sudetic or Variscan main orogenic phase (PFEIFFER, 1971; TEISSEYRE, 1976) the Normanian - Mid German highs were also incorporated in the Variscan orogenic system, with new underthrust zones developing along their margins.

Closure of the Central Armorican-Saxothuringian inter-arc basin was achieved during late Visean to Namurian times. This was followed by the deposition of local Westphalian neo-autochthonous series (e.g. Plessis, Saale and Pilzen basins) and an intense late- to post-orogenic magmatism that continued well into Permian times. In the Saar successor basin sedimentation continued however, throughout the Late Carboniferous with little interruption.

For the southern parts of the Variscan geosynclinal system, the Bretonic phase is considered as forming the onset of the Variscan orogeny (COGNÉ, 1974). However, progressive narrowing of the Central Armorican-Saxothuringian Basin probably goes back to the Acadian and the Caledonian events and possibly even further.

The Variscan geosynclinal system underwent a long and complex history, during which geanticlinal areas were affected by repetitive orogenic events. Periods of active compression alternated with periods of regional extension during which inter-arc basins were accentuated and, as is the case for the Variscan Foredeep, new basins formed in areas that were folded up previously. In the course of time the Variscan front moved northwards. Consolidation of the European Variscides was completed by the end of the Westphalian.

The northern foreland of the Variscides was only slightly affected by the Variscan orogeny. Late Westphalian uplifting of the Texel-IJsselmeer High in the northern Netherlands (BLESS ET AL., 1977) may be related to the mild inversion of the hypothetical Devonian-Early Carboniferous southern North Sea Graben. Similarly uplifting of the Malvern High and mild folding of the sedimentary fill of the Irish and Scottish grabens may be explained in terms of foreland inversion tectonics (inversion of aulacogens).

The palaeogeographic maps of figures 4 to 6 have not been palinspastically restored in areas south of the Variscan deformation front for want of adequate information on the amount of crustal shortening and subduction achieved during the Variscan collision of the African and the North American-North European plate. This amount is likely to have been substantial as illustrated by the intensity and widespread nature of the Variscan late- to post-orogenic plutonism (ZWART, 1975).

In North-Western Europe there is little evidence for the closure of large oceanic basins during the Variscan diatrophism as postulated by ANDERSON (1975), JOHNSON (1975) and BURETT & GRIFFITHS (1977). Major ophiolite belts representing remnants of oceanic crust are absent. Devonian and Lower Carboniferous volcanics occurring in the Variscan Foredeep in the Saxothuringicum and in Moravia display a clearly continental affinity (KREBS, 1977). Therefore it can only be hypothesized that in the Variscides possibly ophiolite nappes were obducted during the terminal suturing phase of the Gondwana and the Laurasian plates thus destroying all evidence of preexistent oceanic basins (so-called cryptic sutures: DEWEY, 1977; BURKE ET AL., 1977). Alternatively it may be assumed that the Variscan geosynclinal system of Central Europe lacked extended oceanic domains and was largely floored by a thinned continental crust (BEBIEN ET AL., 1977).

PERMO-CARBONIFEROUS FAULT TECTONICS

In Europe the Variscan orogeny came to an end with the late Westphalian Asturian compressional phase. The Stephanian and Lower Permian development of the Variscides and their northern foreland was characterized by the emplacement of a complex fault system and an intense postorogenic volcanism that spread far to the north into the Variscan foreland.

In the Uralides, the southern Appalachians and possibly also in the Mauretanides, orogenic movements persisted well into the Permian. ARTHAUD & MATTE (1977) present evidence for a Late Carboniferous - Early Permian right-lateral intracontinental transform fault system linking the southern end of the Uralides with the northern Appalachians. The near-surface expression of this fault system is a complex pattern of conjugate shear faults and secondary extension faults which came into evidence during the Stephanian and Early Permian. This resulted in a fragmentation of the European Variscides and their foreland. Main elements of this fault system are the Agadir or South Atlas Fault, the Chedabukto Fault, the Bay of Biscay Fault and the Tornquist-Teisseyre Lineament (Fig. 7).

In the Arctic-North Atlantic Late Carboniferous and Early Permian rifting may have compensated part of the transform movements between the African and the North American-European plates. Details of the Late Variscan shear fault pattern have been mapped by ARTHAUD & MATTE (1975, 1977) for Spain, the Massif Central and the Armorican and Bohemian massifs. In these areas rapidly subsiding Stephanian-Autunian basins are intricately linked with transcurrent faults which form part of this shear pattern. Similarly the occurrence of Lower Permian volcanics is closely related to this fault system.

In North-Western Europe mapping of the late Variscan fault pattern is hampered by a thick Mesozoic and Tertiary overburden and is thus limited in many areas to geophysical information and well data. Main fault systems that were probably all emplaced during the Stephanian and Autunian are the Tornquist-Teisseyre Lineament, the Rheingraben-Gifhorn, the Elbe-, the Rostock-Gramzower and the Neuruppiner lineaments (BAUMANN ET AL., 1976) and possibly the southern border fault of the Hunsrück. Furthermore also the faults limiting the Harz Mountains, the Osning zone and the Thüringer Wald may have already been emplaced during the Late Carboniferous to Early Permian. The Ruhr Graben, the West Netherlands-Solepit Basin fault system and the Emsland Trough were probably also emplaced during the Late Carboniferous and Early Permian. From figure 8 it is evident that the Tornquist-Teisseyre Lineament forms the boundary between the stable East European craton and the fragmented West European platform. In Poland this lineament is marked by a set of northwest-southeast striking faults (POZARYSKI, 1970).

In the western Baltic and in the Kattegat, the Tornquist-Teisseyre Lineament is represented by a complex fault system referred to as the Fennoscandian border zone. The pattern of this fault system is strongly suggestive of strike-slip displacement. During the emplacement of this fault system Cambro-Silurian shelf sediments were strongly dissected and in part uplifted and eroded to the extent that thick Lower Palaeozoic

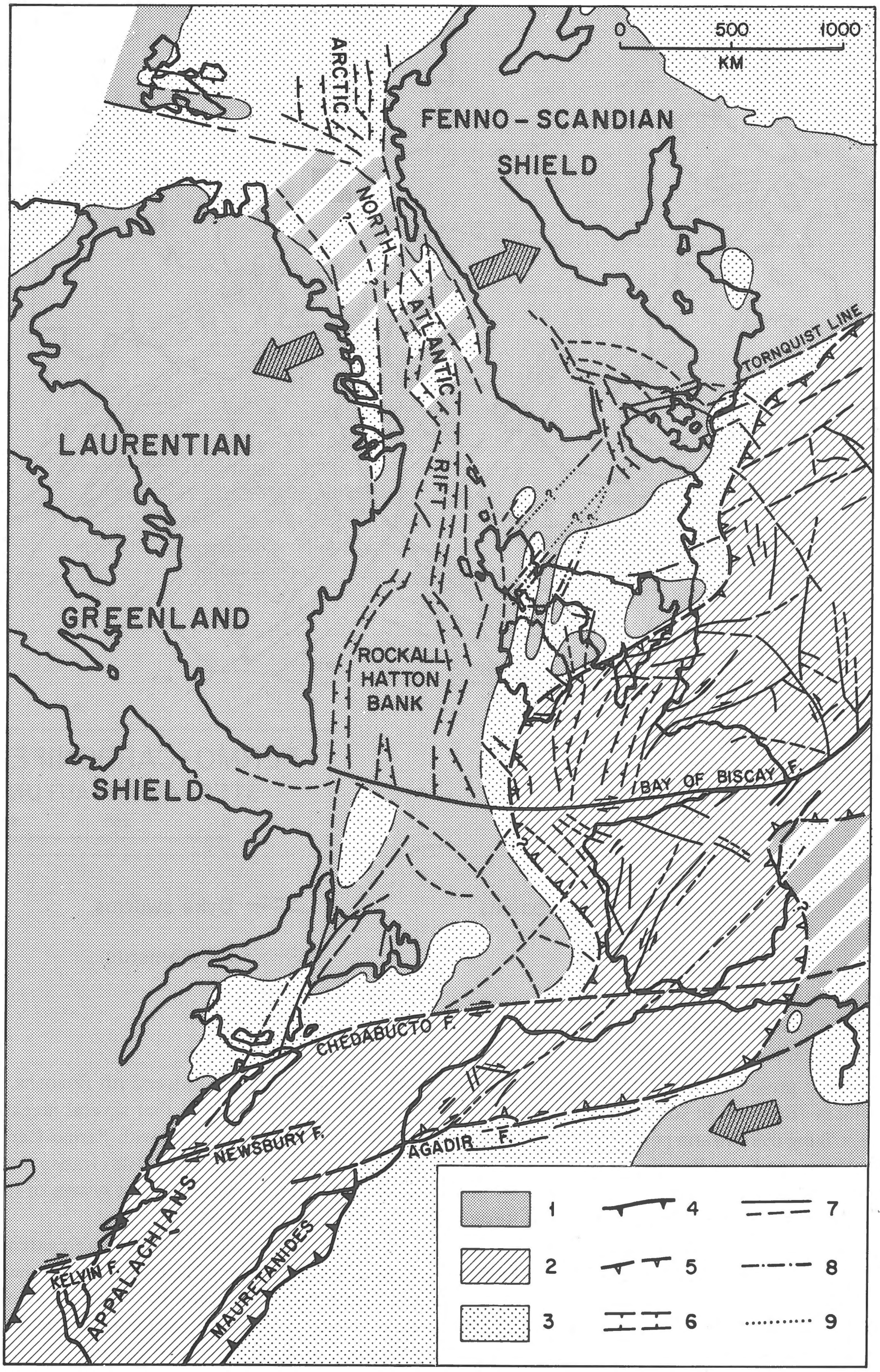

Fig. 7
Arctic-North Atlantic Late Variscan fault pattern (Continental fit after Le Pichon, 1977).
1: pre-Variscan stable elements; 2: Variscan foldbelt; 3: Carboniferous basins in Variscan foreland; 4: Alleghenian deformation front; 5: Asturian deformation; 6: grabens, rifts; 7: faults; 8: dyke swarms; 9: alinements.

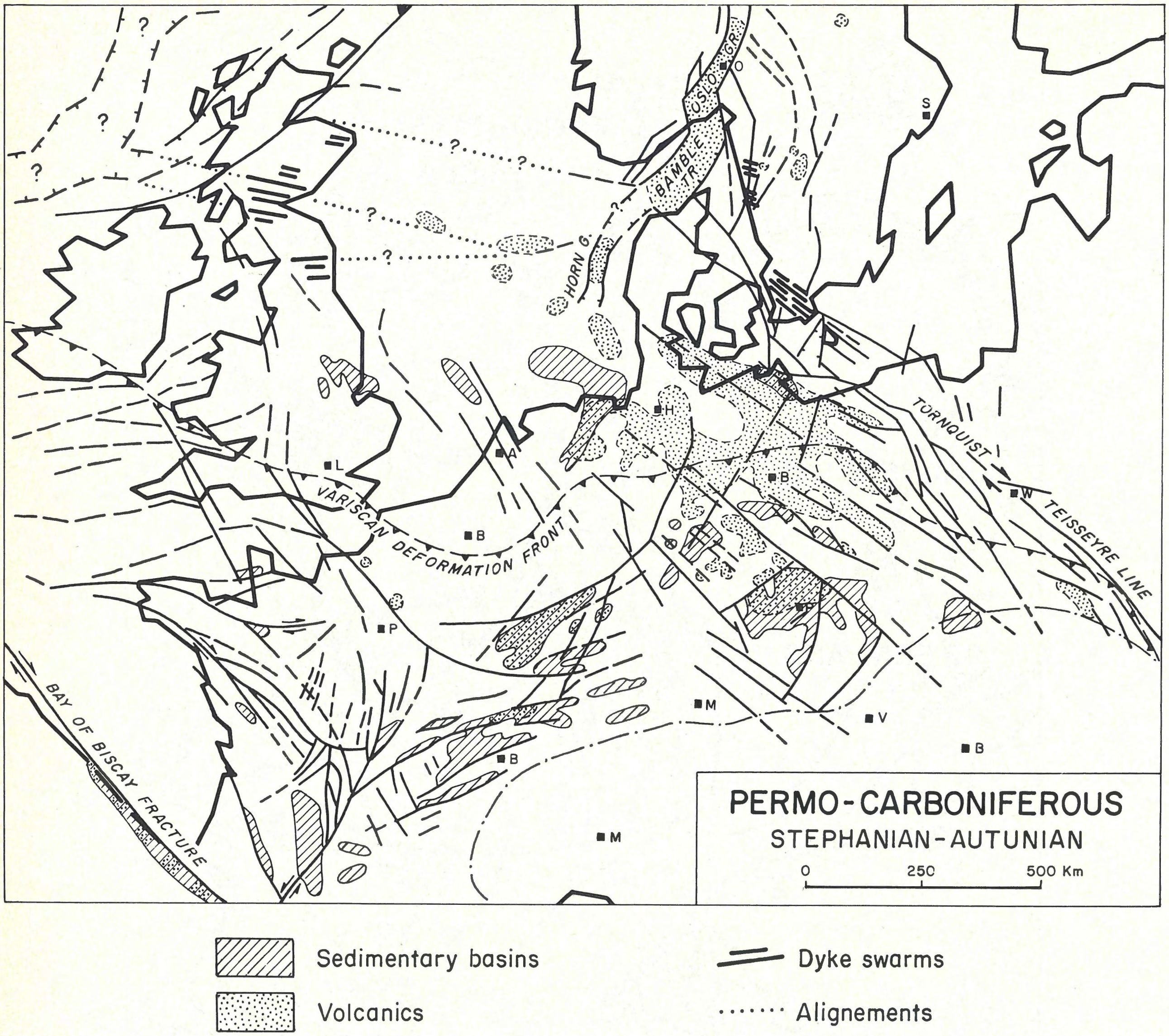

Fig. 8
Stephanian-Autunian palaeogeography.

series are now only preserved in relatively narrow downthrown fault blocks (Encl. I). In southern Sweden a northwest-southeast striking dyke swarm permits dating of faulting as Late Carboniferous to Early Permian (PRIEM ET AL., 1968; KLINGSPOR, 1976).

The Oslo Graben which is located at the north-western termination of the Tornquist-Teisseyre Lineament began to open during the latest Westphalian to Stephanian (STOREDVEDT ET AL., 1978). Igneous activity started in the southern parts of the Oslo rift and gradually spread to the north (SUNDVOLL, 1978). This indicates a progressive northward opening of this rift presumably by fracture propagation in response to transcurrent movements along the Tornquist-Teisseyre Lineament. Thus the Oslo Graben can be considered as a pull-apart feature at the termination of a transcurrent fault, rather than as a mantle-plume induced rift (ZIEGLER, 1978). In this context it should be noted that several megafracture zones which are in part associated with Permo-Carboniferous igneous centres extend from the Oslo Graben through southern Sweden and link up with the fault system of the Fennoscandian border zone (Fig. 8).

Southwards, the Oslo Graben probably extends through the Bamble Trough into the Horn Graben. The latter crosses the Mid North Sea-Ringkøbing-Fyn-Møns trend of highs. These highs came into evidence for the first time during the Early Permian. The margins of the Ringkøbing-Fyn-Møns High are not so much marked by major faults but rather by gentle flexures and a number of minor faults. The Elbe Lineament appears to terminate at its intersection with the Rheingraben-Gifhorn Lineament and does not extend into the North Sea.

Stratigraphically dated Lower Permian volcanics are widespread in the subsurface of Northern Germany (BUSCH & KIRYUCHIN, 1972; GLUSCHKO ET AL., 1975; POKORSKI & WAGNER, 1975; SCHMIDT ET AL., 1977); they reach a maximum thickness of 2000 m along major faults and lineaments and at their intersections (PLEIN, 1978). Areas with maxima of volcanic thicknesses may be associated with pull-apart structures at the termination of subsidiary wrench faults subparalleling the Tornquist-Teisseyre Lineament. Alternatively 'leaking' transform faults may be visualized for the emplacement of e.g. the volcanism in the Nahe Trough. Permian volcanics occur on both flanks of the Ringkøbing-Fyn High as well as in the Horn Graben but are largely absent in the northern and southern North Sea (Fig. 8).

Lower Permian volcanics are highly alkaline in the Oslo Graben (OFTEDAHL, 1968; RAMBERG, 1976) but only mildly alkaline in the immediate foreland of the Variscan fold belt. In the Variscan domain proper Lower Permian volcanics generally display a calcalkaline chemism that is typical of a post-orogenic volcanism (KRAMER, 1977).

In the central and northern North Sea, the importance of late Variscan faulting is difficult to assess. Clear evidence of late Westphalian-early Stephanian tectonism is only provided by the east-west striking tholeiitic dyke swarms which transsect the Carboniferous Midland Valley Graben and the Northumberland Basin (FRANCIS, 1978). Whether a continuous fracture system connects these dyke swarms with the Oslo-Horn Graben remains an open question.

There is no evidence that the Viking and the Central grabens started to subside already during the Late Carboniferous to Early Permian.

Along the Atlantic seaboard of France, Ireland and the U.K. there is little to no stratigraphic evidence that could support the hypothesis of Late Carboniferous to Early Permian faulting and rifting. However, the few wells that have reached the pre-Mesozoic have either failed to encounter Late Palaeozoic series or these could not be more accurately dated than Permo-Triassic. Yet, bearing in mind that the Bay of Biscay fault zone is considered to be one of the main Late Carboniferous-Early Permian transform faults (ARTHAUD & MATTE, 1977), it is reasonable to assume that the fault systems of the Porcupine Trough, the Celtic Sea and the Western Approaches basins were emplaced at the same time and formed part of a conjugate shear pattern. In Permian times, the Bay of Biscay Fault probably did not extend significantly into the present day Labrador Sea (Fig. 7); thus it must be assumed that strike-slip displacement along this fault gradually decreased westwards and was taken up by rifting in the Rockall Trough as well as possibly in the Proto-Iceland Basin. This is in keeping with Permo-Carboniferous rifting as documented from Eastern Greenland (HALLER, 1970) and possibly also the Barents Sea. Based on magnetic data (TALWANI & ELDHOLM, 1977) it is very unlikely, however, that crustal separation was already achieved in the Arctic-North Atlantic during the Late Palaeozoic as postulated by RUSSELL (1976) and RUSSELL & SMYTHE (1978).

This implies that Late Palaeozoic transform movements along the Bay of Biscay Fault were not in the range of 100 to 200 km as proposed by RUSSELL & SMYTHE (1978) but rather in the order of tens of kilometres. The majority of the lateral displacement between the North American-European and the African plates was therefore probably taken up along the Chedabukto and possibly the South Atlas (Agadir) Fault.

Thus, a modification of plate movements during the last suturing phases of the Pangean Megacontinent apparently caused intense fracturing of the European Variscides and their foreland. This had wide implications for the subsequent evolution of North-Western Europe and the Tethys during which many of the Permo-Carboniferous faults were repeatedly reactivated. In the Arctic-North Atlantic the fault pattern that was used during the Mesozoic and Tertiary break-up of the North American-European plate was probably already emplaced during the Carboniferous and early Permian.

PERMIAN VARISCAN FORELAND COLLAPSE

Following the Early Permian consolidations of the Appalachian - Mauretanides and the Uralides the transform fault system linking these fold belts became inactive. With this the volcanism in the Variscides and their foreland became largely extinct at the onset of the Saxonian (late Early Permian). The Saxonian and Thuringian development of NW Europe was characterized by the subsidence of two large basins in the Variscan foreland, the post-orogenic uplift and partial collapse of the Variscan fold belt and continued rifting activities in the Arctic-North Atlantic. Enclosure I provides a geological map of North-Western Europe showing the distribution of the Palaeozoic series subcropping against the base of the Permian sedimentary series (Saalian unconformity).

The Northern Permian Basin which extends from the Moray Firth to the Oslo Graben (Fig. 9) overlays the central North Sea Old Red Basin in the west and transgressed over Lower Palaeozoic sediments and metamorphics in the east. Magmatism in the Oslo Graben persisted throughout the Permian, yet there is no evidence for Upper Permian extrusives in the sedimentary record of adjacent areas. The Northern Permian Basin showed only a moderate subsidence tendency during the Saxonian; however, due to the limited control available the geometry of this basin is only poorly known. Sediments consist of 'Rotliegendes' red beds ranging from conglomerates to shales; these reach maximum thicknesses of some 600 m.

The Northern Permian Basin is separated from the Southern Permian Basin by the Mid North Sea-Ringkøbing-Fyn-Møn trend of highs which came into evidence during the Late Carboniferous and Early Permian. The Southern Permian Basin extends from Poland to England over a distance of some 1500 km. It overlays the Variscan foredeep basin but encroaches in the east on the Variscan fold belt (Fig. 9).

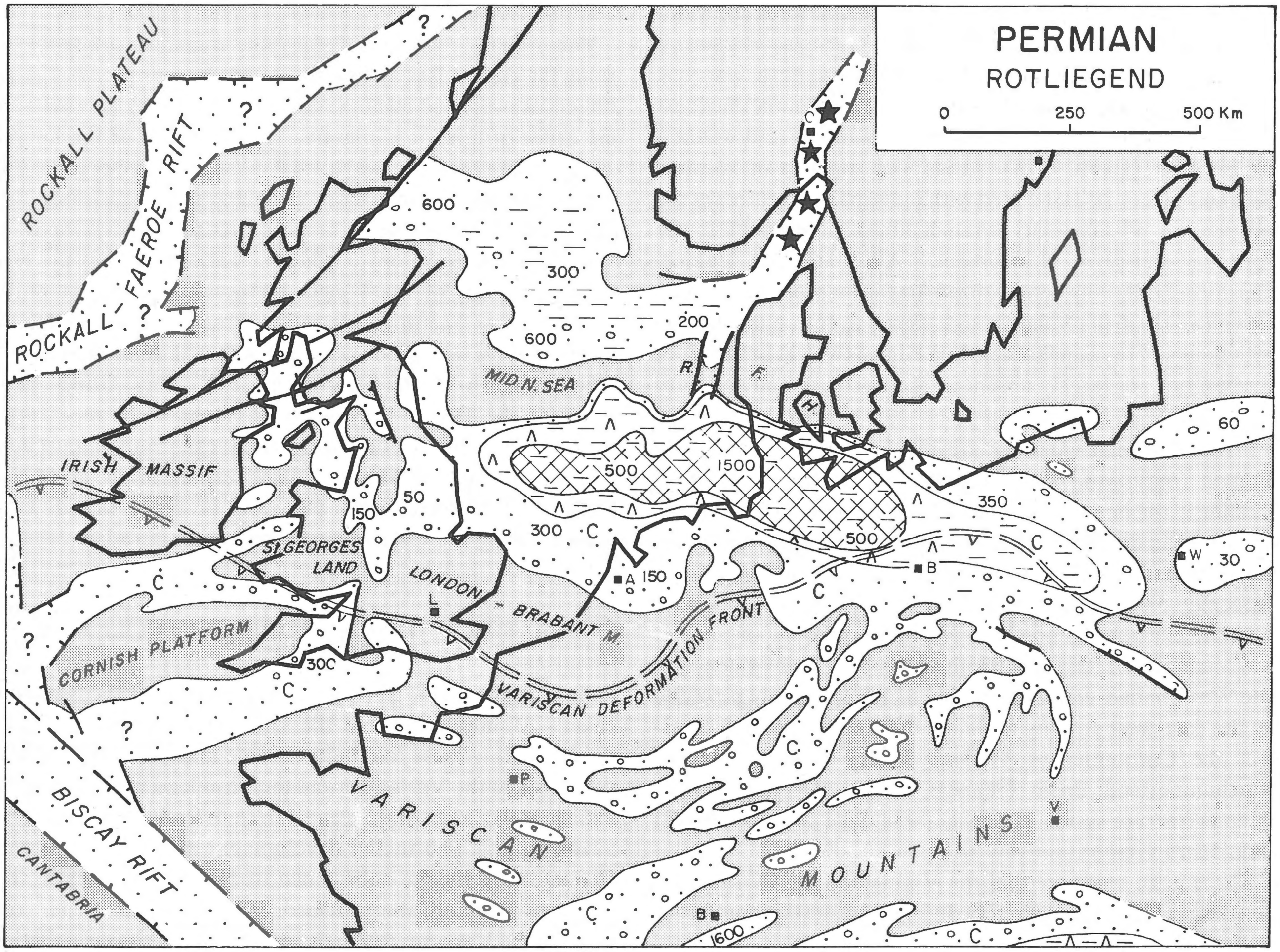

Fig. 9
Rotliegend palaeogeography.

During the Saxonian, clastics derived from the rapidly degraded Variscan Mountains were deposited in this basin under aeolian and sebkha conditions as the classical sequence of Rotliegend red beds (GLENNIE, 1972).

In the central parts of the basin these red beds are interbedded with massive halite sequences. Maximum Rotliegend thicknesses are in the order of 1000 to 1500 m. Several en-echelon WNW-ESE striking subsidence centres are recognized (PLEIN, 1978). This points to continued activity along faults emplaced during the Stephanian-Autunian (KATZUNG, 1975).

In the Southern and Northern Permian basins, subsidence exceeded the rate of deposition during the Saxonian; this led to the development of large topographic depressions that were located well below the sea level of the Permian oceans. Continued rifting movements in the Arctic-North Atlantic and/or an eustatic sea-level rise led at the onset of the Thuringian (Late Permian) to the establishment of a seaway extending from the Arctic Permian basins (Sverdrup, Barentsz Sea, Pechora) southwards through the area of the future Norwegian-Greenland Sea (BIRKELUND & PERCH-NIELSEN, 1976). From this seaway the Zechstein seas transgressed into the two North-West European Permian basins under possibly catastrophic conditions (Fig. 10).

The Zechstein seas probably entered the North-Western European basins through the northern North Sea; however, there is no concrete evidence that at that time a graben had already started to subside in this area. Furthermore, the Zechstein seas may have extended southwards into the Faeroe-Rockall rift (RUSSELL & SMYTHE, 1978) and may have reached the Southern Permian Basin via the Irish Sea and the Severn-Ouse depression. It is, however, very unlikely that Zechstein marine ingressions reached as far south as the Grand Banks area or into the Porcupine Trough, the Celtic Sea Basin or the Western Approaches Basin, which all probably started to subside during the Late Permian.

In the Northern and Southern Permian basins the rapid Zechstein transgression was followed by the accumulation of

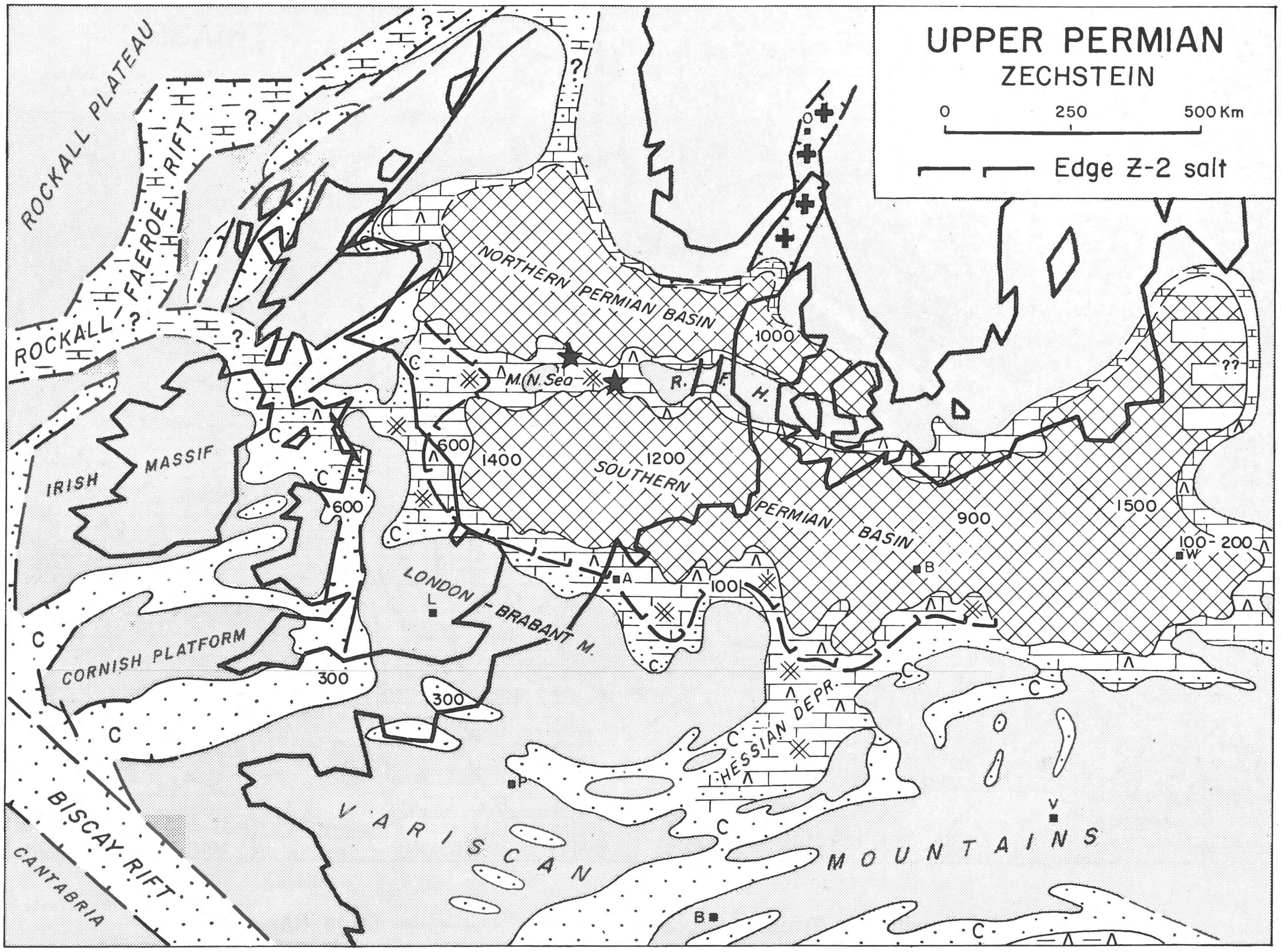

Fig. 10
Zechstein palaeogeography.

thin deep-water carbonates and laminated anhydrites in basinal areas and thick shallow-water carbonate and sulphate banks on the basin margins and on local highs. An arid climate, a restricted influx of seawater and periodic eustatic sea-level changes led to the rapid infilling of the two basins with the cyclical Zechstein evaporite series. These reach thicknesses of some 1000 m in the Northern and in the order of 1500 km in the Southern Permian Basin. The excellent correlation of the Zechstein depositional cycles in the two basins indicates that these stood in free communication, presumably across the western parts of the Mid North Sea High.

Continued subsidence was accompanied by the progressive overstepping of the basin margins. This is particularly evident in the North Danish Basin which started to subside during the Zechstein. Furthermore Zechstein seas transgressed southward through the incipient Hessian depression deep into the Variscan fold belt. Minor Zechstein volcanics have been recorded from the eastern part of the Mid North Sea High, an area that started to subside rapidly during the Triassic. Whereas the Horn Graben subsided differently during the Zechstein, there is no evidence that the Bamble Trough and the Oslo Graben did so as well.

At the transition from the Permian to the Triassic the marine connection between the Arctic and the North-West European Permian basins was interrupted, possibly due to the emplacement of a major rift dome in the Norwegian-Greenland Sea area. This led to the return of a continental depositional regime in the European Permian basins.

The tectonic setting of the Southern Permian Basin relative to the Variscan fold belt is comparable to the present day Black Sea Basin relative to the Alpine fold belt. Both basins have similar dimensions and can be considered as early post-orogenic foreland collapse basins. Subsidence of such basins is not caused by rift tectonics in the conventional sense but may rather be an integral part of the regional isostatic rebound phenomena that characterizes the post-orogenic development of major fold belts. The subsidence mechanism of such 'mediterranean' type basins is little understood but may be related

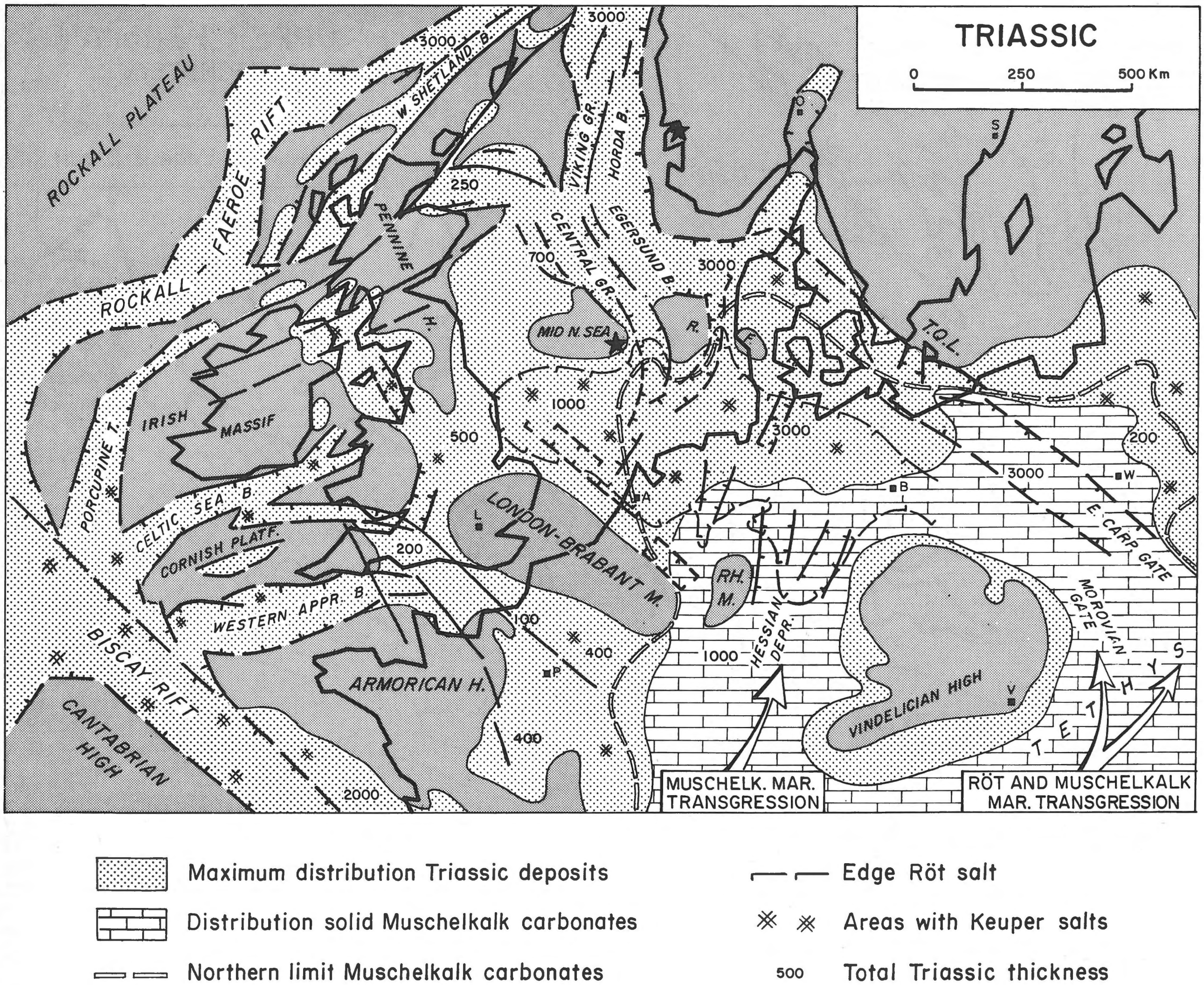

Fig. 11
Triassic palaeogeography.

to lateral ductile flow in the upper mantle (BOTT, 1964). Such a flow may be triggered by the post-orogenic isostatic rebound of the thickened lithosphere of fold belts.

TRIASSIC; ONSET OF PANGEA BREAK-UP

The Permian basins of North-Western Europe continued to subside during the Triassic. However, their structural framework was gradually modified by the emplacement of a new set of grabens and flexure-bound troughs that transsected in part the Permian tectonic elements (Fig. 11). This went parallel with intensified rifting in the northern North Atlantic and the Norwegian-Greenland Sea (HALLAM, 1971; JANSA & WADE, 1975). Along the margins of the Tethys transform faulting and rifting during the Triassic caused the subsidence of a complex graben system. This was accompanied by widespread marine transgressions (OLSEN & LEYDEN, 1973; LAUBSCHER & BERNOULLI, 1977; BIJU-DUVAL ET AL., 1977). Overall Triassic extension tectonics heralded the break-up of the Pangean Megacontinent. However, until crustal separation was achieved in the central Atlantic during the Early to Middle Jurassic, in the northern North Atlantic during the Early Cretaceous and in the Norwegian-Greenland Sea during the early Tertiary large areas around the future plate margins were subjected to regional extension. This particularly affected North-Western Europe that was already partially fragmented by the Late Carboniferous-Early Permian fault system. During the Mesozoic the metastable craton of North-Western Europe was bounded to the south and west by the active rift zones of the Tethys and the Arctic-North Atlantic; to the north-east the Tornquist-Teisseyre Lineament partly limited it against the stable Fennoscandian-Russian platform.

During the Triassic, regional tensional stresses caused the rapid subsidence of the fault-bounded Polish Trough (POZARISKY & KUTEK, 1976) and the North Danish Basin in which Triassic series reach maximum thicknesses of 3000 m and 6000 m respectively. These graben-shaped basins overlay the Permo-Carboniferous transcurrent fault system of the Tornquist-Teisseyre line (Fig. 11, Encl. II). The Oslo-Bamble-Horn rift displayed an asymmetric subsidence pattern during the Triassic. Plutonism in the Oslo Graben had come largely to an end during the Late Permian (RAMBERG & SPJELDNAES, 1978). However, only minor thicknesses of the presumably Lower Triassic red Brumunddal sandstone series are preserved in its northern parts. These may however be interpreted as an erosional remnant of an originally possibly thicker and more widespread Triassic cover. In contrast, both the Bamble Trough and the Horn Graben subsided rapidly during the Triassic. In these, Triassic series attain thicknesses of several thousand metres. The Horn Graben clearly breaches the Permian Ringkøbing High.

In the northern and central North Sea the over 1000 km long Viking-Central Graben system came into evidence during the Triassic. This rift, which transsects the Northern Permian Basin and cuts across the Mid-North Sea-Ringkøbing High, presumably developed from the north to the south by fracture propagation. In the southern North Sea the Central Graben merges with the Horn Graben and loses its identity in the West Netherlands Trough located off the west coast of Holland (HEYBROEK, 1974, 1975). Rapid Triassic subsidence also characterizes the half-graben of the Horda-Egersund Basin which flanks the south-west coast of Norway.

Although not documented by stratigraphic evidence it must be assumed that the Rockall-Faeroe rift was also an area of active Triassic subsidences. This would be in keeping with the rapid subsidence of the West Shetland-Minch Graben in which Permo-Triassic series reach thicknesses in the order of 4000 m (BINNS ET AL., 1975; STEEL & WILSON, 1975). Based on seismic data also the West Hebrides and the Slyne-Erris Trough (RIDDIHOUGH & MAX, 1976; BAILEY ET AL., 1977) are interpreted as containing thick Permo-Triassic sediments. Branching off from the Bay of Biscay are the Porcupine Trough, the Celtic Sea, Bristol Channel and the Western Approaches basins which all started to subside during the Late Permian. These basins which display clear graben features (KENT, 1975) each contain appreciable thicknesses of Triassic sediments. The Worcester and Severn grabens (AUDLEY-CHARLES, 1970) and the partly fault-bounded Manx-Furness Basin (COLTER & BERR, 1975) provide an offshoot from this graben system into the Irish Sea.

Along the southern flanks of the Southern Permian Basin a number of essentially NNE-SSW striking troughs came into evidence during the Triassic. These are from east to west the Thuringian-Westbrandenburg, the Hessian and the Emsland depressions (GRAUL, 1970; NÖLDKE & SCHWAB, 1977; PRIEMKE & RADZINSKI, 1976; WOLBURG, 1961).

In the southern North Sea the fault-controlled NW-SE striking Solepit and West Netherlands basins, which were already established during the Permian, continued to subside differentially during the Triassic. Further Triassic subsidence centres are the Glückstadt Graben in Schlesig-Holstein (northern Germany) and the Rønne Graben located off the west coast of Bornholm.

Although Triassic volcanism is widespread along the northern margin of the Tethys Basin (LAUBSCHER & BERNOULLI, 1977; BIJU-DUVAL ET AL., 1977) and is also observed along the Atlantic rift zone (VOGT, 1973; BALLARD & UCHUPI, 1975; BERTRAND & WESTPHAL, 1977; MANSPEIZER ET AL., 1978), only very little Triassic volcanics have been recorded in North-Western Europe. Minor Triassic volcanics have been encountered in the area of the Central Graben where it cuts through the Mid-North Sea-Ringkøbing High and on the south-west coast of Norway (ZIEGLER, 1978; FAERSETH ET AL., 1976). Overall, the absence of an intense Triassic rift volcanism in North-Western Europe is very striking, particularly as some of the Triassic rifts have proportions that are readily comparable to such volcanic rifts as the Tertiary Rhine-Graben or segments of the East African Rift. This speaks in favour of the hypothesis that the emplacement and subsidence of the European Triassic rifts is caused by regional crustal extension rather than by local subcrustal hotspots.

During the Triassic a gradual rise of the global sea level (VAIL ET AL., 1977) was accompanied by the progressive overstepping of the Permian Basin margins. In the North Sea this led to the gradual burial of the Mid-North Sea-Ringkøbing-Fyn-Møn High. Continued subsidence of the Polish Trough and the Hessian Depression brought about a link up between the Triassic basins of North-Western Europe and the Tethys. From the latter, marine transgressions reached the southern North Sea area during the Late Bunter and Muschelkalk (Late Scythian to Ladinian). Röt transgressions entered the area via the Moravian and East Carpathian Gates (Poland) but during the Muschelkalk also via the Hessian and Emsland depressions (TOKARSKI, 1965; WURSTER, 1968).

A renewed regional regression marked the onset of the Upper Triassic Keuper (late Ladinian to Norian). Keuper salts are well developed in the grabens branching off from the Bay of Biscay rift. In the northern North Sea the entire Triassic is represented by red beds, that do not permit a ready lithostratigraphic subdivision of these up to 3000 m thick series.

In the Southern Permian Basin where the Triassic occurs in its classical tripartite Germanic facies the onset of rifting movements can be dated as late Scyntian, whereby the Hardegsen unconformity gives evidence for a first regionally significant tectonic pulse (WOLBURG, 1961; W. H. ZIEGLER, 1975; PRIMKE & RADZINSKI, 1976; BEUTLER & SCHÜLER, 1978) which caused the uplifting of positive elements and the active downwarping of the intervening lows. Although the effects of this early rifting pulse can be traced from Poland to the southern North Sea its significance in the northern North Sea and along the Atlantic seaboard of Scotland and Ireland cannot as yet be documented for want of sufficient well penetrations and a ready lithostratigraphic zonation of the thick Triassic red beds

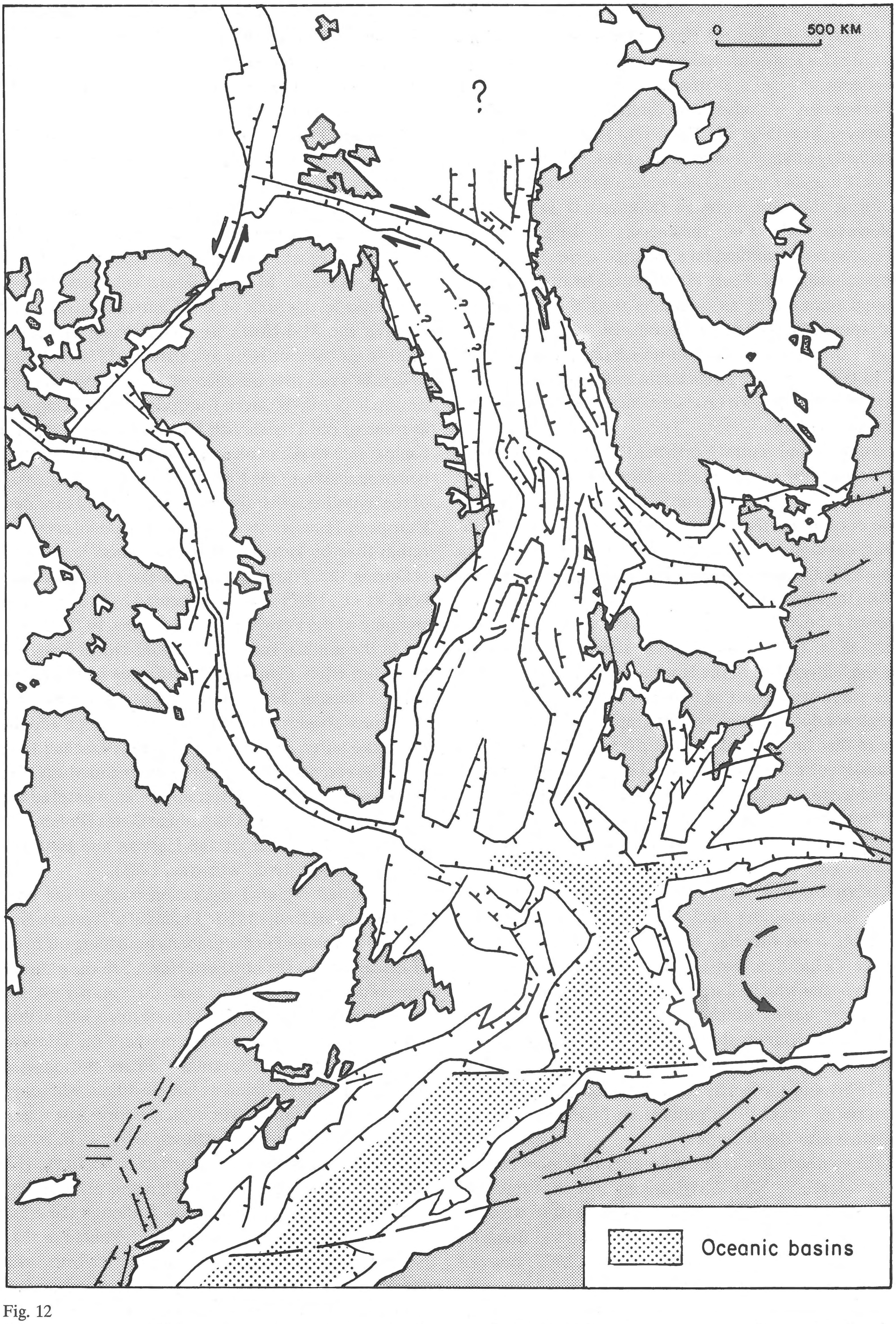

Fig. 12
Schematic patterns of Mesozoic Arctic-North Atlantic rift system (continental fit approximately early Cretaceous times).

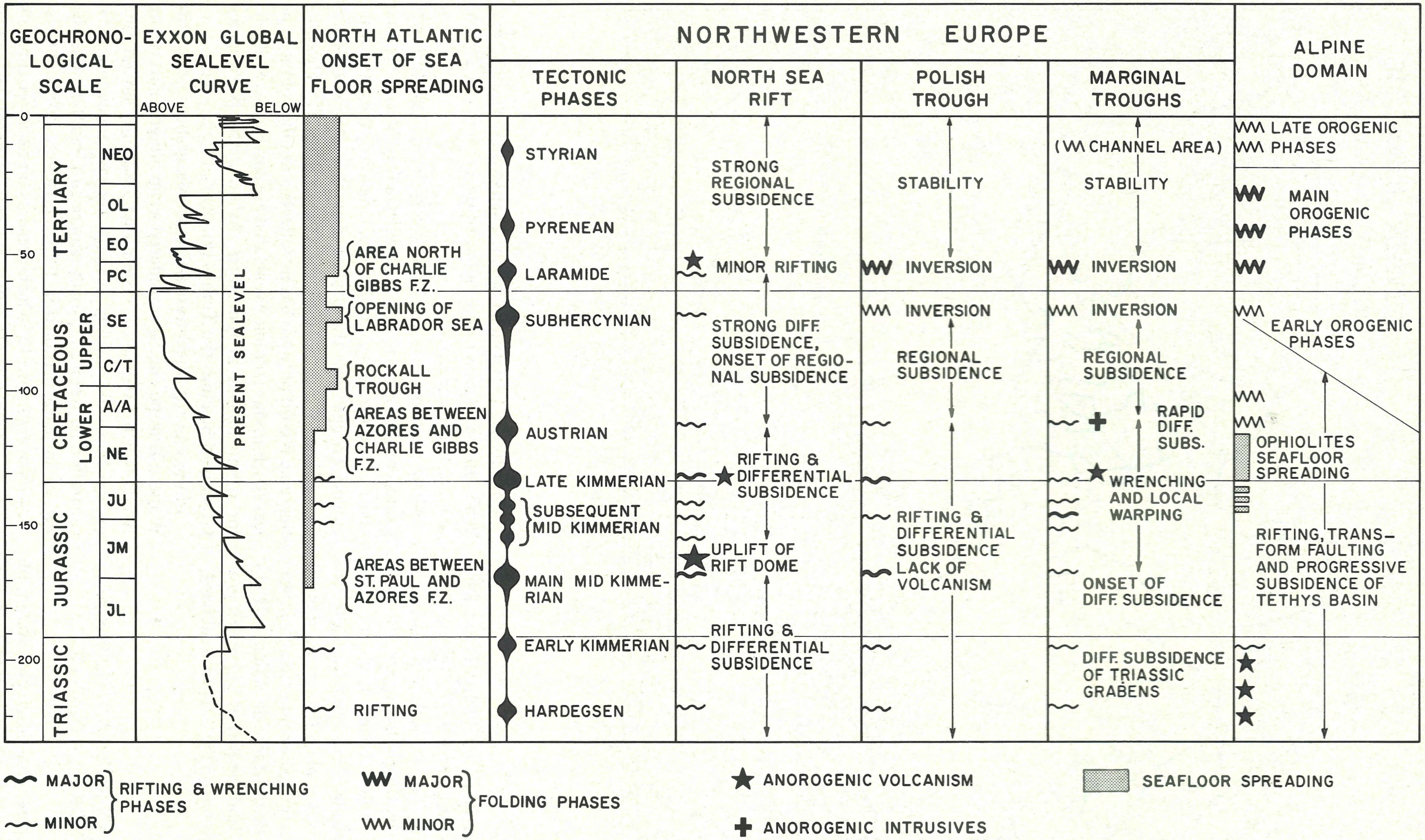

Table II
Correlation of tectonic events in the Atlantic, the NW European rift system and the Alpine orogenic belt.

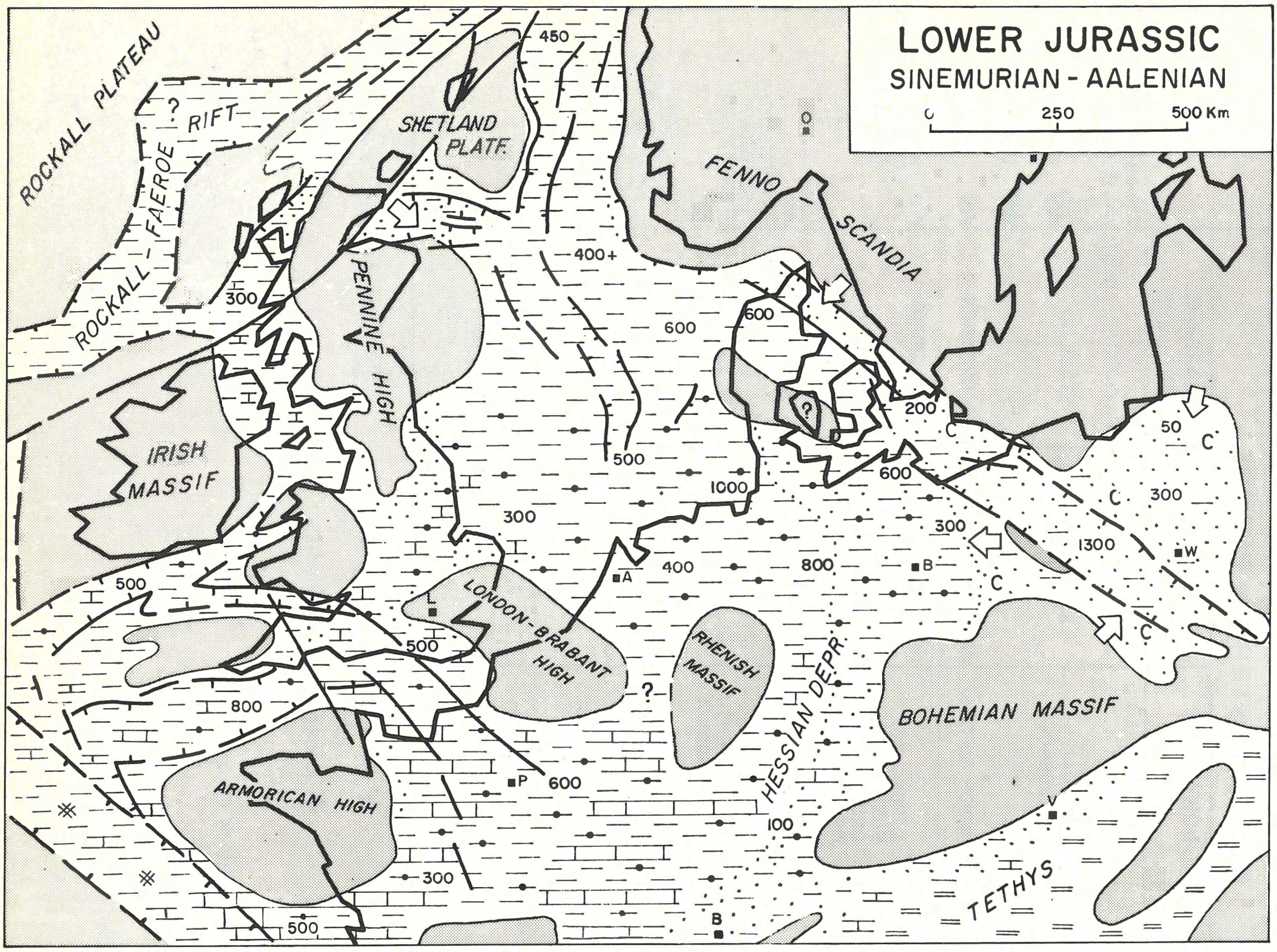

Fig. 13
Lower Jurassic palaeogeography.

series occurring in these areas.

In the Permian basins, diapirism of the Zechstein and Rotliegend salts was triggered during the Keuper by the thick Triassic overburden. During the Triassic sedimentation rates generally remained in balance with subsidence rates. By Late Triassic times the Variscan fold belt was degraded to the point that only disjointed low relief highs emerged from the immense, monotonous tidal flat/flood plain that covered much of North-Western Europe. Clastic influx into this basin was mainly derived from the Fennoscandian shield. Highs bordering the Rockall-Faeroe and the Bay of Biscay rift provided the detrital fill for the grabens on the Atlantic seaboard.

NORTH-WEST EUROPEAN RIFTS AND OPENING OF THE ARCTIC-NORTH ATLANTIC

During the Jurassic, the complex Triassic graben system of North-Western Europe underwent a polarization to a few major rifts, most of which remained active till the Late Cretaceous. In the process of this polarization a number of Triassic grabens became inactive.

Main elements of the North-West European Jurassic-Cretaceous rift system are the North Sea Rift (Viking Graben and Central Graben), the Polish-Danish Troughs, the Porcupine Trough and the graben-shaped Celtic Sea-Bristol Channel and Western Approaches basins (Encl. II). The stratigraphic record of these basins reflects a number of more or less synchronous tectonic events that are correlative with major rifting phases in the North Atlantic, the Norwegian-Greenland Sea and the Tethys (ZIEGLER, 1975).

In this context, the Jurassic-Cretaceous grabens of North-Western Europe can be considered as an integral part of the Arctic-North Atlantic rift system that gradually opened during the Mesozoic, leading in Early Tertiary times to crustal separation between the North American-Greenland and the European plate (LAUGHTON, 1975; LE PICHON, 1977). This is illustrated by figure 12, which presents on an approximately Early Cretaceous continental assembly a schematic plot of

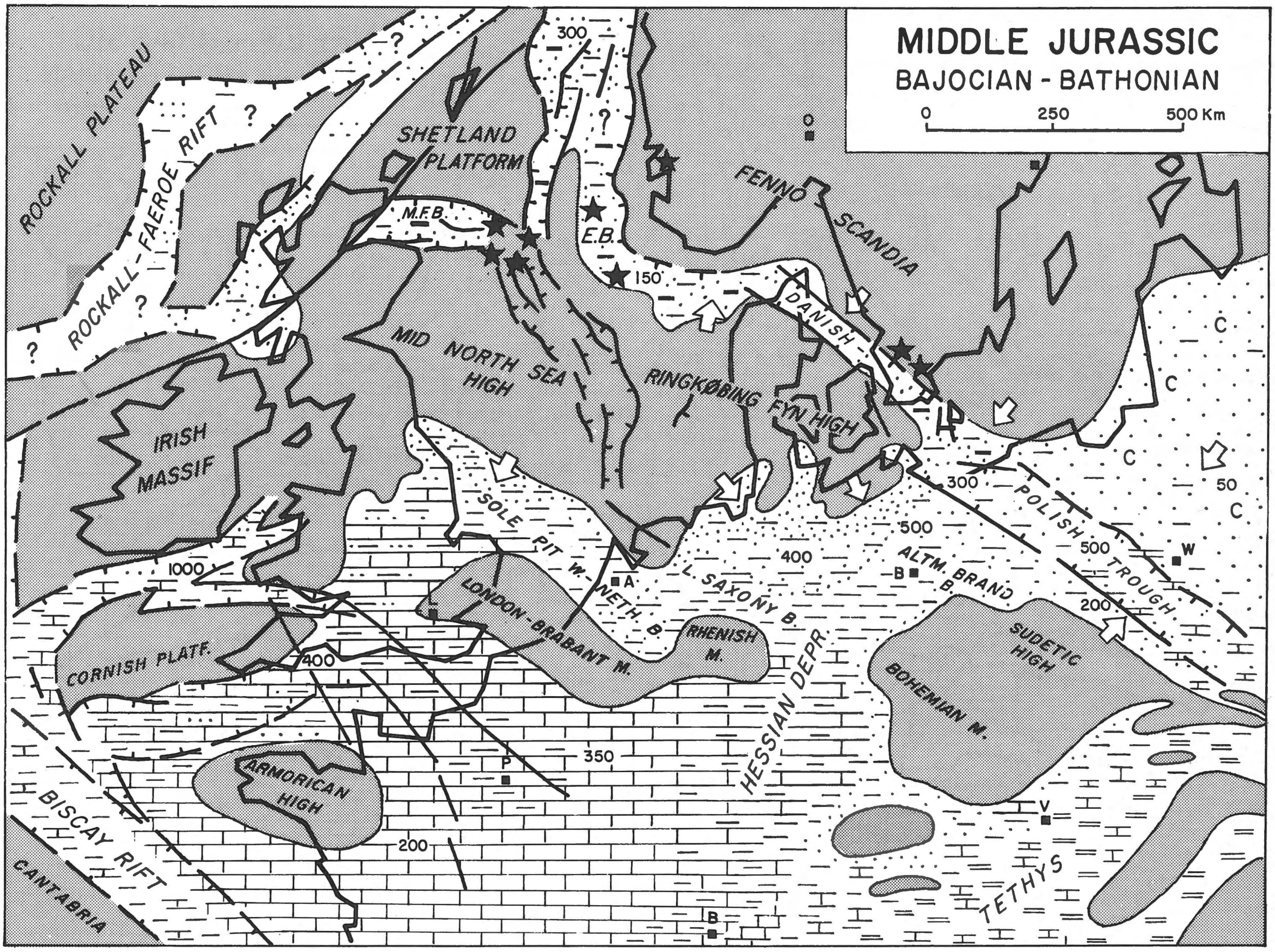

Fig. 14
Middle Jurassic palaeogeography.

major Mesozoic grabens in the Arctic-North Atlantic domain (ZIEGLER & LOUWERENS, 1978). A comparison of the main tectonic events in the North Atlantic, the North Sea and the Polish Trough as well as the Tethys is given in Table II.

EARLY KIMMERIAN PHASE

At the transition from Late Triassic to Rhaetic times, an extensional tectonic pulse referred to as the 'early Kimmerian phase' affected the entire Arctic-North Atlantic and Tethyan graben system. This pulse preceded the Rhaetic to Early Liassic transgression which inundated much of North-West Europe. At the same time a new seaway connecting the North-West European basins with the Arctic basins was opened through the Norwegian-Greenland sea area.

In North-West Europe the early Kimmerian phase caused a mild accentuation of the major positive elements from which clastics were shed into the downwarped intervening lows. This is particularly evident in the northern North Sea where the massive fluviatile Statfjord sands were deposited in the axial parts of the Viking Graben. Also in the Danish Trough Rhaetic sands are well developed, and give evidence for the early Kimmerian reactivation of the Fennoscandian border zone (LARSEN, 1963; BOELAU, 1973). In the Polish Trough, Rhaetic brackish-water clastics transgress unconformably over Middle and Upper Triassic series indicating that this graben was also affected by the early Kimmerian tectonic pulse (SENKOWIZOWA & SZYPERKO-SLIWCZYNSKA, 1975). In northern Germany and in the southern North Sea, marine Rhaetic shales and minor sands overlay the Keuper series largely conformably. Clastics in these areas were derived from Poland as well as from the London-Brabant Massif.

During the Sinemurian, fully marine conditions were established in much of North-Western Europe with transgressions originating from the Tethys and the Arctic-North Atlantic Seaway. In the North Sea area Liassic series are largely developed in a cyclinal open-marine shaly facies (Fig. 13).

During the Liassic minor clastics were derived from the Pennine High and the Scottish Highlands, the Fennoscandian

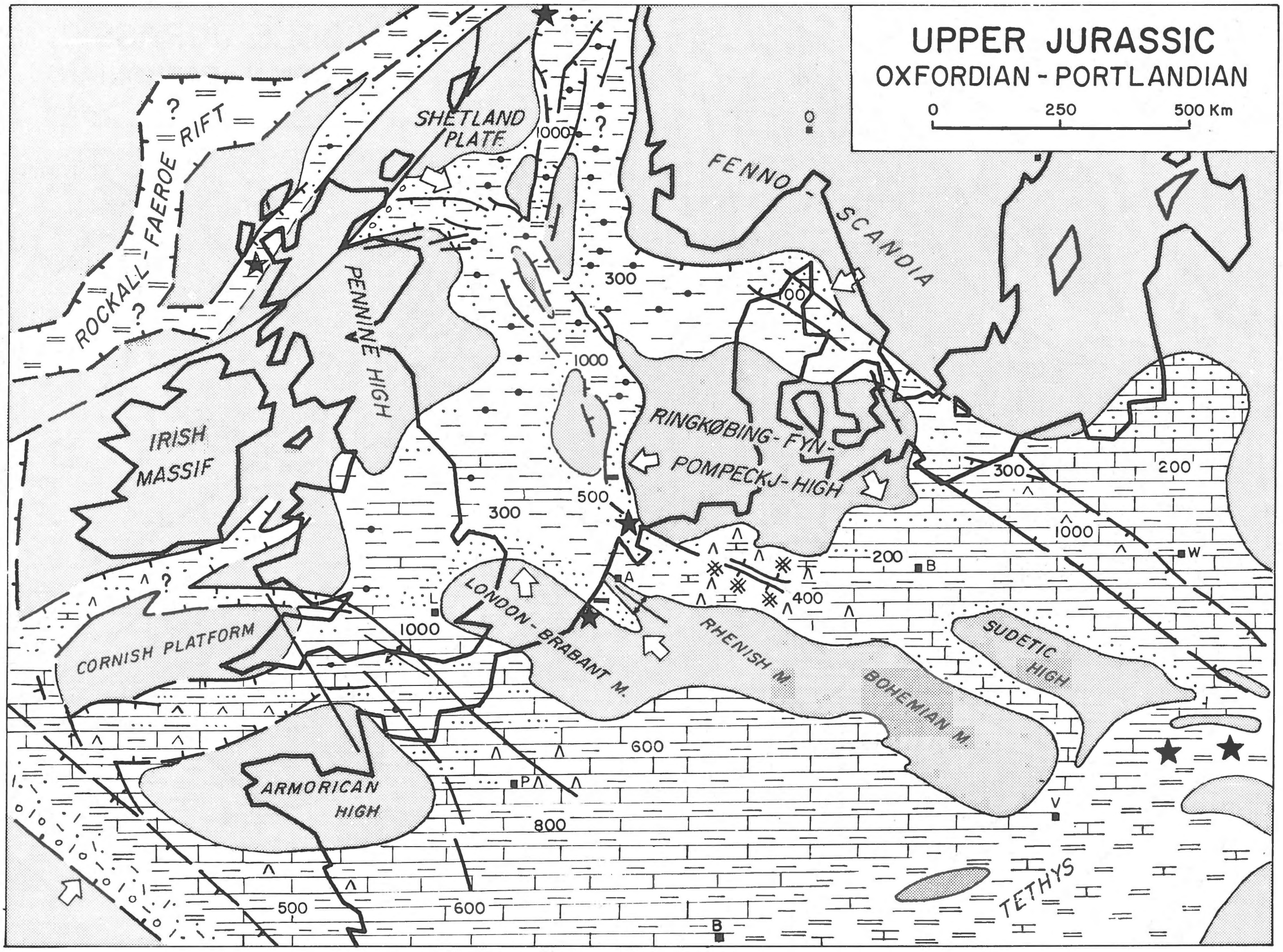

Fig. 15
Upper Jurassic palaeogeography.

border zone as well as from the London-Brabant and the Welsh massifs. In Poland, Liassic series consist of fresh- to brackish-water clastics that were derived from the Bohemian Massif and the Fennoscandian shield. From Poland these clastics were transported westwards into northern Germany where they interfinger with marine shales (HOFFMANN, 1949). In the Paris and Aquitaine basins clastics are essentially lacking, with shales and carbonates being the dominant lithology. Lower Liassic salts occur in the Aquitaine Basin and in Cantabria (Bay of Biscay rift). Liassic series in the Western Approaches, Celtic Sea and Bristol Channel grabens consist of marine shales and minor carbonates. In the South Minch Basin Liassic shales are interbedded with sandstones.

Synsedimentary differential subsidence characterizes the Liassic development of the Viking Graben, the Danish and the Polish troughs as well as the graben system branching off from the Bay of Biscay rift. The Triassic subsidence pattern of the Southern Permian Basin persisted during the early Jurassic. However, the intense diapirism of the Permian salts provides a strong overprinting effect of sharp local subsidence anomalies. The Hessian depression remained, as during the Triassic, an open seaway between the North-West European Basin, the Paris Basin and the Tethys.

MID-KIMMERIAN TECTONISM

During the Middle and Late Jurassic a number of discrete rifting phases affected the entire metastable platform of North-Western Europe as well as the Arctic-North Atlantic rift system and the Tethyan areas. These tectonic events are summarized under the colloquial term 'mid-Kimmerian phases' (P. A. ZIEGLER, 1975).

In the Central Atlantic sea-floor spreading set in between the St. Paul and the Azores fracture zone approximately at the transition from the Early to the Middle Jurassic (PITTMANN & TALWANI, 1972; VOGT, 1973). This coincides roughly with the main mid-Kimmerian phase which caused fundamental palaeogeographic changes in North-West Europe at the Aalenian-Bajocian boundary.

In the central North Sea a large high encompassing the Mid North Sea and the Ringkøbing-Fyn Highs was uplifted during the early Bajocian (Fig. 14). This uplift which separated again the northern North Sea Basin from the southern one, can be considered as a rift dome. Its crestal parts were transected by the Central Graben, the southern parts of the Viking Graben and the fault system of the Moray Firth Basin. At the triple junction of these grabens a major alkaline volcanic centre was emplaced (HOWITT ET AL., 1975; GIBB & KANARIS-SOTIRIOUS, 1976). Subsidiary volcanic centres occurred in the Egersund Basin, the Sunn-Hordland area of SW Norway and in Scania (FAERSETH ET AL., 1976; KLINGSPOR, 1976). This indicates that also the Horda fault system and the Fennoscandian border zone were reactivated by the mid-Kimmerian tectonism. In contrast the Horn and the Glückstadt grabens, as well as the Emsland and West Netherlands troughs, became inactive. Furthermore, the Liassic seaway that extended through the Irish Sea was interrupted by regional uplift.

On the other hand the Celtic Sea-Bristol Channel and the Western Approaches basins continued to subside differentially. To the east the Bristol Channel and the Western Approaches troughs are cut off by the transform fault system of the Sticklepath, the Normandy and the Pays de Bray faults. Tectonic activity along these faults parallelled crustal distension in the Western Approaches, Bristol Channel and Celtic Sea troughs. During the Middle Jurassic this was accompanied by minor volcanic activity as illustrated by the occurrence of the Bathonian Fuller's Earth in southern England. However, the source of this pyroclastic material is as yet unknown.

The Polish Trough continued to subside during the Middle Jurassic whereby a seaway between the eastern part of the North-West European Basin and the Tethys was reopened.

In the area of the central North Sea rift dome, Early Jurassic and older sediments were subjected to profound truncation. Erosion products were shed northwards into the continuously subsiding Viking Graben, the Danish Embayment and the Horda-Egersund basins where they were deposited under paralic and deltaic conditions. Clastics shed southwards from this dome were deposited in the incipient Solepit, West Netherlands, Lower Saxony and Altmark-Brandenburg basins in which marine conditions prevailed (see also Encl. II). These basins, which to the north offset the London-Brabant, the Rhenish and the Bohemian massifs, are referred to as 'Marginal Troughs' ('Randtröge': VOIGHT, 1962). Their subsidence was related to minor right-lateral wrench movements between the Danish-North German block to the north and the Variscan massifs to the south. Such wrench movements were caused by crustal distension in the North Sea rift and in the Polish Trough (P. A. ZIEGLER, 1975). Faults already emplaced during the Early Permian probably played a significant role in the localisation of the Marginal Troughs which can be regarded as 'tension gash' basins. With the emplacement of the Marginal Troughs during the Middle Jurassic, the Southern Permian Basin ceased to subside differentially and to act as one megatectonic unit (NÖLDKE & SCHWAB, 1977).

In the West Shetland-Minch Trough Middle Jurassic series are represented by paralic and marine clastics that rest in part unconformably on older series. Whether similar sediments were deposited in the Rockall-Faeroe rift or whether this area also was uplifted and subjected to erosion during the Middle Jurassic is unknown.

Volcanism in the central North Sea became extinct during the Bathonian. This was followed by the gradual foundering of the central North Sea rift dome during the late Middle to Late Jurassic. Regional subsidence was interrupted, however, by minor yet distinct rifting phases at the end of the Callovian and at the onset of the Kimmeridgian. These two tectonic pulses, which are here referred to as 'Subsequent Mid-Kimmerian' Phases, affected essentially the same tectonic elements as the Main Mid-Kimmerian Phase. Although the worldwide eustatic sea level rose during the Middle and Late Jurassic (VEIL ET AL., 1977) it is intriguing to note that the subsequent mid-Kimmerian pulses also coincide with periods of temporary sea-level drops (Table II).

Continued differential subsidence of the Viking Graben and regional subsidence of the central North Sea rift dome were accompanied by the progressive transgression of the Jurassic seas; these reached their maximum extent during the Kimmeridgian-Portlandian (Fig. 15). By this time deep-water conditions were established in the Viking and Central grabens.

In the central and northern North Sea, Upper Jurassic series consist of in part highly organic shales. In the Central Graben and in the southern Viking Graben these shales are locally interbedded with turbidite sands that were derived from the Shetland platform and from shallow-water sand accumulations along the margins of the highs flanking the Central Graben.

During the Kimmeridgian a renewed marine connection was established between the northern and southern North Sea basins. In the latter Upper Jurassic series display a wide facies variety ranging from carbonates and evaporites in the Altmark-Brandenburg and the Lower Saxony basins to paralic series in the West Netherlands Basin and to shales containing only minor carbonates and clastics in the Solepit Basin.

The Late Jurassic differential subsidence of the North Sea rift and of the Polish Trough went parallel with an accentuation of the Marginal Troughs and the uplifting of the London-Brabant, the Rhenish and the Bohemian massifs. This was accompanied by the closure of the long-standing Hessian Strait and the opening of the Sudetic Strait. The latter is located in the strike prolongation of the Altmark-Brandenburg Basin.

Minor volcanic centres developed during the Late Jurassic in the Dutch Wadden Sea (COTTENÇON ET AL., 1975) and at the edge of the West Netherlands Basin; their emplacement is probably due to local tensional faulting associated with transform movements along the margins of the Variscan massifs.

Late Jurassic tectonic activity is also documented from the Bay of Biscay rift by the occurrence of massive Kimmeridgian

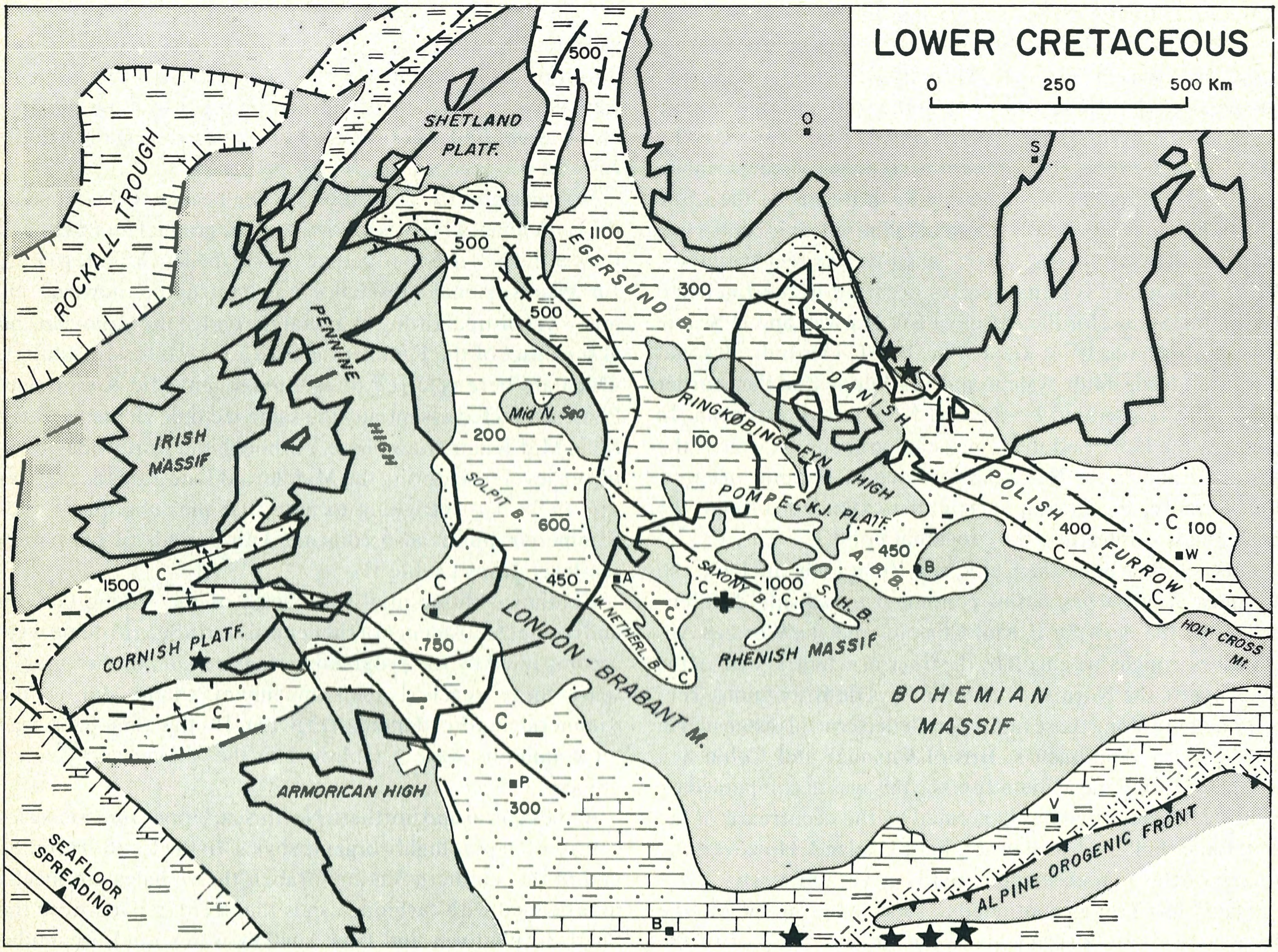

Fig. 16
Lower Cretaceous palaeogeography.

alluvial conglomerates along the coast line of Cantabria. These clastics, which rest unconformably on Lower Jurassic series, were shed from southern sources into the Bay of Biscay rift.

During the Late Jurassic the Western Approaches and the Celtic Sea-Bristol Channel basins continued to subside differentially. Contemporaneous minor transform movements along the Pays de Bray and Normandy faults can be documented from the Paris Basin and the Channel area.

The Rockall-Faeroe rift area was probably domed up during the Late Jurassic. Marine series were deposited only in the West Shetlands and Minch basins. From the updomed and eastward-tilted Shetland Platform, clastics were shed into the Moray Firth Basin and into the southern Viking Graben.

A Late Jurassic date has been obtained from a dyke in the northernmost part of the North Sea, an area that was subjected to Late Jurassic uplifting and erosion. In addition, Late Jurassic pyroclastics on the Isle of Skye in western Scotland (KNOX, 1977) testify to volcanic activity in the general area.

CRETACEOUS AND EARLY TERTIARY RIFTING PHASE

During the early Early Cretaceous a major rifting pulse, the late-Kimmerian phase, affected the entire Arctic-North Atlantic rift system. This tectonic pulse which coincides with a sharp eustatic sea-level drop (VAIL ET AL., 1977) was followed by the onset of sea-floor spreading in areas between the Azores and the Charlie Gibbs fracture zones during the Neocomian (Table II).

Following the early Aptian Austrian tectonic phase the Bay of Biscay started to open whereby Spain began to rotate counter-clockwise away from the NW European craton. The Austrian tectonic pulse finds widespread expression in the basins of NW Europe (MONTADERT ET AL., 1977) and coincides with an other eustatic sea-level drop (VAIL ET AL., 1977).

In the Rockall Trough, limited sea-floor spreading probably took place during the late Early Cretaceous and early Late Cretaceous (LAUGHTON, 1975; ROBERTS, 1975). In the Labrador

Sea, sea-floor spreading is thought to have started during the middle Senonian (LAUGHTON, 1971). This coincides approximately with the Subhercynian tectonic phase which in the North Sea is expressed as a mild rifting pulse accompanied by a possible temporary eustatic lowering of the sea level.

The Early Tertiary Laramide rifting phase which resulted in major palaeogeographic changes in North-Western Europe preceded the onset of sea-floor spreading in the Norwegian-Greenland Sea and between the Rockall-Hatton Bank and Greenland (LAUGHTON, 1975; ROBERTS, 1975). Also the Laramide tectonic pulse was accompanied by a sharp eustatic sea-level drop.

Overall it can be observed that the onset of sea-floor spreading in the different parts of the North Atlantic was preceded by major rifting phases that affected the entire Arctic-North Atlantic fault system. Major rifting phases appear to be accompanied by sharp eustatic sea-level drops (Table II). Periods of sea-floor spreading in the Arctic-North Atlantic rift system correlate to periods of relative tectonic quiescence and a gradual rise of the sea level.

North Sea area

The late Kimmerian phase strongly affected the entire North Sea area. In the Viking Graben this rifting pulse resulted in the accentuation of the existing sea-floor topography, giving rise to a strongly block-faulted submarine relief of up to 1000 to 2000 m. In the Central Graben rift tectonics are less obvious due to the interference of an intense Zechstein diapirism (ZIEGLER, 1978).

The late Kimmerian downfaulting of the Viking and Central grabens was accompanied by the temporary uplifting and emergence of their rift flanks. Early Cretaceous crustal distension in the North Sea rift was accompanied by a further accentuation of the Marginal Troughs. This went parallel with the uplifting and emergence of the Pompeckj Platform and the London-Brabant-Bohemian Massif from which clastics were shed into the adjacent basins.

In the North Sea the late Kimmerian break in sedimentation was followed in emergent areas by a rapid transgression that prevented the influx of clastics into the Viking and Central grabens. During the Early Cretaceous the topography of this rift system was gradually infilled by up to 1200 m thick relatively deep-water shales (Fig. 16). In the continuously subsiding Horda-Egersund Basin Lower Cretaceous shales reach thicknesses of some 300 to 1000 m.

Early Cretaceous tectonic activity along the Fennoscandian Borderzone and along the Great Glen fault is documentated by the occurrence of Lower Cretaceous sands in the Danish Trough and in the Moray Firth Basin.

The early Aptian Austrian rifting phase was again followed by a short-lived emergence of the flanks of the North Sea rift. Tensional movements in the North Sea were accompanied by a renewed sharp accentuation of the Marginal Troughs.

In the Lower Saxony Basin the Austrian tectonism led to the emplacement of the deep-seated, presumably basic, Bramscher Massif laccolith which intruded along faults already active during the Late Jurassic and Early Cretaceous (STADLER & TEICHMÜLLER, 1971; NODOP, 1971). Aptian volcanic activity has also been reported from Scania, indicating that the Fennoscandian border zone was once again re-activated by the Austrian tectonism (PRINZLAU & LARSEN, 1972; KLINGSPOR, 1976). In the area of the North Sea rift proper, however, there is no evidence for Early Cretaceous volcanic activity.

Throughout the North Sea area the Austrian phase was followed by a regional transgression that culminated in the Senonian. With the onset of the Late Cretaceous sedimentation in North-Western Europe changed over from shales and clastics to carbonates (Fig. 17). The purity of these chalks and limestones is an indication to what extent the Late Cretaceous seas had inundated the highs flanking the North Sea area.

In the central and northern North Sea, Late Cretaceous times were tectonically quiet with exception of the Mid-Senonian Subhercynian tectonic pulse which gave rise to a subregional disconformity, corresponding possibly to a worldwide eustatic sea-level drop. The Viking and Central grabens continued to subside differentially during the Late Cretaceous. Chalk series consisting mainly of coccolith oozes reach thicknesses of some 1200 m in the Central and the Southern Viking grabens. Northwards, these carbonates grade into equally thick marls and calcareous shales. On the highs flanking the North Sea rift Upper Cretaceous series reach thicknesses of some 100 to 300 m only. By the close of the Late Cretaceous most of the North Sea rift topography had apparently been infilled.

The early Palaeocene Laramide rifting phase caused a renewed rapid subsidence of the Viking and Central grabens. This was accompanied by the temporary emergence/uplifting of their rift flanks. In North-West Europe regional palaeogeographic changes induced by the Lamaride tectonism resulted at the end of the Danian in a return to a clastic depositional regime (Fig. 17). In the North Sea rift upper Palaeocene and Eocene series are represented by deeper-water sediments.

Bay of Biscay area

In the area of the Bay of Biscay the 'late Kimmerian' tectonic phase is expressed as a major rifting and transform-faulting event. Uplifting of the margins of the Bay of Biscay rift resulted in erosion and the eastward shedding of clastics into the Celtic Sea Trough, the Hampshire and the Paris basins. In the grabens branching off the Bay of Biscay this was accompanied by block faulting but partly also by warping and buckling of the basin fill in response to local wrench movements. During the Early Cretaceous the Celtic Sea and the Western Approaches troughs subsided differentially. In these basins clastic Weald series reach thicknesses in excess of 1000 m (Fig. 16). A

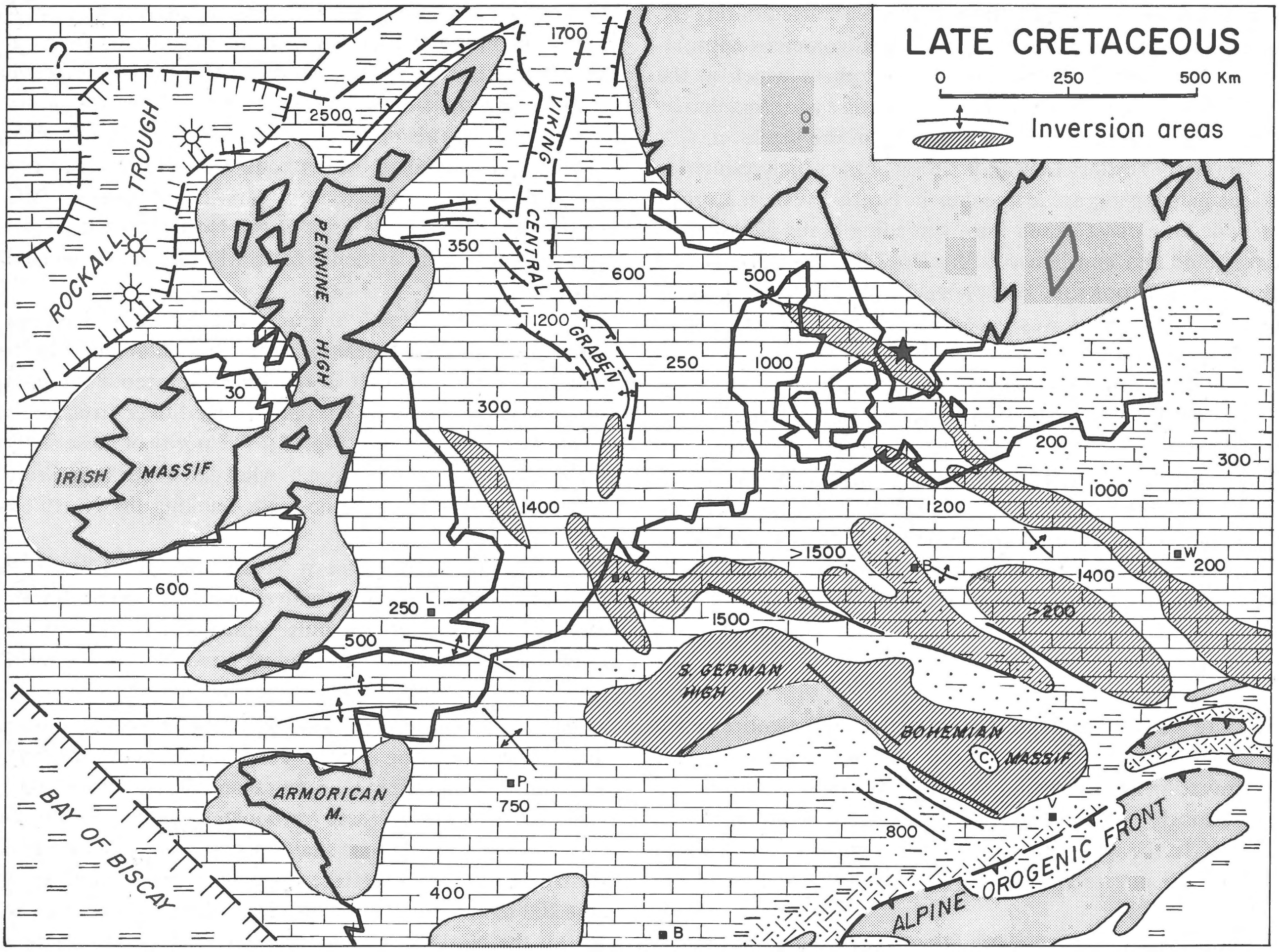

Fig. 17
Late Cretaceous palaeogeography.

regional unconformity corresponding to the Austrian phase marks the base of the Aptian-Albian Greensand Series. Lower Cretaceous crustal distension of the Western Approaches and Celtic Sea troughs was accompanied by the extrusion of the Wolf Rock phonolites which yielded isotopic ages of 130 ± 6 Ma (Valanginian) and 112 ± 2 Ma (Aptian) (HARRISON ET AL., 1977). Pre-Greensand warping, possibly induced by wrench faulting, is evident in the Channel area.

Geophysical data and results of wells drilled on the continental slope of the Celtic Sea indicate that sea-floor spreading in the Bay of Biscay started during the Barremian to early Aptian (MONTADERT ET AL., 1977). By this time the Celtic Sea-Bristol Channel and the Western Approaches troughs had largely become inactive. Similarly to the North Sea area, carbonate deposition set in on the Celtic Sea shelf with the onset of the Late Cretaceous and persisted until early Palaeocene times (Fig. 17). Subsidence of the Celtic Sea shelf during the Late Cretaceous was relatively uniform with only mild differential subsidence of the Western Approaches and Celtic Sea grabens. Maximum chalk thicknesses are in the order of 600 to 800 m near the shelf edge. The Laramide rifting phase cannot be recognized as such in the Western Approaches and Celtic Sea grabens.

Rockall-Faeroe rift

Only limited stratigraphic data are available to unravel the Cretaceous and Early Tertiary evolution of the Rockall-Faeroe rift. On the base of geophysical and limited drilling data ROBERTS (1975) and MONTADERT ET AL. (1977) postulate that sea-floor spreading took place in the Rockall Trough during the late Early to early Late Cretaceous.

On the West Shetland shelf the late-Kimmerian rifting phase accentuated the pre-existing block-faulted relief resulting in possibly subareal erosion. Lower Cretaceous series are generally thin and consist of marine sands. This may indicate that much of the Rockall-Faeroe rift was probably domed up and subjected to erosion during the Early Cretaceous. An unconformity at the base of the Aptian-Albian corresponds to the Austrian tectonic phase.

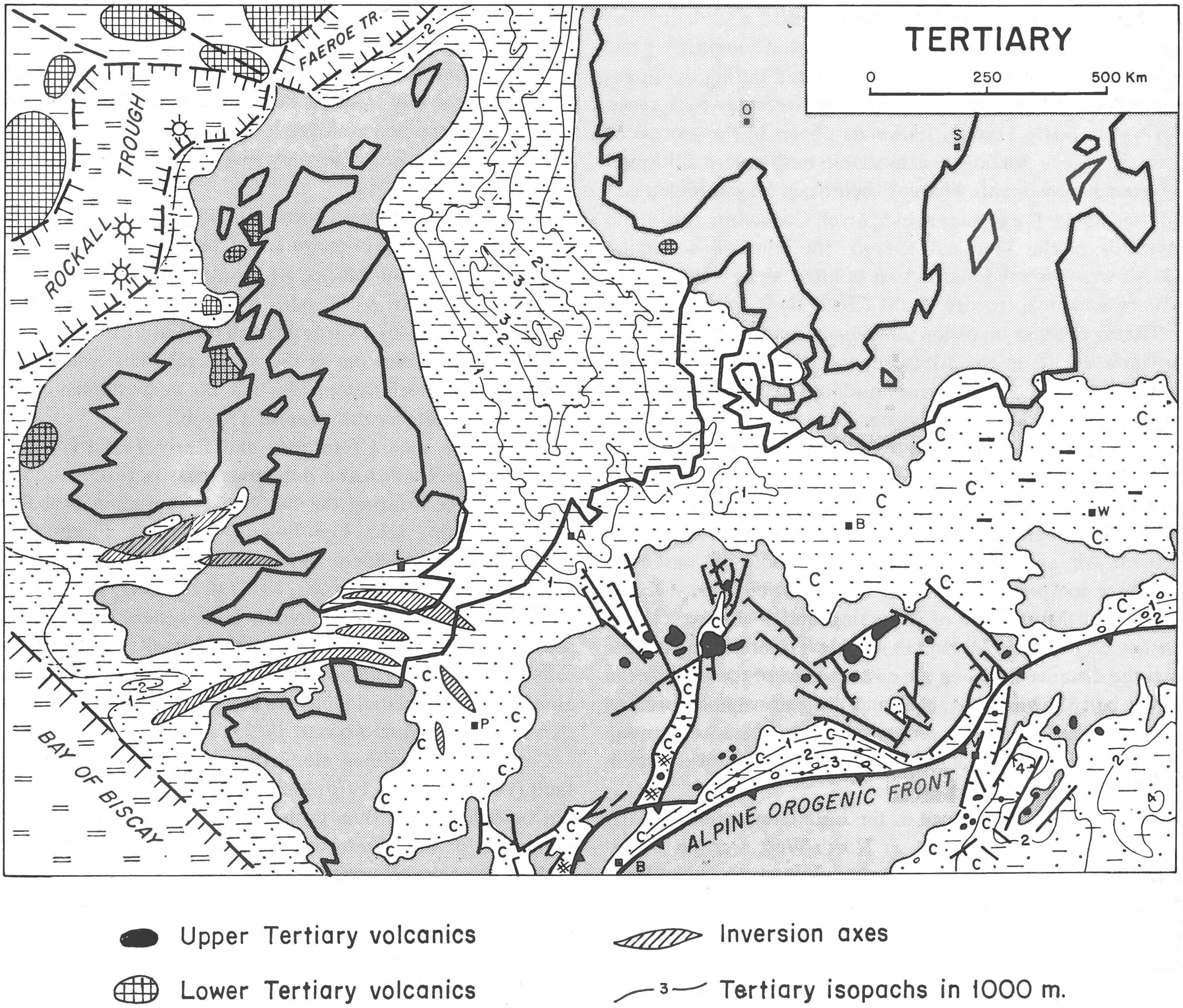

Fig. 18
Tertiary palaeogeography.

Upper Cretaceous series consist of up to 2500 m thick marls, chalky limestones and minor sands. These form a basinward thickening wedge that infills a block-faulted relief (CASHION, 1975). This is indicative for a tectonically quiescent period corresponding to the general subsidence of the Rockall-Faeroe rift dome.

This trend was reversed, however, by the Early Tertiary Laramide rifting phase which again caused a renewed updoming and eastward tilting of the West Shetland-Hebrides shelf from where clastics were shed eastwards into the North Sea Basin. Similarly, the West Irish shelf areas were uplifted during the Early Tertiary. This was accompanied by the emplacement of a number of major Palaeocene-Eocene volcanic centres in western Scotland and Ireland (Fig. 18). Simultaneously the Rockall-Faeroe plateau was uplifted and covered by widespread flood basalts. Uplifted areas started again to subside during the Eocene by which time sea-floor spreading had starter in the Norwegian-Greenland Sea and between Greenland and the Rockall-Hatton Bank. There is no evidence that sea-floor spreading had taken place in the Rockall Trough during the Early Tertiary (ROBERTS, 1975).

LATE CRETACEOUS AND TERTIARY DEFORMATION OF THE ALPINE FORELAND

Late Cretaceous and Early Tertiary tectonics in the central and northern North Sea as well as on the West Shetland and Irish shelves were purely extensional. This contrasts with the Marginal Trough, the Polish and the Danish troughs and the southern parts of the North Sea rift in which the Subhercynian and Laramide tectonism was of a tangential compressive nature. These basins became mildly inverted during the intra-Senonian Subhercynian phase. Main inversions took place during the Early Tertiary Laramide phase. In the process of inversion these previously extensional basins were deformed by wrench movements whereby their basin fill was folded and uplifted above the erosional base level. Concomitant with the inversion of the Marginal Troughs the Rhenish-Bohemian Massif was dissected and in part uplifted along a number of wrench and steep reverse faults (Encl. II).

Timing of these inversion movements coincides with major orogenic events in the Alpine domain (P. A. ZIEGLER, 1975; MALKOVSKY, 1976). These are considered to be the expression of continent-to-continent collision between the Eurasian and African plates. Resulting compressional stresses apparently also affected the fragmented Alpine foreland, causing tilting and uplifting of the Variscan massifs and inversion of the main Mesozoic troughs located up to 800 km to the north of the present Alpine deformation front. A model for basement involving compressional foreland deformation is provided by the Rocky Mountains of Wyoming and Colorado (USA) (SMITHSON ET AL., 1978). In this respect it is interesting to note that the distance between the eastern edge of the Cordilleran thrust belt (Sawtooth Range) and the easternmost foreland upthrust near Denver is comparable to the distance between the Alpine front and the northernmost inversion structures in the North Sea and the Kattegat.

The regional importance of the Late Cretaceous to Early Tertiary inversion tectonics in North-West Europe is best illustrated by a comparison of the Tertiary subcrop map (Encl. III) and the reconstructed Late Cretaceous palaeogeographic map (Fig. 17). In this context it shoud be borne in mind that in areas surrounding the Rhine Graben the presentday distribution of Mesozoic series has been strongly influenced by Eocene and younger erosion across the Rhine Graben rift dome. Thus, based on facies consideration, it is likely that Upper Cretaceous series originally extended unbroken from the Paris Basin to eastern Bavaria, upper Austria and into the Alpine domains.

Steep reverse faults and small-scale overthrusts play a significant role in the tectonic style of such strongly inverted basins as the West Netherlands (HEYBROEK, 1974) and the Lower Saxony basins (BOIGK, 1968; NODOP, 1971; KELLER, 1976; RICHTER-BERNBURG, 1977).

In less-intensely inverted basins such as the Solepit Basin and the Dutch parts of the central North Sea Graben, inversion tectonics are characterized by regional warping at shallow levels and block faulting at depth, whereby movements on pre-existing extension faults were in part reversed (BLAIR, 1975; HEYBROEK, 1975). Inversion of the Central Graben dies out northwards in Danish waters.

Strong inversion of the Polish Trough resulted in the upwarping of the Polish or Kujawic Anticlinorium (POZARYSKI & KUTEK, 1976; POZARYSKI ET AL., 1978; POZARYSKI & BROCHWIZ-LEWINSKY, 1978). This major inversion structure extends southwards under the Carpathians and northwards into the Rønne Graben located to the east of Bornholm. Bornholm itself was probably uptilted during the Laramide inversion phase. The Grimmen anticline located to the south of Rügen Island is also an Early Tertiary inversion feature (WEGNER, 1966).

From Scania (southern Sweden), where the Precambrian basement is involved in major Late Cretaceous to Early Tertiary upthrusted fault blocks, a Senonian volcanism has been reported (PRINZLAU & LARSEN, 1972). The Scania inversion zone strikes north-eastwards through the Kattegat into northern Jutland and dies out in the Skagerrak. The axis of this complex anticlinorium coincides with the deepest parts of the Mesozoic and Palaeozoic Danish Trough.

During the Late Cretaceous and Early Tertiary deformation of the Rhenish and Bohemian massifs, reactivation of faults emplaced during the Stephanian-Autunian probably played a major role. Uplifting of the Harz, Flechtinger, Lausitz, and East Sudetic blocks took place along steep reverse faults (BAUMANN ET AL., 1975; MALKOVSKY, 1976). Late Cretaceous movements along the fault system marking the south-western border of the Bohemian Massif is stratigraphically documented (SCHRÖDER, 1976). Deformation patterns along these and related faults are in part indicative for wrench movements (SCHÖNENBERGER, 1973).

Compressive features along the south Hunsrück border fault (FALKE & BANK, 1970; KEUPER, 1966) unfortunately cannot be dated closer than post-Permian but may possibly be indicative for Late Cretaceous to Early Tertiary upthrusting and tilting of the Hunsrück-Taunus block. Seen in a regional perspective this appears all the more plausible as the Hunsrück-Taunus structural element takes in an intermediate position between the strongly inverted West Netherlands and Lower Saxony basins and the Early Tertiary Alpine deformation front.

Inversion of the Channel area and the Western Approaches Basin was mild during the Early Tertiary. Main inversions took place during the Miocene at a time when the inverted troughs in the North-West European Basin were already stabilized (Fig. 18). This discrepancy in timing of the main inversion movements between the two areas is thought to be related to a modification of plate movements during the Alpine late-orogenic phases (DEWEY ET AL., 1973; BIJU-DUVAL ET AL., 1977). During the Late Cretaceous and Early Tertiary a predominantly N-S convergence of the Italo-Dinarid subplate and the European craton resulted in the folding of the Carpathians and Eastern Alps and in the inversion of the Mesozoic troughs in the northern Alpine foreland. The Late Tertiary late-Alpine orogenic phases affected mainly the Swiss and Western Alps. At this time the northern Carpathians and the Eastern Alps had already entered into a post-orogenic stage.

This is indicative of predominantly westward directed convergence of the Italo-Dinarid subplate and the European Craton during the terminal phases of the Alpine Orogeny

(LAUBSCHER, 1974; BIJU-DUVAL ET AL., 1977). Correspondingly, such previously not or little inverted Mesozoic troughs located in the north-western Alpine foreland as the Hampshire and Channel basins, the Western Approaches and the Bristol Channel troughs and the eastern parts of the Celtic Sea Trough were inverted during the Miocene. Updoming of the Pays de Bray Anticline in the Paris Basin is also thought to have taken place during the Miocene (Fig. 18).

CAINOZOIC BASINS OF NW EUROPE

The distribution and thickness of Cainozoic sediments in North-Western Europe is summarized on Encl. III by depth contours drawn at the base of the Tertiary clastics.

By far the largest Tertiary and Quaternary basin is the North-West European Basin; it extends over a distance of over 2000 km from the northern North Sea to Poland. Subsidence of this mega-basin is all but uniform. In the North Sea sub-basin Tertiary and Quaternary sediments reach thicknesses of up to 3500 m whereas in the eastern parts of the North-West European Basin Cainozoic series are generally less than 1000 m thick.

In comparison, the dimensions of the Tertiary Alpine and Carpathian foredeep basins, the Rhine and Rhône grabens, the Paris Basin and the Atlantic shelf basins of France, Ireland and Scotland are much smaller.

The tectonic origin of the various Cainozoic basins of North-Western Europe differs considerably. The development of the Cainozoic North Sea Basin and of the Atlantic shelf basins was strongly influenced by the onset of sea-floor spreading in the Norwegian-Greenland Sea during the early Eocene. With this the Mesozoic rifts underlaying these areas became inactive and regional subsidence set in, and in part still continues.

The foredeep basins of the Alps and Carpathians strongly subsided during the Tertiary. During the late-Alpine orogenic phases these basins were in part overridden and in part scooped out by thrust sheets. By Late Tertiary times these foredeep basins ceased to subside and are now being uplifted and eroded as a consequence of the regional post-orogenic isostatic rebound of the Alpine fold belt.

The Rhine and Rhône grabens as well as the Vienna and Pannonic basins form part of the Upper Tertiary and Quaternary collapse system, which affects the entire Alpine fold belt and its southern and northern forelands.

The Cainozoic North Sea Basin

As referred to in a previous paragraph the Laramide tectonism and its associated sea-level drop caused profound palaeogeographic changes in the North Sea area. Apart from the renewed rapid differential subsidence of the North Sea rift, the Shetland platform was uplifted and tilted eastwards. This gave rise to an eastward-directed drainage system. As a result of this an outbuilding clastic foreset wedge was deposited during the Palaeocene and Eocene on the shelves located to the east of the Shetland and Orkney Islands. Slope failure of this foreset sequence triggered density currents, which supplied sands to the downfaulted rift valleys of the Viking and Central grabens in which water depths were in the order of several hundreds of metres (PARKER, 1975).

At the Palaeocene-Eocene transition, volcanism along the Rockall-Faeroe rift reached its peak scattering tuffaceous material over much of the North Sea area causing the deposition of the nearly basinwide early Eocene tuffmaker. Time-equivalent volcanism is suspected to have also occurred in the Skagerrak (ÅM, 1973).

During the Eocene the supply of clastics from the Scottish Highlands and the West Shetland platform gradually diminished, possibly due to the subsidence of the Rockall-Faeroe rift dome. In the central and southern North Sea Palaeocene and Eocene series are represented mainly by clays and silts.

A regional hiatus marks both the base and the top of the Oligocene. These breaks in sedimentation were probably caused by eustatic sea-level changes. Oligocene series consisting predominantly of clays and silts reach thicknesses of up to 1000 m in the central North Sea.

Miocene and younger series are made up of shallow-marine and paralic sands and clays as well as of Quaternary glacial material. Neogene and Quaternary sediments attain maximum thicknesses of 2000 m in the central North Sea.

Overall, Oligocene and younger time-stratigraphic units expand in thicknesses from the margins of the North Sea Basin towards its centre; the axis of this basin coincides with the trace of the Mesozoic Viking and Central Grabens (ZIEGLER & LOUWERENS, 1978).

Pleistocene uplifting of the Fennoscandian shield resulted in truncation of the north-eastern edge of the Tertiary North Sea Basin. Scouring-out of the sea-bottom relief of the Skagerrak and the Norwegian Trough is attributed to glacial activity.

The saucer-shaped subsidence pattern of the North Sea Basin can be explained in terms of cooling and resorption into the upper mantle of a rift cushion or asthenolith that underlaid the North Sea rift system during the Jurassic and Cretaceous (P.A. ZIEGLER, 1975, 1978). It is likely that this was accompanied by a progressive cooling and a corresponding density increase of the crust, resulting in further subsidence. The present geothermal gradient in the area of the North Sea rift is in the order of 3.5°C/100 m. Toward the margins of the North Sea Basin the geothermal gradient decreases to 2.5°C/100 m or less.

In contrast to the North Sea rift system the inverted Mesozoic troughs and grabens and their surrounding areas remained stable throughout the Tertiary. From this it must be concluded that during their inversion these basins reached a state of thermal and isostatic equilibrium that persisted throughout the Cainozoic. This is particularly evident in the case of the Polish Trough but also applies to the Marginal Troughs and to the post-Miocene history of the Western Approaches and Celtic Sea basins.

Upper Tertiary rifts and volcanism

Subsidence of the Rhine and Rhône grabens started during the Eocene and persisted intermittently up to the present (ILLIES, 1970, 1978; RAT, 1974). These two grabens are linked by a transform fault system crossing the Burgundy area (Bourgogne-Morvan-Bresse system). Subsidence of the Rhine-Rhône rift is concomitant with the late-Alpine orogenic phases. In fact, the southern margin of the Rhine Graben and the eastern flank of the Rhône Graben were partly overrun by thrust sheets during the Pliocene folding phase of the Jura Mountains.

The Rhine rift extends northwards through the Ruhr Graben to the margins of the southern North Sea (HEYBROEK, 1975) and through the Hessian depression to the edge of the North German lowlands. The alkaline volcanism associated with the Rhine rift persisted till subrecent times. In-situ stress measurements indicate that parts of this graben system are at present active (ILLIES, 1978). Geophysical data indicate that a low density asthenolith underlies the Vosges-Black Forest rift dome.

There is no evidence for a Late Tertiary reactivation of the Mesozoic North Sea rift system. In view of the age disparity between the active stages of the North Sea rift and the Rhine-Rhône rift, the two graben systems should not be considered as part of one megafracture zone transecting North-Western Europe. It is, however, likely that during the northward fracture propagation of the Rhine rift pre-existing late Palaeozoic and Mesozoic fault were reactivated.

Also the Neogene uplifting and fracturing of the Massif Central and the Bohemian Massif was accompanied by a widespread alkaline volcanism that set in during the Oligocene and persisted until subrecent times. Uplifting of these massifs as well as of the Rhine graben rift dome caused the erosional disection of the Mesozoic shelf series in the Alpine foreland and the partial isolation of the Paris Basin.

Within the Alpine domain the Vienna and Pannonian basins started to subside during the Miocene. This was accompanied by widespread volcanism. In these basins Neogene sediments reach thicknesses in excess of three kilometres.

In Europe the distribution of volcanic Neogene basins is confined to the Alpine fold belt and its immediate foreland. The Vienna and Pannonian basins may be considered as part of the Neogene Mediterranean collapse system. This late- to post-orogenic Alpine collapse phase may find an analogue in the Permian collapse of the Variscan fold belt and its foreland.

Alternatively, the Rhine-Rhône rift as well as the Pannonian-Vienna Basin and the Bohemian Upper Tertiary volcanic province may be interpreted as forming the northern extension of the Neogene East African and Lybian-Tyrrhenian rift system (RICHTER-BERNBURG, 1968; ILLIES, 1974).

A third hypothesis has recently been advanced by SENGOR ET AL. (1978) who interpreted the Rhine-Rhone rift as an 'impactogene', a graben system that opened as a consequence of plate collision during the late phases of the Alpine orogeny.

Finally transform faults and related pull-apart basins are associated with late-orogenic plate movements in the Mediterranean realm. Fracture systems and grabens formed during this process may have propagated into the northern Alpine foreland.

None of the above geotectonic processes is able to explain all of the phenomena characterizing the Upper Tertiary development of the Alpine fold belt and its foreland. Thus a combination of these processes may be envisaged whereby one or another process may have been in time and space the dominant mechanism leading to basin subsidence and emplacement of volcanic activity.

Overall the Neogene and Quaternary development of the Alpine domain and its foreland may be interpreted as heralding a new break-up phase of the current plate assembly.

NORTH-WESTERN EUROPE: THE CROSS ROADS OF OROGENIC BELTS AND RIFTS

The structural and stratigraphic complexity of North-Western Europe is the result of a long geological evolution during which orogenic events leading to plate suturing alternated with periods of rifting causing fragmentation and disintegration of the newly formed plate assemblies. During Palaeozoic to Cainozoic times three such orogenic and rifting cycles can be recognized.

During the Caledonian diatrophism the Laurentian-Greenland shield was sutured with Fenno-Scandia thus forming the Laurasian continent. Devonian and Early Carboniferous rifting along the Caledonian suture zone indicates the instability of this plate assembly. However, its early break-up was prevented by the Carboniferous to Early Permian Variscan orogeny, during which Laurasia was welded together with Gondwana to form the Pangean Megacontinent. The inherent instability of such a super-plate is illustrated by its progressive disintegration during the Mesozoic and Tertiary rifting phases. This process was in part interrupted and reversed by the Alpine orogeny, which resulted in a renewed suturing of Eurasia and Africa. However, already during the late-Alpine orogenic phases the onset of a new rifting stage can be witnessed. The collapse of the Mediterranean basins was accompanied by the emplacement of new rifts.

Each of these megatectonic cycles left its mark on the geology of North-Western Europe. Tectonic elements formed or emplaced during one cycle became repeatedly reactivated during subsequent deformation phases. As examples the Great Glen Fault or the Tornquist-Teisseyre Lineament may be cited; neither of them has as yet fully come to rest.

In each of the megatectonic cycles, periods of increased tectonic activity alternate with periods of relative tectonic quiescence. However, tectonic phases can only be loosely defined in time and often have a distinct geographic connotation. Rough, empiric correlations can be established between major tectonic phases and temporary global sea-level drops (excluding those caused by glaciation). On the other hand, it is often difficult to distinguish in the sedimentary record of a basin between tectonically induced regressions and those resulting from eustatic sea-level drops. In view of this the concept of a correlation between tectonic phases and sea-level changes needs further substantiation on a scale that goes beyond the confines of North-Western Europe. Despite this, the occurrence of more or less distinct tectonic phases is in little doubt (STILLE, 1924; SCHWAN, 1977). Even so, the mechanics of such a 'Pulsating Earth' (UMBGROVE, 1947; MILANOVSKY, 1978) is difficult to comprehend.

During the development of the sedimentary basins of North-Western Europe many different geotectonic processes were active. In many areas basins of various geotectonic origins are stacked on top of one another, resulting in very great sedimentary thicknesses. This applies particularly to areas north of the Variscan internides. In the North-West European Basin the top of the Caledonian or Precambrian basement is often located at depths that are beyond the resolution power of conventional reflection seismic surveys as carried out by the petroleum industry. As insufficient refraction and/or deep sounding data are available it is at present not possible to construct a basin-wide structure map for the top of the crystalline basement.

In the North-West European Basin the deepest regionally mappable reflection seismic event corresponds to the base of the Zechstein salts. Enclosure IV presents a structure map of this horizon. In areas outside the Permian salt basins and north of the Variscan front the mapped interval corresponds roughly to the total thickness of the Mesozoic and Cainozoic sediments. In the Alpine domain the thickness of the neo-autochthonous Tertiary series is shown. Stippled contours indicate that values shown are of a tentative nature only. In areas left blank the thickness of the mapped interval is too uncertain to be represented by contours.

In combination with the Permian subcrop map (Encl. I) the Upper Permian to Cainozoic isopach map (Encl. IV) provides an impression of the distribution and dimensions of the sedimentary basins in North-Western Europe.

SUMMARY

North-Western Europe has undergone a long geological evolution during which its megatectonic setting changed repeatedly. In the course of its geological history, a number of genetically different sedimentary basins were formed; some were stacked on top of each other while others were partly destroyed by subsequent events.

During Early Devonian times much of North-Western Europe was occupied by Caledonian fold belts marking the suture between the North American-Greenland and the Fennoscandian-Russian plates. Remnants of a lower Palaeozoic continental shelf sequence are preserved in the Baltic. The London-Brabant Massif formed a Caledonian intramontane stable platform. The Mid-European and North German-Polish Caledonides grade south- and eastwards into the Variscan geosynclinal system, the main elements of which are the Central Armorican-Saxothuringian and the Cantabrian-Pyrenean inter-arc basins and the Averno-Lugian-Moldanubic geanticline.

Devonian transcurrent movements of major proportions between the North American-Greenland and the Fennoscandian-Russian plates caused the subsidence of the fault-controlled Old Red basins in the Arctic-North Atlantic domain. In the area of the Mid-European Caledonides the Cornwall-Rhenish Basin subsided during the Devonian and Early Carboniferous; this was accompanied by extension tectonics and a distinctly bimodal rift volcanism. Rift tectonics also characterized the Carboniferous development of the Norwegian-Greenland Sea and the northern parts of the British Isles.

During the early Carboniferous, underthrusting along the margins of the Averno-Lugian geanticline marked the onset of the Variscan orogeny. By late Visean times underthrusting also set in along the margins of the Normanian-Mid German High; by this time the Cornwall-Rhenish rift had become inactive and the Variscan foredeep basin developed in its place.

Whereas in Europe the Variscan orogeny came to a close during the late Westphalian, crustal shortening persisted in the Appalachians and Urals until Mid-Permian times. A transform fault system linked these fold belts and caused in Europe the emplacement of a complex shear fault system and the subsidence of related grabens and troughs. This was accompanied by widespread volcanism. Extinction of this volcanism during the Late Permian followed the consolidation of the Appalachians and the Urals and the final suturing of the Pangean megacontinent.

In North-Western Europe the Permian post-orogenic uplift and partial collapse of the Variscan fold belt went parallel with the subsidence of two new intracratonic basins. Rifting in the Arctic-North Atlantic led to the opening of a first seaway between the Arctic and the NW. European basins during Late Permian times.

The Triassic development of North-Western Europe, the Arctic-North Atlantic and the Tethys was dominated by regional crustal extension. A new set of grabens and troughs started to subside, whereby Fractures emplaced during the Early Permian were partly reactivated.

The Jurassic split-up of the Pangean continent led to the opening of the Tethys as well as to progressive rifting in the Arctic-North Atlantic; this was accompanied by the development of major rift systems in North-Western Europe. Of these, only the North Sea Graben experienced a short-lived volcanic phase.

With the Lower Tertiary onset of sea-floor spreading in the

northern North Atlantic and in the Norwegian-Greenland Sea the Mesozoic rifts of North-Western Europe became inactive and started to subside regionally.

Alpine suturing of Eurasia and Africa during the Late Cretaceous and Early Tertiary was accompanied by compression and inversion of the NW European Mesozoic troughs located at distances up to 800 km to the north of the Alpine front. However, the Atlantic seaboard, as well as the North Sea Basin, continued to subside during the Tertiary. Concomitant with the last phases of the Alpine orogeny a new set of rifts developed in the Alpine domain and its immediate foreland. Their subsidence is correlative with the collapse of the Mediterranean basins.

REFERENCES

Alberti, H., S. Schüffler, R. Solanwar, D. Stoppel, H. Wachendorf & O.H. Walliser 1977 Paläogeographische und tektonische Entwicklung des Westharzes - Exkursionsführer Geotagung 1977 Geol. Paläont. Inst. Univ. Göttingen: 171-221.

Åm, K. 1973 Geophysical indications of Permian and Tertiary igneous activity in the Skagerrak - Nor. Geol. Unders. 287 (13): 1-25.

Anderson, T.A. 1975 Carboniferous subduction complex in the Harz Mountains, Germany - Bull. Geol. Soc. Amer. 86: 77-82.

Arthaud, F. & Ph. Matte 1975 Les décrochements tardi-hercyniens du sud-ouest de l'Europe. Géometrie et essais de reconstruction des conditions de déformation - Tectonophysics 25: 139-171.

——1977 Late Paleozoic strike - slip faulting in southern Europe and northern Africa: result of a right-lateral shear zone between the Appalachians and the Urals - Geol. Soc. Amer. Bull. 88: 1305-1320.

Audley-Charles, M.G. 1970 Triassic paleogeography of the British Isles - Q. J. Geol. Soc. London 126: 46-74.

Autran, A. & P.L. Guillot 1977 L'évolution orogénique et métamorphique du Limousin (Massif Central Français) au Paléozoique, Relation entre les cycles Calédoniens et Varisques. In: La Chaîne varisque d'Europe moyenne et occidentale - Coll. intern. CNRS Rennes 243: 211-226.

Bailey, R.J., P.D. Jackson & J.D. Bennell 1977 Marine geology of Slyne Ridge - J. Geol. Soc. London 133: 165-172.

Ballard, R.D. & E. Uchupi 1975 Triassic rift structure in the Gulf of Maine - Amer. Assoc. Petrol. Geol. Bull. 59: 1041-1072.

Baumann, L., O. Leeder & W. Weber 1975 Beziehungen zwischen regionalen Bruchstrukturen und postmagmatischen Lagerstättenbildungen und ihre Bedeutung für die Suche und Erkundung von Fluorit-Baryt-Lagerstätten - Zeitschr. angew. Geol. 21: 6-17.

Baumann, L., G. Tischendorf, K. Schmidt & K.-B. Jubitz 1976 Zur minerogenetischen Rayonierung des Territoriums der Deutschen Demokratischen Republik - Zeitschr. Geol. Wiss. Berlin 4: 955-973.

Bebien J., G. Rocci, P.A. Floyd, Th. Juteau & J.P. Sagon 1977 Le volcanisme Dévono-Dinantien élément déterminant dans la reconstruction du cadre géotectonique de l'Europe moyenne varisque. In; La chaîne varisque d'Europe moyenne et occidentale - Coll. internat. CNRS Rennes 243: 275-291.

Bender, P., W. Eder, W. Engel, W. Franke, F. Langenstrassen, O.H. Walliser & W. Witten 1977 Paläogeographische Entwicklung des östlichen Rheinischen Schiefergebirges, demonstriert an einem Querschnitt - Exkursionsführer Geotagung 1977 Geol. Paläont. Inst. Univ. Göttingen: 1-58.

Bennison, G.M. & A.E. Wright 1972 The geological history of the British Isles - Edward Arnold Publ. (London).

Bernard-Griffiths, J., J.M. Cantagrel & J.C. Duthou 1977 Radiometric evidence for an Acadian tectonometamorphic event in the Western Massif Central Français - Contrib. Mineral. Petrol. 61: 199-212.

Bertrand, H. & M. Westphal 1977 Comparaisons géologiques et paléomagnétiques des tholéiites du Maroc et de la Côte Orientale de l'Amérique du Nord; implications pour l'ouverture de l'Atlantique - Bull. Soc. Géol. France 7: 513-520.

Beutler G. & F. Schüler 1978 Über altkimmerische Bewegungen im Norden der DDR und ihre regionale Bedeutung (Fortschrittsbericht) - Zeitschr. Geol. Wiss. Berlin 6: 403-420.

Biju-Duval, B., J. Dercourt & X. le Pichon 1977 From the Tethys ocean to the Mediterranean Sea; a plate tectonic model of the evolution of the Western Alpine system. In: B. Biju-Duval & L. Montadert (eds.): Structural history of the Mediterranean Basins – Ed. Techniq (Paris): 143-164.

Binns, P.E., R. McQuillin, N.G.T. Fannin, N. Kenolty & D.A. Ardus 1975 Structure and stratigraphy of sedimentary basins in the sea of the Hebrides and the Minches. In: Petroleum and the continental shelf of NW Europe, vol. 1 Geology - Applied Sci. Publ.: 93-104.

Birkelund, T. & K. Perch-Nielsen 1976 Late Paleozoic- Mesozoic evolution of Central East Greenland. In: A. Escher & W.S. Watt (eds.): Geology of Greenland - Geol. Surv. Greenland: 304-339.

Blair, D.G. 1975 Structural styles in North Sea oil and gas fields. In: A.W. Woodland (ed): Petroleum and the continental shelf of NW Europe, vol. 1, Geology - Applied Sci. Publ. 327-335.

Bless, M.J.M., J. Bouckaert, M.A. Claver, J.M. Graulich & E. Paproth 1977 Paleogeography of Upper Westphalian deposits in NW Europe with reference to Westphalian C north of the mobile Variscan belt - Meded. Rijks Geol. Dienst N.S. 28: 101-147.

Boigk, H. 1968 Gedanken zur Entwicklung des Niedersächsischen Tektogens - Geol. Jb. 85: 861-900.

Bölau, E. 1975 Die Kimmerischen Bewegungen im tektonischen Bild Schonens - Geol. Föreningens Stockholm För. 95: 165-180.

Bott, M.H.P. 1964 Formation of sedimentary basins by ductile flow of isostatic origin in the upper mantle - Nature 201: 1082-1084.

Bottke, H. 1978 Zur faziesgebunden Tektonik der Briloner Scholle (Ostsauerland, Rheinisches Schiefergebirge) – Zeitschr. deutsch. geol. Ges. 129: 141-151.

Brinkmann, R. 1948 Die Mitteldeutsche Schwelle - Geol. Rundschau 36: 56-66.

Burke, K., J.F. Dewey & W.S.F. Kidd 1977 World distribution of sutures - The sites of former oceans - Tectonophysics 40: 69-99.

Burrett C. & J. Griffiths 1977 A case for a mid-European Ocean. In: La chaîne varisque d'Europe moyenne et occidentale - Coll. intern. CNRS Rennes 243: 313-328.

Busch, W.A. & L.G. Kiryuchin 1972 Über die Verbreitung subsequenter Effusiva des Jungpalaeozoikums in Mittel Europa - Zeitschr. angew. Geol. 18: 323-328.

Cashion, W.W. 1975 Geology of the West Shetland Basin; Offshore Europe 75 (Conf. Univ. Aberdeen, Sept. 16-19, 1975) - Spearhead Publ. Ltd. paper OE-75 216: 1-7.

Chenevoy, M. 1974 Le Massif Central. In: J. Debelmas (ed.): Géologie de France. Vol. 1 - Vieux massifs et grands bassins sédimentaires: 162-227.

Cogné, J. 1974 Le Massif Armoricain. In: J. Debelmas (ed.): Géologie de France, Vol. 1. Vieux massifs et grands bassins sédimentaires: 105-161.

——1976 Les grandes lignes structurales du Massif Armoricain. In: A. Watznauer (ed.) Franz Kossmat Symposion - Nova Acta Leopoldina NF 224: 177-192.

Colter, U.S. & K.W. Barr 1975 Recent development in the geology of the Irish Sea and Cheshire Basin. In: A.W. Woodland (ed.): Petroleum and the continental shelf of NW Europe, vol. 1, Geology - Applied Sci. Publ.: 61-73.

Cottençon, A., A. Paraut & G. Flacelière 1975 Lower Cretaceous Gasfields in Holland. In: A.W. Woodland (ed.): Petroleum and the continental shelf of NW Europe, vol. 1. Geology - Applied Sci. Publ.: 403-412.

Dewey, J.F. 1977 Suture zone complexities: a review - Tectonophysics 40: 53-67.

Dewey, J.F., W.C. Pitman, B.F. Ryan & J. Bonnin 1973 Plate tectonics and the evolution of the Alpine System - Bull. Geol. Soc. Amer. 84: 3137-3180.

Dornsiepen, U.E. 1977 Ein Überblick über die europäischen Varisziden - Nachr. deutsch. Geol. Ges. 17 (abstract only, full text in press).

Dvorak, J. 1973-a Synsedimentary tectonics of the Paleozoic of the Drahany upland (Sudeticum, Moravia, Czechoslovakia) - Tectonophysics 17: 359-391.

——1973-b Die Quergliederung des Rheinischen Schiefergebirges und die Tektogenese des Siegener Anticlinoriums - N. Jb. Geol. Paläont. Abh. 143: 133-152.

——1975 Interrelationship between the sedimentation rate and the subsidence during the flysch and molasse stage of the Variscan geosyncline in Moravia (Sudeticum) - N. Jb. Geol. Palaeont. Mh.: 339-342.

Dvorak, J., O. Friakova & L. Lang 1976 Block structure of the old basement as indicated by the facies development of the Devonian and the Carboniferous in the Moravian Karst (Sudeticum, Moravia, CSSR) - Geologica Paleontologica 10: 153-160.

Faerseth, R.B., R.M. MacIntyre & J. Naterstad 1976 Mesozoic alkaline dykes in the Sunn Hordland Region, Western Norway; ages, geochemistry and regional significance - Lithos 9: 331-345.

Falke, H. & H. Bank 1970 Zur Geologie und Tektonik der südwestlichen Nahe-Mulde - Sonderheft (Idar-Oberstein) 19: 53-66.

Flick, H. 1977 Geologie und Petrographie der Keratophyre des Lahn Dill Gebietes (südliches Rheinisches Schiefergebirge) - Clausthaler Geol. Abh. 26: 1-231.

——1978 Die chemischen Parameter der Keratophyre und Quarzkeratophyre des Lahn-Dill Gebietes – Zeitschr. deutsch. geol. Ges. 129: 161-170.

Francis, E.H. 1968 Review of Carboniferous-Permian volcanicity in Scotland - Geol. Rundschau 57: 219-246.

——1970 Review of Carboniferous volcanism in England and Wales - J. Earth Sci. Leeds Geol. Ass. 8: 41-50.

——1978-a Igneous activity in a fractured craton - Carboniferous volcanism in North Britain. In: D.R. Bowes & B.E. Leake (eds.): Crustal evolution in NW Britain and adjacent regions - Geol. J. Spec. issue 10: 279-296.

—— 1978-б The Midland Valley as a rift, seen in connection with the late Paleozoic European Rift system. In: I.B. Ramberg & E.R. Neumann (eds.): Tectonics and geophysics of continental rifts - D. Reidel Publ. Co.: 133-148.

Franke, W., W. Eder, W. Engel & F. Langenstrassen 1978 Main aspects of geosynclinal sedimentation in the Rhenohercynian zone – Zeitschr. deutsch. geol. Ges. 129: 201–216.

Gibb, F.G.F. & R. Kanaris-Sotirious 1976 Jurassic igneous rocks of the Forties Field - Nature 260: 23-25.

Glennie, K.W. 1972 Permian Rotliegendes of North-Western Europe, interpreted in the light of modern desert sedimentation studies - Bull. A.A.P.G. 56: 1048-1071.

Gluschko, V.V., G.Ch. Dikenstein & K. Schmidt 1975 The Caledonides of Rügen Island - Dokl. Earth Sci. Sect. 214: 89-90.

Gluschko V.V., G.Ch. Dikenstein, K. Schmidt & K. Goldbecher 1976 Zur tektonischen Rayonierung des Nordteils der DDR nach dem Alter des gefalteten Untergrunds - Jb. Geol. 7/8: 9-16.

Gluschko, V.V., H. Hetzer, G. Katzung, G.Ch. Dikenstein, B.A. Solowjew & S.M. Tschernyschew 1975 Grundzüge des geologischen Baus und der Gasführung des Rotliegenden in der Mitteleuropäischen Senke - Zeitschr. angew. Geol. 21: 253-262.

Graul, H. 1970 Stratigraphische und sedimentpetrographische Untersuchungen im Mittleren Buntsandstein am Ostrand des Rheinischen Schiefergebirges - Notizbl. hess. L.-Amt Bodenforsch. 98: 93-111.

Hallam, A. 1971 Mesozoic geology and the opening of the North Atlantic - J. geol. 79: 129-157.

Haller, J. 1970 Tectonic map of East Greenland - Medd. Grønland 171 (5).

Hamet, J. & C.J. Allegre 1976 Hercynian orogeny in the Montagne Noire (France). Application of R87-SR87 systematics - Geol. Soc. Amer. Bull. 87: 1429-1442.

Harland, W.H. 1973 Tectonic evolution of the Barents Shelf and related plates - A.A.P.G. Mem. 19: 599-608.

Harland, W.H. & R.A. Gayer, 1972 The Arctic Caledonides and earlier oceans - Geol. Mag. 109: 289-384.

Haworth, R.T. 1974 The development of Atlantic Canada as a result of continental collision - evidence from offshore gravity data - Can. Soc. Petrol. Geol. Mem. 4 ('Canada's Continental Margins'): 59-77.

Herrmann, A.G. & K.H. Wedepohl 1970 Untersuchungen an spillitischen Gesteinen der variskischen Geosynkline in Nordwest-Deutschland - Contr. Mineral. Petrol. 29: 255-274.

Heybroek, P. 1974 Explanation to tectonic maps of the Netherlands - Geol. Mijnbouw 53: 43-50.

——1975 On the structure of the Dutch part of the Central North Sea graben. In: A.W. Woodland (ed.): Petroleum and the continental shelf of NW Europe, vol. 1. Geology - Applied Sci. Publ.: 339-352.

Hinz, K. & H.U. Schlüter 1978 The geological structure of the Western Barents Sea - Marine Geol. 26: 199-230.

Hoffmann, K. 1949 Zur Paläogeographie des nordwestdeutschen Lias und Doggers. In: A. Bentz (ed.): Erdöl und Tektonik in Nordwestdeutschland - Hannover-Celle: 97-113.

Howitt, F., E.R. Aston & M. Jaqué 1975 The occurrence of Jurassic volcanics in the North Sea. In: A.W. Woodland (ed.): Petroleum and the continental shelf of NW Europe, vol. 1 Geology - Applied Sci. Publ.: 379-386.

Hubub, V., V. Skocek & R. Tasler 1975 Paleogeography of the late Paleozoic in the Bohemian Massif - Palaeogeography, Palaeoclimatology, Palaeoecology 18: 313-332.

Illies, J.H. 1970 Graben tectonics as related to crust-mantle interaction. In: J.H. Illies & St. Müller (eds.): Graben problems, Internat. Upper Mantle Project Scientific report No. 27 - Schweizerbartsche Verlags Buchhandlung (Stuttgart): 4-27.

——1974 Intra-Plattentektonik in Mitteleuropa und der Rheingraben - Oberrhein. geol. Abh. 23: 1-24.

——1978 Two stages Rhine Graben rifting. In: I.B. Ramberg & E.-R. Neumann (eds.): Tectonics and geophysics of continental rifts - Ds Reidel Publ. Co.: 63-72.

Jäger E. 1977 The evolution of the Central and West European continent. In: La Chaîne varisque d'Europe moyenne et occidentale - Coll. intern. CNRS Rennes 243: 227-239.

——1978 Die Entwicklungsgeschichte des europäischen Kontinents auf Grund von Alterdaten - Zeitschr. deutsch. geol. Ges. 129 (in press).

Jansa, L.F. & J.A. Wade 1975 Geology of the continental margin off Nova Scotia and Newfoundland - Geol. Surv. Canada Paper 74-'30, Vol. 2: 51-105.

Johnson, G.A.L. 1976 Paleozoic accretion of Western Europe - Ann. Soc. Geol. Nord. 96: 347-352.

Juteau, T. & G. Rocci 1965 Étude pétrographique du massif volcanique dévonodinantien de Schirmeck (Vosges Septentrionales) - Bull. Serv. Carte géol. Als. Lorr. 18: 145-176.

——1966 Étude chimique du Massif Volcanique Dévonien de Schirmeck (Vosges septentrionales) Evolution d'une Série spilite-kératophyre - Sci. Terre (Nancy) 11: 68-104.

——1974 Vers une meilleure connaissance du problème des spilites à partir de données nouvelles sur le cortège spilito-keratophyric Hercynontype. In: G.C. Amstutz (ed.): Spilites and spilitic rocks - Union Geol. Sci. Series A 4, Springer Verlag: 253-329.

Katzung, G. 1975 Tektonik, Klima und Sedimentation in der Mitteleuropäischen Saxon-Senke und in angrenzenden Gebieten - Zeitschr. geol. Wiss. Berlin 3: 1453-1472.

Keller, G. 1976 Saxonische Tektonik und Osning Zone - Zeitschr. deutsch. geol. Ges. 127: 297-307.

Klein, C. 1978 Tectogénèse armoricaine et tectogénèse ardennaise, la notion du socle mou - Bull. Soc. belge Géol. 86 (1977): 151-182.

Klingspor, I. 1976 Radiometric age-determinations of basalts and dolerites and related syenites in Skåne, South Sweden - G.F.F. 98: 195-215.

Kneuper, G. 1966 Zur Entstehung der Saar-Nahe Senke - Zeitschr. deutsch. geol. Ges. 112: 312-322.

Knox, R.W. 1977 Upper Jurassic pyroclastic rocks in Skye, West Scotland - Nature 265: 323-324.

Kramer, W. 1977 Vergleichende geochemische Untersuchungen an permosilesischen basischen Magmatiten der Norddeutsch-Polnische Senke und ihre geotektonische Bedeutung - Zeitschr. geol. Wiss. Berlin 5: 7-20.

Krebs, W. 1968 Zur Frage der bretonischen Faltung im östlichen Rhenoherzynikum - Geotekt. Forsch. 28: 1-103.

——1974 Devonian carbonate complexes of Central Europe. In: L.F. Laporte (ed.): Reefs in space and time - selected examples from the recent and ancient - Soc. Econ. Pal. Min. Spec. Publ. 18: 155-208.

——1977 The tectonic evolution of Variscan Meso-Europa. In: D.V. Ager & M. Brooks (eds.): Europe from crust to core - Wiley-Interscience Publ.: 119-139.

——1978a Die Kaledoniden im nördlichen Mitteleuropa - Zeitschr. deutsch. geol. Ges. 129 (in press).

——1978b Das Altpaläozoikum des Lippstädter Gewölbes und seine regional-geologische Stellung in den Kaledoniden Mitteleuropas - Fortschr. Geol. Nordrhein-Westf. 30 (in press).

Kreuzer, H., H. Lenz, W. Harre, S. Matthes, M. Okrusch & P. Richter 1973 Zur Altersstellung der Rotgneise im Spessart Rb/Sr-Gesamtgestein Datierung - Geol. Jb. A 9: 69-88.

Larsen, G. 1966 Rhaetic-Jurassic-Lower Cretaceous Sediments in the Danish Embayment (A Heavy Mineral Study) - Danm. geol. Unders. II (97): 1-127.

Larsen, O. 1971 K/Ar age determinations from the Precambrian of Denmark - Geol. Survey Denmark 2nd series 97: 1-34.

Laubscher, H.P. 1970 Grundsätzliches zur Tektonik des Rheingrabens. In: J.H. Illies & St. Müller (eds.): Grabenproblems, Internat. upper Mantle project, Scientific Report No. 27 - Schweizerbartsche Verlags Buchhandlung: 79-87.

——1974 Evoluzione e struttura delle Alpi - Le Scienze 72: 48-59.

Laubscher, H.P. & D. Bernouill 1977 Mediterranean and Tethys. In: A.E.M. Nairn (ed.): The ocean margins, vol.: Structural history of the Mediterranean basins: 129-132.

Laughton, A.S. 1971 South Labrador Sea and the evolution of the North Atlantic - Nature 232: 612-617.

——1975 Tectonic evolution of the Northeast Atlantic oceans; a review - Norges geol. Unders. 316: 169-193.

Leeder, M.R. 1974 The origin of the Northumberland basin - Scott. J. Geol. 10: 283-296.

——1976 Sedimentary facies and the origin of basin subsidence along the northern margin of the supposed Hercynian ocean - Tectonophysics 36: 167-179.

Legrand, R. 1968 Le Massif du Brabant - Serv. géol. Belg. Mem. 9.

Lehmann, E. 1972 On the source of the iron in the Lahn ore deposits - Miner. Deposita 7: 247-270.

——1974 Environmental effects in magmatic spilitic rocks. In: G.C. Amstutz (ed.): Spilites and spilitic rocks, Intern. Union Geol. Sci. Series A 4 - Springer Verlag: 113-125.

Lenz, H. & P. Müller 1976 Radiometrische Alterbestimmungen am Kristallin der Bohrung Saar 1 - Geol. Jb. A 27: 429-432.

Le Pichon, X. 1977 The fit of the continents around the North Atlantic Ocean - Tectonophysics 38: 169-209.

Lutzens, H. & H.J. Paech 1975 Sedimentologie, Paläogeographie und Paläotektonik während des Flyschstadiums im östlichen Rhenoherzynikum (Harz und Flechtlinger-Rosslauer Scholle) - Zeitschr. geol. Wiss. Berlin 3: 1509-1525.

Malkovsky, M. 1976 Saxonische Tektonik der Böhmischen Masse - Geol. Rundschau 65: 127-143.

Manspeizer, W., J.H. Puffer & H.C. Cousminer 1978 Separation of Morocco and eastern North America; a Triassic-Liassic stratigraphic record - Geol. Soc. Amer. Bull. 89: 901-920.

Martin, R.F. & A.J. Piwinskii 1972 Magmatism and tectonic settings - J. Geoph. Research 77: 4966-4975.

Matthews, S.C. 1977 The Variscan foldbelt of southwest England - N. Jb. Geol. Paläont. Abh. 154: 94-127.

Michot, J., L. Franssen & D. Ledent 1972 Preliminary age measurements on metamorphic formations from the Ardennes anticline and the Brabant massif (Belgium) - Fortsch. Miner. 50: 107-109.

Michot, P. 1976 Le segment varisque et son antécédent calédonien dans le cadre de la Belgique et des regions limitrophes. In: A. Watznauer (ed.): Franz Kossmat Symposium - Nova Acta Leopoldina N.F. 224 (45): 201-228.

Middelton, G.V. 1960 Spilitic rocks in South Devonshire - Geol. Mag. 97: 192-207.

Milanovsky, E.E. 1978 Some problems of rifting development in the earth's history. In: I.B. Ramberg & E.-R. Neumann (eds.): Tectonics and geophysics of continental rifts - D. Reidel Publ. Co.: 385-400.

Miller, J.A. & D.H. Green 1961 Age determination of rocks in the Lizard (Cornwall) area - Nature 23: 1175-1176.

Montadert, L., D.G. Roberts, G.A. Auffret, W. Bock, P.A. Du Peuble, E.A. Hailwood, W. Harrison, H. Kagani, D.N. Lumsden, C. Muller, D. Schnitker, R.W. Thompson, T.L. Thompson & P.P. Timofeev 1977 Rifting and subsidence on passive continental margins in the North East Atlantic - Nature 268: 305-309.

Morris, W.A. 1976 Transcurrent motions determined paleomagnetically in the Northern Appalachians and Caledonides and the Acadian orogeny - Can. J. Earth Sci. 13: 1236-1243.

Neumann, W. 1966 Versuch eines lithostratigraphischen Vergleiches von Grundgebirgsanschnitten im Bereich der Mitteldeutschen Schwelle - Geologie 15: 942-962.

——1972 Die Entwicklung von Variszischer und Saxonischer Tektonik im Ruhlaer Kristallin - Ber. deutsch. Ges. geol. Wiss. A. Geol. Paläont. 17: 797-810.

Nodop, I. 1971 Tiefenrefraktionesseismischer Befund im Profil Versmond-Lubbecke-Nienburg - Fortschr. Geol. Rheinland Westfalen 18: 411-422.

Nöldke, W. & G. Schwab 1977 Zur tektonischen Entwicklung des Tafeldeckgebirges der Norddeutsch-Polnischen Senke unter besonderer Berücksichtigung des Nordteils der DDR - Zeitschr. angew. Geol. 23: 369-379.

Oberc, J. 1977 Besteht ein kaledonisches Tectogen in Süd-Polen? - N. Jb. Geol. Paläont Mh. 1: 56-63.

Oftedahl, C.H. 1968 Magmen-Entstehung nach Lava-Stratigraphie im südlichen Oslo-Gebiet - Geol. Rundschau 57: 203-218.

Olson, W.S. & R.J. Leyden 1973 North Atlantic rifting in relation to Permo-Triassic salt deposition. In: A. Lagon & L.V. Hills (eds.): Permian and Triassic systems and their mutual boundaries - Can. Soc. Petrol. Geol. Mem. 2: 720-732.

Paproth, E. 1976 Zur Folge und Entwicklung der Tröge und Vortiefen im Gebiet des Rheinischen Schiefergebirges und seiner Vorländer, vom Gedinne (Unter Devon) bis zum Namur (Silesium). In: A. Watznaner (ed.): Franz Kossmat Symposion - Nova Acta Leopoldina NF. 224 (45): 45-58.

Paproth, E. & R. Teichmüller 1961 Die paläogeographische Ent-

wicklung der subvariscischen Saumsenke in Nord-West-deutschland im Laufe des Karbons - C.R. 4e Congr. géol. Carbonif. (Heerlen, 1958) 2: 471-490.
Parker, J.R. 1975 Lower Tertiary sand development in the Central North Sea. In: A.W. Woodland (ed.): Petroleum and the continental shelf of NW Europe, vol. 1 Geology - Applied Sci. Publ.: 447-452.
Pfeiffer, H. 1968 Überblick über die Entwicklung des Saxo-Thuringikums vom Beginn des Devons bis zur variszischen Hauptfaltung - Geologie 17: 17-51.
——1971 Die variszische Hauptbewegung (sogenannte Sudetische Phase) im Umkreis der äusseren Kristallinzone des variszischen Bognes - Geologie 8: 945-958.
Pirlet, H. 1976 Les mouvements epeirogéniques importants du Carbonifère belge. In: A. Watznauer (ed.): Franz Kossmat Symposium - Nova. Acta Leopoldina NF 224 (45): 229-236.
Pitman, W.C. & M. Talwani 1972 Seafloor spreading in the North Atlantic - Bull. Geol. Soc. Amer. 83: 619-646.
Plein, E. 1978 Rotliegend - Sedimente im Norddeutschen Becken - Zeitschr. deutsch. geol. Ges. 129: 71-97.
Pokorski, J. & R. Wagner 1975 Stratigraphy and paleogeography of the Permian - Geol. Inst. Bull. Warsaw 252: 115-129.
Pozaryski, W. 1970 Structural development of the Polish Lowlands in the Variscan Epoch - Geol. Inst. Bull. Warsaw 252: 77-92.
Pozaryski W. & W. Brochwicz-Lewinski 1978 On the Polish Trough - Geol. Mijnbouw (this issue).
Pozaryski, W., W. Brochwicz-Lewinski & M. Jaskowiak-Schoeneich 1978 Geologiczna mapa Baltyku - Przeglad Geol. 297: 1-5.
Pozaryski W. & Z. Kotanski 1978 Baikalian, Caledonian and Variscan events in the forefield of the East-European platform - Zeitschr. deutsch. geol. Ges. 129 (in press).
Pozaryski W. & J. Kutek 1976 Problematyka XLVIII Zjazdu Polskiego Towardystwa Geologicznego: Przeglad Publikacji O Mesozoiku i Tectonice Alpejskiej gor Swietokryskich - Przeglad Geol. 280: 445-450.
Pozaryski W., J. Oberc & Ksiazkiewicz 1977 Geology of Poland Vol. 4; Tectonics - Publ. House Wydawnictwa Geologiczne (Warsaw).
Priem, H.N.A., F.G. Mulder, N.A.I.M. Boelrijk, E.H. Hebeda, R.H. Verschure & E.A..Th. Verdurmen 1968 Geochronological and paleomagnetic reconnaissance survey in parts of central and southern Sweden - Phys. Earth Planet. Interiors 1: 373-380.
Priemke, G. & H.H. Radzinski 1976 Zur Gliederung des Mittleren Buntsandsteines (Volpriehausen-bis Solling-Folge) im Subherzynen Becken - Zeitschr. geol. Wiss. Berlin 4: 1473-1481.
Prinzlau, I. & O. Larsen 1972 K/Ar age determination on alkaline olivine basalts from Skåne, South Sweden - G.F.F. 94: 259-269.
Ramberg, I.B. 1976 Gravity interpretation of the Oslo Graben and associated igneous rocks - Norg. geol. Unders. 325: 1-194.
Ramberg, I.B. & N. Spjeldnaes 1978 The tectonic history of the Oslo region. In: I.B. Ramberg & E.-R. Neumann (eds.): Tectonics and geophysics of continental rifts - D. Reidel Publ. Co.: 167-194.
Rat, P. 1974 Le système Bourgogne-Morvan-Bresse (articulation entre le bassin parisien et le domaine peri-alpin). In: J. Debelmas (ed.): Géologie de la France vol. 2: Les chaines plissées du cycle alpin et leur avant-pays.
Richter-Bernburg, G. 1968 Saxonische Tektonik als Indikator erdtiefer Bewegungen - Geol. Jb. 85: 997-1030.
——1977 "Saxonische Tektonik" Hans Stilles Begriff in heutiger Sicht - Zeitschr. deutsch. geol. Ges. 128: 1-23.
Riddihough, R.P. & M.D. Max 1976 A geological framework of the continental margin to the west of Ireland - Geol. J. 11: 109-118.
Roberts, D.G. 1975 Tectonic and stratigraphic evolution of the Rockall Plateau and Trough. In: A.W. Woodland (ed.): Petroleum and the continental shelf of NW Europe, Vol. 1 Geology - Applied Sci. Publ.: 72-89.
Russell, M.J. 1976 A possible Lower Permian age for the onset of ocean floor spreading in the northern North Atlantic - Scott. J. Geol. 12: 315-323.
Russell, M.J. & D.K. Smythe 1978 Evidence for an early Permian ocean rift in the northern North Atlantic. In: E.-R. Neumann & I.B. Ramberg (eds.): Petrology and geochemistry of continental rifts - D. Reidel Publ. Co.: 173-180.
Sawkins, F.J. 1978 Some aspects of the metallogeny of continental riftings events. In: E.R. Neuman & I.B. Ramberg (eds.): Petrology and geochemistry of continental rifts - D. Reidel Publ. Co.: 51-54.
Schmidt, K. 1976 Das "Kaledonische Ereignis" in Mittel und Südwest Europa. In: A. Watznauer (ed.): Franz Kossmat Symposion - Nova Acta Leopoldina NF 224 (45): 381-401.
Schmidt, K. & D. Franke 1975 Stand und Probleme der Karbonforschung in der D.D.R. - Zeitschr. geol. Wiss. Berlin 3: 819-849.
Schmidt, K., G. Katzung & D. Franke 1977 Zur Entwicklung des präpermischen Untergrunds und des Magmatismus im südwestlichen Vorfeld der Osteuropäischen Tafel - Zeitschr. angew. Geol. 23: 426-436.
Schmidt, W. 1952 Die palaeogeographische Entwicklung des linksrheinischen Schiefergebirges vom Kambrium bis Oberkarbon - Zeitschr. deutsch. geol. Ges. 103: 151-177.
Schönenberg, R. 1973 Zur Tektonik des südwest deutschen Schichtstufenlandes unter dem Aspekt der Plattentektonik - Oberrhein. geol. Abh. 22: 75-86.
Schröder, B. 1976 Saxonische Tektonik im Ostteil der Süddeutschen Scholle - Geol. Rundschau 65: 34-54.
Schwab, W. 1974 Flysch, Olistostrome und Gleitdecken im Harz - Zeitschr. deutsch. geol. Ges. 125: 253-267.
Schwan, W. 1977 Höhepunkte der Geodynamik bei alpinotyper Orogenese und bei Ocean-floor spreading b.z.w. Plattenbewegungen - Zeitschr. deutsch. geol. Ges. 128: 143-152.
Sengor, A.M.C., K. Burke & J.F. Dewey 1978 Rifts at high angles to orogenic belts tests for their origin and the Upper Rhine graben as an example - Amer. J. Sci. 278: 24-40.
Senkowiczowa, H. & A. Szyperko-Sliwczynska 1975 Stratigraphy and paleogeography of the Trias - Geol. Inst. Bull. Warsaw 252: 131-147.
Smithson, S.B., J. Brewer, S. Kaufman & J. Oliver 1978 Nature of the Windriver thrust, Wyoming, from Cocorp deep reflection data and gravity data - Geology 6 (in press).
Stadler, G. & R. Teichmüller 1971 Zusanmenfassender Überblick über die Entwicklung des Bramscher Massifs und des Niedersächsischen Tektogens - Fortschr. Geol. Rheinland Westf. 18: 547-564.
Steel, R.J. 1976 Devonian basins of Western Norway-sedimentary response to tectonism and varying tectonic context - Tectonophysics 36: 207-224.
Steel, R.J. & A.O. Wilson 1975 Sedimentation and tectonism (?Permo-Triassic) on the margin of the north Minch Basin, Lewis - Quart. J. Geol. Soc. London 131: 183-202.
Stille, H. 1924 Grundfragen der vergleichenden Tektonik - Borntraeger (Berlin).
Stoppel, D. 1977 Schlammstrom Sedimente im Oberdevon des Südwest Harzes und des Südlichen Kellerwaldes - Zeitsch. deutsch. geol. Ges. 128: 81-87.
Storedvedt, K.M. 1973 A possible large-scale sinistral displacement along the Great Glen fault in Scotland - Geol. Mag. 111: 23-30.
Storedvedt, K.M., S. Pedersen, R. Løvlic & E. Halvorsen 1978 Paleomagnetism in the Oslo Rift Zone. In: I.B. Ramberg & E.-R. Neumann (eds.): Tectonics and geophysics of continental rifts - D. Reidel Publ. Co.: 289-296.
Sundvoll, B. 1978 Rb-Sr relationship in the Oslo igneous rocks. In: E.-R. Neumann & I.B. Ramberg (eds.): Petrology and geochemistry of contintal rifts - D. Reidel Publ. Co.: 181-184.
Talvani, M. & O. Eldholm 1977 Evolution of the Norwegian Green-

land Sea - Geol. Soc. Amer. Bull. 88: 969-999.
Teichmüller, R. 1973 Die palaeogeographisch-fazielle und tektonische Entwicklung eines Kohlenbeckens am Beispiel des Ruhrkarbons - Zeitsch. deutsch. geol. Ges. 124: 149-165.
Teisseyre, H. 1976 Das Problem der Hauptfaltung der Sudeten. In: A. Watznauer (ed.): Franz Kossmat Symposion - Nova Acta Leopoldina NF 224 (45): 83-92.
Thorez, J. & M.J.M. Bless On the possible origin of the lower Westphalian D Neeroeteren Sandstone (Campine, Belgium) - Meded. Rijks Geol. Dienst N.S. 28: 128-132.
Tokarski, A. 1965 Stratigraphy of the Salinary Röt of the fore-Sudetic monocline - Acta geol. Polonica 15: 105-129.
Umbgrove, J.H.F. 1947 The pulse of the Earth, 2nd ed. - Nijhoff (Den Haag).
Vail, P.R., R.M. Mitchun, R.G. Todd, J.M. Widmier, S. Thompson, J.B. Sangree, J.N. Bubb & W.G. Hatfield 1977 Seismic stratigraphy and global changes of sealevel. In: C.E. Payton (ed.): Seismic stratigraphy. Applications to hydrocarbon exploration - Amer. Ass. Petrol. Geol. Mem. 26: 49-212.
Vogt, P.R. 1973 Early events in the opening of the North Atlantic. In: Tarling & S.K. Runcorn (eds.): Implications of continental drift to earth science, Vol. 2 - Academic Press (London): 693-712.
Voight, E. 1962 Über Randtröge der Schollenränder und ihre Bedeutung im Gebiet der Mitteleuropäischen Senke und Angrenzender Gebiete - Zeitschr. deutsch. geol. Ges. 114: 378-418.
Waterlot, G. 1977 Le Paléozoique du Nord de la France et de la Belgique (Ardennes et Boulonnais). In: J. Debelmas (ed.): Géologie de la France. Vol. 1 Vieux massifs et grands bassins sédimentaires: 42-62.
Watznauer, A., K.A. Tröger & G. Möbus 1976 Gleichheiten und Unterschiede im Bau der Saxothüringischen Zone westlich und östlich des Elbelineamentes. In: A. Watznauer (ed.): Franz Kossmat Symposion - Nova Acta Leopoldina NF 224 (45): 93-110.
Wegner, J. 1966 Strukturbau und Tektonik im Nordosten der DDR - Geophys. Geol. 9: 44-56.
Wjalow, O.S. & A.P. Medwedew 1977 Die präalpidische Struktur der Westlichen Ukraine und Südpolens und die Wechselbeziehung zwischen Tafel- und Geosynklinalgebieten - Zeitschr. angew. Geol. 23: 517-521.
Wills, L.J. 1952 A paleogeographical atlas of the British Isles and adjacent parts of Europe - Blackie and Son Ltd. (London & Glasgow).
Wolburg, J. 1961 Sedimentationszyklen und Stratigraphie des Buntsandsteines in NW Deutschland - Geotekt. Forsch. 14: 7-74.
Wurster, P. 1968 Palaeogeographie der deutschen Trias und die palaeogeographische Orientierung der Lettenkohle in Südwest-Deutschland - Eclogae geol. Helv. 61: 157-166.
Ziegler, P.A. 1975 Geologic evolution of North Sea and its tectonic framework - Bull. A.A.P.G. 59: 1073-1097.
——1977 Geology and hydrocarbon provinces of the North Sea - Geo Journal 1: 7-31.
——1978 North Sea rift and basin development. In: I.B. Ramberg & E.-R. Neumann (eds.): Tectonics and geophysics of continental rifts - D. Reidel Publ. Co. (in press).
Ziegler, P.A. & Louwerens 1978 Tectonics of the North Sea. In: E. Oele et al.: The Quaternary history of the North Sea - Acta Univ. Ups Symp. Univ. Ups Annum Quingentesimum Celebrantis 2, Upsala (in press).
Znosko, J. (ed.) 1968 Geological areas of Poland, 1: 2,000,000 - Geol. Inst. Warsaw.
——1974 Polish Carpathian foreland. In: Tectonics of the Carpathian Balkan regions, platforms and foreland - Geol. Inst. Dionyz Stur Bratislava: 431-445.
Zwart, H.J. 1975 Hercynian orogeny in Europe - Progr. Geodyn. 13: 80-84.
——1978 The tectonic framework of Central and Western Europe - Geol. Mijnbouw (this issue).