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ORIGIN OF THE OSLO GRABEN IN RELATION TO THE HERCYNIAN–ALLEGHENIAN OROGENY AND LITHOSPHERIC RIFTING IN THE NORTH ATLANTIC

MICHAEL J. RUSSELL and DAVID K. SMYTHE

Department of Applied Geology, University of Strathclyde, Glasgow G1 1XJ, Scotland (Great Britain)
Institute of Geological Sciences, 19 Grange Terrace, Edinburgh EH9 2LF, Scotland (Great Britain)

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ABSTRACT

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The contemporaneous extrusion of basalts in the Oslo Graben and intrusion of dolerites in northern Britain and southern Sweden at ~ 295 Ma calls for a common explanation. Two hypotheses are investigated: (1) the Graben and dykes resulted from extensional stresses associated with progressive lithosphere separation to the northwest of Europe in the late Carboniferous; (2) the dykes, and therefore the Graben, were related in some way to oblique collision of plates in the Hercynian orogeny which was developing to the south. The first hypothesis is mechanically more satisfying, and makes a number of testable predictions. It states that in late Carboniferous times the lithosphere separated in two places along the orogenic grain to the west of Britain and Norway. The two embryonic oceanic rifts were divided by thick cold lithosphere with an Archaean crust to the north of Scotland. Extensional stresses were focussed in this region, fanning out in an arcuate zone to the south and east, causing failure where the lithosphere was relatively thin. In Norway the strain was restricted to a zone previously thinned and weakened in the Early Palaeozoic, i.e. the Oslo Graben. In Britain the Caledonoid grain is oblique to the expected direction of extensional strain, and a dyke swarm, trending E–W and about 300 km wide, was formed. The first hypothesis predicts that the dykes should die out to the west but continue along an arc and widen to the east-northeast under the western North Sea. Interpretation of aeromagnetic maps shows that the dykes behave as predicted by hypothesis one, but that their trends and extent are at variance with the expectations of hypothesis two. The apparent contradiction of rifting to the northwest of Europe occurring at the same time as compression and oblique collision in the heart of Europe is resolved in principle by two plate tectonic reconstructions of Pangaea drawn for late Carboniferous and early Permian times.

The Oslo Graben was conceived in mid-Carboniferous times and born towards the end of the Carboniferous as the thin lithosphere failed and allowed the extrusion of basalt magma. It was then abandoned as the two collinear oceanic rifts to the west and northwest joined up, but the Graben carried on a life of its own, as the mafic magma cushion caught in the density trap beneath the crust continued to differentiate, and alkali magma pods rose buoyantly to freeze in the upper crust or extrude on the Graben floor.

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INTRODUCTION

The main questions regarding the formation of continental rifts are (1) What are the peculiar stress conditions that cause rifting? (2) Do previous crustal weaknesses control their siting and orientation? (3) If there are no weaknesses of sympathetic trend, do extensional stresses get relieved in some other way? There is now so much known about the Oslo Graben (Ramberg, 1976; Dons and Larsen, 1978) that an all-embracing theory must be attempted. Part of the reason that the Graben is so well described geologically, petrologically, and geophysically is that it is one of the shortest and narrowest rifts given this status (Ramberg, 1981). Because of this contrast in dimensions with, for example, the East African Rift system, our explanation cannot hold for rifts in general.

In this paper we develop the hypothesis (Russell, 1976a; Russell and Smythe, 1978) that the Oslo Graben formed in response to extensional stresses focussed in the North Sea and its surroundings in the late Carboniferous. In our model these stresses relate to the difficulty encountered in lithosphere separation in the region of Archaean crust to the northwest at that time. In Britain these stresses resulted in a dyke swarm, whereas basaltic volcanism occurred in the Graben. The model correctly predicts an arcuate continuation of this dyke swarm into the North Sea. In Norway the stresses were relieved in a single graben because a previous crustal weakness of the requisite trend was available for exploitation.

DEFINITION OF THE OSLO GRABEN

The general trend of the Oslo Graben is ENE, although a rhomb porphyry dyke outside the graben and igneous centres within the graben are aligned just to the west of N–S. The Oslo Graben as we know it today began to develop in the middle Carboniferous as a broad downwarp (Olaussen, 1981). Minor precursor magmatism to the southwest (Touret, 1970) heralded a sudden and short-lived (Oftedahl, 1967) outpouring of basalt lavas at 292 ± 8 Ma (Sundvoll, 1978). The basalt pile is about 2 km thick in the south of the graben, but is considerably thinner in the centre and absent altogether in the north. The pre-basalt Carboniferous sequence also thins from south to north (Henningsmoen, 1978). The first basalts apparently just preceded the period of major faulting (Ramberg and Larsen, 1978). Clearly the Graben propagated northwards with time, then essentially died out (Ramberg, 1976). Ramberg (ibid.) calculates a total extension of about 4 km across the southern end of the Graben. Subsequent igneous intrusion and extrusion of syenomonzonite magmas (Neumann, 1978) resulted from differentiation of a mafic magmatic cushion caught in a density trap at the base of the crust under the rift (Ramberg, 1976). This later activity is not discussed further because we are only concerned here with the initiation and early history of the Graben.

Contiguous with the Graben to the south-southwest is the Oslo Graben Gravity

High (Andersen, 1978; Ramberg and Spjeldnaes, 1978) parallel to the SW-trending Skagerrak coast, which is governed by Precambrian basement trends and faults of the same orientation. Trends are more nearly N–S on the western margin of the Graben itself, but the rift developed over a narrow precursor basin with an early Palaeozoic history. This is revealed by deposition of 400–500 m of shales in the Oslo area, contrasting with 100–200 m of limestone in Estonia to the east during the Cambro-Silurian (Skjeseth, 1952; Bockelie, 1978). Also, facies boundaries in the Lower Palaeozoic lithologies often correspond with Permian fault directions (Bockelie, 1978). The total thickness of the marine Lower Palaeozoic sequence is up to 1.4 km in the Oslo region. Upper Silurian rocks of Old Red Sandstone facies overlie the marine sequence in the centre and south of the region where they are 1.2 km thick (Turner, 1974).

Ramberg and Larsen (1978) have pointed out that the Cambrian Fen Carbonatite (~ 570 Ma; Faul et al., 1959) lies on a line that coincides with the NNE-trending western border of the Graben, and conclude that the Oslo Rift exploited a previously existing significant structural weakness.

DOLERITE INTRUSIVES

While the massive pile of generally undersaturated basalts (but including some tholeiite) was being built in the Oslo Graben region (292 ± 8 Ma; Sundvoll, 1978; Weigand, 1975) dolerite dykes and sills were intruded in Scania, southernmost Sweden (294 ± 4 Ma; Priem et al., 1968; Klingspor, 1976), and dykes and sills of tholeiitic and transitional composition were intruded in northern Britain (295 ± 5 Ma; Dunham and Kaye, 1965; Fitch et al., 1970; Macdonald et al., 1981). Volumetrically, the Graben and northern Britain mafic igneous fields are the more important. The pre-erosional volume of basaltic extrusives in the Oslo Graben is calculated at around 2000 km^3 (Oftedahl, 1952; Ramberg, 1976). This compares with the 125 km^3 in the Scottish Midland Valley sill, and the 215 km^3 in the Whin Sill of northern England (Francis, 1982). Francis (ibid.) considers the latter value to be only a fraction of the total, as the sill appears to thicken eastwards under the North Sea.

In Britain the dykes crop out discontinuously for a hundred kilometres or more and are up to tens of metres wide (Richey, 1939). Their general trend is about E–W, and the swarm is about 300 km across from north to south, although the strongest development is near the middle of the zone (Fig. 1). Like the later dyke swarms of the eastern U.S.A. (May, 1971; Swanson, 1982), they are generally independent of structural grain, although there is some local deviation across major discontinuities such as the Highland Boundary Fault zone (Institute of Geological Sciences, 1979). In contrast, the Scania dykes of southernmost Sweden have taken advantage of an older structural weakness, the Tornquist line or Fennoscandian Border Zone.

Anderson (1951) notes that, in contrast to the N–S compressive stresses involved

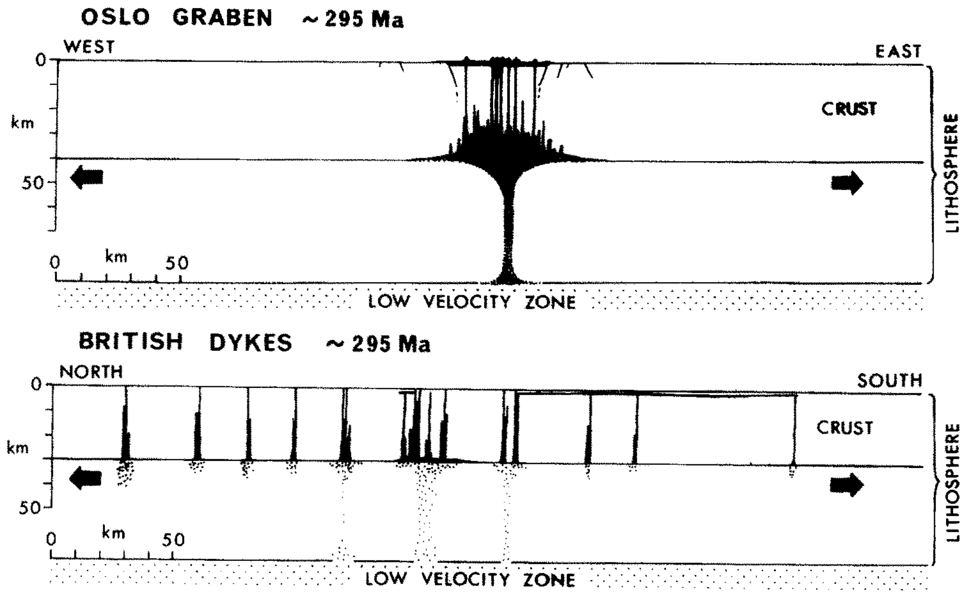

Fig. 1. Cross sections to illustrate comparison of the Oslo Graben with the coeval dolerite dykes of northern Britain. Note the sill formation in Britain in contrast to the plateau basalts of the Oslo Graben.

in the development of the Hercynian orogeny to the south, a short period of extensional stress with trajectories oriented N–S is required to explain the dykes and faulting in northern Britain. He called this condition the Borcovician.

We have previously argued that the dykes in Britain formed in response to high strain rates related to final separation of the lithosphere to the northwest of Britain and Norway in the late Carboniferous (Russell, 1976a; Russell and Smythe, 1978). We outline a modified hypothesis in the next section and then introduce a rival theory due to Francis (1978a) in the succeeding section. The two theses make different predictions regarding the trends of the dykes as they extend eastwards under the North Sea.

A LATE CARBONIFEROUS OCEANIC RIFT (HYPOTHESIS I)

Following a period of quiescence in late Devonian and earliest Carboniferous times, there was a sudden onset of basin formation in Britain and Ireland towards the end of the Tournaisian, ~ 360 Ma (Table I). A major, though short-lived period of hydrothermal activity ensued (Russell, 1968; 1976b) and a longer period of basaltic volcanism was initiated. The volcanics are best developed in the Midland Valley of Scotland, where the lava piles approach a thickness of 600 m (MacDonald and Whyte, 1981). Basins continued to subside in Britain and were joined by subsidence in the Oslo Graben in early Westphalian times (Olaussen, 1981). In the

TABLE I

Correlation between tectonic and magmatic events in Ireland, northern Britain and Norway during the late Palaeozoic

AGE Ma	BASIN DEVELOPMENT	MAGMATISM	INFERRED STRESS REGIME	INFERRED REGIONAL TECTONICS
270	Fault-bounded New Red Sandstone	Major plutons and volcanics	Unstable young	150 - 200 km
280	troughs, half-grabens (Britain	(North Sea); syenites	continental margin	sea-floor
290	North Sea) and Oslo Graben	(Oslo Graben)	and shelves	spreading
295		(Dykes (Britain, North (Sea, Scania) (Lavas (Oslo Graben)	Focussed tension	Final separation
300	Uplift (Britain)	Intermittent alkali	Stretching :	Up to 50 km crustal stretching along proto
310	Downwarping (Oslo Graben)	basalts	minimum principal	North Atlantic rifts
320	Coal basins (Britain)	Main period	stress trajectory	Culmination of continental rifting (Britain)
330		of	trends	
340	Starved	alkali	varying from	General
350	basins	basalt	W - E to	basin and
360	(Britain, Ireland)	volcanism	NW - SE	rift development

mid Westphalian, subsidence ceased (Haszeldine, 1982) possibly because of lithosphere separation in Rockall Trough and the Eastern Norwegian Sea (Fig. 2). Separation in these two regions was encouraged by the pre-existing orogenic grain, possibly aided in the northern Rockall Trough by a N–S weakness (Russell, 1976b). It should be noted that the ensialic Caledonian basin of East Greenland, which has a history spanning Riphean to Vendian, does not extend into the British Isles. The Atlantic began to open along the easternmost margin of this basin, but apparently could not find a way of joining with the Rockall Rift across the old cold Lewisian crust and lithosphere. Instead the extensional stresses took advantage of the previously weakened lithosphere in the Oslo area and the relatively thin crust and lithosphere in northern Britain (Fig. 2). Nevertheless the two proto-Atlantic rifts did finally join up, so that the Oslo Graben and the dykes were abandoned as the site of a nascent oceanic rift. Following a period of ocean-floor spreading in the proto-Atlantic at the end of Carboniferous times the new, gravitationally unstable Atlantic margins subsided partly by block subsidence (McLean, 1978) and partly by oceanward sagging. The latter process finally led to the southward transgression of the boreal Zechstein Sea across northwestern Europe (Fig. 4b; Russell 1976a).

Hypothesis I predictions

The mainland Britain E–W dykes should trend ENE into the North Sea, but westwards they should adopt a NW trend before dying out. The swarm should be at

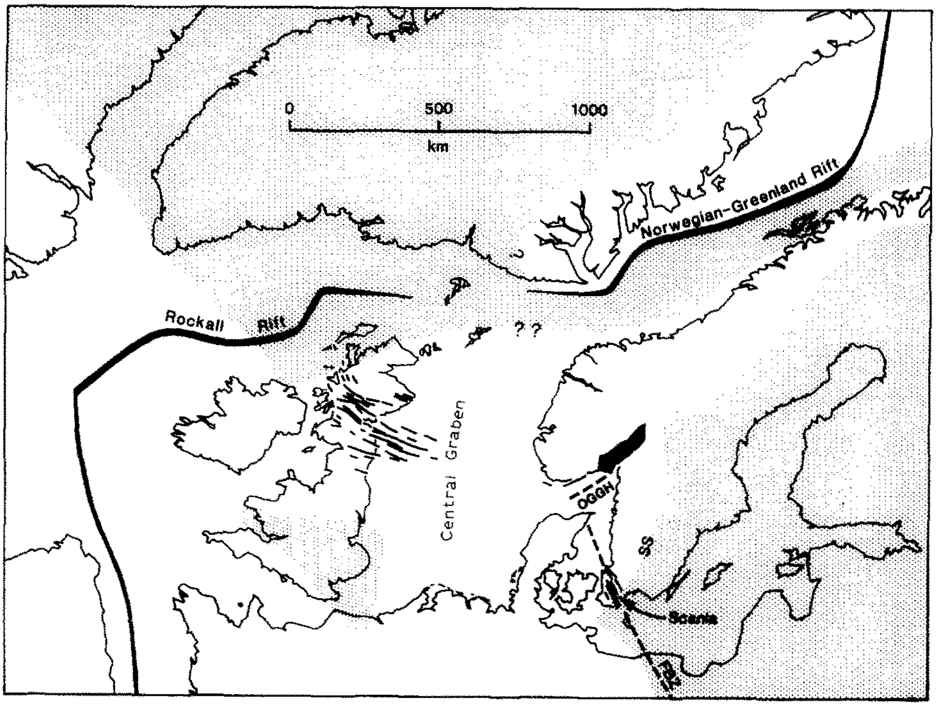

Fig. 2. Palaeogeography at 295 Ma, illustrating hypothesis one. In this early stage the proto North Atlantic has developed as two separate rifts which have exploited previous crustal weaknesses. The old, cold pre-Grenville crust and lithosphere (dot ornament) has prevented their meeting. Instead, the extensional stresses have been partly resolved by dolerite dyke intrusion in Britain and the western North Sea, and by the Oslo Graben and its southwesterly continuation defined in the Skaggerak by the Oslo Graben Gravity High (*OGGH*). We suggest that the Norwegian–Greenland Rift may have exploited the eastern margin of the Riphean–Vendian basin of East Greenland. Note that although there is probably continuity of Grenville and Caledonian thrusts from northern Scotland into southeast Greenland, they will be trending nearly perpendicular to the rifts, and cutting basement of at least 1800 Ma in age. The anomalous Scania region lies on the intersection of two major crustal lineaments, the Fennoscandian Border Zone (*FBZ*) and the Småland Suture (*SS*).

its thickest, in terms of dilation of the crust, below the North Sea, and possibly be associated with slightly later (~ 280 Ma) intrusives. Northwest of the Shetlands we might expect to find evidence of coeval igneous activity paralleling the line of the Faeroe–Shetland Trough, where the two oceanic rifts finally joined up (Fig. 2). Although the tensile stress trajectories concentrated through the Faeroes region would fan out over Greenland in a mirror image of the pattern over northwest Europe, extensive development of similar intrusives is not to be expected in southeast Greenland because the lithosphere there would have been much thicker.

LINKS BETWEEN THE HERCYNIAN OROGENY, DYKES AND OSLO GRABEN (HYPOTHESIS II)

Francis (1978a), in noting the remarkable contemporaneity between peak activity in the Hercynian orogenic belt and the late Carboniferous igneous episode in northern Britain and southern Scandinavia, has suggested that the latter is a result of stresses associated with oblique collision of plates in the Hercynian following the closure of the mid-European (Rheic) Ocean as envisaged by Lorenz (1976) (Fig. 3). In this hypothesis we presume the Oslo Graben to be a tensional structure related to the relative eastward translation of the North European and North American Plate, although this is not exactly specified by Francis.

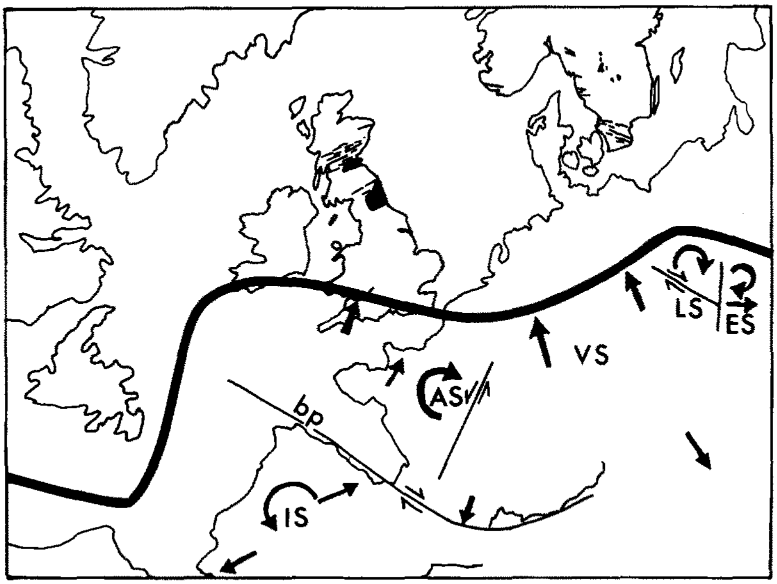

Fig. 3. Late Hercynian palaeogeography redrawn from Lorenz (1976, fig. 1) and Francis (1978a, fig. 8), illustrating hypothesis II. Francis suggests that Stephanian (295 Ma) dykes in northern Britain and southern Sweden were formed as the crust fractured in response to oblique collision of the North Europe and North America plate with a South Europe plate or one of several rotated plates, in the manner depicted by Lorenz. Francis (1978b) considers that the ENE-trending tholeiite dykes of northern Britain should continue below the North Sea with easterly to southeasterly trends, to reappear in southern Sweden. Our analysis of offshore geophysical surveys shows that this view is now untenable, as the dykes continue in an arcuate trend towards the east-northeast, as shown in Fig. 2. Note that, apart from Scania (Fig. 2), the dykes and sills (black) in Scandinavia redrawn here (Francis, 1978a, fig. 8) are, in fact, Precambrian (Lundegårdh, 1958; Priem et al., 1968; Storetvedt and Gidsgehaug, 1968; Mulder, 1971; Abrahamsen, 1974).

Ornamentation as in Lorenz (1976, fig. 1): thick lines—continental margins of bordering plates; thick arrows—direction of migrating fold-belts; thick curved arrows—directions of rotating subplates relative to the Variscan subplate (*VS*); *AS* = Armorican subplate; *LS* = Lugian–Silesian subplate; *ES* = East Sudetan subplate; *IS* = Iberian subplate; *bp* = Biscay–Pyrenees wrench fault.

Hypothesis II predictions

Following Hjelmqvist (1939), Francis (1978a, b; 1982) expects the E–W-trending dykes in Britain to link up under the North Sea with the NW-trending dykes in Scania (Fig. 3). In this way they should retain their trend, which approximately parallels the Hercynian belt. They should also continue westwards or southwestwards from Britain showing no influence of the Rockall Trough, which, in this hypothesis, is assumed not to exist until ~ 200 My later. No systematic variation in dyke thickness, cumulative thickness, or intensity of dyking is predicted.

TEST OF HYPOTHESES

We have put the two rival hypotheses to the discriminating test of how the dyke swarm behaves east and west of Britain, by compiling published information on trends, ages (both isotopic and palaeomagnetically inferred), together with IGS and commercial offshore geophysical surveys in the North Sea. The main results, which will be published in more detail elsewhere, are as follows:

Outcropping quartz-dolerites

(1) West of Britain the swarm trends WNW–ESE; dykes in the southern Outer Hebrides (Institute of Geological Sciences, 1981) have been dated (Rb/Sr) at around 285 Ma (J.R. Mendum, pers. commun., 1980).

(2) The ESE-trend swings smoothly into an ENE-trend as the swarm is traced towards the east coast of Britain. This regional arc is complicated somewhat by the tendency for dykes to swing round normal to and parallel to the Great Glen and Highland Boundary faults, respectively, within about 20 km of these faults.

(3) Near Dunbar, east Scotland, we have established by our own ground magnetic surveys, published aeromagnetic maps continuing offshore (Institute of Geological Sciences, 1972) and dyke outcrops both onshore (Francis, 1962) and offshore (Thomson, 1978) that characteristic linear positive magnetic anomalies are indeed due to the reversely magnetised dykes (Powell, 1963).

(4) Along the southeastern coast of Norway, dykes dated palaeomagnetically and/or isotopically as Permo-Carboniferous, trend roughly coast-parallel, towards the Oslo Graben (Storetvedt and Gidskehaug, 1968; Halvorsen, 1970, 1972). The WNW-trending tholeiites of Egersund, southwest Norway, and near Gothenburg, southwest Sweden, depicted by Francis (1978a, fig. 8), presumably in support of hypothesis II above, are Precambrian in age (Lundegårdh, 1958; Storetvedt and Gidskehaug, 1968; Abrahamsen, 1974).

Offshore continuation of the dyke swarm

(5) IGS and commercial aeromagnetic maps of the North Sea show that the dyke swarms continue offshore below the Permian and younger cover. The ENE-trending anomalies can be traced as far as the Central Graben (Fig. 2), but are not present on the Norwegian side. Modelling of the magnetic anomalies has shown that individual dykes are up to 500 m wide. Widths of the order of hundreds (rather than tens) of metres are also indicated by the fact that the dykes show up as prominent diffraction patterns on commercial multichannel seismic reflection sections.

(6) The absence of anomalies below the Central Graben and on the Norwegian side of the North Sea could be due either to absence of dykes or, more probably, greater depth of burial (see, for example, Day et al., 1981, plate 1), since linear anomalies re-appear off the southern Norwegian coast where basement is shallower than about 2 km. NE–SW-trending linear anomalies interpretable as dyke-like bodies are also found in the Skaggerak (Åm, 1973) in line with the Oslo Graben (Fig. 2).

Result of discrimination test

The results quoted above clearly corroborate hypothesis I, and effectively refute hypothesis II. We can explain, in principle, the Scania quartz-dolerites (which obviously do not fit in with the first hypothesis) as a local second-order effect of intraplate re-adjustments along the Fennoscandian Border Zone at a time of plate tectonic upheaval (discussed below). There is no positive evidence for continuation of the Scania swarm offshore to the west (J. Bergström, pers. commun., 1981), neither does the swarm reach the island of Bornholm, 40 km to the southeast. Scania lies at the intersection of two major crustal lineaments, and has suffered five phases of sub-silicic intrusive activity, from 1600 Ma to early Cretaceous in age (Klingspor, 1976). We conclude, therefore, that as far as the regional tectonics of the late Carboniferous tholeiitic episode of northwest Europe is concerned, Scania can be considered a local anomaly.

Further testing of hypothesis I

Unpublished work by IGS on the late Palaeozoic tectonic/magmatic history of the northwest European shelf area includes:

(1) Finite element modelling of the stresses inferred to have caused the arcuate dyke swarm and Oslo Graben (Skuce, 1980).

(2) Finite element modelling of Scotland, to account for the local deviations from the regional arc of the dyke swarm near to major faults (A.G. Skuce, pers. commun., 1980).

(3) Three-dimensional modelling of circular gravity and magnetic anomalies in

the North Sea, to show that the major intrusive activity spatially associated with the dyke swarm was probably of early Permian age (Beamish et al., 1980).

PLATE TECTONIC SYNTHESIS

Apparent paradoxes

Why do we postulate that the two major collinear rifts separating Europe from Greenland at 295 Ma are oceanic, when (a) the whole region lies in the heart of the contemporary northern supercontinent of Laurasia (Bott, 1978), and (b) when the conventional view of the more southerly of these, the Rockall Trough, is that it developed in the mid-Cretaceous (Roberts, 1974; Roberts et al., 1981)? Furthermore, how can we reconcile the creation of the Oslo Graben, the north British dyke swarm, and new oceanic crust northwest of Britain, with the culmination of the Hercynian orogeny not far to the south? Answering the first of these problems is beyond the scope of this paper, as it requires a detailed discussion of the geophysical evidence for the nature of the crust underlying the proto-North Atlantic (Smythe, 1983; Smythe et al., 1983). The discussion below does, however, attempt to place the initiation of the proto North Atlantic rift zone in late Carboniferous times (cf. Ziegler, 1981, figs. 7 and 8) in a plate tectonic framework; whether the rift is underlain by oceanic crust, as we assert, or by subsided continental crust (Talwani and Eldholm, 1972; 1977) is not critical to the hypothesis.

Assembly of the Pangaean supercontinent

Although there are many uncertainties in late Palaeozoic reconstructions, we show in Figs. 4 and 5 a solution in principle to the problems mentioned above. The crucial assumptions are:

(1) The Hercynian–Alleghenian orogeny was diachronous, so that the mid-European Rheic ocean (Fig. 4a) closed in the Westphalian, whereas the Phoibic ocean (McKerrow and Ziegler, 1972) closed in the Stephanian to early Permian (see also Dewey and Burke, 1973; Ross, 1979; Cook et al., 1979; Piqué, 1981).

(2) One of the major dextral wrench faults active in late Carboniferous–early Permian time was the Biscay–Pyrenees fault (Arthaud and Matte, 1975; 1977). Its displacement, of the order of 200 km, is required to translate Iberia northwest from its position at the end of the Hercynian orogeny to the position required, relative to "stable" Europe, prior to the Cretaceous opening of the Bay of Biscay (Le Pichon et al., 1971). Since 200 km or so of transcurrent displacement cannot be extended up the proto Labrador Sea, the only feasible alternative is to transform the displacement into a new rift to the northeast, i.e. the Rockall Trough (Fig. 4b). Therefore we have called this dextral fault the proto-Bay of Biscay transform fault (Russell and Smythe, 1978).

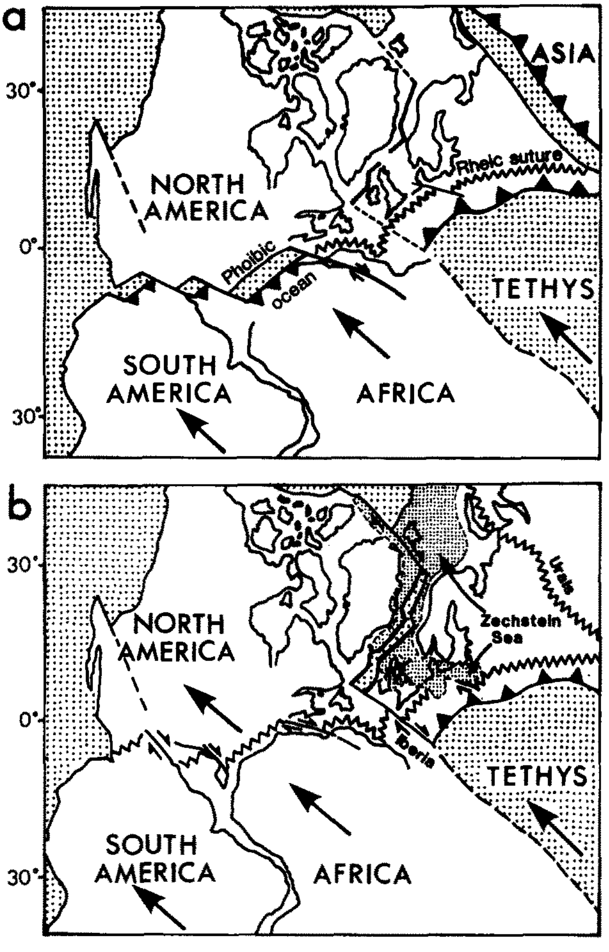

Fig. 4. a. Diagrammatic Pangaean palaeogeography at ~ 300 Ma (end Westphalian time). Rheic suture marks the site of the newly-closed mid-European (Rheic) ocean (McKerrow and Ziegler, 1972).
b. Pangaea at ~ 280 Ma (early Permian) but with the addition of the Zechstein Sea (~ 250 Ma). Gondwanaland is colliding with the North American plate while Tethys continues to subduct below Europe. The proto-North Atlantic Ocean (Rockall Trough to Eastern Norwegian Sea) opens, mainly following the Caledonian fold-belt, but transformed in the south along one of the dextral wrench faults developing as a result of the diachronous collision of Laurasia and Gondwanaland. Arrows indicate motion relative to Scandinavian Europe. Palaeogeography is based on Keppie (1977).

Looked at from the global point of view, the collision of Gondwanaland with North America in Stephanian to early Permian time produced a "knock-on" effect, whereby Greenland (part of the North American plate) was pulled away from Europe, producing an oceanic rift (Fig. 5) along the line of least resistance (Fig. 2) in the lithosphere of the nearly-assembled Pangaea. At the end of the early Permian, Pangaea was thus assembled, but with an oceanic rift trapped in its heart.

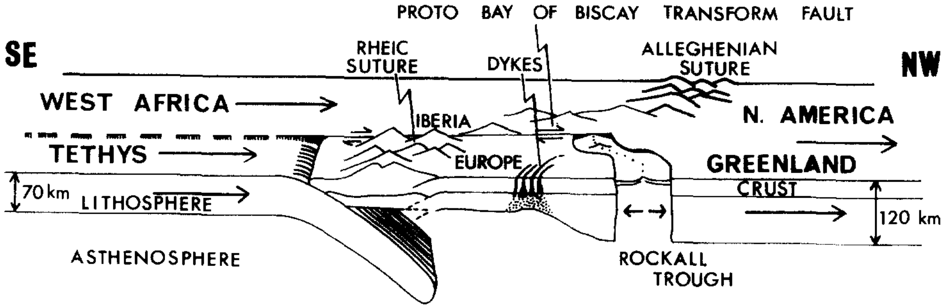

Fig. 5. Perspective diagram of the mechanism of proto-North Atlantic opening postulated in Fig. 4.

In this model we also assume that the Tethys was coupled to Africa, so that it must have begun to subduct below southern Europe in the late Carboniferous (Figs. 4 and 5; Dewey and Burke, 1973, fig. 2).

CONCLUSIONS

The proto-North Atlantic oceanic rift formed as a natural geometric consequence of the diachronous Hercynian–Alleghenian orogeny, in late Carboniferous–early Permian time. In the creation of this rift, the Oslo Graben was formed as an aborted oceanic rift (Fig. 1). It is not a "failed arm", but developed over an aulacogen (*sensu stricto*) with an orientation sympathetic to the extensional stress trajectories suddenly imposed across southern Scandinavia towards the end of the Carboniferous period. Similar stresses in Britain, but of dissimilar orientation relative to the Caledonoid grain, resulted in fracturing of the lithosphere across a zone 300 km wide, unaided by previous crustal weaknesses. In this the dykes are comparable to joint sets in a brittle layer, with a master joint spacing of the order of 20–25 km, judging from the large dykes revealed by magnetics in the North Sea (Figs. 1 and 2).

The overall extension in the south of the Oslo Graben is about 4.5 km (Ramberg, 1976). Extension across dykes in northern Britain, where the stresses should have been similar, is an order of magnitude less than this, but the remainder of the extension may be taken up by E–W faults (see Anderson, 1951; Francis, 1978a).

The formation of the Oslo Graben and the concomitant dyke swarm in Britain is a special case of extensional strain, from which we can draw no general conclusions regarding the origin of other rifts.

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