

Rockall Trough—Cretaceous or Late Palaeozoic?

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SYNOPSIS

The Rockall Trough is the most southerly and widest part of the pre-Tertiary 'proto North Atlantic' rift zone running from the Porcupine Bank region west of Ireland to the Vøring Plateau off central Norway. Although the northerly part of this rift is intra-continental, the southern part is quasi-oceanic in origin, but of uncertain age. The many arguments for Cretaceous sea floor spreading are evaluated in turn; the few apparently valid ones remaining are shown to relate not directly to the Rockall Trough, but to a newly-identified spreading phase of approximately mid-Cretaceous age which partially opened up the Hatton-Rockall Basin. The opening of the Rockall Trough predates this. Stratigraphic evidence suggests that the proto North Atlantic is pre-Cretaceous, and probably even pre-Jurassic, in age. The rival arguments for late Palaeozoic (late Carboniferous—early Permian) sea floor spreading are all consistent with an important phase of rifting at that time, but they provide no direct evidence for opening. No detailed arguments have yet been proposed for Jurassic, Triassic, or late Permian sea floor spreading. New modelling of the magnetic anomaly over Rosemary Bank by MV Wood supports a Triassic or earlier age, but the pre-Upper Cretaceous sedimentary infill of 2–3 km in the Trough seems to be rather thin for such an early age. However, by combining the pre-Cretaceous stratigraphic constraint on the age of opening with the assumption that the major rifting episode was an immediate precursor of spreading, a tentative conclusion is that the Rockall Trough was initiated as a rift, and then opened by a quasi-sea floor spreading mechanism, during the late Carboniferous to early Permian.

INTRODUCTION

The NE Atlantic margin

The Rockall Trough and Rockall Plateau played a part in the development of plate tectonic theory twenty-five years ago. The classic 'Bullard' fit of the North Atlantic continents at the 500 fathom contour (Bullard *et al.* 1965) required that Rockall Bank—comprising Rockall, Hatton, and George Bligh Banks—be retained as microcontinental fragments to fill a large gap left in the fit between Europe and Greenland. The refit suggested a number of predictions, two of which were that the Rockall Plateau should be continental, and that the Rockall Trough be oceanic.

The late Cretaceous to recent opening history of the North Atlantic is well understood, being calibrated mainly by magnetic anomalies 34 and younger.

Figure 1 shows a reconstruction to anomaly 13 time (35 Ma), just after spreading in the Labrador Sea had finished. The earlier phases are represented in the Figure by the shaded strips between anomalies 34 (80 Ma) and 24 (55 Ma for anomaly 24B), and by the blank Y-shaped zone created by spreading at a triple junction between anomaly 24 and anomaly 13 time. Clearly the Rockall Trough and the Bay of Biscay are older than anomaly 34.

Although the Rockall Plateau—or at least the Rockall Bank part of it—has been proved to be continental (see, for example, Scrutton 1970, Roberts *et al.* 1973), the age of the 250 km wide Rockall Trough remains debatable. This continuing uncertainty affects the pre-Tertiary history of the whole North Atlantic, from Biscay to Svalbard. Figure 2 shows that the Rockall Trough is the most southerly segment of an essentially continuous strip of deeply buried crust bordering the NW European margin. This strip can be referred to as the proto North Atlantic, as it represents the first, abortive, attempt at opening of the North Atlantic ocean.

Aim of the review

The aim of this discussion is to review, and where necessary to refute, the various hypotheses that have been postulated concerning the age of the Rockall Trough. This discussion is necessary (*cf.* Ziolkowski 1972) to refresh and/or dispose of some of the arguments of the last twenty years or so, even though many of them would no longer be supported by their original authors. The ground is thereby prepared for a relatively straightforward summary of the problem as it appears at present.

In the last decade a great deal of commercial exploration has been carried out over the NW European margin, but practically all of this remains confidential. The problem of referring to and publishing confidential commercial data within a sound scientific methodology has been discussed before (Smythe *et al.* 1983, pp. 374–375). Fortunately, the main results of the stratigraphic test well 163/6-1A, drilled in the northern Rockall Trough, can now be quoted, although the full results remain confidential until 1990.

Outstanding problems—age and origin

Why is the age of the Rockall Trough important? Clearly it is of some interest to the oil industry, as the region is a possible future hydrocarbon province, but it also has a wider significance, as will be shown. In summary, two principal ages (both assuming a sea floor spreading origin) have been most frequently quoted and discussed—Cretaceous and late Palaeozoic—of which the former is generally most favoured. However, the age of the opening is still uncertain and controversial. The discussion below is a critical review of the published evidence, which, despite coming to some novel conclusions regarding the pre-anomaly 34 spreading

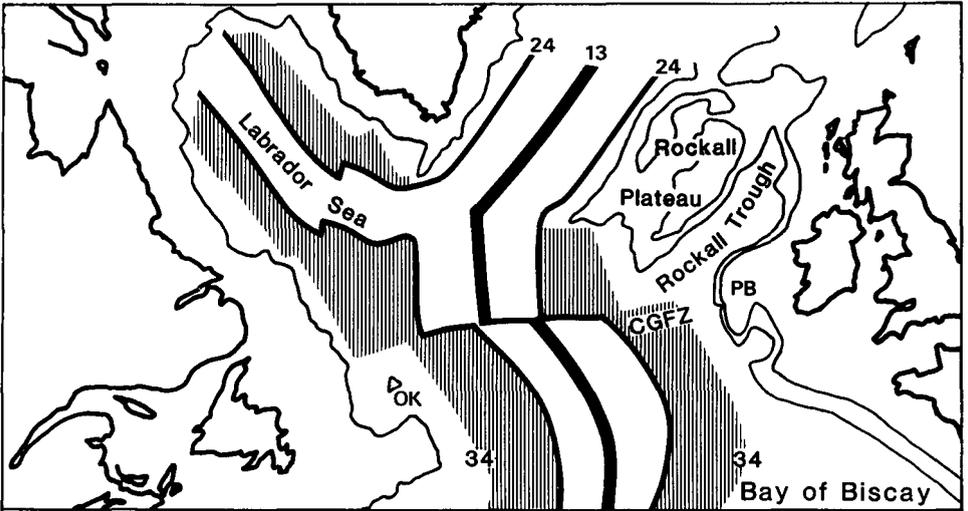


FIG. 1. North Atlantic reconstruction for anomaly 13 (c. 35 Ma). Shaded area is crust created between anomaly 24 and 34 time. CGFZ—Charlie Gibbs fracture zone. OK—Orphan Knoll. PB—Porcupine Bank.

history of the NE Atlantic, demonstrates that the age question is still far from solved.

Before the discussion of the age problem it is useful to review the current status of ideas of the origin of the Rockall Trough, in the light of the recent geophysical work that has been carried out after a decade or more of little progress. This is intended to demonstrate that the problem of origin of the lithosphere under the Trough is probably now more semantic than scientific, and that it has little bearing on the more important and interesting age problem.

CONTINENTAL OR OCEANIC?

By the early 1970s it was known that the crust under the Rockall Trough is thin (e.g. Scrutton 1972). This result implied that it was oceanic in origin, but by the late 1970s it was known that crust of as little as 5–6 km thick at passive margins could be continental in origin. More detailed knowledge of crustal structure—especially velocities and velocity gradients—is needed nowadays before one can distinguish continental from oceanic in a thin subsided crust.

The results from wide-angle seismic reflection/refraction measurements along two E–W trending lines across the Rockall Trough, shot in 1986 (Fig. 3), have been reported briefly by Roberts *et al.* (1988). They arrive at a “definite determination” that the crust in the region of Anton Dohrn seamount is continental, despite the admission that data quality varies from “fair to poor”.

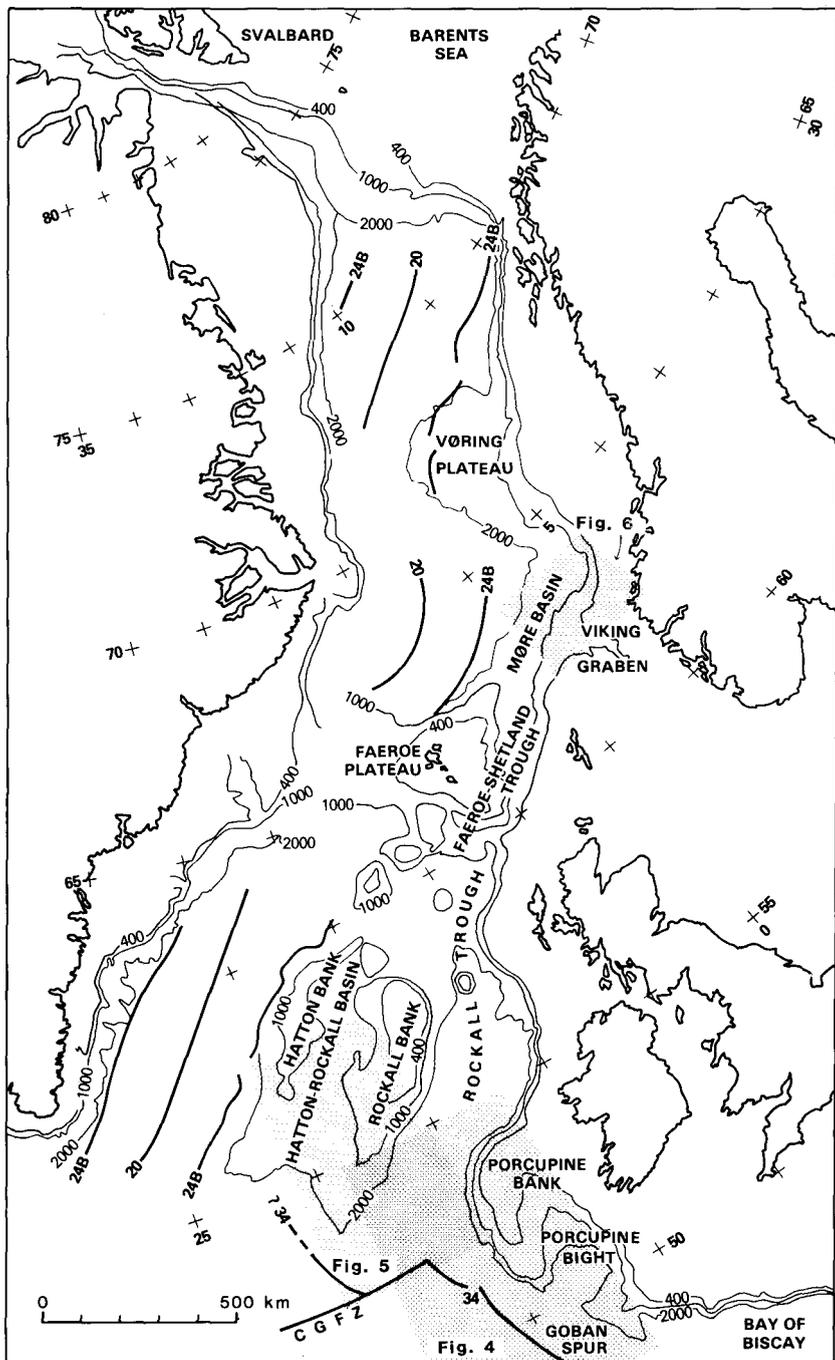


FIG. 2. North Atlantic reconstruction for anomaly 20 time (c. 45 Ma), showing oldest recognisable Tertiary anomaly 24B (c. 52 Ma). The 'proto North Atlantic' comprises the pre-Tertiary deep-water strip including the Rockall and Faeroe-Shetland Troughs, Møre Basin and inner Vøring Plateau. CGFZ—Charlie Gibbs fracture zone. Stippling shows areas detailed in Figures 4, 5 and 6. This reconstruction is similar to that of Nunns (1983, fig. 5), but avoids the overlap of Greenland onto the Svalbard shelf evident in the latter. Transverse Mercator projection, central meridian 15°W.

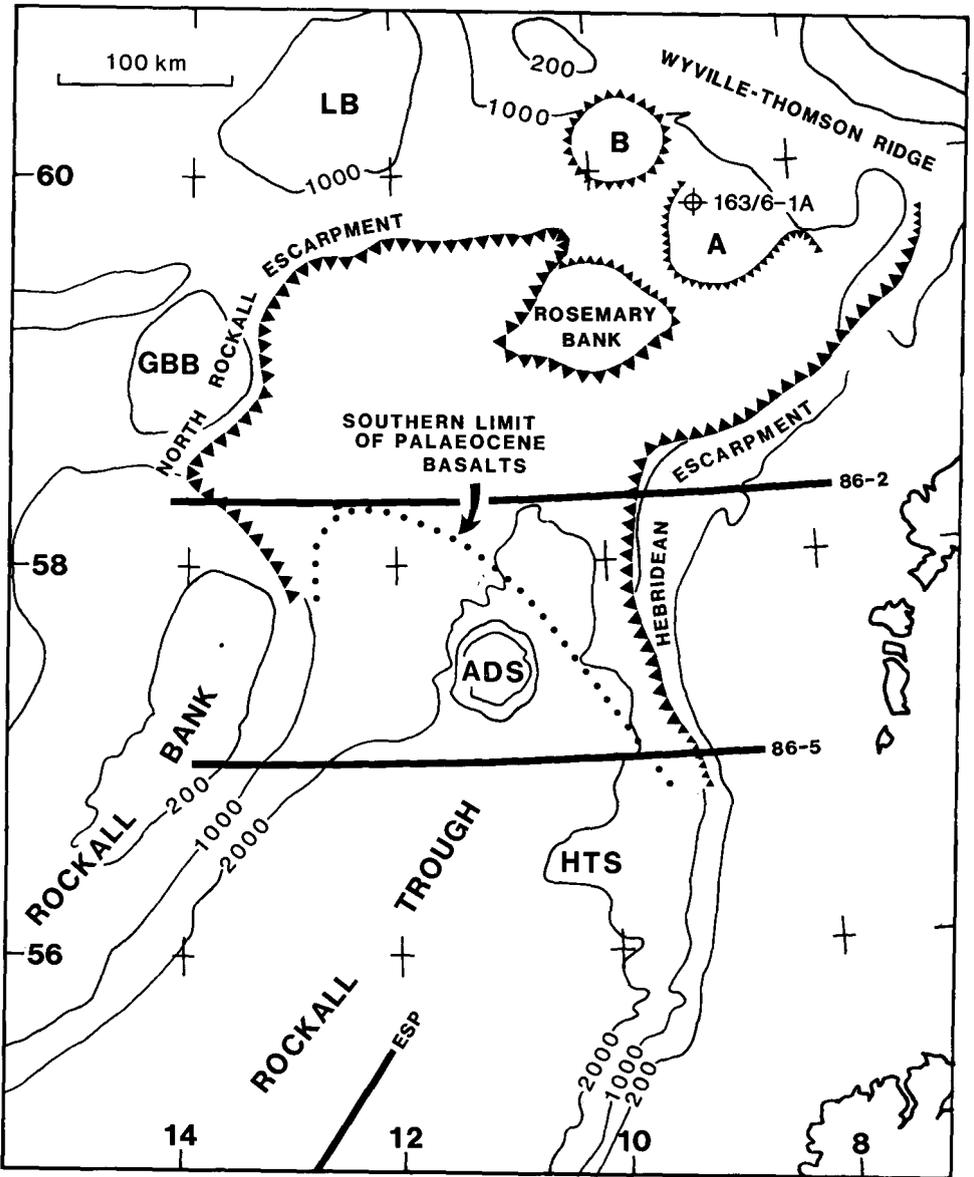


FIG. 3. Central and northern Rockall Trough region showing subcrop of buried basaltic escarpments (hachures) bounding thick sequences of Eocene age basalts covering the northern Rockall Bank, George Bligh Bank (GBB), Lousy Bank (LB) and Wyville-Thomson Ridge. Thinner underlying flows of late Palaeocene age underlie most of the northern Rockall Trough, ending in the region of the dotted line, south of which sills and intrusives of presumed Palaeogene age are common. Buried volcanic centres A and B (Roberts *et al.* 1983) are mainly escarpment-surrounded and form buried structural highs. The escarpments are depicted here in highly simplified form; the northern part of the Hebridean Escarpment is a complex series of steps in the top basalt structure, and in places there are windows through to the underlying sediments. Wide-angle reflection/refraction profiles 86-2 and 86-5 have been reported by Roberts *et al.* (1988). ESP is a two-ship expanded spread profile (Joppen and White, submitted). ADS—Anton Dohrn seamount. HTS—Hebrides Terrace seamount. Bathymetry in metres.

Although their conclusion may very well be correct, it is unjustified by the data and arguments presented, for the following reasons:

(1) No upper mantle refraction arrivals (P_n) were observed anywhere, due to the high noise levels and supposed "poor transmission properties" in the Trough. However the geology of the Trough cannot really be blamed, as the Durham University Hebridean Margin Seismic Experiment (HMSE) of 1975 acquired very good P_n phases along an E-W line at 58°N, in between the two 1986 lines (Armour 1977, Bott *et al.* 1979). The dominant phase on one of the record sections displayed has zero horizontal slowness and comprises pulses at a one-second period—presumably a clock signal. So the lack of P_n really means either that the data are extremely poor, or that P_n has been misinterpreted as the Moho reflection P_mP at extremely wide angles.

(2) Modelling uses fairly old ray and reflectivity methods, which are essentially one-dimensional, and therefore unsuited to the very pronounced lateral variations in crustal structure at the Trough margins. Initial models are based on the known crustal structure of the thick continental section at each end of the profiles. It is easy to extrapolate the two-layer crustal structure here by thinning out these layers below the centre of the Trough, but without having to model lateral velocity changes as well. This would result in a very approximate fit of the model to the data. What has not been demonstrated is a good example of a record section from the flat structure in the centre of the Trough, showing well-constrained phases.

(3) The sedimentary section has been modelled initially using published information, which is scanty and unreliable. A much better constraint would have been to use the wealth of multichannel reflection data in the region, to which the authors had access.

(4) The two-layer crustal model below the Trough is based on the supposed wide-angle reflections. These phases appear either to be non-existent over the ranges shown on the pair of "representative" record sections shown, or mis-match the modelled arrival times by up to half a second. There is, therefore, no convincing evidence for the so-called continental crustal velocity structure, other than the poorly defined head wave (P_g) through the top of the crust.

(5) The comparison made with the Armorican margin of the Bay of Biscay is misleading. The continental crust at the latter margin thins gradually over 200 km distance from normal continental thickness to an 'oceanic' thickness at the continent-ocean boundary. The Rockall Trough crustal structure, in contrast, has an extremely abrupt transitional thickness zone of about 80 km width at either side, according to Roberts *et al.*'s own results.

In 1985 the Universities of Cambridge and Durham observed an expanding spread profile using two ships, on a NE-SW line along the axis of the Trough. This location was chosen to be clear (as far as practicable) of the deleterious effects of the sills and lavas in the sedimentary column further north, and to minimise the lateral variation in structure. Results are very good (Joppen and White, submit-

ted), although the interpretation is more problematic. There is crustal basement of 5.2 km s^{-1} (P-wave velocity) at a depth of 6.7 km, with the Moho at 12.9 km. The crust is thus some 6 km thick. The coincident multichannel reflection line shows that the upper part of this crust comprises a well-layered flat-lying reflector sequence, which Joppen and White interpret as intercalated lavas and sediments. The crustal structure and layering is not typical of normal oceanic crust, but could be highly attenuated continental crust, heavily intruded by igneous material. The authors draw an analogy with the Gulf of California.

The crustal column identified by Joppen and White is clearly neither continental nor oceanic, and the attempt to discriminate between one and the other becomes a matter of semantics. For example, if 4 km out of the 6 km of crustal column is continental, then the crust is more continental than oceanic. On the other hand, the extreme attenuation of the continental crust implied by this—an original 30 km thick crust thinning to 4 km or so, or a stretching (β) factor of 7 or 8—means that the Rockall Plateau has moved NW by over 200 km relative to Europe, and has thus 'opened' in a quasi-oceanic way. The thermal behaviour of the Trough's lithosphere, subsequent to this stretching/intrusion/opening period, would be similar to that of oceanic lithosphere. It seems, therefore, most appropriate to call the Rockall Trough crust 'quasi-oceanic' while bearing in mind that it is not truly oceanic.

THE ARGUMENTS FOR CRETACEOUS SPREADING

The reasons for the widespread adoption in the early 1970s of a Cretaceous age for sea floor spreading in the proto North Atlantic, in preference to the previously assumed Permo-Triassic age (Bott and Watts 1971; discussed below), appear to have originated in the acceptance of a late Triassic—early Jurassic age for the start of opening in the Central Atlantic (i.e. between Africa and North America). This was combined with the reasonable assumption that Atlantic rifting advanced progressively northwards (e.g. Hallam 1971; Pitman and Talwani 1972). Thus the possibility of an earlier separation of Europe from Greenland, for example in the Permian or Triassic, seemed to be precluded.

The preferred Cretaceous dating of this opening episode has been refined from early Cretaceous to late Cretaceous over the decade 1974–1984 approximately. In order to understand best how the arguments developed, they are reviewed below in a generally chronological sequence.

Early Cretaceous spreading

Given the above conclusion, of a post-Triassic constraint on the age, the speculative suggestion of opening throughout the Cretaceous (Hallam 1971) was revised to an early Cretaceous episode by Roberts (1974), for the following

reasons:

(1) *Faunal provinciality*. The provinciality of Jurassic ammonites in the northern hemisphere, with the Boreal fauna of east Greenland distinct from the Tethyan fauna of Europe (which is found as far north as the Hebrides) "implies a physical barrier" (Roberts 1974, p. 347) which would therefore preclude the existence of Jurassic or older ocean floor between these localities.

This view was soon refuted by the discovery of a Middle Jurassic Boreal ammonite in a well core from the Viking Graben (Callomon 1975). But in any case the invocation of an actual physical barrier as an explanation for faunal provinciality was already out-moded, having been replaced by climatic considerations (cf. Casey and Rawson 1973).

(2) *Orphan Knoll*. DSDP hole 111 on Orphan Knoll encountered continental Bajocian sands containing derived anthracite fragments with South Wales coalfield affinities. This suggested that Orphan Knoll was attached to the European continent until at least post-Bajocian time.

This evidence, even if taken at face value, is only a constraint on the date of separation of Orphan Knoll itself from the Porcupine Bank area (Fig. 1). It does not preclude an earlier opening of the Rockall Trough, if, for example, a transform-rift-transform geometry such as that used by Russell and Smythe (1978, fig. 1) is envisaged. In any case, the only sound conclusion which should be drawn from such evidence is that coal measures were being eroded within a few kilometres of the site during the middle Jurassic.

(3) *Seaways*. "The more complete geological history of the British Isles suggests a seaway, perhaps as early as the Valanginian" (Roberts 1974, p. 351).

Evidence of seaways is certainly suggestive of rift zones, but is not, of course, proof of an oceanic floor. However, there has long been speculative evidence for a seaway between east Greenland and the British Isles at various epochs, not merely back to the early Cretaceous as Roberts implies, but back to the mid-Permian (Callomon *et al.* 1972). More specifically, it has been inferred that a seaway existed to the NW of Scotland in the mid-Permian, to connect the Bakevella sea to the northern ocean (Pattison *et al.* 1973). Exploratory oil wells drilled NW of Donegal have confirmed the presence of late Permian evaporites (Haszeldine 1984, Tate and Dobson 1989), making the connection of the Bakevella Sea to the north *via* the Rockall region plausible. Thus from this sort of evidence it can be concluded that there may have been a rift zone (whether intra-continental or oceanic) in existence in the region of the Rockall Trough by mid-Permian time.

(4) *Sedimentation rates*. Estimated sedimentation rates of the undated sedimentary pile in the Rockall Trough below a seismic reflector 'Y', dated as 76 Ma, and above supposed oceanic basement, suggested formation of the oceanic crust in early Cretaceous time.

Not only are such sedimentation rate estimates "notoriously unreliable" (Roberts 1975a, p. 494), but Roberts *et al.* (1981) later substantially revised the age

of reflector 'Y', to the late Palaeocene or early Eocene (52–55 Ma). Furthermore, the reflector originally identified by Roberts as top oceanic basement is locally 1–2 s of two-way reflection time (TWT) above the reflector now recognised to be the top of the quasi-oceanic crust (Joppen and White, submitted; see also the discussion above). This revision has been made by correlating commercial multichannel reflection profiles with old crustal refraction profiles (my unpublished work), and is corroborated by the recent Cambridge/Durham wide-angle experiment referred to above.

The discrepancy in identification of the top basement reflector can also be seen by comparison of the original time-to-basement map of Roberts (1975a, fig. 18) with the more recent version of Roberts *et al.* (1981, fig. 4), compiled from better-quality multichannel reflection data available to 1977. Clearly the extrapolation of sedimentation rates, particularly when the 'known' stratigraphy is subject to such drastic revision every few years, is a futile exercise.

(5) *Magnetic anomalies.* The last of Roberts's (1974) arguments cited a then-unpublished magnetic map, apparently showing that oceanic linear magnetic anomalies could be traced from west of Porcupine Bank into the Bay of Biscay, where, it was argued, they were of late Jurassic to early Cretaceous age.

The map was subsequently published (Roberts and Jones 1979), but the age of the anomalies was re-evaluated (Roberts *et al.* 1981). This important evidence is discussed below.

More arguments for Early Cretaceous spreading

Two more arguments supporting early Cretaceous opening were put forward soon after Roberts's (1974) exposition:

(1) *Wyville-Thomson Ridge.* This trends NW–SE across the northern end of the Rockall Trough (Fig. 3). Bott (1975) suggested, from a thesis by Himsworth (1973), that it may be floored by oceanic crust contemporaneous with that of the Rockall Trough. The 'crust' underlies two sequences of sediments of which the uppermost is Oligocene and younger, separated by the widespread Eocene-Oligocene unconformity R4 (Roberts 1975a) from a thin lower sequence which may be "earliest Tertiary or Mesozoic". These inferences are "consistent with an early Cretaceous age for . . . the Rockall Trough and Faeroe-Shetland Channel" (Bott 1975, p. 115), notwithstanding Himsworth's own conclusion that the reversely magnetised basaltic nature of the ridge complex suggested Permian sea floor spreading.

The supposed oceanic basement here is now recognised (Roberts *et al.* 1983) to be the top of the Palaeocene-Eocene basalts underlying most of the northern Rockall Trough (Fig. 3). This was proved by the stratigraphic test well 163/6-1A (Morton *et al.* 1988), as suggested by Roberts (1970). It thus has no relevance to the age (or origin) of the underlying crust.

(2) *Cimmerian tectonism*. The second supporting argument for early Cretaceous spreading related the mid Jurassic to early Cretaceous phase of extensional tectonism newly recognised on the continental shelf around the British Isles (cf. Ziegler 1975) to the initiation of spreading in the Rockall Trough (Roberts 1975b, p. 91). This has the corollary that all such earlier phases back to late Palaeozoic times could be relegated to "post-Hercynian orogenic collapse" (Roberts 1974, p. 346) and/or a long period (c. 160 My) of rifting prior to sea floor spreading in the North Atlantic.

The importance of a late Palaeozoic rifting event in the North Atlantic is now widely acknowledged. For example, Ziegler (1982) portrays 'Rockall' and 'Faeroe' rifts on his Stephanian-Autunian palaeogeographic map (enclosure 12), although he still favours Cretaceous sea floor spreading. Therefore evidence of rifting provides more support for late Palaeozoic spreading than for Cretaceous spreading. The earlier Devonian and Devonian-Carboniferous basins can be ascribed to post-Caledonian orogenic collapse.

Continental reconstructions supporting late Cretaceous opening

Kristofferson (1978) revised the identification of magnetic anomalies 31 and 32 in the North Atlantic to numbers 33 and 34 respectively. Anomaly 34 (c. 80 Ma) runs across the mouth of the Rockall Trough, where it is offset by the Charlie-Gibbs fracture zone (Fig. 2). Kristofferson also noted the contrast in the magnetic signature within different parts of the Rockall Trough; south of about 55°N it is "noisy" and correlatable with the oceanic crust further south, whereas north of 55°N it is "very smooth", consistent with formation by spreading during a single geomagnetic polarity epoch, or with subsided continent (1978, p. 281). He inferred that if the crust north of 55°N formed by sea floor spreading, then it probably did so during the Cretaceous 'long normal' epoch (108–80 Ma); but his reconstructions implicitly reject this assumption of oceanic crust, showing instead subsided continent (1978, fig. 11). He concluded that the continental subsidence of the central Rockall Trough took place simultaneously with the spreading that created the "noisy magnetic" crust in the southern Trough, during the late Cretaceous, between 90 or 95 Ma and anomaly 34 time, 80 Ma, (Kristofferson 1978, p. 287).

Srivastava (1978) independently came to a similar conclusion, favouring a late Cretaceous opening date for the Rockall Trough, although this was arrived at as a by-product of plate tectonic reconstructions for the North Atlantic, rather than by specific study of the Trough itself. The absence of recognisable anomalies in the Trough is explicable he says, since "they would largely be formed during the Cretaceous normal polarity epoch" (1978, p. 351).

Both Kristofferson's and Srivastava's conclusions regarding the Rockall Trough rely on the long-recognised constraint that it is a quiet magnetic zone (Heirtzler

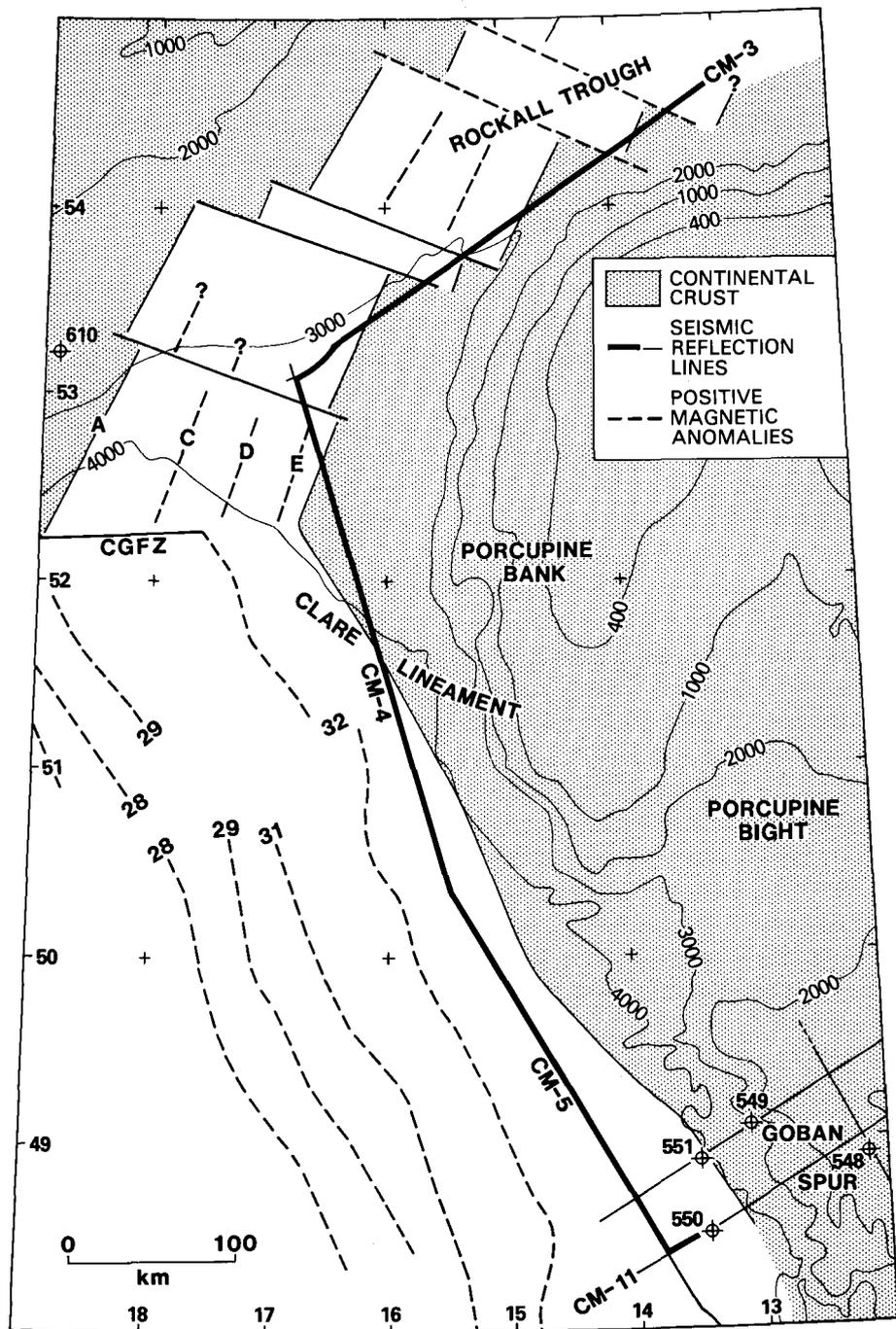
and Hayes 1967), together with the assumption that spreading (if any) occurred just before the time of anomaly 34, contemporaneous with spreading west of the Porcupine Bank and in the Bay of Biscay. Thus their North Atlantic opening histories imply spreading in the Rockall Trough during the mid to late Cretaceous rather than during the early Cretaceous.

Revision of date to mid-late Cretaceous

After publication of the magnetic map of the Rockall Trough (Roberts and Jones 1979), Roberts *et al.* (1981) published a detailed argument in favour of a Cretaceous opening, but revised the date to late Cretaceous (100–70 Ma) rather than the early Cretaceous date (pre-120 Ma) previously postulated (Roberts 1974, 1975a, b). The four new lines of argument presented are discussed in turn.

(1) *Seismic stratigraphy.* Roberts *et al.* (1981) discuss seismostratigraphic units in the southern Rockall Trough (west of Porcupine Bank; Fig. 4). These are bounded by four reflectors above basement referred to as R4, X, Y and Z, in the mapping and terminology of Roberts (1975a). See Table 1. Reflector Y is assigned a late Palaeocene–early Eocene age, instead of the previous late Cretaceous estimate. The lowest unit lies between reflector Z and the top basement. It contains strong reflectors which rest on basement “both within the Rockall Trough and beneath its margin and thus, in part at least, post-date its formation, although they may be partly contemporaneous with rifting at the margins”. The pre-Z unit is dated as post-Albian by tying in the seismic profiles to DSDP holes 400A and 402A in the Bay of Biscay. Since one of Roberts’s co-authors (D G Masson) was a scientist aboard Deep Sea Drilling Project Leg 80, their stratigraphy was presumably also tied in to DSDP 550 (de Graciansky *et al.* 1981) drilled in June 1980 on the oceanic crust west of Goban Spur (Fig. 4). However, this additional link is not explicitly mentioned in the 1981 paper, which states that to the north of the mouth of the Rockall Trough the correlation of the sediments (implying post-Albian oceanic crust) “does become more tenuous in Rockall Trough itself”.

A number of questions are raised by this sort of regional correlation exercise. Firstly, even short-range stratigraphic extrapolation oceanward along seismic line CM-11 (Fig. 4), away from the basement high apparently sampled by DSDP 550, demonstrates that there are pockets of sediment up to 600–700 m thick lying in the lows between the tilted block-faulted oceanic crust. These sediments are undoubtedly older than the late Albian sediments drilled on the top of the high; the question is, how much older? Clearly the ocean crust itself is even older. The dating by Roberts *et al.* of the oceanic crust some 500 km further north, in the mouth of the Rockall Trough, as ‘post-Albian’, is over-optimistically precise. Taking their seismostratigraphic correlations further north, into the Rockall Trough proper, appears to be even more unsatisfactory as a way of dating the



spreading in the Trough, since:

(a) Basement is significantly deeper in the Trough proper than west of Porcupine Bank, being buried by up to 2–3 km of pre-Z sediments,

(b) The mapping of reflectors X and Y by Roberts (1975a) on old single channel airgun data can be shown to be unsound, when compared with the multichannel data available by 1977, the locations of which are shown in Roberts *et al.* (1981). For example, a reflector on the multichannel data correlated as Y in the area of 56.3°N, 11.5–12°W becomes reflector X when tied back to the single channel data some 20 km NE.

(c) No examples of the multichannel data in the Rockall Trough are presented by Roberts *et al.* (1981)—only line drawing interpretations of four unmigrated time sections. While it is generally accepted that the only practicable method of publishing regional seismic data and interpretations therefrom is to use line drawings, some short samples of the data themselves should have been presented to demonstrate the authors' identifications of reflectors and basement types. No justification is offered, for example, for interpreting the undulating basement on the drawing of one line (E–F) as oceanic, whereas on another, line G–H, with very similar basement structure, it is labelled continental (Roberts *et al.* 1981, fig. 2).

The correlation of reflectors along a solitary seismic profile some 900 km from DSDP 550 into the Rockall Trough (Fig. 4)—the only multichannel line available to date—is clearly rather difficult. It has been attempted again by Bentley (1986, figs. 3.8 and 3.17) using a slightly simplified version of a digitised line drawing used by myself for the same purpose in 1984. Although our independent interpretations are remarkably similar, Bentley's appears to me to be better. Furthermore, he has compared his reflector identifications with those of previous authors; his correlations (Bentley 1986, table 3.1) are shown in the first six columns of Table 1. The main change in reflector dating since Roberts *et al.*'s paper is that the old reflector R4 is now equated with reflector R2 of Miller and Tucholke (1983), from the results of DSDP 610 (Fig. 4) drilled in the southern Rockall Trough (Masson and Kidd 1986). Bentley's reflector dating R1–R7 takes this new result into account. However, Bentley did not map or correlate all the reflectors of these other two pairs of authors, so his numerical 'R' notation becomes deficient. I have multiplied Bentley's numbers by 10 to give a new notation for the sequence of reflectors R10 to R80 (Table 1). R stands for 'Rockall', and the decade series allows for extra numbers to be inserted, by analogy with Fortran statement

FIG. 4. Roberts *et al.*'s (1981) magnetic anomaly identification and continental crust extent in the southern Rockall Trough. Area of map is located in Figure 2. A, C, D and E are linear positive magnetic anomalies (see also Fig. 5). Anomaly 32 is now generally accepted as anomaly 34 (see Figs. 1 and 2). Seismic reflection lines CM-3, CM-4, CM-5 and CM-11, are used to tie seismic stratigraphy from Deep Sea Drilling Project (DSDP) well 550 to the Rockall Trough. CGFZ—Charlie Gibbs fracture zone.

TABLE 1

Seismic reflector correlations in the Goban Spur and southern/central Rockall Trough region.

The correlations in the six left-hand columns are from Bentley (1986). Some of Bentley's work has been published by Bentley and Scrutton (1987) and Scrutton and Bentley (1988). The numerical ages in the right-hand column are based on the timescales of Odin *et al.* (1982, fig. 1) and Kennedy and Odin (1982, table 14). u/c—unconformity.

Jones <i>et al.</i> (1970)	Roberts (1975a) Roberts <i>et al.</i> (1981)	Dingle <i>et al.</i> (1982)	Miller & Tucholke (1983)	Masson & Kidd (1986)	Bentley (1986) <i>et al.</i>	This paper	Stratigraphic age span	Generalised name and age (Ma)
			R1	Yellow	R1	R10	latest Miocene	Top Miocene (5)
				Purple		R15	mid-middle Miocene	Middle Miocene event (≈ 15)
R	R4	Challenger	R2	Green	R2	R20	late early Miocene - middle Miocene	Top Lower Miocene (≈ 20)
			R3			R30	latest Oligocene - earliest Miocene	Top Oligocene (23)
					R4	R40	late Eocene - early Oligocene	Top Eocene (34)
	X (?Y)	Charcot	R4	Brown	R5	R50	earliest Eocene	Top Palaeocene (53)
						R55	not mapped	Top Cretaceous (65)
	X or Y			Blue	R6	R60	?late Campanian - early Maastrichtian	Top Campanian (72)
				Pink		R65	not correlated to north	
	Y (?Z)	Shackleton		Orange	R7	R70	?middle - late Albian	Top Lower Cretaceous (95)
	Z	Reflector 1		Grey	u/c	R80	early Albian and older	Top oceanic layer 2 or top metamorphic basement

numbering convention in computer programs. This will avoid the confusion that will arise if existing labels like R4 continue in use. The age span of these reflectors is taken from Masson and Kidd (1986) and Bentley (1986, table 3.2), and I have added generalised shorter names in the last column of Table 1. Thus R30—'latest Oligocene to earliest Miocene'—can be referred to as Top Oligocene, and is about 23 Ma. Note that in the Goban Spur to central Rockall Trough region the Top Cretaceous cannot be mapped, although a slightly older horizon (Top Campanian) can.

The most important regional reflector correlations are across the Clare lineament (Fig. 4), where the sedimentary cover thickens considerably on the north side, and overlies deeper basement. Bentley (1986) has recognised that there is a major discontinuity across the lineament, which he showed is the eastward prolongation of the Charlie-Gibbs fracture zone. The correlations across the lineament proposed here have been substantiated by a study of the interval

velocities derived by re-picking the semblance plots created in the processing of reflection line CM-4. These are used to depth-migrate the line-drawing (Raynaud 1988) of the reflectors in that area (my unpublished work). It is interesting to note that corrected basement depth, after removal of a simple 1-dimensional loading effect of the sediments, is around 5.5 km on either side of the lineament. The reflector correlations also agree with those obtained by D G Masson (pers. comm. 1985) from the study of a reprocessed, time-migrated, portion of the seismic section.

The Top Palaeocene reflector and some of the younger ones above it can be correlated across the northern Rockall Trough and outer Hebridean shelf. In these northerly areas the Top Palaeocene corresponds to the top of the widespread late Palaeocene basalts subcropping over the region (Fig. 3). These have been mapped by Wood *et al.* (1987, 1988) and Wood (1988), who referred to them as the top of lava facies C. I have cross-correlated the reflectors from the south (Table 1) into the north of the Rockall Trough, as identified by these authors, and also by Jones *et al.* (1986). This correlation is shown in Table 2. Unfortunately Wood *et al.*'s dating of the younger reflectors is out of date, as it does not take account of the revision of the age of the old R4 (now R20) horizon necessitated by DSDP 610. Instead, they relied upon a confidential commercial report dated 1980 (Wood

TABLE 2

Seismic reflector correlations in the central/northern Rockall Trough and outer Hebridean shelf.

Jones <i>et al.</i> (1986)	Wood <i>et al.</i> (1987, 1988) Wood (1988)	This paper	Stratigraphic age span	Generalised name and age (Ma)
	"Top Oligocene"	R10	latest Miocene	Top Miocene (5)
			R15	mid-middle Miocene
H2	"Top Eocene"	R20	late Early Miocene - middle Miocene	Top Lower Miocene (\cong 20)
		R30	latest Oligocene - earliest Miocene	Top Oligocene (23)
		R40	late Eocene - early Oligocene	Top Eocene (34)
H3	Plateau basalts (facies A)	R45	earliest Eocene - early Eocene	Early Eocene (\cong 50)
H4	Top lavas (facies C)	R50	late Palaeocene	Top Palaeocene (53)
H5				Top metamorphic basement

The three rightmost columns are abstracted from Table 1. Wood's reflector dating was based on a confidential commercial report of 1980 on the dating of reflectors at the 163/6-1A stratigraphic test well in the northern Rockall Trough (Wood 1988). Jones *et al.*'s H5 reflector is defined only on the outer Hebridean shelf.

1988), prepared in connection with the drilling of the stratigraphic test well 163/6-1A (Fig. 3).

It is therefore possible to pick a good Top Palaeocene reflector (R50; Tables 1 and 2) regionally, from the Armorican margin of the Bay of Biscay, to the northern Rockall Trough. The dating is corroborated by the fact that R50 corresponds to the horizon where volcanic ash was encountered in DSDP 550 (Knox 1985, Knox and Morton 1988). This ash marker of the North Sea Sele and Balder Formations ties to the base of the early Eocene basalt escarpments of the Faeroe-Shetland Trough and southern Møre Basin (Smythe *et al.* 1983). There is, therefore, a consistent structural/stratigraphic correlation with the Top Palaeocene horizon in the northern Rockall Trough, which also pinches out at large escarpments, shown schematically in Figure 3.

The only other horizon which can be picked regionally is the Top Lower Cretaceous, R70. Regional identification of this and other horizons is corroborated by a preliminary study of interval velocities shown in Table 3. The velocities at DSDP 610 are simplified from sonic velocity measurements (Bentley 1986, fig. 3.15; data supplied to him by D G Masson); the other interval tabulations are taken from re-picking of semblance plots. 'Central Rockall Trough' refers to 20 semblance plots on a multichannel profile in the area of 56°N, 12°W, and

TABLE 3

Interval velocities from south of the Clare lineament to the Rockall Trough.

Velocities are P-wave, in km s^{-1} . Data for DSDP 610 are simplified from the sonic log after Bentley (1986, fig. 3.15); other data are derived from the re-picking of semblance plots (for details see text). Reflector designation follows Table 1. Note the substantial increase in velocity below the Top Palaeocene (reflector R50), and the probable velocity inversion just below the Top Lower Miocene (reflector R20).

	Clare lineament		DSDP 610	Central Rockall Trough	East-central Rockall Trough
	South	North			
Seabed			1.6		
			R10 ———— 1.7-1.8	2.0	2.2
	2.0	2.2	R15 ———— 2.1-2.6		2.4
			R20 ———— (2.0-2.2)	2.2	2.2
R50				2.8	
	3.0	3.2-3.5		R60 ———— 3.3	
R70					

'East-central Rockall Trough' refers to two dozen or so semblance plots on lines near the margin east of the Hebrides Terrace Seamount area. The data from the Clare lineament area have been discussed above. There is a consistent and substantial increase in velocity below the R50 (Top Palaeocene), from around 2.2 km s^{-1} above, to 3.0 km s^{-1} or greater, below. There is also the interesting suggestion of a velocity reversal below R20, from data where the R15–R20 velocity interval can be measured. Below R70 a 'guesstimate' of about 4.0 km s^{-1} would be appropriate for the interval between R70 and top crustal basement, R80.

The regional stratigraphic correlations discussed above show that there are up to 2.5–3 km of pre-Upper Cretaceous sediment in the central part of the Rockall Trough (i.e. north of about 54°N). This sequence extends across some 200 km of its width (although in places cut out against basement highs), and it is not, therefore, just a local rift feature. It is unlikely that the Trough could have developed fully by presumed sea floor spreading, and then have been covered by such a widespread blanket of sediment, all within the six million years or so of the late Albian. Roberts *et al.*'s (1981) conclusion that the Rockall Trough opened in the late Albian (or later) must therefore be regarded as unsound.

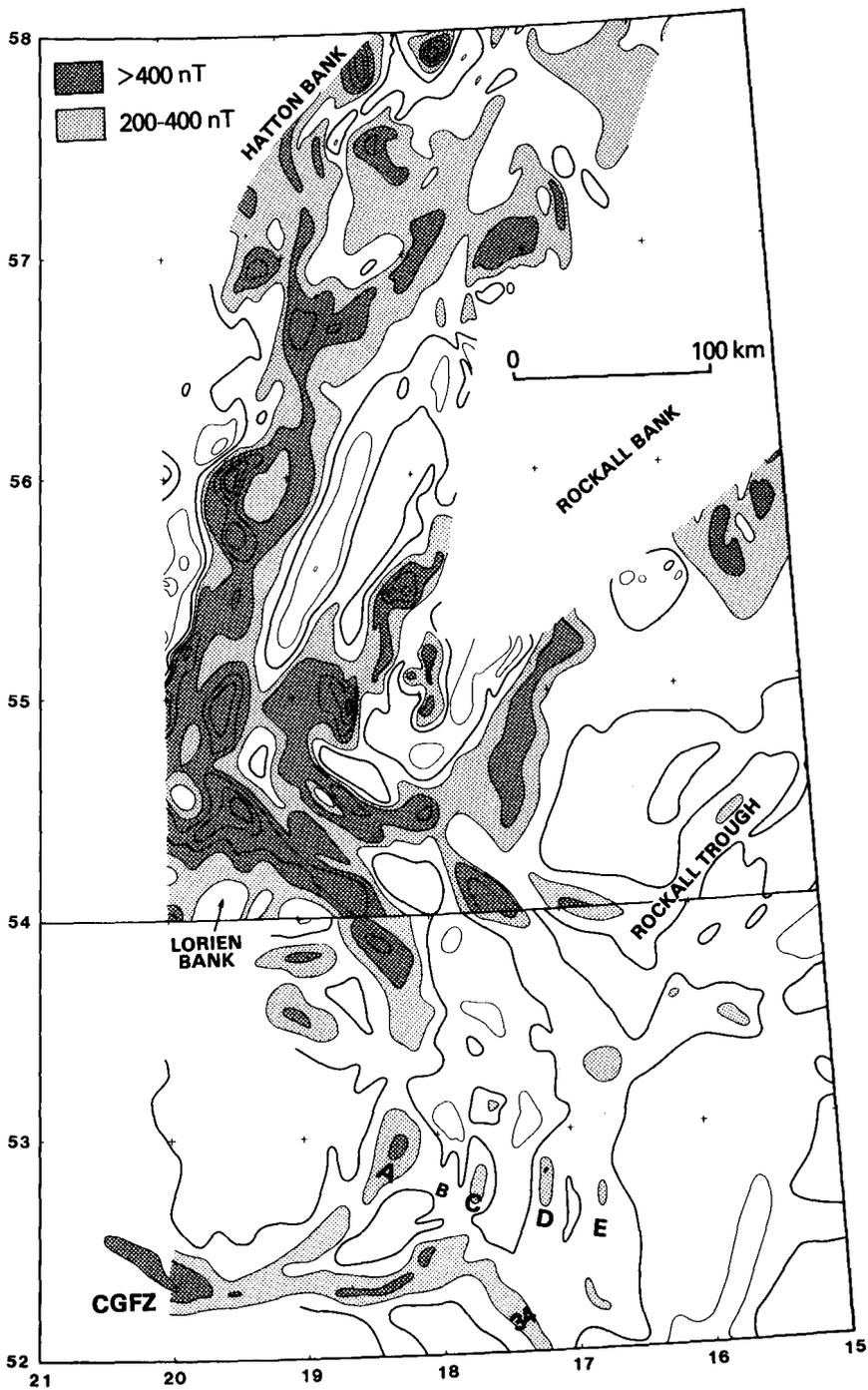
(2) *Magnetic modelling of basement.* Prominent NNE-trending linear magnetic anomalies over the crust west of Porcupine Bank have been modelled by Roberts *et al.* (1981), partly in an attempt to refute the Permian spreading hypothesis of Russell and Smythe (1978). They concluded that the anomalies, which are labelled A, C, D and E in Figure 4, are from late Cretaceous oceanic crust, and that they can be recognised, traced across several fracture zones, in the Rockall Trough itself.

This modelling and interpretation has a number of weaknesses:

(a) Roberts *et al.* (1981) have missed the important point that the mere presence of reversals within the oceanic crust here is sufficient to rule out the possibility of spreading during the late Carboniferous or Permian. Within the period 300–235 Ma (the Kiaman interval; McElhinny 1973) there are only two published normal events (or excursions), at around 260–265 Ma (Creer *et al.* 1971; Valencio and Vilas 1972; Turner and Vaughan 1977). These may represent the same event, and it is very unlikely that a short event (or pair of events) could account for the observed anomalies, which occupy a zone some 120 km wide, and are up to several hundred nanoTeslas in amplitude.

(b) The geometry of opening of the Rockall Trough postulated by Russell and Smythe (1978, fig. 1) implies, in any case, that the area of crust west of Porcupine Bank studied by Roberts *et al.* is younger than the supposed Permian crust of the main Trough.

(c) Their method of discriminating between 'Permian' and 'Upper Cretaceous' anomalies has little hope of success, because both pairs of vectors (i.e. upward and downward-pointing) project onto the E–W 2-dimensional model profiles in similar directions, the projected Cretaceous vectors being somewhat larger than



those of the Permian. There are no independent constraints on the positions of the magnetised blocks, nor on the magnetisations assumed within them. It is not surprising, therefore, that their 'Permian' model anomalies turn out simply to be a lower-amplitude version of their 'Cretaceous' anomalies (fig. 5 of Roberts *et al.* 1981).

(d) Even assuming that the anomalies in the mouth of the Rockall Trough can be accounted for by reversals within ocean crust, "their northward change to a magnetic quiet zone remains problematic" (Roberts *et al.* 1981, p. 123). A simple rejection of the assumption that the anomalies continue north-eastwards removes this 'problem' of the change to a quiet magnetic zone; Figure 5 shows how the same anomalies can be correlated in an S-shaped pattern, running into the Hatton-Rockall Basin, and avoiding the main Rockall Trough altogether. The data in Figure 5 north of 54°N come from unpublished commercial aeromagnetic maps; however, examination of the older, published shipborne magnetic data (Roberts and Jones 1979), on which Roberts *et al.*'s (1981) interpretation is based, show that the anomalies do follow this S-bend trend, and that they cannot be convincingly traced north-eastwards into the Rockall Trough. The implications of this re-interpretation are discussed further below.

(e) As anomaly 32 west of Porcupine Bank (Roberts *et al.* 1981) is now accepted by at least two of the three co-authors as anomaly 34 (Masson and Miles 1984), this raises the problem of the origin of the post-late Albian, pre-34 anomalies. Although there are one or two documented reversals within the long Cretaceous normal polarity epoch (e.g. Pechersky and Khramov 1973; Van Hinte 1976), and a mixed polarity zone within the Albian has been sampled by drilling both at DSDP sites 263 and nearby 550, these occurrences do not seem to be sufficiently substantial reversals to account for the observed pre-anomaly 34 anomalies. P R Miles (pers. comm. 1985) suggests the possibility that there are other reversals as well, still undocumented, within the long normal epoch, but this must be regarded as speculation. In view of the very weak 'post-late Albian' constraint on the age of the oceanic crust, derived from the seismic stratigraphy discussed above, one solution would be to regard this age as only approximate,

FIG. 5. Magnetic anomalies in the southern Rockall Trough and Hatton-Rockall Basin, at 200 nT contour interval. South of 54°N they are marine data redrawn from Roberts and Jones (1979), and as modelled by Roberts *et al.* (1981). North of 54°N they are based on the aeromagnetic survey flown in 1973 by Fairey Surveys (now Clyde Surveys Ltd), and released through the British Geological Survey, with the permission of the Director. Flight height was 300 m, and the E-W line spacing is about 15 km. Note the general continuity of the linear group of anomalies A-E in an S-shaped pattern running from the Charlie Gibbs fracture zone (CGFZ) northwards into the southern Hatton-Rockall Basin, between Lorien and Rockall Banks. Whatever the origin of the anomalies, it is evident that they do not continue into the Rockall Trough. The same general S-shaped pattern can be seen on the published marine magnetic map.

and to suggest that the crust in question is somewhat older—early Cretaceous, for example. The anomalies could then represent two or three reversals within the M-sequence of the geomagnetic polarity reversal time-scale. This is preferable to the alternative of postulating major, but as yet undiscovered, anomalies within the late Cretaceous long normal epoch (100–70 Ma).

Bentley (1986) recognised that the magnetic anomalies labelled A–E in Figure 5 curve anticlockwise into a NW trend, and pointed out that there is a fairly close correlation between the positive lineations and linear structural highs at the base of the sedimentary pile. He called this region the Barra Volcanic Ridge System (BVRS; see also Scrutton and Bentley 1988). Making an analogy with the Porcupine Median Volcanic Ridge (PMVR) in Porcupine Seabight (Tate and Dobson 1988), Scrutton and Bentley (1988) concluded that the BVRS may be of mid early Cretaceous age (Valanginian-Barremian). Whether it was intruded into and extruded over oceanic crust or attenuated continental crust is not clear; however, it does correspond to a major stretching/intrusive event. The linear magnetic anomalies in the region of 54°N modelled by Scrutton and Bentley continue NW into the Hatton-Rockall Basin (Fig. 5).

In conclusion, the anomalies have no direct bearing on the opening of the Rockall Trough.

(3) *Rosemary Bank*. The magnetic anomaly over Rosemary Bank (Fig. 3) has been re-modelled by Miles and Roberts (1981), following a previous attempt by Scrutton (1971). After removal of the small positive anomaly over the crest of the seamount, the main negative anomaly has been modelled in three dimensions, leading to the conclusion that the causative body formed in high palaeolatitudes, appropriate to late Cretaceous or more recent time. Onlap of the Top Lower Miocene reflector R20 precludes a late Tertiary or younger age. Miles and Roberts concluded that their result is consistent with a mid-Cretaceous origin for the Rockall Trough, and ruled out the tentative Permian age inferred by Scrutton, which was used as supporting evidence of early opening by Russell and Smythe (1978).

Miles and Roberts have therefore apparently shown that Rosemary Bank cannot be cited as evidence for a Permian age for the Rockall Trough. However, the assertion by Roberts *et al.* (1983, p. 141) that the Tertiary lavas of the northern Rockall Trough have “no obvious relationship” to Rosemary Bank is untenable, because the North Rockall Escarpment, as mapped on commercial seismic reflection data, curls around the bank as shown in Figure 3. It appears that Miles and Roberts have merely succeeded in modelling the magnetic edge effect of the early Tertiary basalts, which have no direct bearing on the age of the Rockall Trough. Wood (1988) recognised this problem. He remodelled the residual magnetic anomaly after removal of the effects both of the Tertiary basalts, and a presumed re-magnetised/intrusive feeder zone in the centre of the Bank. His results indicate a poor fit of modelled to real anomaly for remanent vectors of

early, mid or late Carboniferous and early Permian ages, but a good fit for late Permian or Triassic ages. Younger ages gives a poor fit. In conclusion, Rosemary Bank does, after all, lend support to a pre-Jurassic opening of the Rockall Trough.

(4) *'Sills' in the Møre Basin.* The most recently published argument for Cretaceous spreading in the Rockall Trough (Price and Rattey 1984) draws upon commercial seismic reflection data interpretation of the Møre Basin and eastern Norwegian Sea (Fig. 6). In the Møre Basin sill-like reflectors occur just below Price and Rattey's base Upper Cretaceous horizon, which has been dated by correlation south to wells in the Viking Graben. Price and Rattey (1984) suggest that the intrusion of these sills may be an indication of a quasi-oceanic spreading event, followed by considerable subsidence here and in the Vøring Basin during the late Cretaceous.

From their observation of "strong discontinuous reflectors" in the southern Møre Basin, Price and Rattey (1984) make a series of increasingly speculative leaps in interpretation. Firstly, the events are interpreted as "apparent sills and lavas". Secondly, the 'sills' are "dated as pre-Cenomanian by seismic ties to wells in the North Sea". Thirdly, the 'volcanic events' are said to be "identical" to events seen in the southern Rockall Trough by Roberts *et al.* (1981) on "refraction seismic, gravity and magnetic profiles". Lastly, they are interpreted as "having formed by the accretion of oceanic crust in abnormally shallow water depths with contemporaneous, rapid clastic sedimentation. No single igneous basement surface would form in such circumstances".

Figure 6 summarises the published data on the Møre Basin, together with several interpretations. The location of the Faeroe-Shetland Escarpment is practically identical on the maps of Smythe (1983, fig. 2) and of Bøen *et al.* (1984, fig. 1). Similarly, the locations of the Palaeocene basalt feather edge (or lava front) are closely comparable. Minor differences in the area of 63°N, 2°E are due to the latter authors interpreting some events as lavas rather than sills, as I did. The location of the lava front on maps by Hamar and Hjelle (1984) and Bukovics *et al.* (1984) are also similar, but that by Price and Rattey (1984, fig. 3) is 50 km further south than the other four versions. As their sample of seismic data (Price and Rattey, fig. 5) is also apparently mislocated some 25 km south of its proper position, cartographic error is suggested. The unexplained oval region, some 130 km long by 70 km wide, on Price and Rattey's map is an "area where pre-Cenomanian volcanic beds are inferred in the Møre Basin" (I Price, pers. comm. 1984). If Price and Rattey's outline is moved northwards by 25–50 km to place it in the position its authors presumably intended, this area approximates to the more complex zone of 'eastern lavas' mapped by Hamar and Hjelle (1984, fig. 6; stippled area in Fig. 6 herein).

There are two ill-founded arguments in Price and Rattey's (1984) interpretation of the reflectors in question as representing mid-Cretaceous oceanic crust:

(a) *Eruption or intrusion?* No independent evidence for an origin by eruption

has been presented, but, in contrast, some of the events in the region cross-cut the sedimentary pile (see Bøen *et al.* 1984, fig. 16). There is, therefore, no justification for interpreting them as lavas rather than as sills. Concordancy with bedding is not sufficient reason to prefer an eruptive over an intrusive origin. Francis (1982) has described the mechanisms of emplacement of sills, with particular reference to the Stephanian (c. 295 Ma) sill complexes of northern Britain. It is clear that on a regional scale such sills are essentially 'smooth', and concordant with bedding over areas on the order of 10^4 km². They were intruded some 0.5–2 km below the contemporary land surface. At the depths at which the sill-like reflectors in the Møre Basin are observed, seismic reflection cannot resolve the small-scale structure, such as the step-and-stair transgressions seen in the field.

However, Hamar and Hjelle (1984) assumed that the features are all volcanic in origin, erupted at "as many as four stratigraphic levels". In their example (their plate 12; line B-3-74 part B on Fig. 6), which is adjacent to the portion of the same line reproduced by Price and Rattey (see Fig. 6; line B-3-74 part A), the lowest of these supposed 'lava' events appears to be a water-column peg-leg multiple of the uppermost one. The observations that:

(a) They are 'thin' events (i.e. with the top and bottom not resolved as separate reflectors anywhere, and with good transmission of energy through each of them), and

(b) they occur at various stratigraphic levels (multiples omitted) throughout the upper, mid and lower Cretaceous, strongly imply that even the concordant events are intrusive rather than eruptive. A basalt field subcropping over such a large region would be expected to show some thickness variations and, in places, features such as escarpments, internal bedding, and signs of intrusive centres (cf. Gatliff *et al.* 1984). It is highly unlikely that several such sub-provinces would occur without any of these features, one above the other, over an interval of 20–50 Ma, as Hamar and Hjelle's 'lava' interpretation implies.

Nelson and Lamy (1987) interpreted the zone of sills SE of the Palaeocene basalts (Fig. 6) as a huge edifice of subaerial volcanics of late Cretaceous age. Although their paper is entitled a 'review', the authors seem to be unaware of the earlier work referred to above. They interpret the edges of the sill reflectors as indirectly indicating the presence of "cliffs [which] would have been very steep". Their supposed cliffs, as illustrated by one migrated seismic section (their fig. 12) appear to be vertical and of the order of 400–500 m high. No sign of this impressive and long-lived late Cretaceous shoreline is seen in the seismic stratigraphic character of the sediments burying the cliffs, nor is the inference of half-eroded individual volcanoes within the edifice demonstrated by any detailed maps showing a radial structure (cf. Gatliff *et al.* 1984).

Given that the case for at least some of the reflector events originating from lavas or volcanoes, rather than sills, has not been made, there is no justification for dating these events as pre- or intra-Cenomanian (Hamar and Hjelle 1984), nor for

invoking the late Cretaceous volcanic episode of Nelson and Lamy (1987). There is no reason to alter the conclusion of Hinz *et al.* (1982) that the seismic reflection events are simply intrusives of Tertiary age, and are related to the late Palaeocene—early Eocene basalts to the west (Fig. 6). Bøen *et al.* (1984, p. 262) reached the same conclusion on regional grounds. The close temporal and spatial relationships of the early Tertiary volcanics and intrusives has been demonstrated further SW in the Faeroe-Shetland Trough (Smythe *et al.* 1983, fig. 5), where sills as well as lavas have been drilled (Gatliff *et al.* 1984). However, limited occurrences of late Cretaceous intrusions are also likely (cf. Ridd 1983). In the Møre Basin the sill events are 0.5–4 km below the top Palaeocene. Assuming shallow water at that time, this estimate of contemporary intrusion depth is quite reasonable for sill intrusion during the late Cretaceous and Palaeocene.

(b) *Dating.* Price and Rattey (1984) dated the reflector “immediately above the ‘volcanic events’” as intra-Cenomanian, by tying to wells in the Viking Graben to the south. This correlation is not well established as Price and Rattey imply. If it were, then presumably the Norwegian Petroleum Directorate interpreters (Bøen *et al.* 1984), using a larger regional data base, would not have dated the same horizon as base Cretaceous. Isochrons on this horizon are shown in Figure 6, redrawn from Bøen *et al.* (1984, fig. 10). Similarly, the mapping by Norske Shell (Bukovics *et al.* 1984) shows a ‘near base Cretaceous marker’ (labelled horizon T30) subcropping over the Møre Basin and tied to wells at the NE end of the Viking Graben. Bukovics *et al.* (1984, fig. 3A) illustrate the well-ties, in contrast to Price and Rattey, by reproducing a ‘geoseismic section’. The location of this is shown in Figure 6 as Geoprofile 3A. Furthermore, the “firm stratigraphic control for the regional profiles” supposedly provided by drilling on the mid Norwegian margin at Haltenbanken (Price and Rattey 1984, p. 985) simply does not exist, as regional ties from that area to the Møre Basin are made by jump-correlating over major fault zones (e.g. Price and Rattey 1984, fig. 3). The jump-correlations over faults are shown better by Bukovics and Ziegler (1985), which has larger and clearer figures than those in Bukovics *et al.* (1984).

Clearly it is premature, given our present limited understanding of the deeper stratigraphy and structure of the Møre Basin, to try to draw any firm conclusions about the age of opening of the Rockall Trough, or about whether or not a contemporaneous phase of opening or extension is found as far north as the Møre Basin itself. Similar caution is required when considering the intervening Faeroe-Shetland Trough, although here there is clear evidence emerging for a long, probably pre-Mesozoic, basin history (Haszeldine *et al.* 1987).

Discussion of Cretaceous spreading

It is generally agreed that there was a phase of mid-Cretaceous spreading represented by a strip of oceanic crust landward of anomaly 34, and seaward of the

southern Porcupine Bank and Goban Spur. This strip is shown in Figure 4 south of the Clare lineament where, however, anomaly 34 is labelled in its former guise as 32. The crust is reliably dated as late Albian (or possibly just older) by DSDP 550 (Fig. 4), and, in common with other ocean crust of that age, it lacks magnetic reversals (Scrutton 1985). This date also fits neatly into the geometric opening history of the area south of 52°N, involving Iberia, Europe and North America, as outlined by Masson and Miles (1984). However, two problems emerge if this crust is traced northwards. Firstly, it gives rise to large magnetic anomalies (Fig. 5). These are either:

(a) oceanic in origin, which is inconsistent with a mid- or late Cretaceous age prior to anomaly 34, or

(b) they are caused by the intrusive/extrusive volcanic complex proposed by Scrutton and Bentley (1988), which intruded a pre-existing crust (of uncertain affinity) during the early Cretaceous.

Secondly, this 'magnetic' crust is not traceable into the Rockall Trough proper, but instead trends NW into the Hatton-Rockall Basin.

As has been shown, none of the arguments for Cretaceous spreading relating to the main part of the Rockall Trough (i.e. north of 54°N) can be sustained. Furthermore, if one extrapolates southwards from the Norwegian Sea through the Møre Basin and Faeroe-Shetland Trough—basins which are all supposedly (on geometric grounds) underlain by crust continuous with that in the Rockall Trough—the presently available evidence suggests that most of the crust in these northerly regions is of pre-Cretaceous age. It is certainly older than the Albian age proved west of Goban Spur. On the other hand, there is evidence of a major change in tectonic regime north of 60°N, beginning at around the early-late Cretaceous boundary, as outlined by Price and Rattey (1984, p. 991), together with considerable subsidence and sedimentation in the Faeroe-Shetland Trough, Møre Basin and Vøring Basin (but not the Rockall Trough) during the late Cretaceous. This suggests that a phase of opening or of intra-continental rifting had only just finished. Figure 7 shows an attempt to answer some of these problems.

Figure 7 is simply the anomaly 34 fit of North America to Europe of Kristoffersen (1978, fig. 6), with a shift in the position of Greenland (the justification for this alteration is discussed below). The figure shows that the pre-anomaly 34 'mid-Cretaceous' crust which opened the Bay of Biscay and the area south of the Charlie-Gibbs fracture zone correlates satisfactorily with the intrusion/opening phase which produced the S-shaped pattern of magnetic anomalies (Fig. 5) and which partially opened the Hatton-Rockall Basin.

West of the Goban Spur the pre-anomaly 34 oceanic crust shows weakly developed linear magnetic anomalies (Roberts and Jones 1979), which can be modelled as variations in magnetisation within the normally magnetised crust formed during the long Cretaceous normal geomagnetic polarity epoch (Scrutton

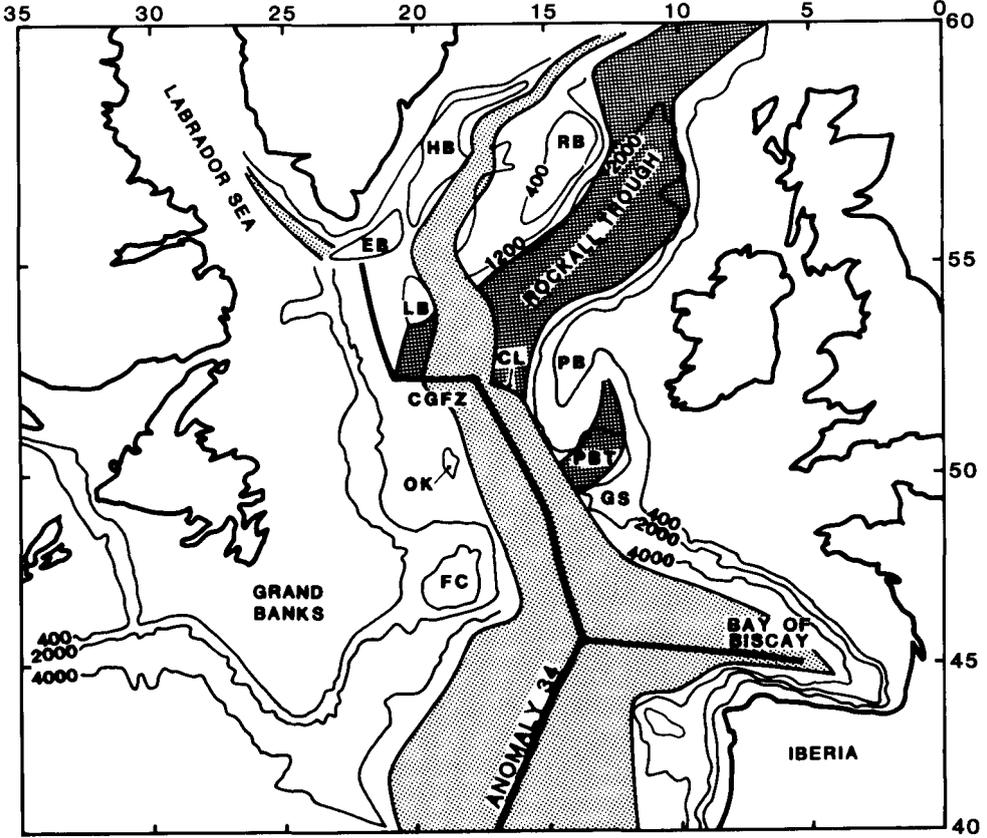


FIG. 7. North Atlantic reconstruction for anomaly 34 time (c. 80 Ma, early Campanian), redrawn from Kristoffersen (1978, fig. 6) with the fit of North America to Europe, and the location of anomaly 34 unchanged, but with Greenland some 100 km further south (see text). The 'mid-Cretaceous' opening phase (light stipple) corresponds to the partial opening of the Hatton-Rockall Basin, not the Rockall Trough as proposed by Roberts *et al.* (1981); (see Fig. 4 above), the older quasi-oceanic crust of which is shown by the coarse stipple. Note that this older strip terminates to the south at the Clare lineament, and is therefore inconsistent with the concept of a progressively northward-opening Atlantic. CGFZ—Charlie Gibbs fracture zone; EB—Edoras Bank; FC—Flemish Cap; GS—Goban Spur; HB—Hatton Bank; LB—Lorien Bank; OK—Orphan Knoll; PB—Porcupine Bank; PBT—Porcupine Bight; RB—Rockall Bank.

1985). North of the Charlie-Gibbs fracture zone the anomalies bend to the NW, and are of higher amplitude. However, they can still be interpreted as due to linear zones of intrusion and extrusion (Scrutton and Bentley's (1988) Barra Volcanic Ridge System) of mid-Cretaceous age.

There was an incipient triple junction complex developing at around 55°N, 20–23°W, incorporating minor motions of the Edoras and Lorien Banks, as the Labrador Sea began to open, but spreading north of 52°N then shifted wholly

west, to initiate the Charlie-Gibbs fracture zone, at anomaly 34 time. The earlier opening north of 57°N or so in the Hatton-Rockall Basin was probably very limited, as Figure 7 implies, and is represented further north by a phase of intra-continental extension, the evidence for which has been mentioned above.

In summary, the 'mid-Cretaceous' spreading/opening/rifting phase by-passed the Rockall Trough, which was already in existence. The Clare lineament (Figs. 4 and 7) represents a precursor of the Charlie-Gibbs fracture zone (Bentley 1986), and now juxtaposes the mid-Cretaceous crust with the older crust of the Rockall Trough proper. Seismic stratigraphic evidence from the south indicates that the Trough is probably of pre-Cretaceous age. If the Rockall Trough is indeed part of a continuous strip of 'proto North Atlantic' crust (Fig. 2), then the seismic stratigraphic evidence from the areas north of 60°N or so points to a pre-Cretaceous, and possibly even pre-Jurassic, age.

THE ARGUMENTS FOR LATE PALAEOZOIC SPREADING

The importance of the quiet magnetic zones bordering the North Atlantic continents was recognised early on (Heirtzler and Hayes 1967), and it was speculated that the sea floor beneath these zones could have developed during the Permian 'Kiaman interval' of reversed geomagnetic polarity. The quiet magnetic zone, extending northwards through the Rockall Trough (Roberts 1970) into the eastern Norwegian Sea (Avery *et al.* 1968), east of the magnetically striped Tertiary sea floor (Fig. 2), is still an important constraint on the permissible ages of early sea floor spreading in the proto North Atlantic, although it also allows the alternative hypothesis of intra-continental subsidence (Talwani and Eldholm 1972).

Development of the arguments for late Palaeozoic spreading

Bott and Watts (1971) proposed that the Rockall and Faeroe-Shetland Troughs formed in Permo-Triassic time, contemporaneous with the initiation of spreading between North America and Africa. They also mentioned several possible mechanisms whereby normal-faulted sedimentary basins could form on the shelf either "during the initial split" or later. They thus proposed a way of inferring the initiation of spreading from the effects of the relative horizontal tension on the adjacent shelf, in other words, what is nowadays referred to as the rift phase of plate separation and passive margin formation. However, there remains the practical difficulty of identifying the start of a rifting phase and, in a complex shelf area like NW Europe, of correctly associating it with the formation of a particular passive margin. Russell (1973) tried to relate changes in the tensional stress regime of northern Britain to the inception of spreading in the Rockall Trough at the end of the Carboniferous. He also introduced the idea of associating tholeiitic magma

generation in the late Carboniferous with lithosphere separation; a concept readily acceptable in the British Isles, given the obvious analogous association of tholeiitic magmatism and the start of sea floor spreading in the early Tertiary.

Later, Russell (1976) developed a fuller analogy with the younger tectonic history of the Central Atlantic. He proposed that end-Carboniferous lithosphere separation, leading to spreading in the Rockall Trough during the early Permian, provided a more consistent explanation of tectonic and magmatic events in the North Atlantic region than the Cretaceous opening, which was by then the orthodox view. A new feature of Russell's (1976) hypothesis was the inference that the late Permian (Zechstein) seaway, between east Greenland and NW Europe (Callomon *et al.* 1972), implied the existence of an oceanic rift. In particular, the contemporaneous incursion of the distinct Bakevellia Sea into NW England from the Hebridean area (Pattison *et al.* 1973) implied that a seaway existed to the west of Scotland, as well as between east Greenland and Norway.

Russell and Smythe (1978) elaborated on the opening geometry of the supposed 'proto North Atlantic' rift suggested by Russell (1976), by plotting their reconstruction on an oblique Mercator projection (cf. Le Pichon 1968). This demonstrated graphically the feasibility of opening the North Atlantic before the Central Atlantic, using a transform-rift-transform geometry. They also suggested that the supposed Permian age of the Rosemary Bank (Scrutton 1971) was a constraint on the minimum age of the Rockall Trough.

The conventional explanation (in contrast to Russell's (1973) hypothesis) for the late Carboniferous tholeiitic activity in northern Britain, and also for the Oslo Graben, was that it was a by-product of the Hercynian orogenic collision taking place simultaneously 500 km further south (see, for example, Francis 1978). Russell and Smythe (1983) accepted that this could be so, but postulated that the effect was indirect. They suggested that the proto North Atlantic rift was a by-product of the diachronous Hercynian-Alleghenian collision forming Pangaea, while the tholeiitic magmatism of NW Europe, with its peculiar arcuate trend, was, in turn, a by-product of rifting to the west and north. Their rifting history and explanation for the 90° swing in the trend of the intrusives has been tested quantitatively by finite element modelling of the stresses acting on the European plate during the rifting/intrusion phase (Russell *et al.*, submitted).

In parallel with the development of the quantitative late Palaeozoic rift model discussed above, Haszeldine (1984) undertook a synthesis of regional palaeogeographic evidence for and against rifting in the North Atlantic region during the late Palaeozoic. He concluded that the evidence from Upper Carboniferous rocks is consistent with a rift hypothesis, but not with the rival "megashear" or subduction hypotheses. He tried to date the rifting/opening in the Rockall region by assuming that the dextral movement on the transform fault zone bounding the south end of the proto North Atlantic rift (presumed to run through the Biscay-Pyrenees area) was marked by similar displacements on faults bounding

the small 'fosse' basins in Cantabria, northern Spain. Movement on these ceased in latest Stephanian time. Haszeldine (1984) therefore suggested that the entire rifting/opening episode forming the Rockall Trough occurred during the late Carboniferous, and did not continue through the early Permian, as Russell and Smythe assumed.

Discussion of the late Palaeozoic hypothesis

There is no need to scrutinise arguments for late Palaeozoic spreading in detail, because they all have the same overall weakness. They all point (indirectly) to a major rifting episode in the late Carboniferous, but provide no direct evidence for the nature, width, or even the location of the rift. All the geological evidence presented in support of late Palaeozoic opening is equally consistent with a 'Rockall-Faeroe' rift zone, perhaps only 50 km wide, as it is with a supposed late Palaeozoic strip of oceanic crust more than 200 km across. Even the numerical modelling of the European plate (Russell *et al.*, submitted), suggesting that its NW margin became completely decoupled from the Greenland plate, may only indicate that the continental lithosphere had been rifted to the stage where horizontal tensile stresses could not be transmitted across the rift. Whereas this inference leads to the suggestion that sea floor spreading might have been about to start, it does not follow that 200 km or more of spreading occurred immediately after the rifting phase.

Another serious objection to the late Palaeozoic opening hypothesis is the fact that the pre-Upper Cretaceous sedimentary infill of the Rockall Trough is only 2.5–3 km thick. Although the extrapolation of sediment accumulation rates is highly imprecise (as discussed above), this thickness implies a remarkably low average rate of deposition during the 180 million years or so that the Trough is supposed to have been in existence prior to the late Cretaceous.

Scrutton (1986) argued that sea floor spreading normally follows the youngest identified rifting event, which in the Rockall region he states is of late Jurassic—early Cretaceous age. He concluded that the Rockall Trough is therefore younger than early Cretaceous. Although his reasoning may well apply at those passive margins where there is a single, well defined phase of opening, the problem in applying it here is that there have been several phases of spreading in and around the region, and several phases of rifting. However, Scrutton's argument highlights the assumption behind the 'early opening' arguments, that because the late Palaeozoic phase was the most important one, it is therefore most likely to have been the precursor of spreading. The link between the well-documented late Palaeozoic rifting phase and the postulated late Palaeozoic spreading/opening phase would remain highly speculative, were it not for the Rosemary Bank, which sets a constraint on the age of the Rockall Trough as Triassic or older.

DISCUSSION

Outstanding problems

In the Introduction it was pointed out that the age of the Rockall Trough is more than just a local problem in determining the evolution of the NE Atlantic. Answers to a number of important questions are, in fact, dependent on the age. These questions can be summarised under three headings—global, regional and local:

Global problems include:

(1) Do tholeiitic dyke swarms indicate the initiation of a spreading phase, or are they just evidence of local intra-continental tension, with no wider significance?

(2) Are the seaward-dipping reflector wedges seen at many passive margins underlain by thinned continent, or are they wholly or partly a product of sea floor spreading?

(3) Did the Central and North Atlantic open progressively from south to north (in which case a post-early Cretaceous Rockall Trough fits the picture)?

(4) Do new mid-ocean ridges start by splitting apart some old continental lithosphere, rather than by occupying the site of an earlier, aborted spreading ridge?

(5) Do extension events on a continental shelf correlate in any systematic way with spreading phases nearby?

Regional problems include:

(6) How much (if any) of the proto North Atlantic rift zone (Fig. 2) is oceanic? How, if at all, do phases of North Atlantic opening/rifting correlate with the rift phases of the basins west of the British Isles, and with those of the North Sea and east Greenland?

(7) Is the late Palaeozoic North Atlantic rifting (and ?opening) a consequence of diachronous collision episodes further south culminating in the Hercynian-Alleghenian orogeny?

(8) What is the age and subsidence history of the seamounts in the Rockall and Faeroe-Shetland Troughs? Do they sit on a relict mid-ocean ridge? Have they been reactivated? Do their ages correlate with the intrusive episodes on the adjacent shelves?

Local problems include:

(9) What is the precise age of the 'mid-Cretaceous' spreading phase which partially opened the Hatton-Rockall Basin? Is this phase truly oceanic or is it in part intra-continental?

(10) What are the details of the spreading geometry of the area between the SW Rockall Plateau, the Goban Spur, and the Grand Banks, with the numerous microcontinental fragments in between?

(11) Where are the continent-ocean boundaries located around the Rockall Trough region?

The origins of some of these questions have been indicated above; the relevance of the others is discussed below.

Importance of the sequence of opening

The first opening between the Goban Spur (Europe) and the Grand Banks (Greenland–North America) is part of the same phase which began to open the Hatton–Rockall Basin (Fig. 7), according to the magnetic anomaly evidence discussed in detail above. The Rockall Trough (and Porcupine Bight) were both fully open before this phase started. It follows that the concept of the Atlantic splitting progressively northwards from the Central Atlantic is untenable, since there is no oceanic crust (nor extensively thinned continental crust) of the required age and width (c. 200 km) south of 52°N (Fig. 7) to correspond to that in the Rockall Trough.

The reconstruction shown in Figure 7 for anomaly 34 time south of 52°N is essentially the same as that calculated by Kristoffersen (1978), and also corresponds to the opening geometry postulated more recently by Masson and Miles (1984). However, to the north it is fundamentally different, in that the Rockall Trough is shown as open, whereas Kristoffersen's reconstruction shows it closed. The reason for this difference is that in Figure 7, seaward dipping basalt reflector wedges, now recognised at many passive margin localities around the Atlantic, have been used as a new criterion for achieving a refit. The method of identifying the continent–ocean contact beneath them is described by Smythe (1983).

The quality of fit, and the consistency or otherwise of the geometric opening history derived from it, can be regarded as a test of my interpretation of the seaward dipping reflectors as a product of 'subaerial sea floor spreading' (Smythe 1983). This explains the reference above to the Rockall Trough age problem as having a bearing on the global problem number (2) above, of whether the dipping reflector wedges are a product of sea floor spreading or of continental attenuation. The outcome of the test, as Figure 7 suggests, is that a consistent geometric refit and opening history can indeed be devised by assuming that the seaward-dipping reflector zones are essentially oceanic in origin (White *et al.* 1987). In contrast, the great width of the zones of seaward-dipping wedges between SE Greenland and the Hatton Bank leads to problems in achieving a satisfactory geometric reconstruction, if one assumes that they are underlain by attenuated continental crust.

If the multi-stage opening history implied by Figure 7 is valid, the only feasible geometric solution for the abrupt southerly termination of the proto North Atlantic rift (the coarser stipple in Figure 7) is to adopt something like the transform-ridge-transform geometry of Russell and Smythe (1978); this is irrespective of whether the Rockall Trough and its northerly continuation is underlain by truly oceanic, or by attenuated continental, crust. In either case, the 200 km or more of opening between the European plate and the Rockall Plateau (part of the Greenland–North America plate at the time) has to be transformed out

to the SE and effectively lost in the poorly known plate geometry of the Tethys. Correlations of Precambrian outcrops across the closed Labrador Sea preclude the possibility of such a large transform motion being accommodated in that region NW of the southern Rockall Trough. Adoption of this kind of opening geometry implies:

(1) that the proto North Atlantic rift developed first, and independently of the other Mesozoic phases of spreading in the Central and North Atlantic, and

(2) that it is therefore geometrically feasible for the rift to have opened at any prior time, as far back as the formation of Pangaea in the late Palaeozoic.

CONCLUSIONS

It has not been necessary to analyse at length the evidence for the origin of the thin, deeply buried crust of the Rockall Trough, as the question of its age is largely independent of the problem of its origin. The latest evidence, reviewed above, indicates a quasi-oceanic origin for the Rockall Trough. However, reference to 'opening', although normally implying a sea floor spreading origin, can also be understood to include (considerable) continental attenuation, as for example in the Vøring Basin or the Hatton-Rockall Basin. Now that large horizontal displacements of the continental lithosphere are believed to be necessary to form extensional basins, it is quite reasonable to talk, for example, about the 'opening' of the North Sea. Use of either meaning of the imprecise phrase 'opening' is possible in the synthesis which follows.

The required pre-drift geometric fit

This is very tight, and takes us back to the classic Bullard *et al.* (1965) fit, which was also a tight reconstruction, contrasting with the various published refits of the 1970s, which were comparatively loose. The loose fit of Le Pichon *et al.* (1977) is probably the most frequently cited. The opening history outlined below depends very much on the use of a new, tight reconstruction to constrain the various opening phases. The justification for a tight fit is partly the use of seaward dipping basalt reflector wedges to identify continent-ocean boundaries (Smythe 1983, White *et al.* 1987), and partly the restoration of attenuated continental crust at passive margins to its presumed pre-rifting thickness and aerial extent. Details of the new reconstructions used here are, however, beyond the scope of this review.

Late Palaeozoic rifting

Evidence for an important phase of late Carboniferous rifting is now good; it includes the systematic pattern of tholeiitic dykes and intrusions of the northern Britain-North Sea-Oslo Graben region (Russell 1976, Russell and Smythe 1978,

1983). The tensile stresses inferred from these can be quantitatively modelled in terms of a proto North Atlantic rift (Russell *et al.*, submitted). There is also the recent exploratory drilling evidence of late Carboniferous freshwater and marine sediments west of Britain and in the Porcupine Bight (Haszeldine 1984, Croker and Shannon 1987, Tate and Dobson 1989), in addition to the classic half-graben-controlled rift geology of onshore east Greenland. Stein (1988) has synthesised new evidence of Carboniferous rifting west of Scotland. The importance of the rifting phase is now generally acknowledged, as signified, for example, by its prominence in the most recent synthesis of Ziegler (1982). As mentioned above, the evidence for the post-rifting phase marine incursion from the Arctic *via* a route west of Britain in the late Permian is now also strong.

The four phases of opening

Phase 1. This comprised the formation of a contiguous strip of crust including the Rockall Trough, Faeroe-Shetland Trough, Møre Basin and inner Vøring Plateau (Fig. 2). This is some 200–250 km wide in the south, but terminates abruptly at around 52°N, although the Porcupine Bight further south (Fig. 7) presumably developed at the same time. As discussed above, it is only an assumption—‘rift to drift’—that opening followed on from the rifting without a significant pause.

The NW–SE opening in the southern part of this proto North Atlantic rift was presumably transformed out into the Tethys along a closed Bay of Biscay lineament—the ‘proto Bay of Biscay’ transform fault (Russell and Smythe 1978). Stratigraphic evidence from northern Iberia suggests, indirectly, that this transform fault was active only until the Stephanian, which would put the entire rifting-opening episode into the late Carboniferous (Haszeldine 1984). However, if we look instead at the global picture of the formation of Pangaea, the transform fault may have also been the main lineament along which the early-to-mid Carboniferous Hercynian orogenic collision of western Europe was decoupled from the slightly younger Alleghenian orogeny to the SW, involving the collision of Africa into the North America. Russell and Smythe (1983) suggested that the opening of the proto North Atlantic could have been a by-product of this diachronous collision, which terminated at the end of the early Permian. If this global view is correct, it would suggest that the opening phase spanned Stephanian to early Permian time. This time-span disposes of the trivial objection to the early rifting/opening hypothesis raised recently by Leeder (1988), that the tholeiitic intrusion episode should now be placed in the early Permian, and not in the Stephanian, due to a revision of the Carboniferous-Permian boundary date.

These conjectures are all consistent with the important stratigraphic constraint that the minimum age for the opening of the Rockall Trough is pre-Cretaceous, and probably pre-Jurassic. If the late Permian to Triassic age of the Rosemary

Bank recently inferred by Wood (1988) from palaeomagnetic remanent vector modelling is to be believed, then the development of the Rockall Trough must have occurred prior to 200 Ma.

Phase II. This phase, approximately mid-Cretaceous in age, by-passed the Rockall Trough, but partially opened up the Hatton-Rockall Basin. The new crust formed is shown by the light stipple in Figure 7. In general terms this phase is contemporaneous with, or slightly younger than, the opening of the Bay of Biscay, and it also comprises the first opening between the Goban Spur and Flemish Cap, i.e. between North America (south of the Labrador Sea) and Europe. Such stratigraphic evidence as has been cited in support of a Cretaceous age for the Rockall Trough, and which has not been completely invalidated, in general applies to this phase of spreading. For example, global interpretations of the North Atlantic such as those of Hanisch (1984) and Price and Rattey (1984), which draw, in particular, upon the evidence of Cretaceous rifting and subsidence in the Norwegian Sea, are equally consistent with this Phase II as with a supposed Cretaceous opening of the Rockall Trough.

Phase III. Just before anomaly 34 time (80 Ma), Phase II spreading was modified to begin opening the Labrador Sea, with the inception of the Charlie-Gibbs fracture zone (Fig. 7). Apart from the tighter pre-drift geometry, with a more southerly initial position of Greenland relative to North America, this phase is essentially as described by Srivastava (1978).

Phase IV. At around 54–55 Ma, just before anomaly 24B time, spreading began between Greenland and NW Europe again, but this time the location of the oceanic rift was west of the Faeroes and Hatton Bank. The early stages of this phase involved the completion of opening of the Hatton-Rockall Basin, along with small, but not insignificant, independent motions of the separate fragments between the Faeroe Plateau and Hatton Bank (see Fig. 2). An interesting feature of this initial fragmentation phase is that Lousy Bank (Fig. 3) may have moved NW with Greenland for some 50 km or more before being left behind. This implies that the crust around the Bank, in the NW of the Rockall Trough, may be quasi-oceanic, and of Eocene age, i.e. coeval with the eruption of the Tertiary basalts which now subcrop over the northern Trough area (Fig. 3). Thus a small corner of the Rockall Trough is neither Palaeozoic nor Cretaceous, but is of early Eocene age.

There was a triple junction south of Greenland which persisted until the cessation of spreading in the Labrador Sea just after anomaly 13 time (35 Ma). Since then, spreading has continued between Greenland and Europe to open up the North Atlantic as we know it today.

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