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INTERNAL DOCUMENT 196

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THE DEVELOPMENT OF MESOZOIC SEDIMENTARY BASINS AROUND THE MARGINS OF THE NORTH ATLANTIC AND THEIR HYDROCARBON POTENTIAL

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Internal Document No. 196

December 1983

NATURAL ENVIRONMENT RESEARCH COUNCIL
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Work carried out under contract to the Department of Energy

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ABSTRACT

The distribution of Mesozoic basins around the margins of the North Atlantic has been summarised, and is discussed in terms of a new earliest Cretaceous palaeogeographic reconstruction for the North Atlantic area. The Late Triassic-Early Jurassic rift basins of Iberia, offshore eastern Canada and the continental shelf of western Europe are seen to be the fragments of a formerly coherent NE trending rift system which probably formed as a result of tensional stress between Europe, Africa and North America. The separation of Europe, North America and Iberia was preceded by a Late Jurassic-Early Cretaceous rifting phase which is clearly distinct from the earlier Mesozoic rifting episode and was little influenced by it. The two periods of rifting are separated by a middle Jurassic tectonically quiet period. The distribution of hydrocarbon finds within the rift basin suggests that the best prospects are in areas where the two rifting episodes are superimposed. Lack of mature source rocks in the later Mesozoic rift basins and an unfavourable temporal relationship between hydrocarbon generation and tectonic activity in the early Mesozoic basins are proposed as explanations for the apparently poor hydrocarbon prospectivity of large areas of the Mesozoic basins.

INTRODUCTION

A number of authors have proposed that the evolution of the North Atlantic Ocean north of the Newfoundland Ridge - Azores - Gibraltar boundary began with a Late Triassic rifting phase (e.g. Pegrum and Mounteney, 1978; Montadert et al., 1979; Boillot et al., 1979a, b). This is based primarily on the identification of red beds and evaporites of Late Triassic and Early Jurassic age in rift basins on the Grand Banks and along the western margins of Europe (Jansa and Wade, 1975; BRGM et al., 1974; Wilson, 1975; Jansa et al., 1980; Naylor and Shannon, 1982, Ziegler, 1982). This rifting phase was followed by a period of relative quiescence before the main Late Jurassic and Early Cretaceous rifting which preceded the initiation of sea-floor spreading between North America, Europe and Iberia (e.g. Boillot et al., 1979a, b; Montadert et al., 1974, 1979; Roberts et al., 1981; Masson et al., in press).

The purpose of this paper is to compare the distribution of the Late Triassic rift basins with those formed during the Late Jurassic and Early Cretaceous, to assess the relationship between these rifting episodes and the Mesozoic sea floor spreading history of the North Atlantic, and to evaluate the correlation between basin age and hydrocarbon potential. This has been achieved by plotting the relevant geological data on a revised North Atlantic reconstruction. Note that we are discussing rift basins only and that we are not implying that lateral connections between these basins, in the form of epicontinental seas, did not exist.

THE NORTH ATLANTIC RECONSTRUCTION

The reconstruction used in this paper (Fig. 1) concentrates on the relative palaeopositions of the European, Iberian and North American plates. It is based on the magnetic anomaly identification of Kristoffersen (1978), augmented by a considerable volume of both published and unpublished magnetic data held by the Institute of Oceanographic Sciences. Particular attention has been devoted to the identification of an ocean-current boundary (OCB) at the margin of each continental block, in order to constrain, as far as possible, the reconstruction to the 'time of initial opening'. A full description of this reconstruction will be published elsewhere (Masson and Miles, in press; Miles and Masson, in prep.).

The oldest magnetic lineation which can be clearly mapped in the North Atlantic is anomaly 34 (Kristoffersen, 1978) although some doubt exists as to its identification in the Bay of Biscay. Reconstruction to anomaly 34 time (84 Ma) is relatively straightforward; beyond 84 Ma to the 'time of initial opening' the reconstruction depends on OCB identification, with limited supplementary geological and geophysical constraints. For Europe, the OCB is well-defined in the Bay of Biscay and west of Goban Spur (Montadert et al., 1979; Masson et al., in press). For North America, it is also reasonably constrained from Flemish Cap northwards (IOS unpublished data). This allows an accurate North America - Europe reconstruction which is also constrained by the proposed spreading direction in the southern Rockall Trough (Roberts et al., 1981).

To find the initial position of Iberia, it is first necessary to compensate for the Tertiary convergence between Iberia and Europe which gives rise to the overlap between Iberia and North America on the anomaly 33 reconstruction of Kristofferson (1978) (Grimaud et al., 1982). This was achieved by a 6.4^{o} clockwise rotation of Iberia around a pole at $34\frac{1}{2}^{o}$N, $19\frac{1}{2}^{o}$W (Masson and Miles, in press; Grimaud et al., 1983). From its position at anomaly 34 time, defined primarily on the basis of North Atlantic anomaly 34 coincidence, Iberia was then rotated 32^{o} clockwise to close the Bay of Biscay and the Iberian-Newfoundland Basin (Masson and Miles, in press; Miles and Masson, in prep.). This rotation was controlled by the well-defined OCB in the northern Bay of Biscay (Montadert et al., 1979), the OCB in the Newfoundland Basin proposed by Sullivan (1983) and a magnetic anomaly lineament west of Iberia which is also likely to mark the position of the OCB (Masson and Miles, in press). Note that a 32^{o} clockwise rotation also satisfies the palaeomagnetic evidence (Pitman and Talwani, 1972).

The new reconstruction places Galicia Bank east of Flemish Cap, rather than to the south of it as suggested by, for example, Le Pichon et al. (1977) or Lefort (1980). We can find no evidence to support their palaeoposition of Galicia Bank which necessitates its movement northwards relative to Iberia during the early evolution of the North Atlantic. We note that our reconstruction gives rise to an apparent 'gap' between the south-eastern Grand Banks and Iberia. However, this is a phenomenon common to all realistic reconstructions of the North Atlantic region (e.g. Le Pichon et al., 1977; Lefort et al., 1980). Le Pichon et al. (1977) have suggested that this area might be composed of either older (?Hercynian) ocean floor or thinned and subsided continental crust. The width of the 'gap' might also be lessened if allowance were made for a spreading centre propagating from the south during the late Lower Cretaceous, as suggested by Sullivan (1983) and Masson and Miles (in press).

LATE TRIASSIC-EARLY JURASSIC RIFT BASINS

Rift basins containing a characteristic redbed and evaporite sequence of Triassic and Lower Jurassic age (Jansa et al., 1980) have been identified on the Grand Banks (Jansa and Wade, 1975), west and south-west of the British Isles (Pegrum and Mounteney, 1978; Reeves et al., 1978; Kammerling, 1979; Naylor and Shannon, 1982; Ziegler, 1982), in western Portugal (Wilson, 1975) and in south-west France (Winnock, 1971; BRGM et al., 1974) (Fig. 2). Some authors have tended to label the redbed sequence "Permo-Triassic" following classical British stratigraphic nomenclature (e.g. Evans et al., 1981; Naylor and Shannon, 1982) but there are, as yet, no published examples of unequivocal Permian dates, and the formation of the rift basins probably began in Triassic times as suggested by Pegrum and Mounteney (1978) and Jansa et al. (1980). Redbed and evaporite deposition was followed, in the Early and Middle Jurassic, by normal marine sedimentation with deposition of shales, carbonates and sandstones (Pegrum and Mounteney, 1978).

Superposition of the distribution of these 'Lower Mesozoic' basins on our revised reconstruction clearly demonstrates that the scattered basins are the components of a formerly coherent rift system. The Lusitanian Basin (Fig. 2), traced offshore by Rehault and Mauffret (1979), is continuous to the north-east with the Western Approaches Basin (Figs. 2, 3). This correlation is enhanced by the occurrence of a thick pre-latest Jurassic sediment sequence in the vicinity of DSDP sites 400 and 401 on the North Biscay margin (Montadert et al., 1979; Fig. 2). Similarly, the Porcupine Basin (Fig. 2) is a northeastward continuation of the basin complex on the Grand Banks. In this case, the correlation is made through one or possibly two previously undescribed Lower Mesozoic basins in the region between Flemish Cap and Orphan Knoll (Fig. 2).

These have been identified from seismic reflection data by comparison with similar data across known Lower Mesozoic basins on the Grand Banks (L.M. Parson, pers. comm).

However, there is little evidence for a south-westerly continuation of Triassic or Lower Jurassic age to the Bristol Channel - Celtic Sea - Fastnet basin complex (Fig. 2). Published maps of this basin complex (e.g. Pegrum and Mounteney, 1978; Robinson et. al., 1981; Naylor and Shannon, 1982) show that it does not extend to the shelf edge south-west of Ireland. Boillot et al. (1979a) have speculatively interpreted a "lower Mesozoic" basin west and south-west of Galicia Bank, directly to the south-west of the Fastnet Basin. However, this speculation is not confirmed by dredge data which seems to indicate that Late Jurassic rocks directly overlie Palaeozoic basement (Boillot et al., 1979a).

The south-west truncation of the Celtic Sea-Fastnet Basin complex appears to be controlled by north-westerly trending strike-slip faults (Robinson et al., 1981). This strike-slip direction is clearly important in the Early Mesozoic evolution of the North Atlantic area (Lefort, 1980 and in press) and has been detected in the Porcupine Basin (Lefort and Max, 1983), Bristol Channel Basin (Kammerling, 1979), Kish Bank Basin (Jenner, 1981) and Western Approaches Basin (Ziegler, 1982), as well as in the Celtic Sea-Fastnet Basin complex. It might also be invoked to explain the configuration of the offshore extension of the Lusitanian Basin as proposed by Rehault and Mauffret (1979), although Boillot et al. (1979) preferred a NE-SW offset direction in this area. It is not clear to what extent such an offset direction occurs in the Grand Banks area.

Lefort (1980 and in press) has noted the possible association between the NW-SE strike-slip direction and the postulated Biscay-Labrador transform fault which Laughton (1972) considered to be an important element in the early history of the North Atlantic. However, there is no direct evidence for a Biscay-Labrador fault and its occurrence need only be postulated if the rifting and possible sea-floor spreading in the Rockall Trough are older than the rifting between Goban Spur and Flemish Cap (Fig. 1), which is now known to be late Lower Cretaceous in age (Masson et al., in press). Postulated ages for the formation of the Rockall Trough vary between Permian (Russell and Smythe, 1978) and early

Late Cretaceous (Roberts et al., 1981) although no conclusive evidence has yet been produced. We note that the Rockall Trough is parallel to other Lower Mesozoic rift basins in the North Atlantic area, and that the NW trending transform direction proposed by Roberts et al., (1981) in the southern Rockall Trough is parallel to the NW strike-slip direction observed in other basins on the western European shelf. However, Ridd (1981) has shown that an important rifting event west of the Shetland Isles ended around the end of the Lower Cretaceous. This is compatible with Lower Cretaceous rifting and possible Albian to early Late Cretaceous sea-floor spreading in Rockall Trough, and suggests that this area had a similar history to that of Goban Spur (Masson et al., in press). Accordingly, we cannot support the proposed Biscay-Labrador transform fault although it is clear, at least on the European continental shelf, that a pervasive, NW trending, predominantly sinistral strike-slip fault system was operating during the formation of the Lower Mesozoic basins. The magnitude of these strike-slip motions appears to have been small, with the main effect being the transfer of extensional movement between basins. For example, the south-west truncation of the Celtic Sea and Fastnet Basins might be compensated for by the apparent southward increase in extension in the Porcupine Basin (Buckley and Bailey, 1975). North-west trending strike-slip faults are clearly documented in this area (Fig. 2; Robinson et al., 1981; Lefort and Max, 1983).

The remaining areas of doubt concerning the distribution of Lower Mesozoic basins in the North Atlantic area all occur along the margins of Iberia. To the north, it has been proposed by Winnock (1971) and Montadert et al. (1974, 1979) that the proto-Bay of Biscay area was the site of a Triassic rift system, linking the Aquitaine Basin with the Trevelyan Escarpment region where a thick pre-late Jurassic sediment sequence is known (Fig. 2). However, our Lower Mesozoic reconstruction (Fig. 3) shows the Trevelyan Escarpment area to be part of a NE-SW trending rift system at this time. Furthermore, a NE-SW rift axis has also been proposed in the Aquitaine Basin during the Late Triassic (Biju-Duval et al., 1977). We suggest, therefore, that two distinct NE-SW trending basins crossed the proto Bay of Biscay area during the Lower Mesozoic and that a deep E-W trending rift basin was not formed until the Late Jurassic-Early Cretaceous, as is documented onshore in the Parentis Basin (Dardel and Rosset, 1971) which we propose is the true onshore extension of the E-W trending Bay of Biscay rift-system (Fig. 4). Further evidence for a Late Jurassic-Early Cretaceous age for the rifting in Biscay comes from the Armorican marginal basin, the deeper sediment fill of which is "probably mainly of Lower Cretaceous age" (Montadert et al., 1974). It is not clear, however, whether a shallow NE-SW seaway connected the Aquitaine Basin with the Western Approaches/Lusitanian Basin complex during the Lower Mesozoic or whether this area was the site of a NE trending basement ridge linking the Hercynian massifs of Iberia and Brittany (Fig. 3).

The largest area of uncertainty in the Lower Mesozoic reconstruction is the apparent 'gap' between Iberia and Newfoundland. Various authors have interpreted this region, which includes the Tagus Abyssal Plain, as being underlain by thinned and subsided continental crust (e.g. Le Pichon et al., 1977; Sullivan, 1983), but there is no data relating to the distribution of possible Lower Mesozoic sediments. As discussed previously, the present authors are sceptical regarding evidence for possible Lower Mesozoic sediments west and south-west of Galicia Bank (Boillot et al., 1979a). A full description of the plate tectonic history of this region will be presented elsewhere (Masson and Miles, in press).

MIDDLE JURASSIC QUITE PERIOD

Several authors who have worked in the Aquitaine Basin and around the margins of Iberia note that the Late Triassic-Early Jurassic and Late Jurassic-Early Cretaceous periods of active rifting are separated by a 'middle Jurassic' tectonically inactive period, although this term is not well-defined (Winnock, 1971; BRGM, 1974; Boillot et al., 1979a; Montadert et al ., 1979; Roberts et al., 1981).

The middle Jurassic tectonic quiet period is best seen in the Aquitaine Basin where a thin, uniform succession of shallow water carbonates was laid down between lower Bathonian and lower Kimmeridgian times (Winnock, 1971; BRGM, 1974). There is no evidence for the strongly differential sedimentation patterns which dominate in Triassic-Liassic time and from the Upper Kimmeridgian onward (BRGM et al., 1974 plate 1).

Evidence for a middle Jurassic quiet period on the northern margin of the Bay of Biscay (Montadert et al., 1979; Roberts et al., 1981) appears to be based entirely on a westward extrapolation of the Aquitaine Basin data. However, since we have shown that the Aquitaine Basin and the Bay of Biscay may not have formed a continuous rift basin prior to the Late Jurassic (Figs. 2, 3) the validity of this extrapolation is obviously suspect.

A large volume of geological data is available concerning the basins on the continental shelf south-west of the British Isles where it is clear that the Middle Jurassic saw a slowing down of basin-forming tectonic activity over most of the area. In the Bristol Channel and Fastnet Basins, thick Triassic and Lower to lower Middle Jurassic sediments are followed by the patchy development of a regressive Upper Jurassic facies (Kammerling, 1979; Robinson et al., 1981). Similarly, in the Celtic Sea Basin, an Upper Jurassic section including "appreciable quantities" of non-marine sediments unconformably overlies a middle Jurassic sequence (Naylor and Shannon, 1982). In the Porcupine Bank, and perhaps further afield at DSDP Site 111 on Orphan Knoll, Middle Jurassic sediments of continental facies may also represent a regressive facies which corresponds to a cessation of fault-controlled basin subsidence (Ziegler, 1982; Laughton, Berggren et al., 1972).

In contrast to the above, the latter part of the Middle Jurassic and the early Late Jurassic was a period of major transgression in the Scotian Basin, to the south-west of the Grand Banks (Jansa and Wade, 1975; Fig. 3). These authors also suggested that transgression affected the eastern Grand Banks, even though an influx of clastic material was observed at this time; they explained the clastic input by proposing uplift of the source area. However, we would propose that the clastic influx is yet further evidence for a Middle Jurassic regression which apparently affected the marine basins in the North Atlantic north of the Newfoundland, Azores-Gibraltar boundary, although this regression was apparently contemporaneous with a transgression in the Scotian Basin.

LATE JURASSIC-EARLY CRETACEOUS RIFT BASINS

The main phase of rifting which preceded the initiation of sea-floor spreading in the North Atlantic north of the Newfoundland-Azores Fracture Zone is widely believed to have occurred during the Late Jurassic and Early Cretaceous (Montadert et al., 1974, 1979; Boillot et al., 1979a, b; Group Galice, 1979; Roberts et al., 1981; Masson et al., in press). Examination of the distribution of the Late Jurassic-Early Cretaceous rift basins, hereafter referred to as the Late Mesozoic basins, indicates that they occur almost exclusively on the present North Atlantic continental margins, and that in general they have margin parallel trends. This is in marked contrast to the consistent north-easterly trend of the Lower Mesozoic basins, which are thus often cross-cut by the later continental margins.

The later Mesozoic evolution of the margins of Iberia and the Bay of Biscay, including the Lusitanian and Aquitaine Basins, has been studied by Dardel and Rosset (1971), Montadert et al. (1974, 1979); Wilson (1975); Boillot et al. (1979a, b) and Group Galice (1979). An important rifting phase appears to have begun in the Oxfordian or Kimmeridgian and to have terminated in the Aptian. Thick Lower Cretaceous syn-rift sections may be present (e.g. Dardel and Rosset, 1979; Montadert, 1974; Group Galice, 1979). On the opposing Grand Banks margin, it is clear that an important tectonic rejuvenation occurred during the Late Jurassic-Early Cretaceous (Jansa and Wade, 1975) although little detailed geological data is available because a major erosional episode (Avalon Unconformity, Jansa and Wade, 1975) occurred on the Grand Banks shelf during the Early Cretaceous, and the deeper water areas of the margin are deeply buried under later sediments. Fault controlled sedimentation during the Early Cretaceous is however known from Flemish Pass (Fig. 4, McKenzie, 1981).

Further north, the main rifting phase between Goban Spur and Flemish Cap began somewhat later in Hauterivian or earliest Barremian time (Leg 80 Scientific Party, 1982; Masson et al., in press). It is not known to what degree this rifting episode affected the Porcupine Seabight or the Rockall Trough. A published cross-section through the Porcupine Seabight (Ziegler, 1982) suggests that the most intense period of faulting occurred within the "Permo-Triassic" and Jurassic, but that some faults remained active into the Early Cretaceous. In the Labrador Sea, earliest Cretaceous volcanics are followed by Hauterivian to middle Cenomanian sediments deposited in fault bounded basins (Umpleby, 1979), indicating a late Early Cretaceous rifting phase.

In detail, therefore, two distinct Late Mesozoic rift systems can be recognised; one between Iberia and Europe/North America which began to form in the Late Jurassic, and a second, between Europe and North America which was not initiated until the Early Cretaceous. This is likely to be related to the episodic northwards propagation of North Atlantic sea-floor spreading, which may have begun as early as the Hauterivan immediately north of the Newfoundland-Azores Fracture Zone and which had propagated into the Bay of Biscay by the Upper Aptian (Masson and Miles, in press, Fig. 5). A new spreading axis developed between Goban Spur and Flemish Cap during the Albian (Leg 80 Scientific Party, 1982; Masson et al, in press) - this may have penetrated northwards into Rockall Trough (Roberts et al., 1981). Yet another change in the spreading configuration occurred towards the end of the Cretaceous, when a spreading axis was initiated in the Labrador Sea (Srivastava, 1978).

DISCUSSION

The evidence cited in the previous sections clearly shows that the pre-seafloor spreading history of the proto-North Atlantic area during the Mesozoic can be divided into three main phases, namely a Late Triassic-Early Jurassic rifting phase, a 'Middle' Jurassic quite period and a Late Jurassic-Early Cretaceous rifting phase. The second rifting phase may itself be sub-divisible into a Late Jurassic-Early Cretaceous phase which rifted Iberia from Europe/North America and an Early Cretaceous phase which rifted Europe from North America.

On the western side of the Atlantic, geological similarities between the Scotian Basin and the basin complex on the Grand Banks clearly indicate that the Lower Mesozoic tensional episode is related to the initial rifting between Africa and North America (Jansa and Wade, 1975). When plotted on our reconstruction, the obviously coherent nature of the entire north-easterly trending Lower Mesozoic rift system strongly implies that the effects of the tensional episode which eventually resulted in the separation of Africa and North America extended at least as far north as the latitude of northern Britain. We note that the north-westerly 'transform' direction, particularly well-displayed off south-west Britian, (Fig. 3) is parallel to the initial direction of opening between Africa and North America as defined by Le Pichon et al. (1977) (Fig. 4). It is not entirely clear how the Aquitaine Basin fits into this overall picture, since its formation is likely to have been affected by tectonic events in the Tethys as well as in the proto-North Atlantic rift system (Biju-Duval et al., 1977; Ziegler, 1982).

The change to a less active tectonic regime which occurred just prior to or during the early part of the Middle Jurassic apparently correlates with the separation of Africa and North America, which can be dated between Sinemurian and Bajocian time (e.g. Pitman and Talwani, 1972; Jansa and Wade, 1975; Vogt and Einwich, 1979; Hinz et al., 1982). Lateral movement between Europe/North America and North Africa was accommodated by a transform fault along the southern margin of the Grand Banks (Auzende et al., 1970; Le Pichon et al., 1977) and tensional movements north of this transform apparently ceased. The regressive sediments deposited in many of the Early Mesozoic basins during the Middle and early Late Jurassic reflect the cessation of rifting, probably because decreasing subsidence rates permitted filling of the rift basins giving rise to shallow marine or even non-marine sedimentation.

During the Late Jurassic-Early Cretaceous, a new phase of rifting was initiated, firstly between Iberia and Europe/North America and later between Europe and North America. Only in the south, between Iberia and the Grand Banks, did these rifts follow the Early Mesozoic northeasterly trend. Further north, WNW-ESE trends predominated in the Bay of Biscay region, with NW-SE trends in the European-North American rift zone. Indeed, the Early Mesozoic rift basins had remarkably little influence on the later continental break-up.

HYDROCARBON POTENTIAL

Much of the area under discussion can be regarded as 'frontier territory' in terms of hydrocarbon exploration, since large parts of it lie far offshore, have water depths in excess of 200m and are subject to severe weather conditions. Consequently, much of it is little explored, although scattered hydrocarbon occurrences are known from the Labrador Sea in the north-west to the Parentis Basin in the south-east (Fig. 6).

The Parentis Basin, where exploration commenced as early as 1951, is as yet the only oil producing basin in the study area (Dardel and Rosset, 1971). However, commercial quantities of oil have recently been discovered in the Hibernia Field to the east of Newfoundland (McKenzie, 1981) and in the Porcupine Basin west of Ireland (Naylor and Shannon, 1982), and as yet unevaluated oil finds have been made in the Asturian Basin off north-west Spain and in the Celtic Sea basin (Soler et al., 1981; Naylor et al., 1982. Noroil, 1983). Commercial gas fields have also been discovered in the Celtic Sea and Northern Irish Sea Basins (Colley et al., 1981; Ebbern, 1981) while the Labrador Shelf Basin may also be a potential gas producer (Umpleby, 1979).

Despite the successes listed above, a very large number of dry holes have also been drilled, particularly in the Lower Mesozoic basins south-west of the British Isles and, with the exception of the Hibernian area (Fig. 6) in the Lower Mesozoic basins on Grand Banks. A comparison between the distribution of the various rift basins, their history of development, and the success or failure of hydrocarbon exploration is discussed below (Fig. 6).

The most obvious point to emerge from figure 6 is that most of the significant oil discoveries to date occur in areas of Lower Mesozoic rift basins which have been involved in the later Mesozoic rifting event. All these areas have a history of sedimentation beginning in the Triassic and extending through to the Tertiary, and are the sites of some of the thickest sedimentary accumulations on North Atlantic margins. For example, over 15 km of sediment may occur in the area of the Hibernia field (McKenzie, 1981) over 5 km in the Porcupine Seabight (Roberts et al., 1981; Naylor and Shannon, 1982) and over 8 km in the Parentis Basin (Dardel and Rosset, 1971). In contrast, the majority of the areas involved only in the later Mesozoic rifting phase, i.e. those areas underlying the present day continental slopes, are generally sediment starved (e.g. Roberts et al., 1981), although exceptions such as the Armorican marginal basin, wich contains thick lower Cretaceous syn-rift sediments (Montadert et al., 1974) and the Orphan and Labrador Sea

Basins, which contain exceptional thicknesses of Tertiary sediments (A.C. Grant, personal communication) are known to occur. Lack of deep burial and resulting thermal immaturity are thus likely to prevent generation of hydrocarbons in the majority of the later Mesozoic rift basins, although this has not yet been proven by drilling in many areas, principally on account of the great water depths in which a large proportion of these basins occur.

An exception is the Labrador Shelf Basin (distinct from and to the west of the Labrador Sea Basin) which has water depths of less than 400m (Umpleby, 1979). A number of wells have been drilled in this basin, three of which have detected significant amounts of gas. However, Umpleby (1979) points out that well temperature data suggests that even the most deeply buried Cretaceous sediments in the Labrador Basin should only be capable of generating oil. He suggests that the gas accumulations indicate higher heat flow in the geological past. This would presumably be related to Late Cretaceous-Early Tertiary sea-floor spreading in the Labrador Sea (Srivastava, 1978). However, he does not consider gas derivation from within the "economic basement", here consisting mainly of Pre-Cambrian metamorphics but with significant amounts of Ordovician and Carboniferous sediments. A Carboniferous gas source has been considered a possibility in the Celtic Sea (Naylor and Shannon, 1982) and is highly likely for the Morecambe Gas Field in the North Irish Sea Basin, where the Permo-Triassic basin fill has virtually no source rock potential, indicating that the gas source must be located in the underlying Carboniferous.

Lack of deep burial cannot be cited as a reason why no significant hydrocarbon finds have been made in the purely Lower Mesozoic basins on the Grand Banks, and, with the exception of the North Celtic Sea graben (Naylor and Shannon, 1982), in the Lower Mesozoic Basins south-west of the British Isles. Sediment thicknesses reach 6 km on the Grand Banks (Jansa and Wade, 1975) and between 3 and 9 km in the basins south-west of the British Isles (Kammerling, 1979; Naylor and Shannon, 1982) although it should be noted that the lower part of these sequences consists largely of Triassic and lower Jurassic clastics and evaporites (e.g. Jansa and Wade, 1975) which do not contain appreciable quantities of source rocks. However, mature source rocks do occur in the Jurassic of the Celtic Sea, for example, as shown by the large number of wells which have given hydrocarbon shows or tested small quantities of hydrocarbons (Naylor and Shannon, 1982).

The major unknown concerning the Lower Mesozoic basins relates to the timing of hydrocarbon generation compared to the timing of tectonic events which could form potential hydrocarbon traps but could also allow escape of earlier formed hydrocarbons. It might be suspected that increased heat flow leading to hydrocarbon maturation could have occurred during the Late Jurassic-Early Cretaceous rifting episode which preceded the formation of the North Atlantic. If, for example, hydrocarbon generation occurred prior to the Early Cretaceous uplift and erosion on the Grand Banks (Jansa and Wade, 1975) or prior to the Upper Cretaceous and Palaeocene inversion of the Celtic Sea Basin (Naylor and Shannon, 1982), then potential hydrocarbon accumulations might have been lost. On the other hand, the Kinsale Gas Field occurs in an Early Tertiary anticline (Colley et al., 1981), although, of course, this may be a feature of secondary migration initiated by the Early Tertiary earth movements.

In conclusion, the most attractive areas for future hydrocarbon exploration would appear to occur where Lower Mesozoic rift basins intersect continental margins formed during the Late Mesozoic. In particular, the little explored Flemish Pass - Porcupine Basin trend and the southern part of the South-West Approaches - Lusitanian Basin trend seem to be attractive, although deep water over much of these areas makes exploration uneconomic at the present time. The presence of mature source rocks coupled with the low success rate of hydrocarbon exploration wells drilled in the purely Lower Mesozoic Basins of the Grand Banks and the continental shelf south-west of Britain and Ireland suggests that relative timing of hydrocarbon generation and tectonic activity may have been largely unfavourable to hydrocarbon accumulation and preservation. However, isolated successes, particularly in the Celtic Sea, are likely to continue to stimulate interest in these areas.

ACKNOWLEDGEMENTS

The work described here is part of a programme of continental margin studies carried out for and funded by the UK Department of Energy. We thank T.J.G. Francis of IOS and A.C. Grant of Bedford Institute of Oceanography, Halifax, Nova Scotia, Canada for critically reviewing an earlier version of this manuscript.

REFERENCES

Auffret, G., Pastouret, L., Cassat, G., DeCharpel, O., Cravatte, J. and Guennoc, P., 1979. Dredged rocks from the Armorican and Celtic margins. In: L. Montadert, D.G. Roberts et al., Initial Reports Deep Sea Drilling Project, 48, U.S. Govt. Printing Office, Washington, 995-1008.

Auzende, J.M., Olivet, J.L., and Bonnin, J., 1970. La marge du Grand Banc et la fracture de Terre-Neuve. C.R. Acad. Sci. Paris, 271, 1063-1066.

Barss, M.S., Bujak, J.P. and Williams, G.L., 1979. Palynological zonation and correlation of sixty-seven wells, eastern Canada. Geol. Surv. Canada, Paper 78-24, 118 pp.

Biju-Duval, B., Dercourt, J. and LePichon, X., 1977. From the Tethys Ocean to the Mediterranean Seas: A plate tectonic model of the evolution of the western Alpine system. In: Structural history of the Mediterranean Basins, Eds. B. Biju-Duval and L. Montadert, 143-164, Technip, Paris.

Boillot, G., Auxietre, J-L. and Dunand, J-P., 1979a. The northwest Iberian margin. A Cretaceous passive margin deformed during Eocene. In: Deep drilling results in the Atlantic Ocean. Continental margins and palaeoenvironment. Maurice Ewing Ser. 3, 138-153, American Geophysical Union.

Boillot, G., Dupeuble, P.A. and Malod, J., 1979b. Subduction and tectonics on the continental margin off northern Spain. Marine Geol. 32, 53-70.

BRGM, ELF-Re, ESSO, REP and SNPA., 1974. Geologie du Basin d'Aquitane. BRGM, Paris.

Buckley, J.S. and Bailey, R.J., 1975. A free-air gravity map of the Irish continental margin. Marine Geophys. Res., 2, 185-194.

Colley, M.G., McWilliams, A.S.F. and Myers, R.C., 1981. Geology of the Kinsale Head gas field, Celtic Sea, Ireland. In: Petroleum geology of the continental shelf of northwest Europe. Eds L.V. Illing and G.D. Hobson, 504-510. Institute of Petroleum, London.

Dardel, R.A. and Rosset, R., 1971. Histoire geologique et structural du Basin de Parentis et de son prolongement en mer. In: Histoire structural du Golf de Gascogne. Eds. J. Debyser, X. Le Pichon and L. Montadert, IV 2-1 to IV 2-28, Technip, Paris.

Ebbern, J., 1981. The geology of the Morecambe gas field. In: Petroleum geology of the continental shelf of northwest Europe. Eds. L.V. Illing and G.D. Hobson, 485-493. Institute of Petroleum, London.

Evans, C.D.R., Lott, G.K. and Warrington, G., 1981. The Zephyr (1977) wells, Southwestern Approaches and western English Channel. Institute of Geological Sciences Rep. 81/8, 44 pages. H.M. Stationary Office, London.

Grimaud, S., Boillot, G., Collette, B.J., Mauffret, A., Miles, P.R. and Roberts, D.G., 1982. Western extension of the Iberian-European plate boundary during the early Cenozoic (Pyrenean) convergence: A new model. Marine Geol., 45, 63-77.

Grimaud, S., Boillot, G., Collette, B.J., Mauffret, A., Miles, P.R. and Roberts, D.G., 1983. Western extension of the Iberian-European plate boundary during the early Cenozoic (Pyrenean) convergence: A new model. Reply to comment by J.L. Olivet, J.M. Auzende and P. Beuzart. Mar. Geol. 53, 238-239.

Group Galice, 1979. The continental margin off Galicia and Portugal: Acoustical stratigraphy, dredge stratigraphy and structural evolution. In: J.C. Sibuet, W.B.F. Ryan et al., Initial Reports Deep Sea Drilling Project. 47b, 633-662. U.S. Govt. Printing Office, Washington.

Hinz, K., Dostman, H. and Fritsch, J., 1982. The continental margin of Morocco. Seismic sequences, structural elements and geological development. In: Geology of the northwest African continental margin. Eds. U. Von Rad., K. Hinz, M. Sarnthein and E. Seibold, 34-60. Springer-Verlag, Berlin and Heidelberg.

Jansa, L.F., Bujak, J.P. and Williams, G.L., 1980. Upper Triassic salt deposits of the western North Atlantic. Canadian J. Earth Sci., 17, 547-559.

Jansa, L.F. and Wade, J.A., 1975. Palaeogeography and sedimentation in the Mesozoic and Cenozoic, southeastern Canada. In: Canada's continental margins and offshore petroleum exploration. Eds. C.J. Yorath, E.R. Parker and D.J. Glass. Canadian Soc. Petroleum Geol., Memoir 4, 79-102.

Jenner, J.K., 1981. The structure and stratigraphy of the Kish Bank basin. In: Petroleum geology of the continental shelf of northwest Europe. Eds. L.V. Illing and G.D. Hobson, 426-431, Institute of Petroleum, London.

Kammerling, P., 1979. The geology and hydrocarbon habitat of the Bristol Channel basin. J. Petroleum Geol. 2 (1), 75-93.

Kristoffersen, Y., 1978. Sea-floor spreading and the early opening of the North Atlantic. Earth and Planetary Science Letters, 38, 273-290.

Laughton, A.S., 1972. The southern Labrador Sea - a key to the Mesozoic and early Tertiary evolution of the North Atlantic. In: A.S. Laughton, W.A. Berggren et al., Initial Reports Deep Sea Drilling Project, 12, 1155-1179, U.S. Govt. Printing Office, Washington.

Laughton, A.S., Berggren W.A. et al., 1972. Initial Reports Deep Sea Drilling Project, 12, U.S. Govt. Printing Office, Washington.

Lefort, J.P., 1980. Un 'fit' structurale de l'Atlantique nord: arguments geologiques pour correler les marqueurs geophysiques reconnus sur les deux marges. Marine Geol., 37, 355-369.

Lefort, J.P., in press. The main basement features recognised in the northern part of the North Atlantic area. In: P.C. De Graciansky, C.W. Poag *et al.*, Initial reports Deep Sea Drilling Project, 80, U.S. Govt. Printing Office, Washington.

Lefort, J.P. and Max, M., 1983. The development of the Porcupine Seabight: the direct relationship between early oceanic and continental crust. Newsletter Geol. Soc. London, 12(1), 16.

Leg 80 Scientific Party. 1982 Goban Spur transect is drilled. Geotimes, May 1982, 23-25.

Le Pichon, X., Sibuet, J-C., and Francheteau, J., 1977. The fit of the continents around the North Atlantic. Tectonophys. 38, 169-209.

Masson, D.G., Montadert, L. and Scrutton, R.A., in press. Regional geology of the Goban Spur continental margin. P.C. de Graciansky, C.W. Poag *et al.*, Initial Reports Deep Sea Drilling Project, 80. U.S. Govt. Printing Office, Washington.

Masson, D.G. and Miles, P.R., in press. Mesozoic sea-floor spreading between Iberia, Europe and North America. Marine Geol.

McKenzie, R.M., 1981. The Hibernia .... a classic structure. Oil and Gas Journal, Sept. 1981, 240-246.

Miles, P.R. and Masson, D.G., in prep. Magnetic anomalies off Iberia and the Grand Banks and the Europe-North America reconstruction.

Montadert, L., Winnock, E., Deltiel, J.R. and Grau, G., 1974. Continental margins of Galicia-Portugal and Bay of Biscay. In: The geology of continental margins. Eds. C.A. Burk and C.L. Drake, 323-342. Springer-Verlag, New York.

Montadert, L., Roberts, D.G., De Charpal, O. and Guennoc, P., 1979. Rifting and subsidence of the northern continental margin of the Bay of Biscay. In: L. Montadert, D.G. Roberts *et al.*, Initial Reports Deep Sea Drilling Project, 48, 1025-1060. U.S. Govt. Printing Office, Washington.

Montadert, L., Roberts, D.G. et al., 1979. Initial Reports Deep Sea Drilling Project, 48, U.S. Govt. Printing Office, Washington.

Naylor, D. and Shannon, P.M., 1982. Geology of offshore Ireland and west Britain. pp.161. Graham and Trotman, London.

Noroil, 1983. Offshore Europe: Eire. Noroil, 11(8), 50-53.

Pegrum, R.M. and Mounteney, N., 1978. Rift basins flanking the North Atlantic Ocean and their relation to the North Sea area. American Assoc. Petroleum Geol. Bull., 62(3), 419-441.

Pitman, W.C. and Talwani, M., 1972. Sea-floor spreading in the North Atlantic. Bull. Geol. Soc. America, 83, 619-646.

Reeves, T.J., Robinson, K.W. and Naylor, D., 1978. Ireland's offshore geology. Irish Offshore Review, 1(3), 25-28.

Rehault, J.P. and Mauffret, A., 1979. Relationships between tectonics and sedimentation around the north-western Iberian margin. In: J-C. Sibuet, W.B.F. Ryan et al., Initial Reports Deep Sea Drilling Project, 48b, 663-682, U.S. Govt. Printing Office, Washington.

Ridd, M., 1981. Petroleum Geology west of the Shetlands. In: Petroleum geology of the continental shelf of northwest Europe. Eds. L.V. Illing and G.D. Hobson, 414-425. Institute of Petroleum, London.

Roberts, D.G., Masson, D.G. and Miles, P.R., 1981. Age and structure of the southern Rockall Trough: New evidence. Earth and Planetary Sci. Letters, 52, 115-128.

Roberts, D.G., Masson, D.G., Montadert, L. and De Charpal, O., 1981. Continental margin from the Porcupine Seabight to the Armorican marginal basin. In: Petroleum geology of the continental shelf of north-west Europe. Eds. L.V. Illing and G.D. Hobson, 455-473. Institute of Petroleum, London.

Robinson, K.E., Shannon, P.M. and Young, D.G.G., 1981. The Fastnet Basin: An integrated analysis. In: Petroleum geology of the continental shelf of north-west Europe, Eds. L.V. Illing and G.D. Hobson, 444-454. Institute of Petroleum, London.

Russell, M.J. and Smythe, D.K., 1978. Evidence for an early Permian oceanic rift in the northern North Atlantic. In: Palaeorift systems with emphasis on the Permian Oslo rift. Vol. 1, Petrology and Geochemistry of continental rifts. Eds. E.R. Neumann and I.B. Ramberg, NATO Advanced Study Inst. ser. C, 36, 173-179. Reidel.

Soler, R., Vilchez, J.L. and Riaza, C., 1981. Petroleum geology of the Bay of Biscay. In: Petroleum geology of the continental shelf of north-west Europe. Eds. L.V. Illing and G.D. Hobson, 474-482. Institute of Petroleum, London.

Srivastava, S., 1978. Evolution of the Labrador Sea and its bearing on the early evolution of the North Atlantic. Geophys. J.R. astr. Soc. 52(2), 313-357.

Sullivan, K.D., 1983. The Newfoundland Basin: ocean continent boundary and Mesozoic sea-floor spreading history. Earth Planet. Sci. Letters, 62, 321-339.

Umpleby, D.C., 1979. Geology of the Labrador Shelf. Geol. Surv. Canada Paper 79-13, pp.34.

Vogt, P.R. and Einwich, A.M., 1979. Magnetic anomalies and sea-floor spreading in the western North Atlantic and a revised calibration of the Keathley (M) geomagnetic reversal chronology, In: B.E. Tucholke, P.R. Vogt et al., Initial Reports Deep Sea Drilling Project 43, 857-876. U.S. Govt. Printing Office, Washington.

Wilson, R.C.L., 1975. Atlantic opening and Mesozoic continental margin basins of Iberia. Earth Planet. Sci. Letters, 25, 33-43.

Winnock, E., 1971. Geologie succinte du bassin d'Aquitaine (Contribution a l'histoire du Golf de Gascogne). In: Histoire structurale du Golf de Gascogne, Eds. J. Debyser, X. Le Pichon and L. Montadert, IV 1-1 to IV 1-30, Technip, Paris.

Ziegler, P.A., 1982. Geological atlas of western and central Europe. Shell Internationale Petroluem, Maatschappij B.V.

FIGURE CAPTIONS

Figure 1. Lower Early Cretaceous North Atlantic reconstruction illustrating the relative positions of the various continents immediately prior to the onset of sea-floor spreading (from Miles and Masson , in prep.). Also shown are the locations of the main geographical features discussed in the text.

*Figure 2. Compilation of geological data used to define the distribution of the Lower Mesozoic rift basins plotted on the North Atlantic reconstruction. (Bathymetric contour interval 1000m but with 200 and 500m contours added). Main data sources: Biju-Duval et al., 1977; Boillot et al., 1979a, b; Dardel and Rosset, 1971; Jansa and Wade, 1975; Jansa et al., 1980; Jenner, 1981; Laughton, Berggren et al., 1972; Masson et al., in press; Montadert, Roberts et al., 1979; Rehault and Mauffret, 1979; Soler et al., 1981; Stevaux and Winnock, 1974; Wilson, 1975; Ziegler, 1982. The northern edge of the Aquitaine basin has been defined as the northern limit of the evaporite basin (Stevaux and Winnock, 1974).

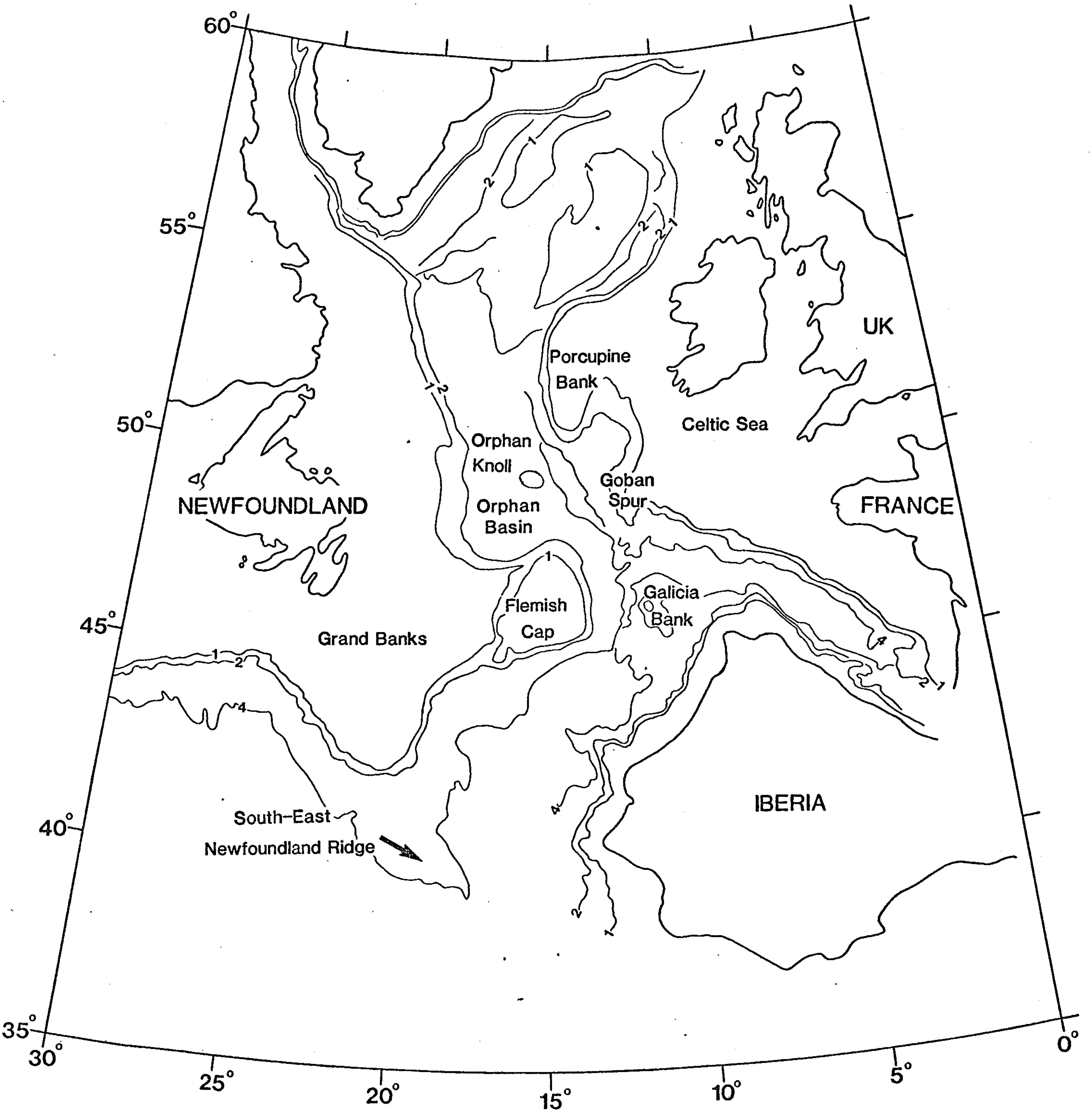
Figure 3. Probable configuration of Lower Mesozoic rift system based on the data summarised in Figure 2 and plotted on the North Atlantic reconstruction. Note that the direction of early opening between Africa and North America (heavy dotted line, Le Pichon et al., 1977) is approximately parallel to the strike-slip direction within the rift system.

Figure 4. Probable configuration of Late Mesozoic rift system superimposed on the North Atlantic reconstruction. Main data sources: Boillot et al. (1979a, b); Dardel and Rosset (1971); Group Galice, 1979; Masson et al. (in press); McKenzie (1981); Montadert, Roberts et al. (1981a, b); Umpleby (1979) and Wilson (1975).

*fold-out, see map pocket.

Figure 5. Summary of the general northward propagation of sea-floor spreading in the North Atlantic during the Late Mesozoic. The ages given are those of the rifting to sea-floor spreading transition.

Figure 6. Compilation of both Early and Late Mesozoic rift basins plotted on the North Atlantic reconstruction with known hydrocarbon occurrences superimposed. 'Not yet evaluated' refers to potentially commerical hydrocarbon discoveries which have not yet been fully evaluated. Note that the majority of hydrocarbon discoveries (particularly oil) occur in basins where a Lower Mesozoic rift has been 'overprinted' by a Late Mesozoic rift. Data concerning hydrocarbon discoveries drawn from Colley et al., 1981; Dardel and Rosset, 1971; Ebbern, 1981; McKenzie, 1981; Naylor and Shannon, 1982; Soler et al., 1981; Umpleby, 1979).


60°
55°
50°
45°
40°
35°
30°
25°
20°
15°
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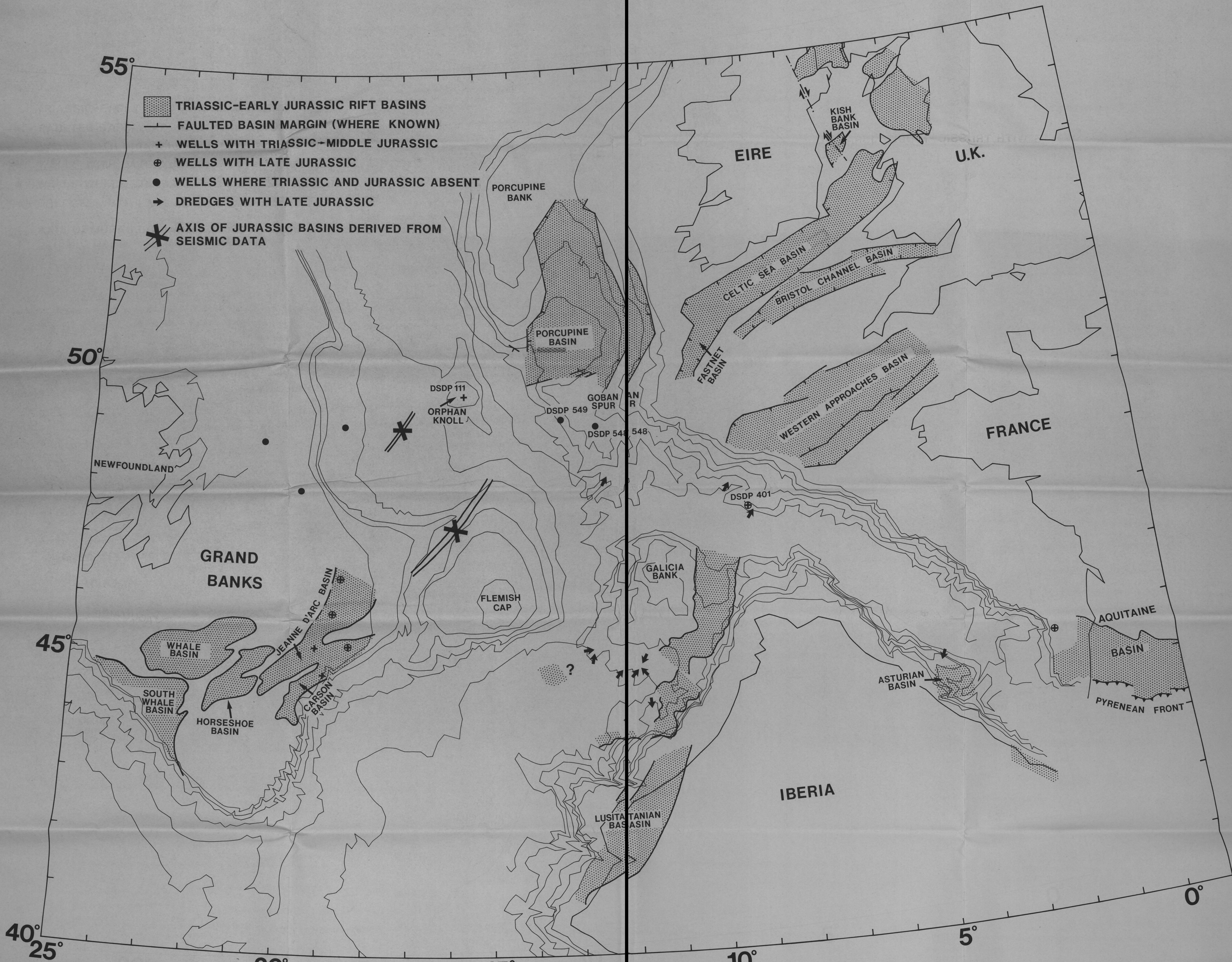
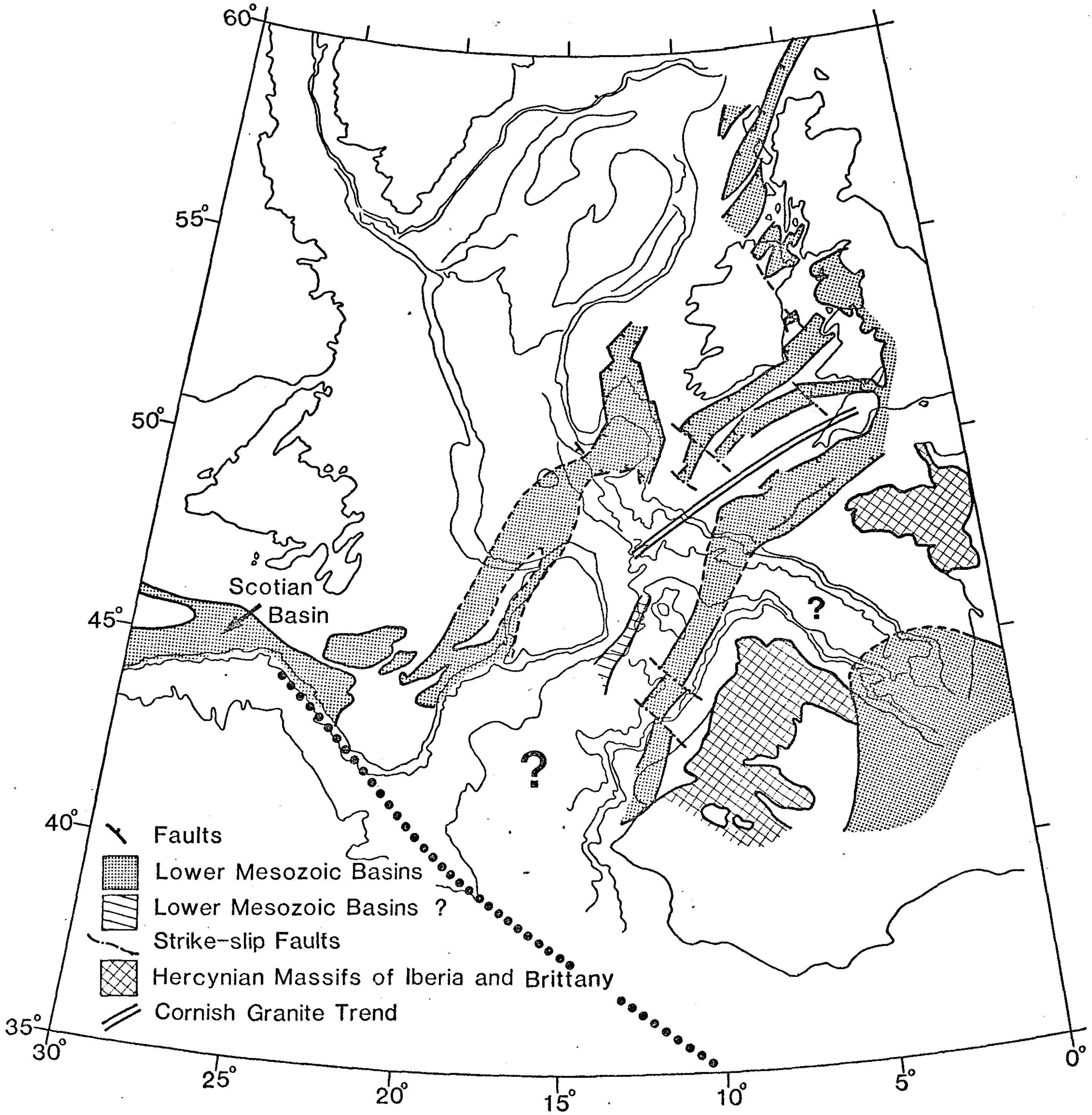
5°
0°
Porcupine Bank
UK
Celtic Sea
Orphan Knoll
Orphan Basin
Goban Spur
FRANCE
NEWFOUNDLAND
Flemish Cap
Galicia Bank
Grand Banks
IBERIA
South-East Newfoundland Ridge



TRIASSIC-EARLY JURASSIC RIFT BASINS
FAULTED BASIN MARGIN (WHERE KNOWN)
WELLS WITH TRIASSIC-MIDDLE JURASSIC
WELLS WITH LATE JURASSIC
WELLS WHERE TRIASSIC AND JURASSIC ABSENT
DREDGES WITH LATE JURASSIC
AXIS OF JURASSIC BASINS DERIVED FROM SEISMIC DATA
55°
50°
45°
40°
25°
20°
15°
10°
5°
0°
EIRE
U.K.
KISH BANK BASIN
PORCUPINE BANK
PORCUPINE BASIN
CELTIC SEA BASIN
BRISTOL CHANNEL BASIN
FASTNET BASIN
WESTERN APPROACHES BASIN
FRANCE
DSDP 111
ORPHAN KNOLL
DSDP 549
GOBAN SPUR
DSDP 548
DSDP 401
NEWFOUNDLAND
GRAND BANKS
JEANNE D'ARC BASIN
WHALE BASIN
SOUTH WHALE BASIN
HORSESHOE BASIN
CARSON BASIN
FLEMISH CAP
GALICIA BANK
AQUITAINE BASIN
PYRENEAN FRONT
ASTURIAN BASIN
IBERIA
LUSITANIAN BASIN

3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Scotian Basin
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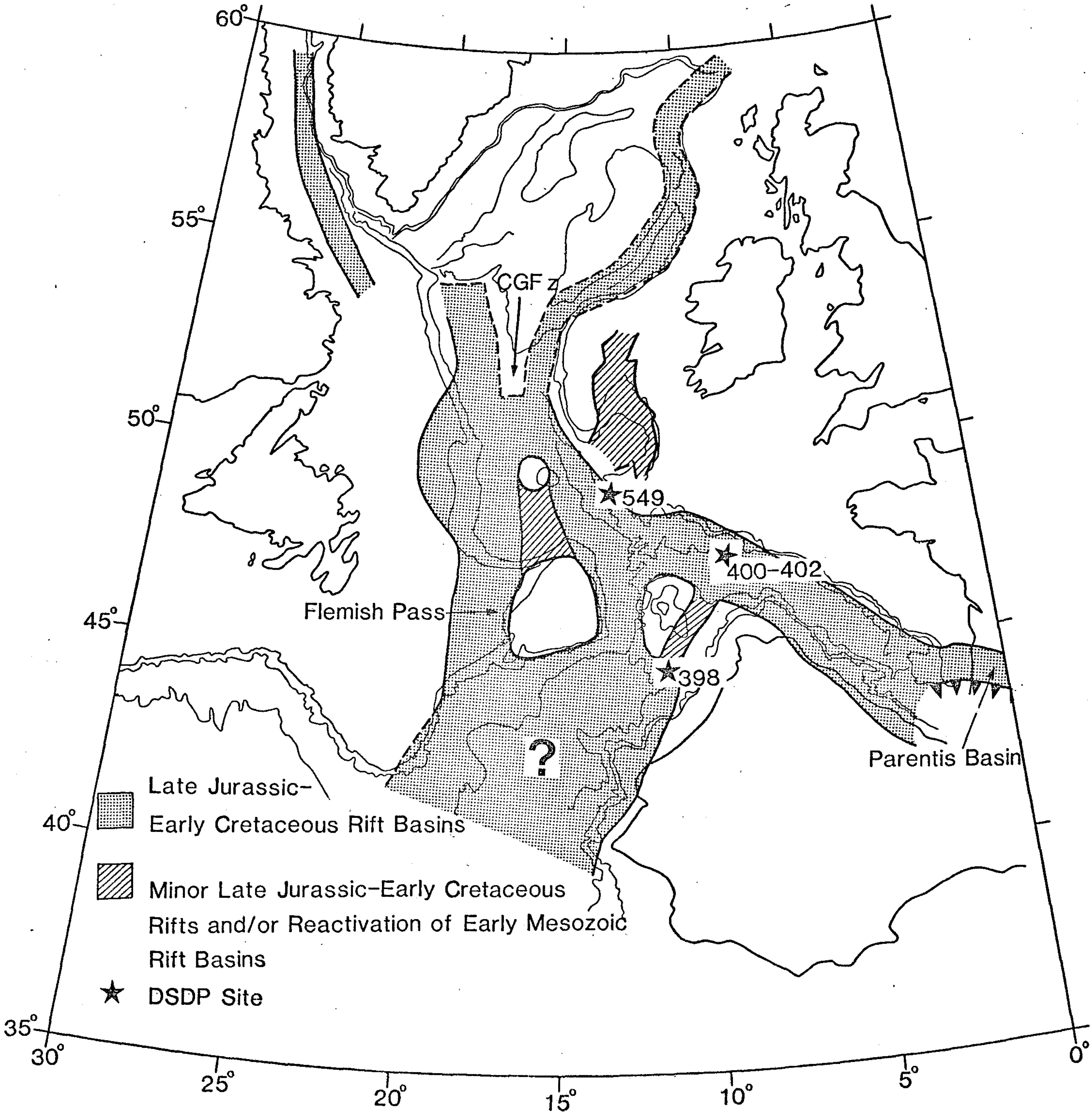
Faults
Lower Mesozoic Basins
Lower Mesozoic Basins ?
Strike-slip Faults
Hercynian Massifs of Iberia and Brittany
Cornish Granite Trend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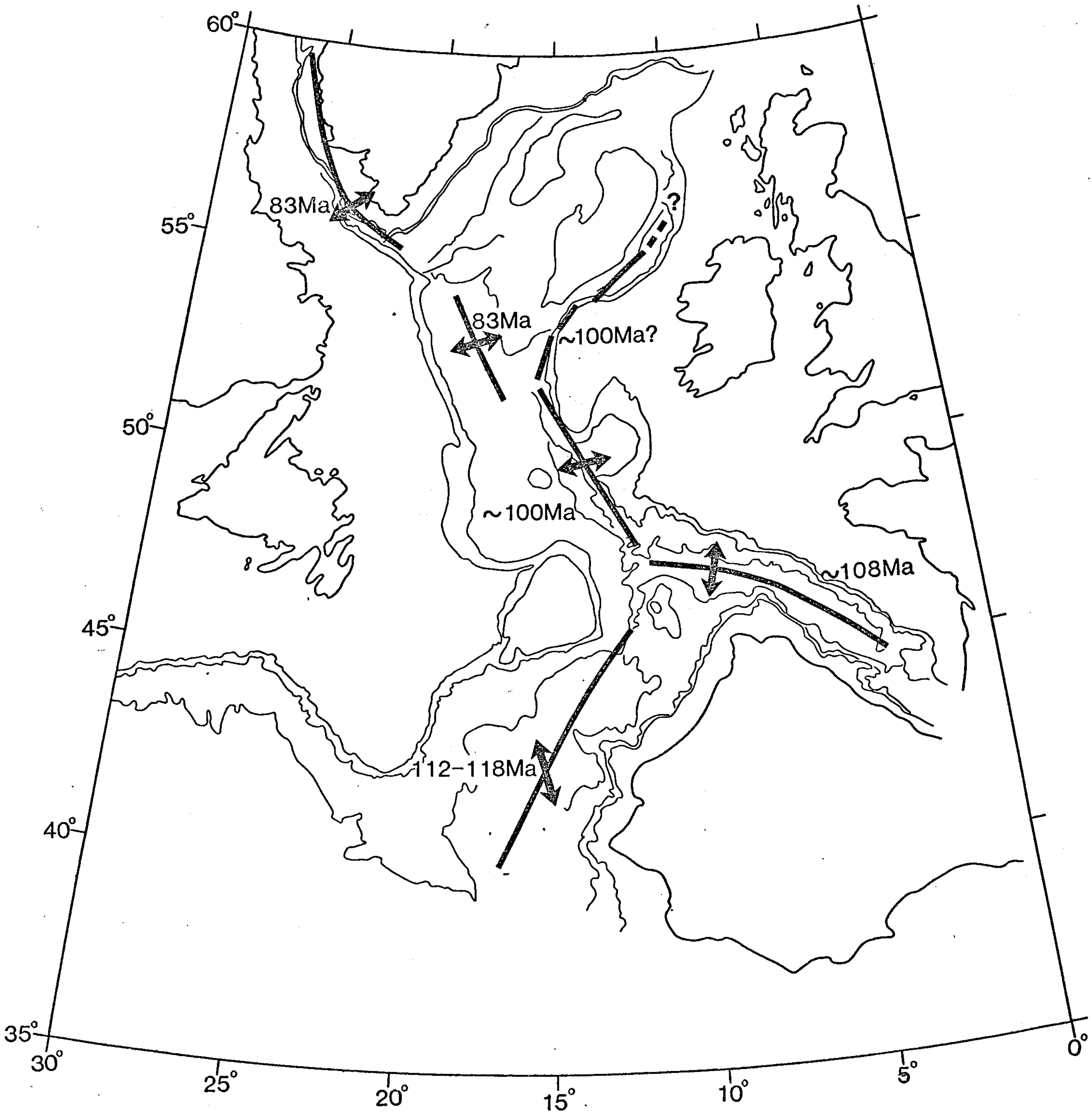
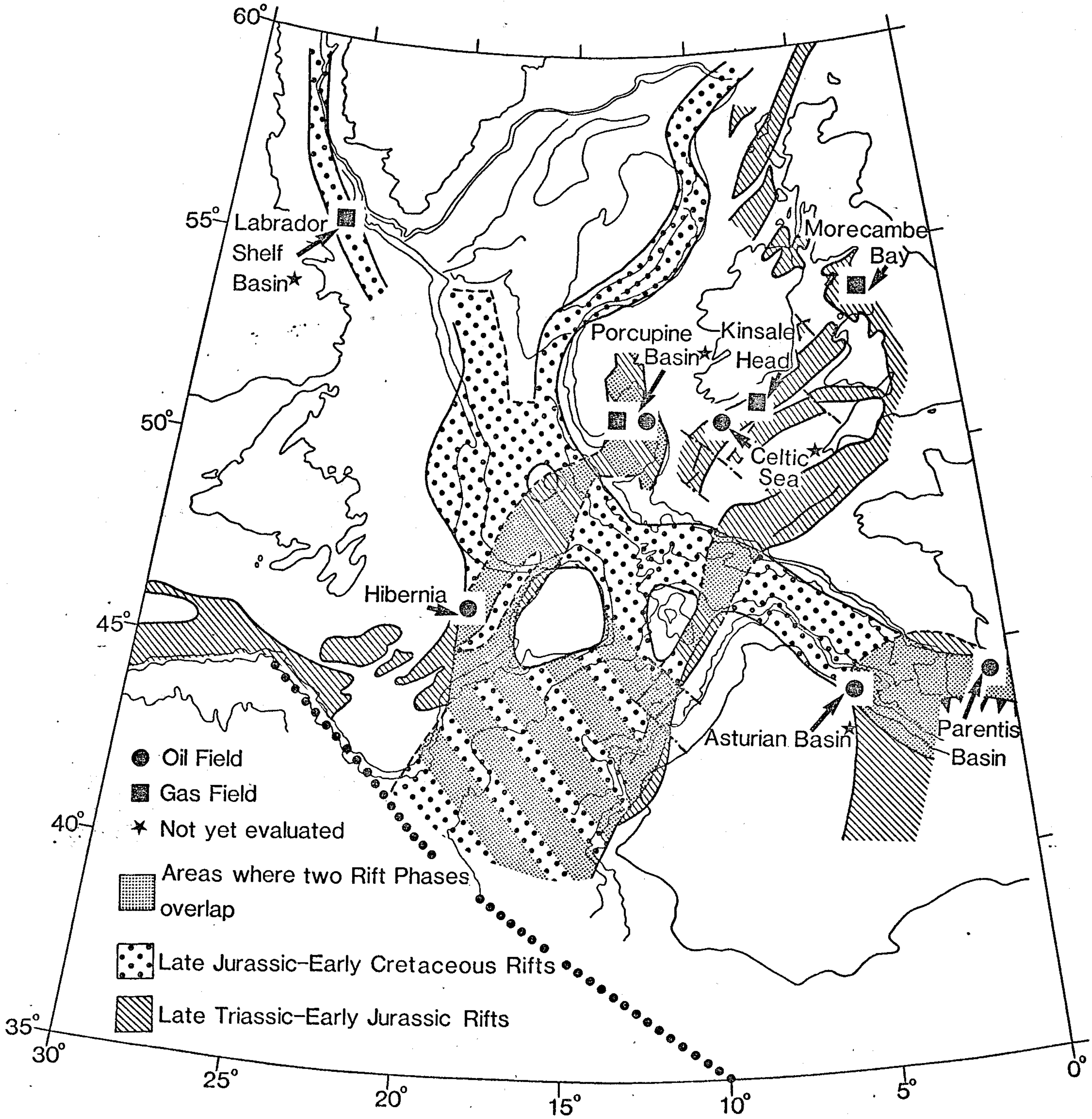
CGF z
549
400-402
Flemish Pass
398
?
Parentis Basin
Late Jurassic-
Early Cretaceous Rift Basins
Minor Late Jurassic-Early Cretaceous
Rifts and/or Reactivation of Early Mesozoic
Rift Basins
DSDP Site



60°
55°
50°
45°
40°
35°
30°
25°
20°
15°
10°
5°
0°
83Ma
83Ma
?
~100Ma?
~100Ma
~108Ma
112-118Ma



60°
55°
50°
45°
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5°
0°
Labrador Shelf Basin
Porcupine Basin
Kinsale Head
Morecambe Bay
Celtic Sea
Hibernia
Asturian Basin
Parentis Basin
Oil Field
Gas Field
Not yet evaluated
Areas where two Rift Phases overlap
Late Jurassic-Early Cretaceous Rifts
Late Triassic-Early Jurassic Rifts