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STRUCTURE AND EVOLUTION OF THE SOUTH WEST APPROACHES AND GRAND BANKS CONTINENTAL MARGINS

BY

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WORMLEY

Structure and evolution of the South West Approaches and Grand Banks continental margins

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ABSTRACT

The history of IOS research on the continental margins of the South-West Approaches, Iberia and the Grand Banks is outlined and a brief review of our current understanding of the geology of these margins is presented. The evolution of the margins is described in three phases: pre-rift, rift and post-rift. The pre-rift geology is characterised by a series of northeasterly trending Triassic and Jurassic basins cutting Palaeozoic and older basement rocks. The rift phase is the period of attenuation of the continental crust which precedes sea-floor spreading. In the upper, brittle crust, stretching is accommodated by 'en echelon' series of listric normal faults; syn-rift sedimentation occurs predominantly in wedge-shaped, actively subsiding half-graben. The post-rift phase is characterised by regional subsidence of the margin, a lack of tectonic activity and the draping of sediments over the topography created during the rift phase.

Finally, the hydrocarbon prospectivity of the continental margins of the relevant part of the North Atlantic is discussed. It is concluded that the Cretaceous and younger syn- and post-rift sequences have poor prospectivity because source rocks are rare and are frequently immature due to insufficient depth of burial. However, good prospects may occur where pre-rift basins containing marine Jurassic rocks with high source potential are overlain by appropriate thicknesses of Cretaceous and younger sediments.

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INTRODUCTION

This report summarises geological and geophysical studies undertaken at IOS within the project "Continental margins: South-West Approaches and Grand Banks" commissioned by the Department of Energy. Included within this project are studies of continental margins between the southern tip of Iberia and the Charlie Gibbs Fracture Zone in the eastern North Atlantic (36° to 52°N, Fig. 1) and the southern and eastern margins of the Grand Banks in the western North Atlantic (41° to 52°N, Fig. 1).

HISTORY OF CONTINENTAL MARGIN STUDIES AT IOS

The Eastern Atlantic

Prior to 1975, IOS activity in the field of continental margin studies was largely concentrated on the Rockall Plateau and Trough, to the north of the area of the eastern Atlantic discussed in this report (e.g. Roberts, 1975), although both geophysical and geological data had been collected from the south-west European margin during reconnaissance surveys and along isolated passage tracks since the early 1960s (e.g. Black *et al.*, 1964; Stride *et al.*, 1969). Systematic study of the western European margin south of the Charlie-Gibbs Fracture Zone began with RRS Discovery Cruise 74 in 1975 (Roberts *et al.*, 1975) during which seismic reflection, magnetic and gravity profiles were occupied on Goban Spur and on the western part of the North Biscay margin.

A similar suite of data was collected on the north-west Iberian margin during Shackleton cruise 6/76 (Roberts *et al.*, 1976); this included passage tracks across the Bay of Biscay and on the North Biscay margin. On the basis of these surveys and additional surveys carried out by French workers, three deep drillsites (Numbers 400-402, Fig. 1) were located on the northern margin of the Bay of Biscay during leg 48 of the International Phase of Ocean Drilling (IPOD) in 1976 (Montadert, Roberts *et al.*, 1979). The drilling results documented, for the first time, the development of a rifted margin from the rifting phase, through the transition to seafloor spreading, to the drifting or post-rift phase.

In 1977, a major multichannel seismic reflection (MCS) survey of the North Biscay and Goban Spur continental margins, consisting of 4350 km of 48 channel profiles, was commissioned by IOS with Department of Energy funding, with the data collection being undertaken by S and A Geophysical Company. An exchange of this data for an equivalent amount of French MCS data collected by the Institut Français du Petrole (Paris) and the purchase of a further 2050 km of speculative MCS data gave a comprehensive seismic reflection coverage between 47° and 51°N.

In 1978, during Discovery Cruise 90, large areas of the northern margin of the Bay of Biscay and the western and north-western Iberian margin were surveyed using the long-range sidescan sonar, GLORIA (Roberts et al., 1978). Underway geophysical studies of the South-West Approaches margin were completed in 1979 when a number of two-ship seismic reflection and refraction experiments were carried out using RRS Shackleton (Cruise 6/79) and the French Ship MV Resolution, with the aim of increasing our understanding of the deep structure of the margin (Whitmarsh et al., 1979).

Further drillsites were occupied on the Goban Spur in 1981 during IPOD leg 80 (sites 548-551, Fig. 1) during which a transect of holes across the continent-ocean transition was drilled and the structure and evolution of the margin were assessed (De Graciansky, Poag et al., in press).

Geophysical and geological data obtained during three Edinburgh University cruises to the Goban Spur margin (see Appendix 1) was compiled with the IOS data base as part of a joint study of the area of these drillsites.

The Western Atlantic

The volume of geophysical data collected by IOS on the Atlantic margin of Canada is much smaller than that from the eastern Atlantic. Studies of this area began in 1979, when a small amount of data was collected by MV Starella on passage from East Greenland to the east coast of the United States (Roberts et al., 1979). In 1980, Discovery Cruise 111 collected GLORIA, seismic reflection, gravity and magnetic data from the southern and south-eastern margins of the Grand Banks, particularly the Laurentian Fan area (Roberts et al., 1980).Finally, the eastern Grand Banks margin between 42° and 52°N was surveyed witha similar underway geophysical package during MV Farnella cruises 1 and 2 in 1981 (Somers, Revie et al., 1982).

Interpretation of seismic reflection data from the Grand Banks margin is facilitated by a single DSDP borehole, site 111 on Orphan Knoll, and by a large number of commercial boreholes drilled on the Grand Banks shelf. A large volume of commercial MCS data has also been released through the agency of the Canadian Government; appropriate lines from this database have also been obtained for use in regional geological studies.

REVIEW OF NORTH ATLANTIC CONTINENTAL MARGIN GEOLOGY

Regional Setting

In general, the evolution of a passive continental margin can be divided into three phases, namely a pre-rift phase, a rifting phase and a seafloor spreading phase. The passive margins under discussion in this report have resulted from rifting and seafloor spreading between the continental masses of Europe, North America and Iberia, formerly part of the Laurasian supercontinent. Seafloor spreading associated with this separation began during the late Lower Cretaceous (Montadert et al., 1979; Masson & Miles, in press; Masson et al., in press) but was preceded by either a complex single rifting episode or two or more separate rifting episodes between Triassic and late Lower Cretaceous time (e.g. Pegrum & Mounteney, 1978; Zeigler, 1982; Masson & Miles, 1983).

The majority of studies concerning the evolution of the northern part of the North Atlantic have concluded that the area was originally structured by a Late Triassic-Early Jurassic tensional phase, during which the Early Mesozoic sedimentary basins now underlying the shelf areas on both sides of the North Atlantic were formed (e.g. Jansa & Wade, 1975; Pegrum & Mounteney, 1978; Montadert et al., 1979; Jansa et al., 1980; Naylor & Shannon, 1982). Masson and Miles (1983) have summarised the distribution of these Early Mesozoic basins and have demonstrated that they are the scattered fragments of a formerly coherent north-easterly trending rift system (Fig. 2). The continental margins of the northern North Atlantic clearly cut across the Early Mesozoic rift system which appears to have had little influence on the position and trend of the later continental break-up. Accordingly, we do not consider the Early Mesozoic rifting event to be a precursor of continental break-up in the northern North Atlantic area, but would suggest that it is a consequence of the rifting between Africa and North America to the south. As such, it is part of the pre-rift rather than the rift phase.

The initiation of the rifting phase which directly preceded continental break-up in the northern North Atlantic has not yet been accurately dated, although it is generally considered to be 'late Jurassic-Early Cretaceous' (e.g. Montadert et al., 1974; Boillot et al., 1979; Groupe Galice, 1979; Roberts et al., 1981). The major uncertainty concerns the significance of shallow water limestones of Late Jurassic age which have been sampled by dredging and drilling on the northern margin of the Bay of Biscay and on the western flank of Galicia Bank (Montadert et al.,1979; Boillot et al., 1979). Montadert et al. (1979) note that these may represent either a pre-rift carbonate platform or a locally developed shallow water facies restricted to the crests of tilted fault blocks formed during the initial stages of rifting. Onshore evidence from the western Iberian peninsula and the Parentis Basin in south-west France is equally equivocal. Both areas exhibit evidence for increased subsidence during the latest Jurassic (BRGM, 1974; Wilson, 1975; Montadert et al., 1979) but a true fault-bounded graben did not develop in the Parentis Basin until the Early Cretaceous (Montadert et al., 1979).

Rifting on Goban Spur has been accurately dated by IPOD Leg 80 drilling, which indicates that it occurred between the Barremian (or possibly late Hauterivian) and the early to middle Albian.

In summary, the rift-phase is here defined as ?Late Jurassic to Aptian or Albian, with all pre-Late Jurassic strata being assigned to the pre-rift phase.

The Pre-rift Phase

Rocks belonging to the pre-rift phase can be subdivided into an 'economic basement' (here defined as Permian and older strata) and a sedimentary cover of Late Triassic to Middle Jurassic age. Knowledge of the 'economic basement' underlying the marginal areas is based on isolated samples obtained from drillholes and dredge sites and is, therefore, fragmentary.

On the Canadian margin, late Pre-Cambrian (Hadrynian) granodiorites outcrop on Flemish Cap (Pelletier, 1971; King et al., in press). The oldest "unmetamorphosed sedimentary rocks" so far recovered on the Grand Banks are Devonian and Carboniferous in age (Jansa & Wade, 1975; Barss et al., 1979), and Devonian reef limestones may outcrop on Orphan Knoll (Parson et al., 1984). Lilly (1966) and Jansa and Wade (1975) note the possibility that Pre-Cambrian and Lower Palaeozoic sedimentary rocks may also occur beneath the Grand Banks shelf, but such occurrences are poorly documented and samples are impossible to date with accuracy. On the European margin, the oldest known 'economic basement' consists of metamorphic and plutonic rocks "comparable to those of the pre-Mesozoic (Hercynian) basement of Iberia" (Boillot et al., 1979) which were sampled by dredging on Galicia Bank. Weakly metamorphosed Devonian sedimentary rocks have been sampled by drilling on Goban Spur (De Graciansky, Poag et al., in press), close to the site of dredged Carboniferous granites (Auffret et al., 1979).

The distribution and composition of the Late Triassic to Middle Jurassic pre-rift unit is relatively well known, it having been penetrated by a large number of commercial boreholes on both sides of the Atlantic. Fault bounded basins on the Grand Banks, in the South-West Approaches and in western Iberia contain a characteristic Late Triassic redbed and evaporite sequence followed by shallow marine Early and Middle Jurassic shales, carbonates and sandstones (Fig. 2; Jansa & Wade, 1975; Wilson, 1975; Pegrum & Mounteney, 1978;

Kamerling, 1979; Jansa et al., 1980; Naylor & Shannon, 1982; Zeigler, 1982).

The Rifting Phase

North Atlantic passive continental margins can be divided into two types, commonly referred to as 'tilted block' and 'dipping reflector' margins, on the basis of the structural style developed during the rift phase (De Charpal et al., 1978; Montadert et al., 1979; Roberts et al., 1979b; Roberts & Montadert, 1980). Briefly, tilted block margins are characterised by listric faulting, rotation of fault blocks and little or no syn-rift volcanism, whereas dipping reflector margins are recognised by thick wedges of oceanward dipping, ?volcanic or volcaniclastic material which generally obscure the deeper structure of the margin. Only the former type is discussed here, since no dipping reflector margins occur within the present study area.

The sediment-starved passive margins of the eastern North Atlantic, in particular the northern margin of the Bay of Biscay and the margin to the west of Goban Spur, are excellent areas for the study of rift-phase tectonics and sedimentation, since the post-rift sediment cover is exceptionally thin. Much of our current understanding of tilted block margin development is based on studies of these margins in which IOS has actively participated (e.g. De Charpal et al., 1978; Montadert et al., 1979; Roberts et al., 1981; Avedik et al., 1982; Masson et al., in press).

Seismic profiles show that the structure of these margins is dominated by a series of margin-parallel, normal, listric faults downthrown towards the ocean, creating a series of tilted and rotated blocks separated by half-graben (Figs. 3, 4). Wedge-shaped sediment accumulations within the half-graben characteristically exhibit a depth-dependent increase in dip, indicating that the sediments were deposited contemporaneously with rifting. Fault spacing is typically 5 to 30 km and fault throws may be as great as 4 km (Figs. 3-5; Montadert et al., 1979; Masson et al., in press). On Goban Spur, many of the tilted blocks have eroded crests, indicating that they were near sea-level during the rift phase (Figs. 4, 5; Masson et al., in press). In contrast, few blocks on the northern Biscay margin show evidence of syn-rift erosion, and Montadert et al. (1979) have deduced that the axis of the rift system may already have been submerged beneath 2000 m of water by the time the first oceanic crust was generated.

Detailed studies of the rift-phase tectonic pattern in the northern Bay of Biscay and beneath Goban Spur have been published by Dingle and Scrutton (1977, 1979), De Charpal et al. (1978), Montadert et al. (1979), Roberts et al. (1981) and Masson et al. (in press), with increasingly complex patterns being recognised with the growth of the seismic profile database. Early tectonic maps included considerable numbers of discontinuities perpendicular to the main margin-parallel fault trends (e.g. Dingle & Scrutton, 1977, 1979; Montadert et al., 1979). These were inferred to accommodate apparent along-strike changes in the fault pattern. More recent studies, based on a denser seismic grid, suggest that the faults occur in 'en echelon' arrays within which individual faults exhibit differential throw along strike. Cross-strike discontinuities are rare, although notable exceptions may occur where older structural lineaments crossing the margin have been reactivated during rifting. Examples of reactivated Early Mesozoic normal faults include the east-northeast trending faults which mark the northern edge of Goban Spur (Fig. 5; Masson et al., in press) and the faults which probably control the trend of Shamrock Canyon on the northern Biscay margin (Montadert et al., 1979).

It is widely accepted that extension and thinning of the continental lithosphere occurs during intra-continental rifting, although the mechanism by which this takes place is still a matter of controversy (McKenzie, 1978; Royden & Keen, 1980; LePichon & Sibuet, 1981; Beaumont et al., 1982; Avedik et al., 1982; Chenet et al., 1983; LePichon et al., 1983). McKenzie (1978) first proposed a simple model based on uniform extension and thinning of the whole lithosphere. Other workers prefer a model in which a lower ductile lithospheric layer is preferentially thinned relative to a brittle upper layer (Avedik et al., 1982; Beaumont et al., 1982; Chenet et al., 1983). The details of the model are important because they affect palaeo-heatflow predictions and their possible effect on hydrocarbon generation (e.g. Royden et al., 1980).

A possible test of the two hypotheses is the comparison of whole crustal extension, as deduced from seismic refraction studies or inferred from gravity anomaly modelling, with the extension observed in the upper crust (the "superficial extension" of Chenet et al., 1983) which can be calculated from seismic reflection profiles. On the north Biscay margin, the whole crustal extension ratio (β) reaches a maximum between 4 and 6 near the continent-ocean transition (Avedik et al., 1982; Chenet et al., 1983). However, published superficial extension values (e) vary widely, relatively high values (~2.2-2.6) being obtained by LePichon and Sibuet (1981) and LePichon et al (1983) and relatively low values (~1.1-1.45) by Montadert et al. (1979), Avedik et al. (1982) and Chenet et al. (1983). This discrepancy occurs because the calculation of 'e' is critically dependent on the correct identification of the top 'pre-rift' surface, the position of which is often ambiguous on the north Biscay margin where the late pre-rift sequence consists of layered early Mesozoic sedimentary strata. Our studies would support the lower 'e' measurements, and we would suggest that the high values result from LePichon and co-workers (1981, 1983) having picked the top of the pre-rift sequence at too great a depth (i.e. within the pre-rift, Fig. 6). Low 'e' values have also been measured on Goban Spur, where the top of the pre-rift Hercynian metasedimentary basement can be picked without doubt (Fig. 7; Masson et al., in press). Furthermore, the Goban Spur data (Fig. 7) suggests that the superficial extension is independent of the whole crustal extension, thus supporting rifting models based on apparent differential thinning between upper and lower lithosphere.

The Post-rift Phase

The post-rift phase begins with the generation of the first oceanic crust and the release of the tensional stresses which dominate the rift phase. In the northern North Atlantic, the beginning of the post-rift phase can only be dated with precision on the Goban Spur margin, where a single DSDP site drilled on the oldest oceanic crust (site 550, Fig. 1) records a late early to middle Albian age (Masson et al., in press). In the Bay of Biscay, a late Aptian age is inferred from drilling results (Montadert et al., 1979) and, further south, between Iberia and the Grand Banks, magnetic anomaly identifications suggest an early Aptian or earlier age (Masson & Miles, in press).

In the region discussed here, the transition between continental and oceanic crust is most easily recognised on the basis of a change in magnetic anomaly character, with anomalies of relatively high frequency and amplitude characterising oceanic crust, and lower frequency and amplitude anomalies indicating continental crust. The continent-ocean transition has only been studied in detail west of Goban Spur (Scrutton, in press; Masson et al., in press), where it comprises a complex zone, some 10-15 km wide, where the continental crust is intruded by and buried beneath basaltic volcanics of oceanic affinity. To the west of the transition, the top of the oceanic crust is characterised by a highly-diffractive surface with considerable (up to 1 km) relief. High quality migrated multichannel seismic reflection profiles show that the structural pattern of the oceanic crust is identical to that generated at present-day mid-ocean ridges.

On continental margins, the post-rift phase is dominated by regional subsidence generally believed to result from thermal contraction of a cooling lithosphere (Sleep, 1971). On the North Atlantic margins discussed in this report, post-rift subsidence has been accompanied by predominantly pelagic and hemipelagic sedimentation with relatively low sedimentation rates (e.g. Montadert, Roberts et al., 1979; De Graciansky, Poag et al., in press). No regional syn-sedimentary tectonic activity (other than regional subsidence) accompanies this post-rift sedimentation, although zones of folding and reverse faulting of Eocene age are associated with the Pyrenean deformation in the eastern Atlantic (Montadert et al., 1979; Grimaud et al., 1982; Masson & Parson, 1983).

Detailed analysis of the northern North Atlantic post-rift seismic stratigraphy, calibrated using drilling results from DSDP legs 12, 47, 48 and 80 and commercial boreholes on the Canadian shelf, show a number of regional 'events' which correlate over the whole area. In general, three post-rift sediment units can be differentiated (Figs. 8, 9); an upper seismically-layered unit of Oligocene and younger strata, a middle weakly-layered to chaotic unit of Campanian to Eocene age, and a lower seismically-transparent 'black shale' sequence of Late Aptian to Early Cenomanian age; the lower and middle units are separated by a highly-condensed sequence or hiatus encompassing much of the lower late Cretaceous (Groupe Galice, 1979; Montadert et al., 1979; Masson et al., in press; Parson et al., in press).

Recent sedimentation and sediment transport patterns on continental margins have been studied using GLORIA sidescan sonar data, in particular on the Iberian margin and over the Laurentian Fan on the Grand Banks margin. In the former area, along-slope sediment transport controlled by contour currents predominates, creating widespread sediment wave fields. Submarine canyons crossing the slope appear to transport terrigenous sediment directly to the abyssal plain, and have little effect on slope sedimentation (Gardner & Kidd, 1983; Roberts & Kidd, 1984). On the Laurentian Fan, in contrast, a complex system of channels and levees indicates a dominance of downslope processes, although the strongly asymmetric nature of the levees again indicates the importance of contour currents and their ability to influence depositional patterns (Piper & Normark, 1982; Normark et al., 1983; Masson et al., in prep.).

Hydrocarbon potential of North Atlantic continental margins

The speculative assessment of the hydrocarbon potential of the North Atlantic continental margins presented here is based on sediment thickness, presence or absence of source rocks (where known) and, perhaps most importantly, on the extrapolation of the known geology and prospectivity of the shelf basins where exploration has already begun. The definition of four categories of prospect, ranging from good through moderately good and moderately poor to poor, has been attempted.

On the western European margin, the Celtic Sea and Porcupine Basins are good prospects with oil and gas reserves proven by drilling (Fig. 10). Sediments within these basins may reach 9 km in thickness and mature source rocks occur in the Jurassic and, speculatively, in the Carboniferous (Reeves et al., 1978; Naylor & Shannon, 1982). Drilling in the adjacent Bristol Channel and Western Approaches Basins has been markedly less successful (Kamerling, 1979), although these basins have had, in general, similar geological histories to the Celtic Sea Basin. Kamerling (1979) explained their lack of prospectivity by a combination of several factors, including the possibility of hydrocarbon generation predating trap formation, insufficient hydrocarbon generation from rather low quality source rocks and a lack of good reservoir rocks. Geologically, the major differences between the Celtic Sea and the Bristol Channel/Western Approaches Basins are in the post-Jurassic history. In particular, the Early Cretaceous is represented by up to 2 km of clastic sediments in the Celtic Sea Basin (Naylor & Shannon, 1982; Zeigler, 1982) but the same period saw erosion of Jurassic strata in the Bristol Channel and (possibly) the Western Approaches Basins (Kamerling, 1979; Naylor & Shannon, 1982). If the main period of hydrocarbon generation occurred during the Early Cretaceous (during the period of high heatflow related to North Atlantic rifting; Kamerling, 1979), then hydrocarbons may have been trapped in the subsiding Celtic Sea basins, while uplift and erosion of Jurassic strata could have allowed escape of hydrocarbons in the Bristol Channel and Western Approaches Basins. Exploration in the Bristol Channel and Western Approaches basins is, however, at a relatively early stage, with only seven wells in the former and ten in the latter, and we would consider that these areas are still a moderately good prospect (Fig. 10). In particular, the area of intersection of the Western Approaches Basin with the continental margin, where little Early Cretaceous erosion is evident and where the Jurassic and older strata are buried beneath up to 2 km of Cretaceous and younger strata, could be an interesting prospect (Montadert et al., 1979; Roberts et al., 1981).

The remaining areas of the western European margin consist predominantly of elevated 'basement' blocks of Caledonian or Hercynian age buried beneath a thin veneer of Cretaceous and Tertiary sediments. Although potential source rocks occur within the Cretaceous sequence (e.g. 'black shale' sequences sampled at DSDP sites 400-402 and 549-551, Montadert, Roberts et al., 1979; De Graciansky, Poag et al., in press; Fig. 1), these are not sufficiently deeply buried to be mature and the overall prospectivity of these areas is poor (Fig. 10). Similarly, the shelf areas to the south-west of France have only a thin sediment cover overlying Hercynian basement and also have poor prospectivity. The deeper water areas of the Bay of Biscay are more difficult to evaluate. Little published information exists regarding possible deepwater extensions of the oil-producing Aquitaine Basin of south-west France (Dardel & Rosset, 1971) or the gas-producing Asturian Basin area of the North Spanish Margin (Soler et al., 1981; Noroil, 1982, 1983). A thick (5-7 km) succession of Lower Cretaceous and younger strata is known in the Armorican marginal basin which lies along the base of the Armorican continental slope (Montadert et al., 1974). This may be the offshore prolongation of the oil-producing Parentis Basin segment of the Aquitaine Basin (Montadert et al, 1979; Masson & Miles, 1983) and as such could be a moderately good hydrocarbon prospect.

The geology of the area between Iberia and the Grand Banks is poorly known and any prediction concering hydrocarbon prospectivity are necessarily speculative. Masson and Miles (1983) have demonstrated that, prior to the opening of the Bay of Biscay in the middle Cretaceous, the Lusitanian Basin of western Portugal (Wilson, 1975), its offshore extension (Montadert et al., 1974; Auxietre & Dunand, 1978) and the Western Approaches Basin were all part of a continuous rift basin. It can, therefore, be inferred that a thick Triassic and Lower Jurassic succession may be present offshore western Iberian with good potential source rocks present within the Jurassic section. The post-Jurassic history, however, differs in that the offshore Iberian basins have been affected by Lower Cretaceous rifting between Iberia and the Grand Banks during which up to 3 km of sediment were deposited (Montadert et al., 1974). This suggests an overall evolutionary history more comparable with the Porcupine or Celtic Sea Basins and suggests that the area may have good hydrocarbon prospectivity.

In the deeper water area between Iberia and the Grand Banks, the sedimentary section is of Lower Cretaceous and younger age (Groupe Galice, 1979; Parson et al., in press). Sediment thicknesses are generally 1-3 km, with the exception of the westernmost Newfoundland Basin which locally contains over 4 km of sediment with a very thick Lower Cretaceous section (Parson et al., in press). Potential source rocks may include Lower Cretaceous 'black shales', although these were not of high quality where sampled at DSDP site 398 on the Iberian margin (Kendrik et al., 1979). Hydrocarbon prospectivity is likely to range between poor and moderately good, with the best prospect being the western Newfoundland Basin.

The hydrocarbon potential of the Canadian margin has been reviewed by McMillan (1982). As with the European margin, the main hydrocarbon prospects occur in areas where Triassic and Jurassic basins have been involved in the Low Cretaceous rifting event and, as a result, have been buried beneath considerabl thicknesses (up to 9 km in Flemish Pass, McKenzie, 1981) of Lower Cretaceous an younger strata. A major oilfield, the Hibernia field, has been discovered in the Jeanne d'Arc Basin (Fig. 10) and further good prospects occur in Flemish Pa and in the Orphan Basin on a trend which, before the opening of the North Atlantic in the late Early Cretaceous, extended from the Jeanne d'Arc Basin to the Porcupine Basin (Fig. 2). Moderately good prospects may occur in the western Orphan Basin, where exceptional thicknesses (over 3 km) of Tertiary sediments overly a poorly-known Cretaceous sequence (Gradstein & Williams, 1981). Further south, the Whale, South Whale and Horseshoe Basins of the Gran Banks would also appear to have moderately good potential, although almost thir wells have been drilled without discovery of significant hydrocarbon accumulation. Swift and Williams (1980) suggest that Lower Cretaceous uplift, which caused deep erosion of potential Jurassic source rock intervals, breachin of potential reservoirs and interruption of the maturation process, may have seriously damaged the hydrocarbon potential of this area.

The remainder of the Grand Banks area and the isolated 'basement' blocks o Flemish Cap and Orphan Knoll consist of Palaeozoic and older strata buried beneath a thin sequence of mainly Late Cretaceous and Tertiary strata. Hydrocarbon potential of these areas is poor.

In summary, proven hydrocarbon reserves appear to occur where deep Triassi and Jurassic basins have been buried beneath significant thicknesses of Cretaceous and younger sediments, the deposition of which was related to riftin and subsidence of North Atlantic continental margins since the Early Cretaceous The majority of mature source rocks appear to occur within the Jurassic; few good source rocks have been proven in the syn- and post-rift Cretaceous and Tertiary sediments which rarely reach thicknesses sufficient to achieve source rock maturity.

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FIGURE CAPTIONS

Figure 1. North Atlantic reconstruction for the time of anomaly 34 (83 m.y., late Cretaceous) showing locations of the main geographical features and of DSDP boreholes discussed in text.

Figure 2. Summary of pre-rift geology plotted on the pre-Aptian (~115 m.y.) North Atlantic reconstruction of Masson and Miles (in press).

Figure 3. Example of a seismic profile across a tilted and rotated fault block on the northern margin of the Bay of Biscay.

Figure 4. Schematic cross section across the Goban Spur continental margin summarising the drilling results of IPOD Leg 80. Note the change in depositional style between the syn-rift Barremian-Aptian unit and the post-rift Albian and younger unit.

Figure 5. Lower Cretaceous rift-phase fault pattern and thickness of syn-rift sediments (in metres).

Figure 6. Tilted fault-block on the North Biscay margin illustrating how varying interpretation of the 'top pre-rift' surface can give widely differing superficial extension values. In this case, we would suggest that BB' is the true top of the tilted block, and that the layered unit between AA' and BB' represents pre-rift Jurassic and older sedimentary rocks. The superficial extension (C) measured from this block is therefore low (~1.4). Note that part of the seismic profile from which this figure was derived is illustrated in Figure 3.

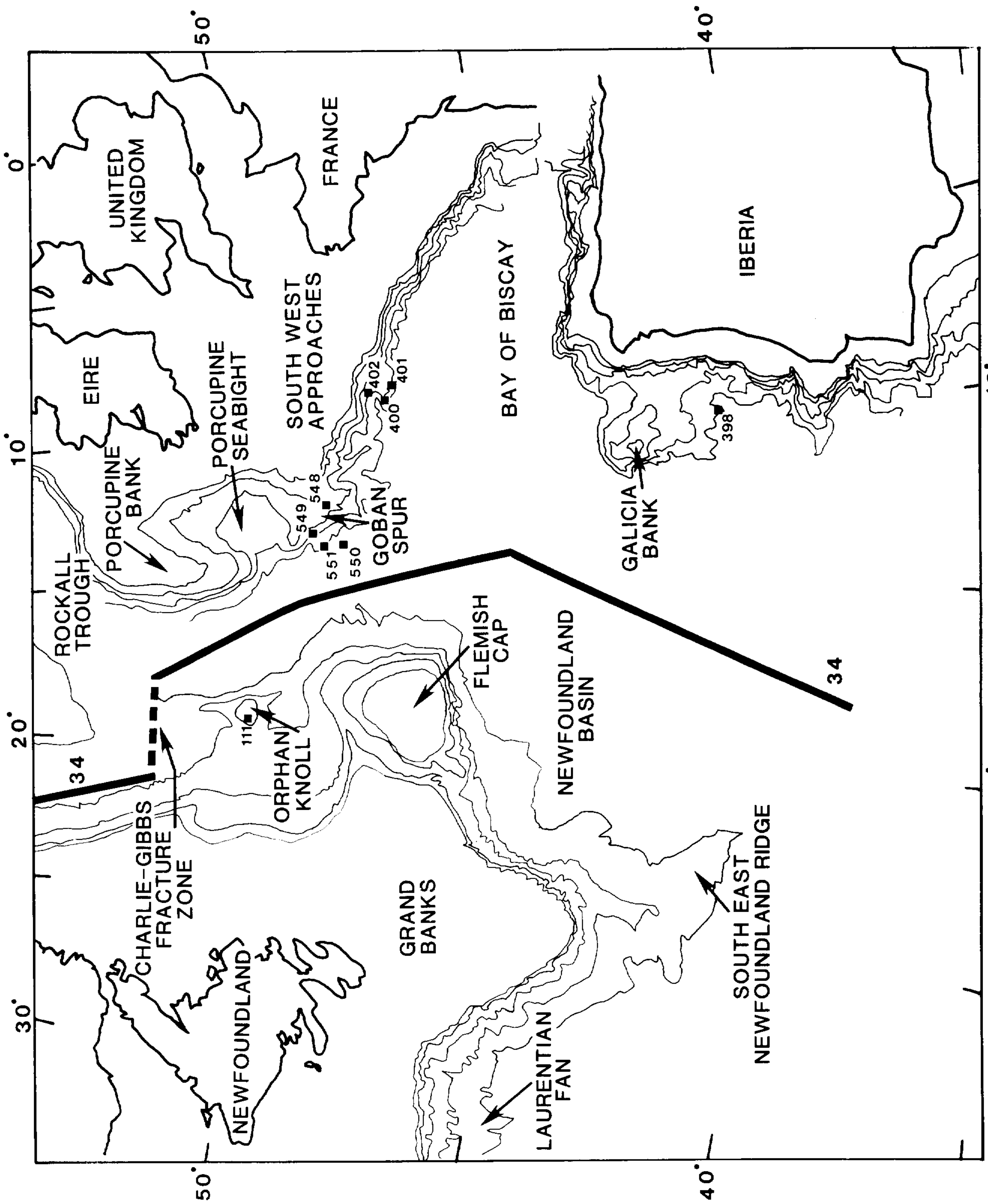
Figure 7. Plots of whole crustal extension (derived from the gravity models of Scrutton, 1979 [profile A] and in press [profile B]) and superficial or upper crustal extension (derived from seismic reflection records) against distance from the ocean-continent transition west of Goban Spur. Each rectangle represents one upper crustal extension measurement, the height of the rectangle showing the possible error in the extension measurement and the length of the rectangle the width of the block. Note that the increase in whole crustal extension near the ocean-continent transition is not shown by the superficial extension.

Figure 8. Summary of continental margin seismic stratigraphy covering the various margins discussed in this report. Numbers refer to

seismostratigraphic units identified in each area; they do not necessarily correlate between areas. Cross-hatching marks hiatuses or highly-condensed sequences.

Figure 9. Schematic cross-section of the western Newfoundland Basin. The ages of the various units are given in Figure 8. Note the position of the J magnetic anomaly, probably marking the ocean-continent transition.

Figure 10. Speculative assessment of the hydrocarbon potential of the North Atlantic continental margins discussesd in this report. Base map is the pre-Aptian North Atlantic reconstruction of Masson and Miles (in press). 1: Porcupine Basin; 2: Celtic Sea Basin; 3: Bristol Channel Basin; 4: Western Approaches Basin; 5: Armorican Marginal Basin· 6: Aquitaine Basin; 7: Asturian Basin; 8: Galicia Bank; 9: Lusitanian Basin; 10: Newfoundland Basin; 11: South Whale Basin; 12: Horseshoe Basin; 13: Whale Basin; 14: Jeanne d'Arc Basin; 15: Flemish Pass; 16: Flemish Cap; 17: Orphan Basin; 18: Orphan Knoll.



UNITED KINGDOM
FRANCE
EIRE
PORCUPINE SEABIGHT
SOUTH WEST APPROACHES
BAY OF BISCAY
IBERIA
PORCUPINE BANK
ROCKALL TROUGH
GOBAN SPUR
GALICIA BANK
FLEMISH CAP
NEWFOUNDLAND BASIN
ORPHAN KNOLL
CHARLIE-GIBBS FRACTURE ZONE
GRAND BANKS
NEWFOUNDLAND
LAURENTIAN FAN
SOUTH EAST NEWFOUNDLAND RIDGE
34
34
402
401
400
398
548
549
550
551
111
0°
10°
20°
30°
10°
20°
50°
40°
50°
40°

Figure 1

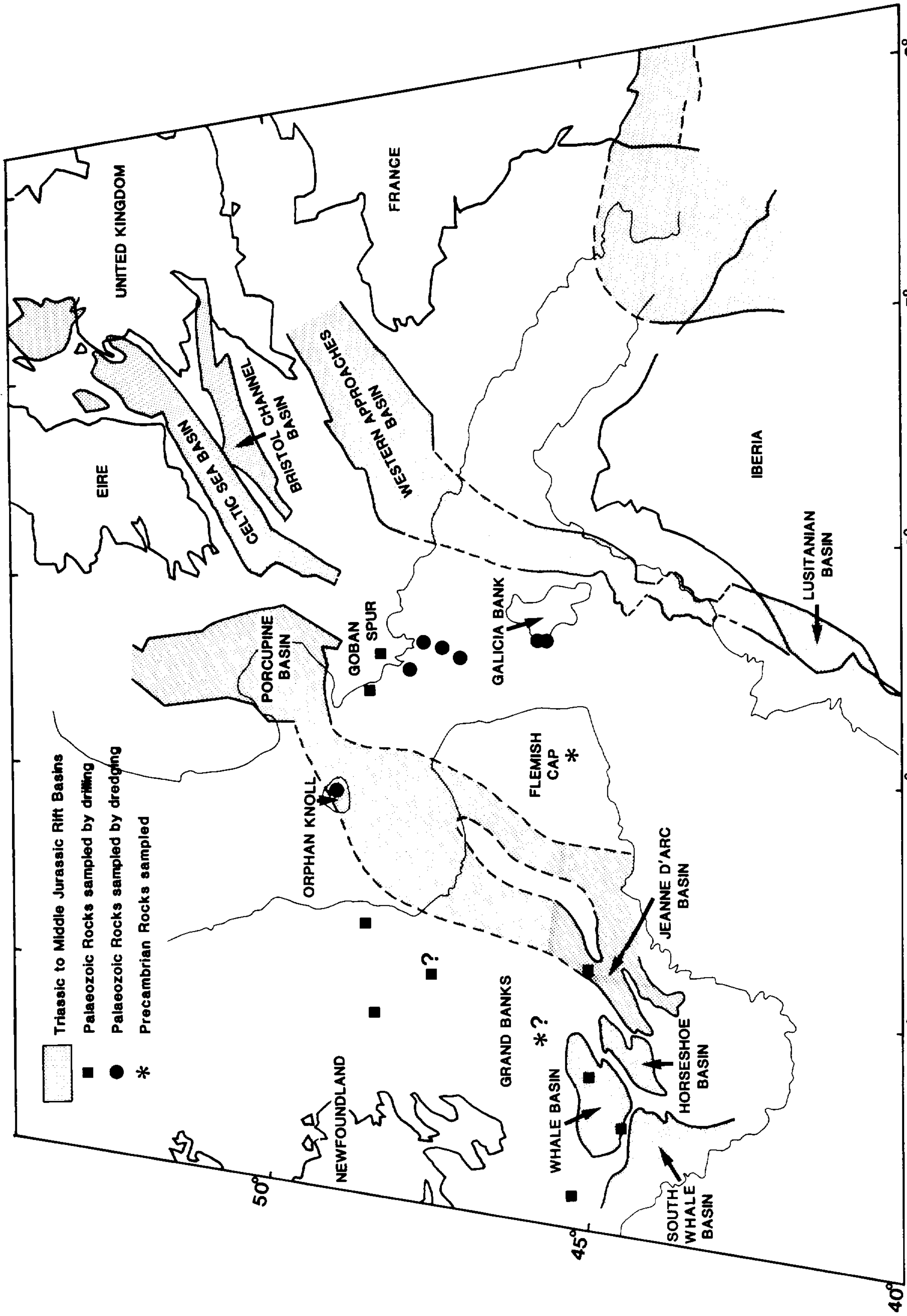

Triassic to Middle Jurassic Rift Basins
Palaeozoic Rocks sampled by drilling
Palaeozoic Rocks sampled by dredging
Precambrian Rocks sampled
UNITED KINGDOM
EIRE
FRANCE
CELTIC SEA BASIN
BRISTOL CHANNEL BASIN
WESTERN APPROACHES BASIN
IBERIA
LUSITANIAN BASIN
PORCUPINE BASIN
GOBAN SPUR
GALICIA BANK
ORPHAN KNOLL
FLEMISH CAP
JEANNE D'ARC BASIN
GRAND BANKS
NEWFOUNDLAND
WHALE BASIN
HORSESHOE BASIN
SOUTH WHALE BASIN
0°
5°
10°
15°
20°
25°
40°
45°
50°

Figure 2

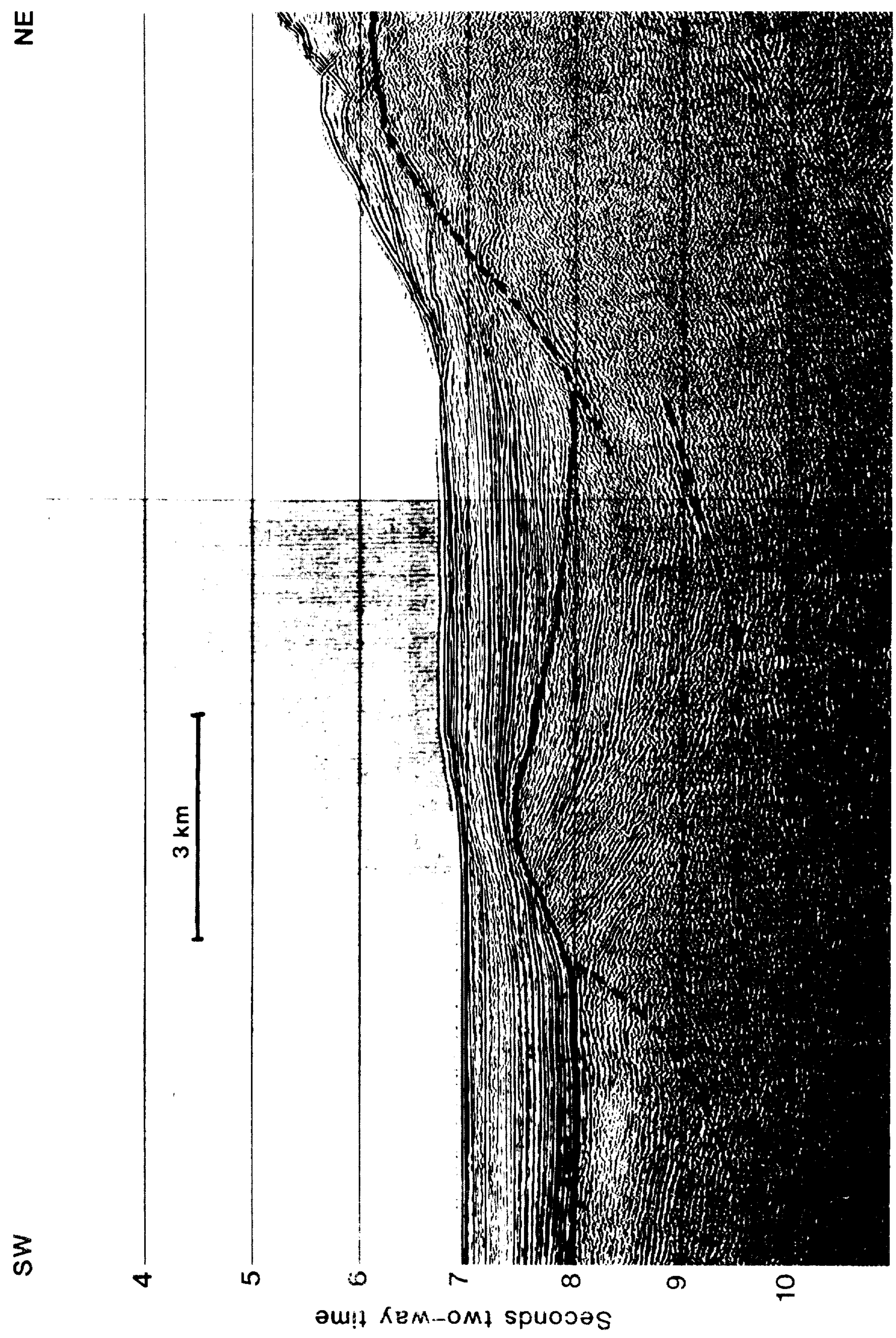


Figure 3

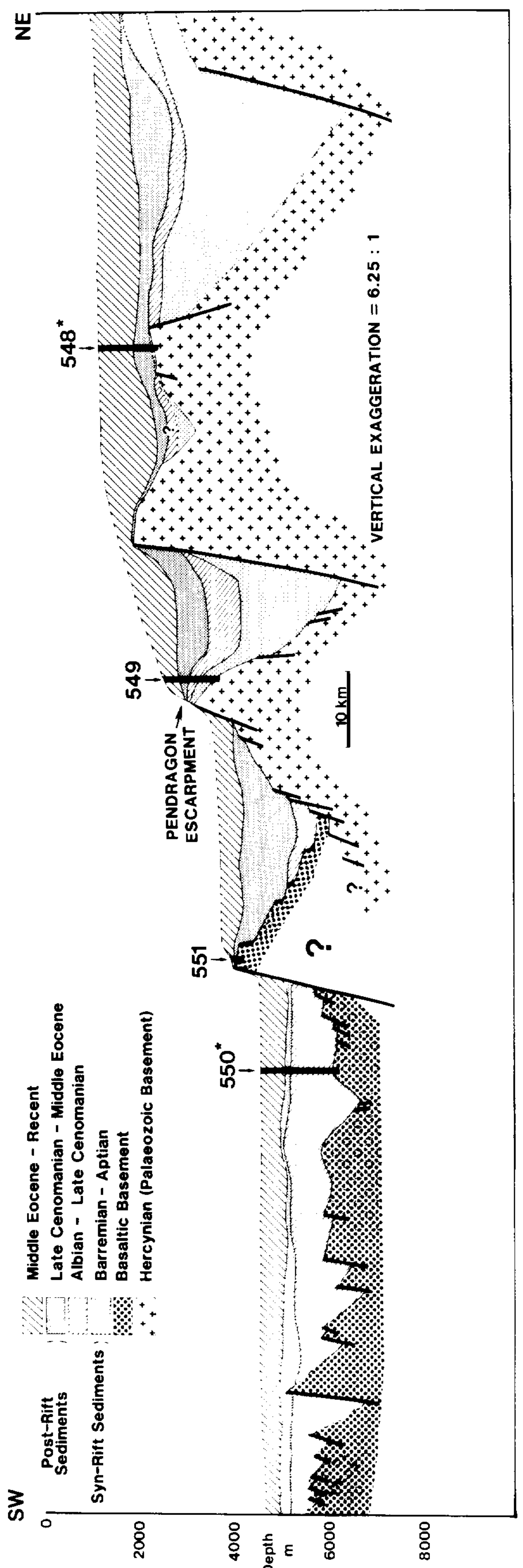
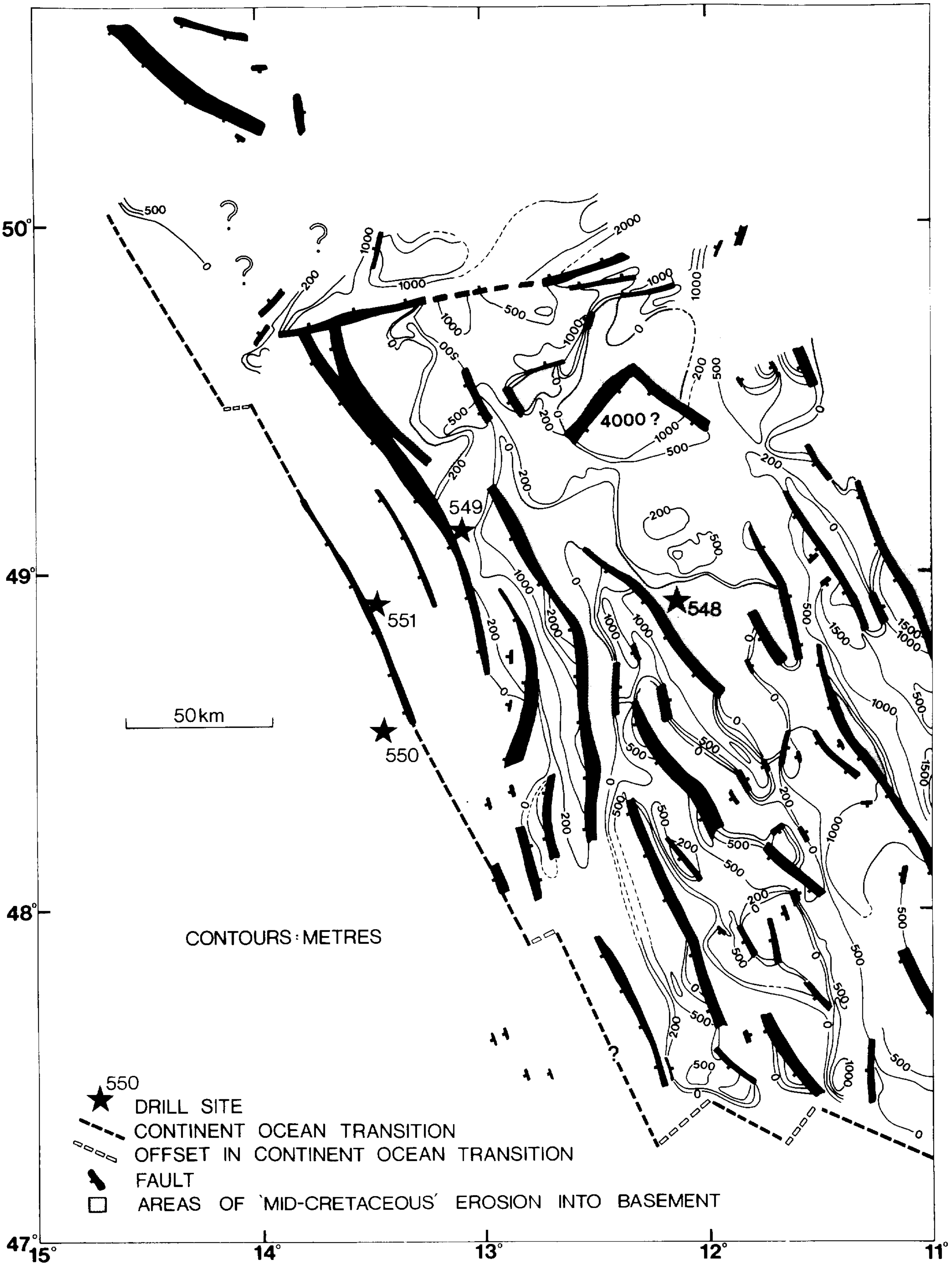

SW
NE
0
2000
4000
6000
8000
Depth m
Post-Rift Sediments
Syn-Rift Sediments
Middle Eocene - Recent
Late Cenomanian - Middle Eocene
Albian - Late Cenomanian
Barremian - Aptian
Basaltic Basement
Hercynian (Palaeozoic Basement)
550*
551
549
548*
PENDRAGON ESCARPMENT
10 km
VERTICAL EXAGGERATION = 6.25 : 1

Figure 4



50°
49°
48°
47°
15°
14°
13°
12°
11°
549
551
550
548
4000 ?
50km
CONTOURS: METRES
550
DRILL SITE
CONTINENT OCEAN TRANSITION
OFFSET IN CONTINENT OCEAN TRANSITION
FAULT
AREAS OF 'MID-CRETACEOUS' EROSION INTO BASEMENT

Figure 5

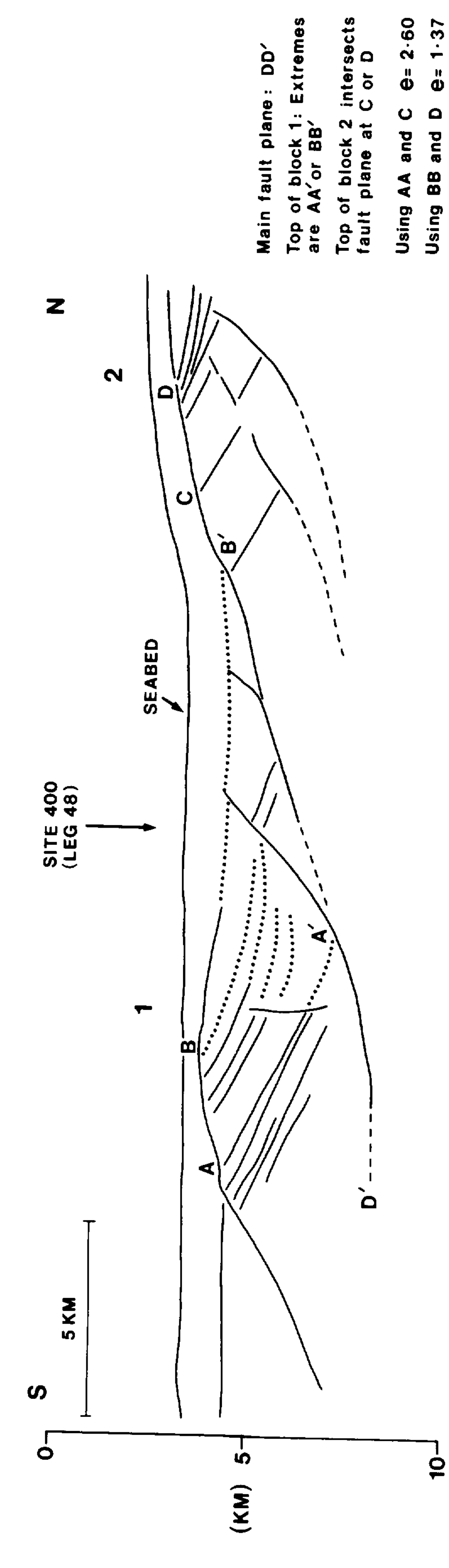

Main fault plane: DD′
Top of block 1: Extremes are AA′or BB′
Top of block 2 intersects fault plane at C or D
Using AA and C e= 2·60
Using BB and D e= 1·37
S
N
5 KM
SITE 400 (LEG 48)
SEABED
1
2
A
B
C
D
A′
B′
D′
(KM)
0
5
10

Figure 6

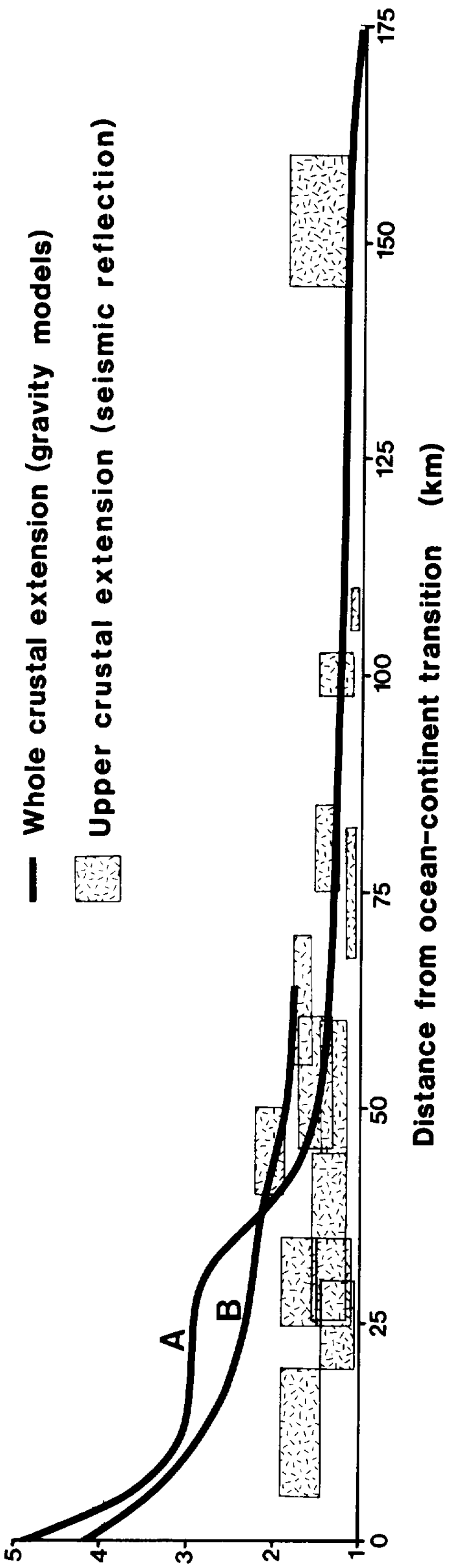

Whole crustal extension (gravity models)
Upper crustal extension (seismic reflection)
A
B
5
4
3
2
1
0
25
50
75
100
125
150
175
Distance from ocean-continent transition (km)

Figure 7

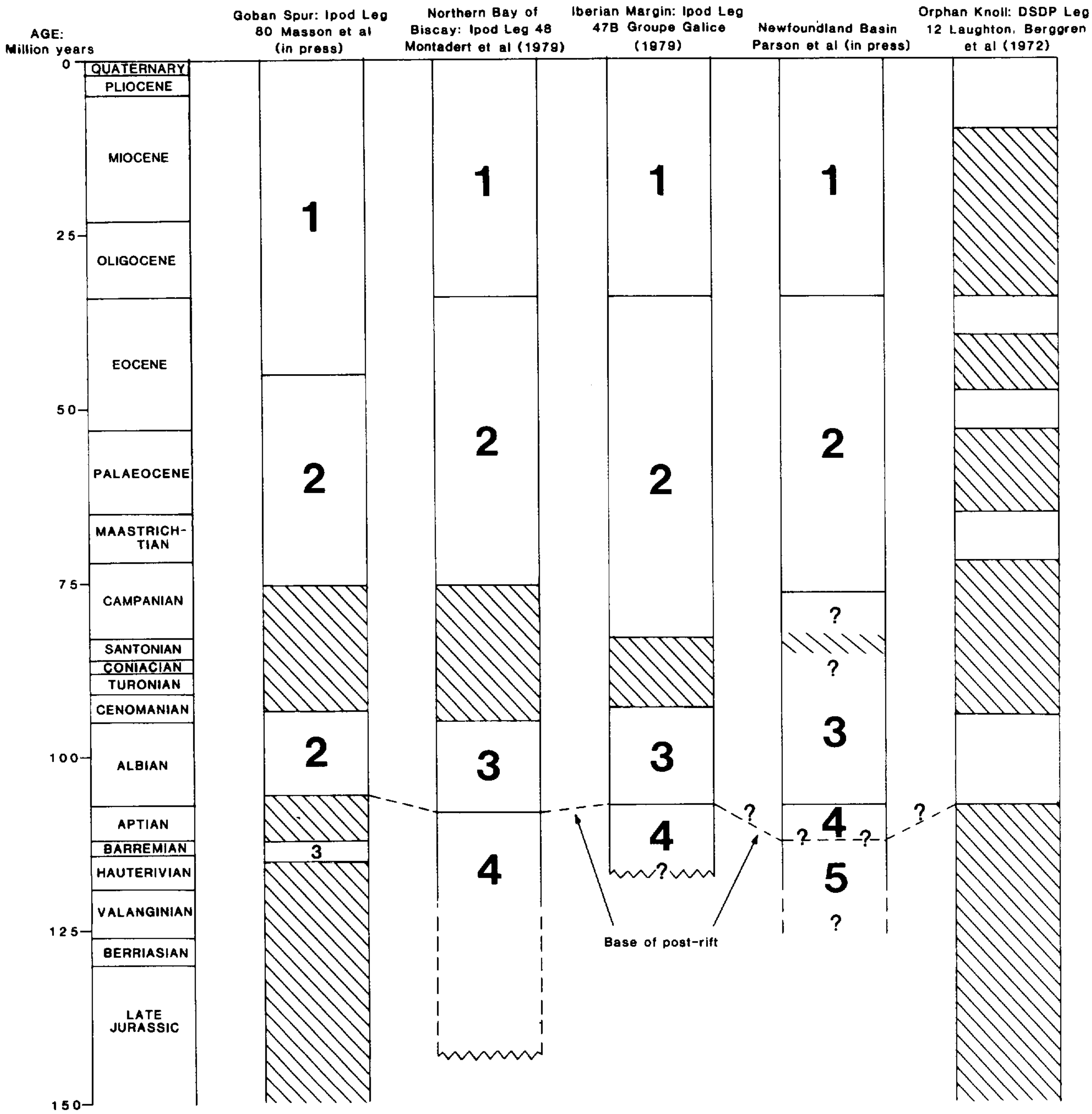

AGE:
Million years
Goban Spur: Ipod Leg 80 Masson et al (in press)
Northern Bay of Biscay: Ipod Leg 48 Montadert et al (1979)
Iberian Margin: Ipod Leg 47B Groupe Galice (1979)
Newfoundland Basin Parson et al (in press)
Orphan Knoll: DSDP Leg 12 Laughton, Berggren et al (1972)
0
25
50
75
100
125
150
QUATERNARY
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
PALAEOCENE
MAASTRICH-TIAN
CAMPANIAN
SANTONIAN
CONIACIAN
TURONIAN
CENOMANIAN
ALBIAN
APTIAN
BARREMIAN
HAUTERIVIAN
VALANGINIAN
BERRIASIAN
LATE JURASSIC
Base of post-rift

Figure 8

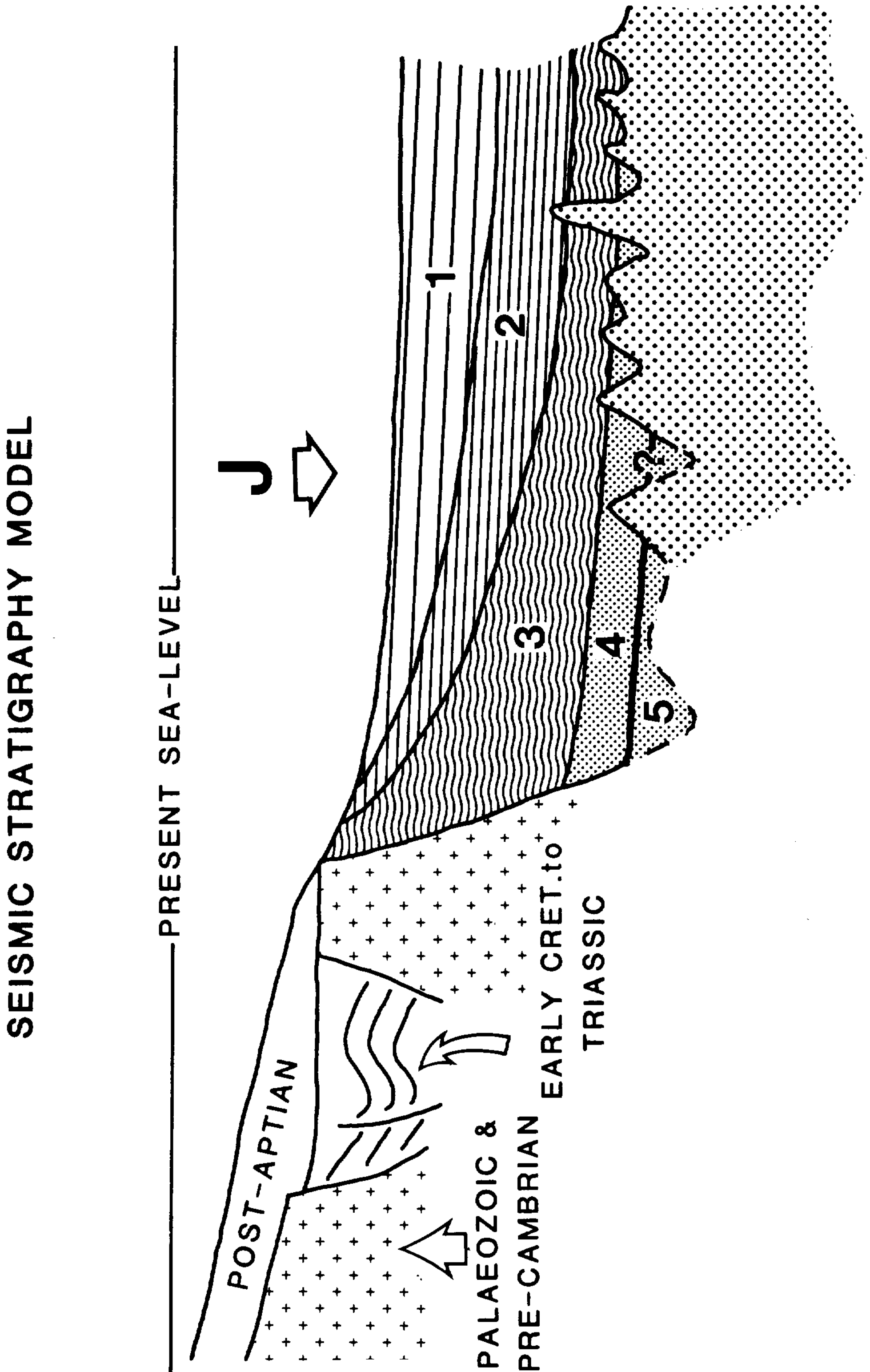

SEISMIC STRATIGRAPHY MODEL
PRESENT SEA-LEVEL
J
1
2
3
4
5
POST-APTIAN
EARLY CRET. to
TRIASSIC
PALAEOZOIC &
PRE-CAMBRIAN

Figure 9

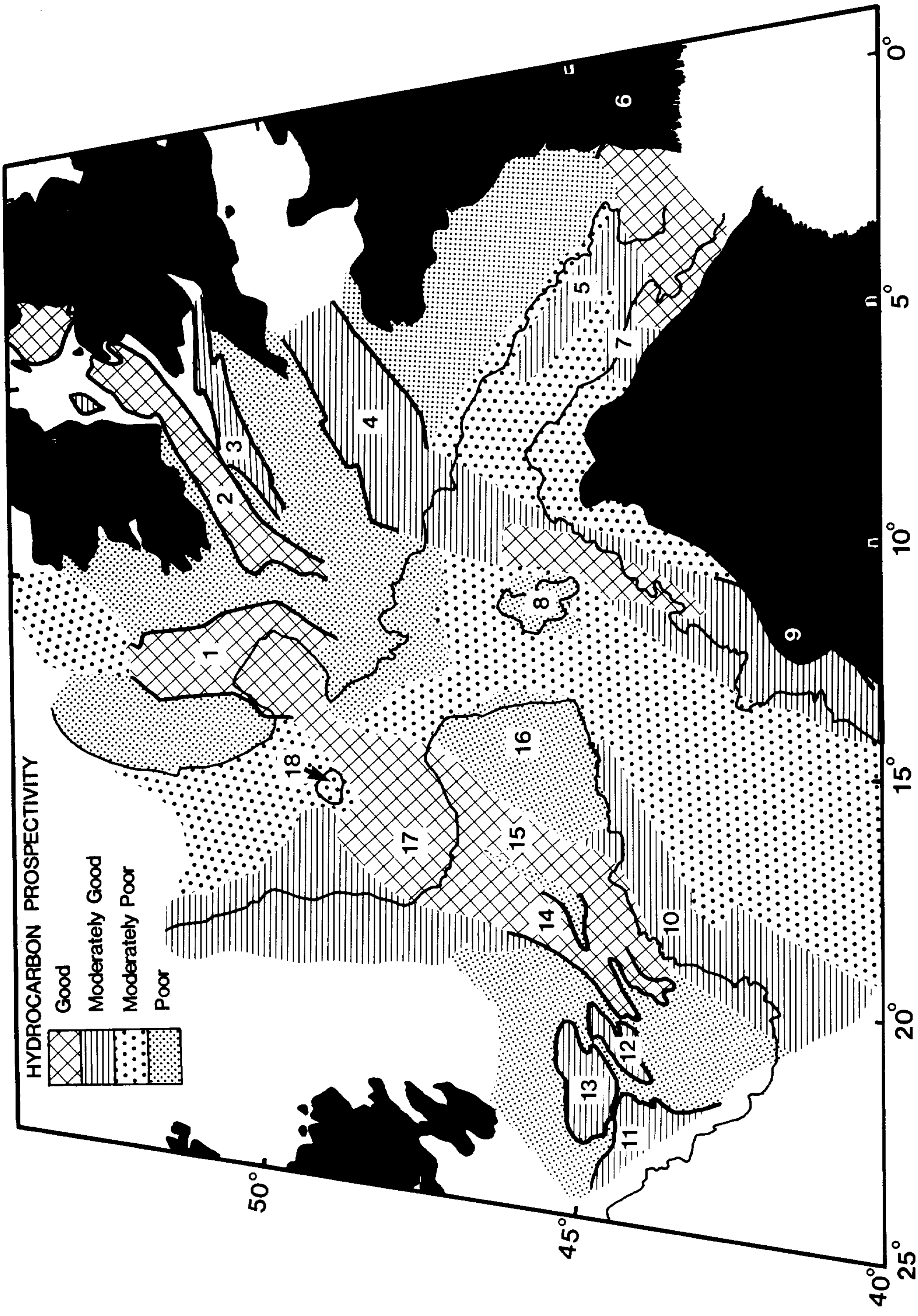

HYDROCARBON PROSPECTIVITY
Good
Moderately Good
Moderately Poor
Poor
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
0°
5°
10°
15°
20°
25°
40°
45°
50°

Figure 10

APPENDIX 1

List of main geophysical cruises to continental margins discussed in this report (Cruises which contributed isolated passage tracks are not included

Survey	Operator	Year	Area surveyed (data collected)
WI Survey	Western Geophysical	1975	Goban Spur and Porcupine Seabight (MS)
Discovery 74	IOS	1975	Goban Spur (SS, M, B)
Shackleton 5/76	Edinburgh University	1976	Goban Spur (SS, G, M, B, D)
Shackleton 6/76	IOS	1976	North-west Iberia, Bay of Biscay (SS, G, M, B, D)
IPOD Leg 48	DSDP	1976	North Bay of Biscay (well data)
CM Survey	S & A Geophysical for IOS	1977	Goban Spur, Porcupine Seabight, Bay of Biscay (MS, G, M, B)
Shackleton 4/77	Edinburgh University	1977	Goban Spur (SS, G, M, B, D)
Discovery 90/91	IOS	1978	North Bay of Biscay, West Iberia (SS, G, M, B, GLORIA)
Shackleton 3/79	Edinburgh University	1979	Goban Spur, Porcupine Bank (SS, G, M, B)
Shackleton 6/79	IOS	1979	North Bay of Biscay (Two-ship seismic refraction and reflection experiment with M.V. Resolution, G, M, B)
Starella 1/79	IOS	1979	Grand Banks (SS, G, M, B, GLORIA)
Discovery 111	IOS	1980	Grand Banks (SS, G, M, B, GLORIA)
IOS Survey	Western Geophysical for IOS	1981	Porcupine Seabight (MS, one line only)
IPOD Leg 80	DSDP	1981	Goban Spur (well data)
Farnella 1 and 2/81	IOS	1981	Grand Banks (SS, G, M, B, GLORIA)
OC Survey	Institut Français du Petrole	1975-1983	Goban Spur and North Bay of Biscay (MS, data from various surveys traded to IOS)

MS - Multichannel seismic reflection
SS - Single channel seismic reflection
G - Gravity
M - Magnetics
B - Bathymetry
D - Dredge samples

APPENDIX 2

Reports and publications resulting from the work described in this report (listed by year)

1975

Laughton, A.S., Roberts, D.G. & Graves, R. Bathymetry of the North-East Atlantic: Mid-Atlantic ridge to south-west Europe. Deep-Sea Res. 22, 791-810.

Roberts, D.G. et al. R.R.S. Discovery cruise 74 leg 2. Seismic reflection profiling across the continental margin in the South West Approaches. IOS Cruise Report No. 33, 20 pp., unpublished manuscript.

1976

Montadert, L., Roberts, D.G., Auffret, G.A., Bock, W., Dupeuble, P.A., Hailwood, E.A., Harrison, W., Kagami, H., Lumsden, D.N., Muller, C., Schnitker, D., Thompson, R.W., Thomson, T.L. & Timofeev, P.P. Glomar Challenger sails on Leg 48. Geotimes 21(12), 19-23.

Roberts, D.G. et al. R.R.S. Shackleton Cruise 6/76. Geophysical studies of south-west Biscay. IOS Cruise Report No. 49, 20 pages, unpublished manuscript.

1977

Montadert, L., Roberts, D.G., Auffret, G.A., Bock W., Dupeuble, P.A., Hailwood, E.A., Harrison, W., Kagami, H., Lumsden, D.N., Muller, C., Schnitker, D., Thompson, R.W., Thompson, T.L. & Timofeev, P.P. Rifting and subsidence on passive continental margins in the north-east Atlantic. Nature, 268, 305-309.

1978

De Charpal, O., Guennoc, P., Montadert, L. & Roberts, D.G. Rifting, crustal attenuation and subsidence in the Bay of Biscay. Nature, 275, 706-711.

Kenyon, N.H., Belderson, R.H. & Stride, A.H. Channels, canyons and slump folds on the continental slope between south-west Ireland and Spain. Oceanologica Acta, 1, 369-380.

Roberts, D.G. *et al.* R.R.S. Discovery cruise 90. Sonar imaging of the European-North African continental margin. IOS Cruise Report No. 68, 22 pp., unpublished manuscript.

1979

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