PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

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Geological setting and principal results of drilling on the margins of the Bay of Biscay and Rockall Plateau during Leg 48

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During Leg 48 of the IPOD phase of the Deep Sea Drilling Project, seven holes were drilled on the margins of the Bay of Biscay and Rockall Plateau to compare the evolution of passive margins of contrasting age and structural development. The geological setting and principal results of the drilling are outlined for each margin. We discuss the history of rifting and subsidence on these margins in relation to the sea floor spreading history of the adjacent ocean basins. Implications of the results for the nature of unconformities at passive margins and anoxic episodes during the Lower Cretaceous are discussed briefly.

Introduction

During Leg 48 of the IPOD phase of the Deep Sea Drilling Project, ten holes were drilled at seven sites on the margins of north Biscay and the Rockall Plateau (figures 1 and 2). In this paper, the principal scientific objectives of Leg 48 are discussed in terms of the regional problems of each margin and the more fundamental problems addressed by the passive margin drilling programme. In conclusion, we attempt to synthesize the results of the leg in terms of these objectives, and also to comment briefly on new problems raised by the results. A detailed description of each hole is given in Montadert *et al.* (1977, 1978).

Curray (this volume) has discussed in detail the formulation of the objectives of the drilling programme by the IPOD Passive Margin Panel and the scientific community. The approach used by the Panel in defining and testing problems of passive margin evolution is in at least one sense uniformitarian. By drilling on present day margins of different age and contrasting structural and sedimentary style considered to represent various stages in their evolution, some

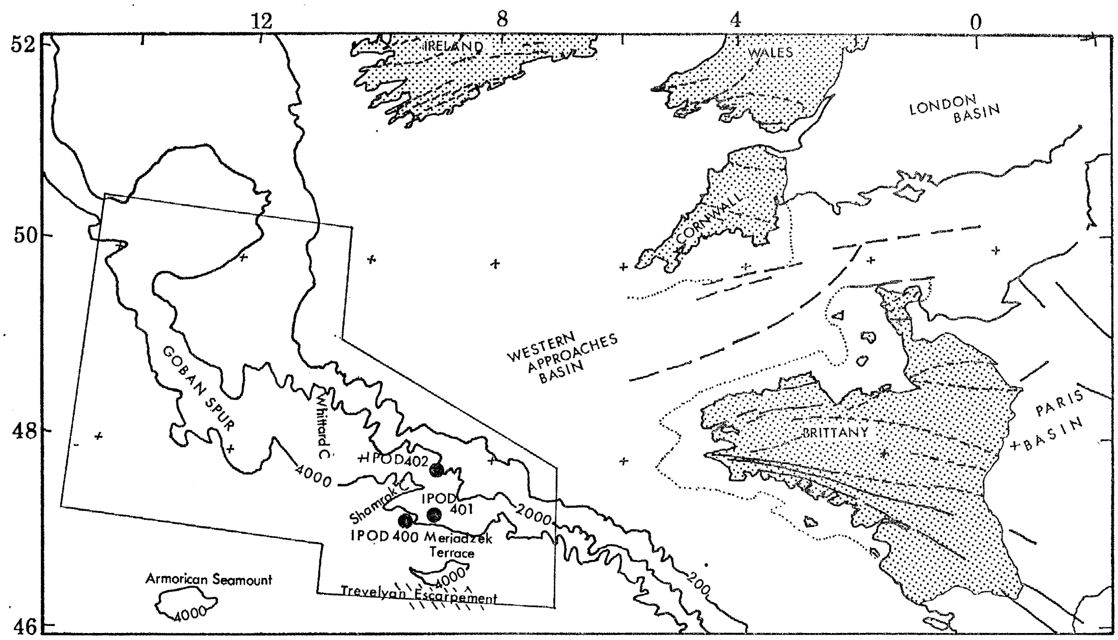

FIGURE 1. Bathymetry and location of D.S.D.P. Sites 400A, 401, 402 on north margin of Biscay. Contours are in metres.

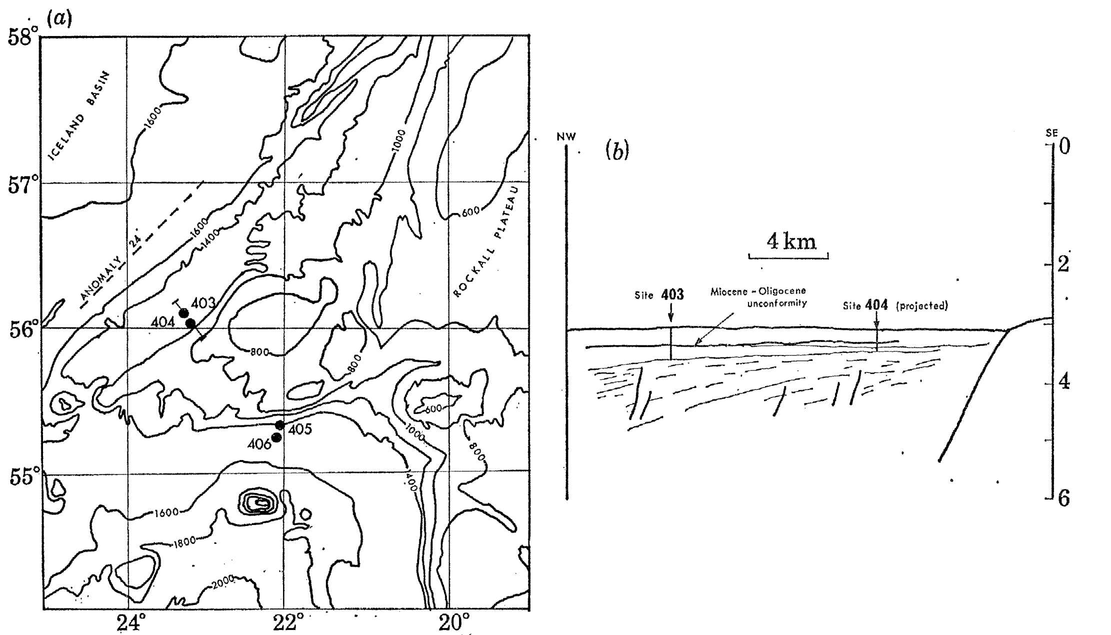

FIGURE 2. (*a*) Bathymetry and location of D.S.D.P. Sites 403, 404, 405, 406 on South West Rockall Plateau. Contours in fathoms (1 fathom = 1.83 m). (*b*) Line drawing of seismic reflexion profile through Sites 403 and 404.

insight can be gained into the geological processes responsible for their evolution through time. Inherent in this approach is the assumption that passive margins were initially structured by rifting and have subsequently subsided throught time.

In developing a kinematic framework of passive margin evolution, a deeper understanding of a number of problems is critical. These include the nature of the pre- and syn-rift environment, especially in relation to rifting within cratons and epicontinental seas. Closely related questions include the altitude of the continent at the continent–ocean boundary at the onset of spreading, the validity of the widely used East African analogue and the role of basement tectonics on rifting and crustal attenuation. The timing, magnitude and history of margin subsidence in relation to rifting, spreading and the major unconformity observed beneath many margins is not understood; nor is the relation between later unconformities and transgression, regression, uplift of the continent and variations in spreading rate (Vail, this volume). These relations are as fundamental to our understanding of facies development as are the closely related changes in ocean circulation revealed as hiatuses, variations in productivity and the carbonate-compensation depth. The nature of early margin palaeoenvironments and their influence on the organic geochemistry of the sediments is also controversial.

The margins of the Bay of Biscay and the Rockall Plateau offered the opportunity to address many of these problems since the thin Mesozoic and Tertiary Sedimentary cover enabled penetration of pre- and syn-rift sediments at shallow depths. The two regions also offered a further comparison, both in age and structure, and this is discussed in more detail below.

Regional geological setting of the Bay of Biscay

The Bay of Biscay is an unusual example of a re-entrant ocean basin whose northern margin consists of a broad shelf, a broad slope cut by many canyons and broken only by the Meriadzek Terrace and the Trevelyan escarpment (figure 1). In contrast, the shelf and slope of the southern or north Spanish margin are both linear and narrow. Geological and geophysical surveys have shown that the southern margin was initially formed by rifting but was subsequently deformed by compression during Upper Cretaceous–Oligocene/Miocene time (Debyser *et al.* 1971; Montadert *et al.* 1975).

Multichannel seismic reflexion surveys made by I.O.S., I.F.P. and C.N.E.X.O. show that the deeply dissected north margin of Biscay consists of thin prograding sediments resting on a series of tilted blocks and half grabens trending subparallel to the margin (figure 3). Beneath the margin and adjacent abyssal plain, the sediments consist of three formations partly penetrated in Joides Sites 118 and 119 (Laughton *et al.* 1972). Correlation with these sites shows that Formation 1 is post-Eocene–Quaternary in age and that its base coincides with the termination of the normal faulting episode observed beneath the outer part of the margin and abyssal plain. Formation 2 is Palaeocene and Eocene in its upper part. Lithologically, formation 1 consisted of turbidites interbedded with pelagic sediments while formation 2 was composed of marls and calcarenites in its upper part; formation 3 was not sampled. Beneath the slope and rise, seismic profiles show that the top of formation 3 is an unconformity and its base is also defined by an unconformity. The thickness and distribution of formation 3 is closely controlled by the tilted block structure. Before Leg 48, evidence for the nature of formation 3 was based on dredging (Pastouret & Auffret 1977). The oldest sediments recovered are of Upper Jurassic age although granites have been dredged recently in 4500 m depth (Pautot *et al.* 1976). In the Meriadzek Terrace area, neritic and reefal Lower Cretaceous sediments have been dredged, as well as Lower Cretaceous conglomerates containing fragments of red beds of presumed Permo–Triassic age. In one suite of dredged rocks there is a transition from Barremian beige and green marls of an external platform facies to Albo–Aptian black marls and limestones characteristic of the infra-tidal zone. However, many of these dredgings have been made close to fault blocks so that their structural and stratigraphic significance has remained equivocal.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
THE ROYAL SOCIETY A
PHILOSOPHICAL TRANSACTIONS OF

In very brief outline, the geological history of Biscay based on the geological and geophysical data available for the offshore and onshore areas (Debyser *et al.* 1971) is as follows:

(1) Rifting of the Hercynian platform of Western Europe during Triassic time with thick evaporite deposition in the Aquitaine, Celtic Sea and Lusitanian Basins. Volcanism may have been important.

(2) A period of gentle subsidence and epicontinental sedimentation until the upper Malm.

(3) During the Upper Malm, a regional phase of epeirogenesis which grew more intense to reach its maximum in Albo–Aptian time in the Aquitaine Basin and Bristol Channel areas. The major post-Lower Cretaceous – pre-Upper Cretaceous unconformity observed on land and possibly beneath the margin may mark the change from rifting to spreading.

(4) Opening of Biscay; there is considerable doubt as to the duration and geometry of the spreading.

(5) A period of tectonic rejuvenation related to the Pyrenean deformation, possibly beginning in Late Upper Cretaceous time and continuing until Oligocene – Miocene time.

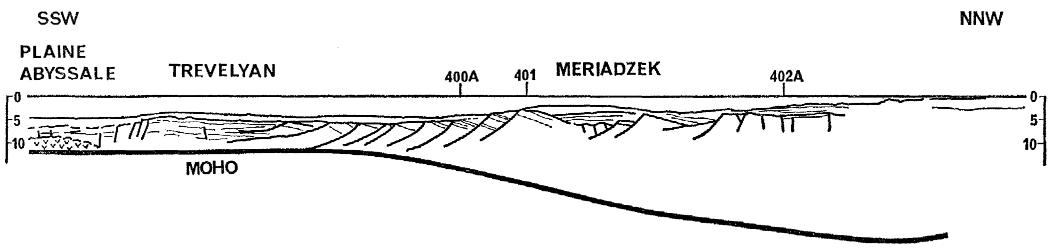

Figure 3. Schematic section across the north margin of Biscay.

The absence of a thick prograding Cretaceous and Tertiary sediment in Biscay offered the opportunity to examine a number of fundamental problems of continental margins within this geological framework. These included:

(1) a comparison of the pre-, syn- and post-rift sedimentary environments by penetration of the 'pre-rift' sequence contained within the tilted and rotated fault blocks;

(2) an examination of the nature of the unconformity at the base of formation **3** in relation to the end of rifting and onset of spreading and the change in depositional environment;

(3) the comparative facies of shelf, slope and rise sediments;

(4) the influence of Cretaceous and Tertiary changes in water conditions on the lithologic and biostratigraphic record;

(5) an examination of the diagenetic and organic geochemical processes in relation to changing thermal conditions on a subsided margin.

Other ancillary objectives included the palaeomagnetic stratigraphy and anisotropy of margin sediments (Hailwood *et al.*, this volume) and the *in situ* measurement of physical properties by well logging techniques (Mann, this volume).

The three sites drilled during Leg 48 form a transect from the mid-continental slope to the rise. The seismic profile of figure **3** passes through Sites 400A and clearly shows the tilted and rotated fault blocks characteristic of much of the Armorican margin of Biscay. Site 400A was drilled to penetrate into the pre-rift sediments contained within these blocks, but this objective was not achieved owing to the loss of the entire drill string. Site 401 on the outer edge of the Meriadzek Terrace was drilled to penetrate pre-rift sediments accessible with the remaining drill string length.

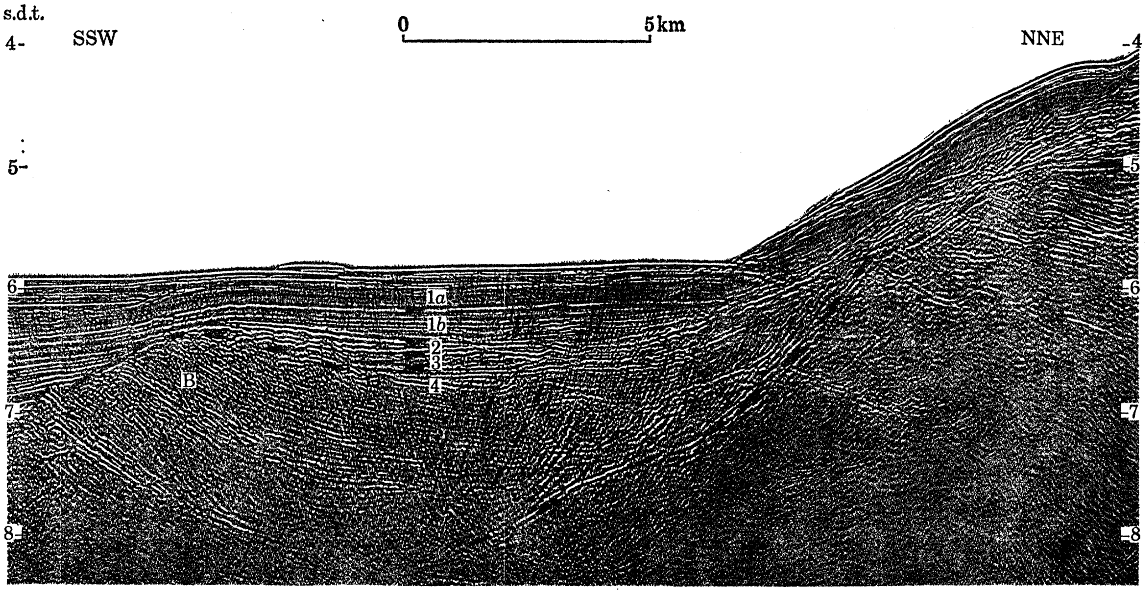

FIGURE 4. Migrated multichannel seismic profile through Site 400A.

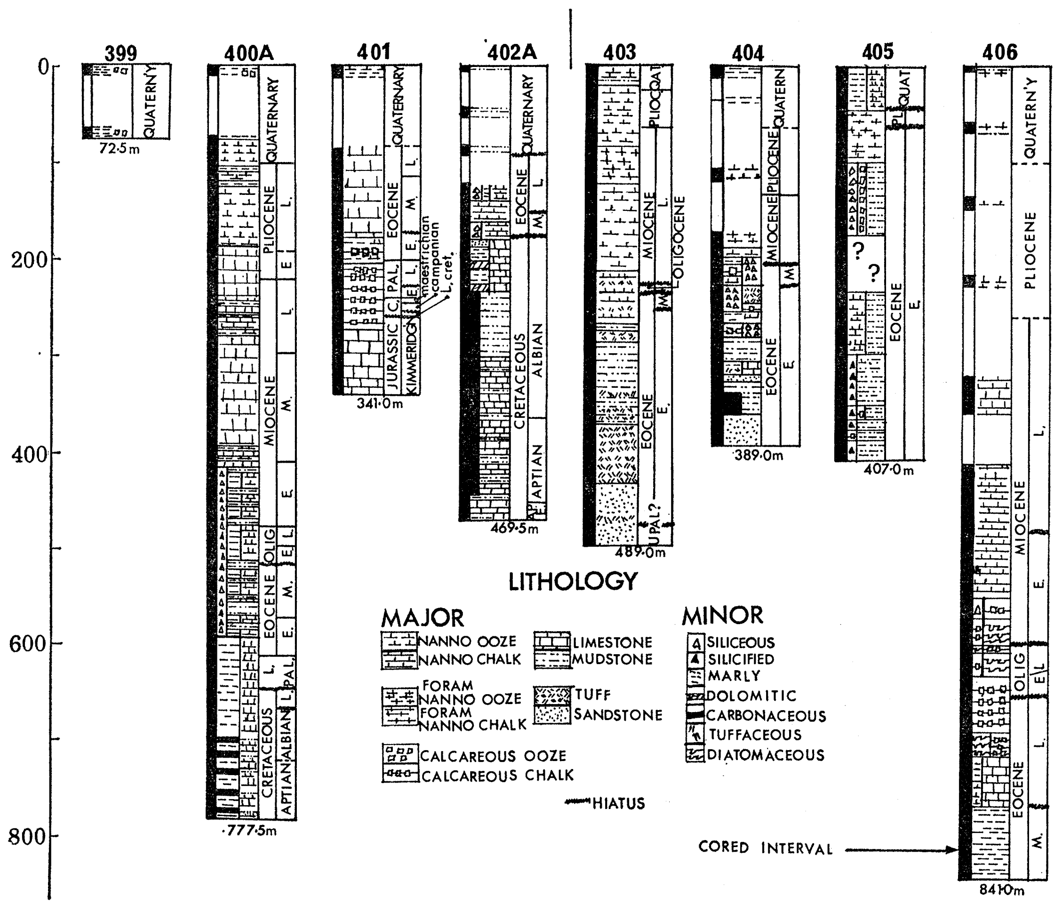

FIGURE 5. Stratigraphy of Leg 48 Sites 400A–406.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

At Site 400A (figures 3–5), the deepest horizons penetrated were Aptian–Albian carbonaceous limestones rhythmically interbedded with marly chalks or calcareous mudstones and apparently deposited in 2000 m water depth. Pyrolysis and palynological studies showed low maturity and a probable detrital origin from terrestrial plants (Tissot *et al.*, this volume; Davey 1979; Batten 1979). A 30 Ma hiatus between the Albian black limestones and deep water Campanian pure chalks is contemporaneous with the well-known transgression. The hiatus may be related to an elevated c.c.d. and/or non-deposition. Hiatuses in the Tertiary section seem best related to changes in ocean circulation (which causes fluctuations in the c.c.d. and surface water productivity) but also correlate with unconformities on the adjacent shelf.

Site 401 (figures 3, 5) on the seaward edge of the Meriadzek Terrace bottomed in shallow water Kimmeridgian–Portlandian reefal limestones overlain by Albian shallow-water limestones that are contemporaneous with the deep water carbonaceous limestones of Site 400A. The difference in Albian palaeodepths that is also supported by seismic evidence, indicates that about 2000 m of submarine relief was then in existence at the Meriadzek Terrace. A prolonged 'Cenomanian–Santonian' hiatus was again present, but in contrast to Site 400A separated shallow-water Albian limestones from bathyl Upper Campanian–Maestrichtian chalks. Within the less complete Tertiary record, hiatuses were present between the Upper and Lower Palaeocene and between the Lower and Middle Eocene.

Site 402A (figures 3, 5) was drilled in a half graben, situated beneath the middle continental slope, to obtain shallow water equivalents of the deeper facies penetrated previously and thus to complete a transect through the margin. The site bottomed in Lower Aptian shallow-water limestones. The overlying lithified Albian–Aptian black limestones contained abundant carbonaceous material of terrestrial origin and were deposited in less than 100 m water depth. Deposition of 'black shales' in water depths ranging from 100 to 2000 m emphasizes the palaeoenvironmental problem imposed by the assumption of reducing conditions throughout the water column. A hiatus was again present above the Albian, but here extends into the Middle Eocene which was probably deposited in water depths of 1000–1500 m.

Regional geological setting of the South West Rockall Plateau

The margins of the Rockall Plateau microcontinent were drilled to gain insight into the effects of contrasting age and structural style on margin evolution. In contrast to the simpler history of the Bay of Biscay, the Rockall Plateau microcontinent is considered to have reached its present isolation as a consequence of three distinct phases of rifting and spreading. The earliest phase opened the Rockall Trough in Lower Cretaceous time. The later phases at 76 and 56 Ma shaped the rectilinear southwest margin by a combination of rifting and transform faulting. The east–west segment of the margin (figure 2*a*), in which Sites 405 and 406 were drilled, was apparently a transform fault which was active between 76 and 56 a and was originally formed during the early opening of the Labrador Sea. The adjacent NE–SW trending margin was apparently formed by rifting along NE–SW lines followed by spreading that began at about 56 Ma (Laughton 1971; Le Pichon *et al.* 1972; Roberts 1974, 1975). In contrast to the Bay of Biscay, the seismic profiles do not show tilted and rotated fault blocks (figure 2*b*). Within 30 km of the oldest magnetic anomaly recorded in the adjacent ocean crust, the margin consists of thick prograding sediments unconformably overlain by a thin sequence of sediments pelagic in its upper part and progradational below. Sites 403 and 404 were drilled in this basin to determine the nature of the unconformity and relation of the facies to rifting and spreading between Greenland and Rockall. Ancillary objectives included an examination of the history of subsidence and the influence of changing circulation on the lithology and biostratigraphy of the margin.

At Sites 403 and 404 (figure 5) foram nanno oozes and chalks ranging in age from Holocene to Upper Miocene were present. At Site 403, hiatuses were found between Upper Miocene and Middle Oligocene chalks, and also between the Middle Oligocene and Middle Eocene siliceous chalks. However, at Site 404, the upper Miocene rested directly on the Middle Eocene. At both sites, the lower Eocene and Upper Palaeocene consisted of tuffs, tuffaceous mudstones and glauconitic mudstones. Tuff beds may cause the prominent reflectors 1 and 2*a* observed on the seismic profile. Site 404 terminated in a polymict conglomerate containing oyster shells, indicative of a littoral environment, that may be the top of the deltaic wedge interpreted on the seismic profile.

The Palaeocene section was probably deposited in marginal marine conditions that subsequently deepened through Lower Eocene time. Palaeobathymetric data (Murray 1978), show that significant deepening of the sites from 75 to 100–180 m occurred at about anomaly 24 time: the onset of spreading between Greenland and Rockall. It is worth noting that before this time, the provenance of the sediments lay to the north west i.e. in the then juxtaposed Greenland continent (Hailwood, this volume). Terrigenous sediments continued to be deposited until intra-Middle Eocene–Oligocene time when the adjoining land areas were submerged to shallow depth, thus cutting off the supply of sediments. The abundant volcanic events within the Eocene sequence are correlative with tuff horizons observed in the North Sea, suggesting widespread subaerial volcanism in the North Atlantic province between 56 and 60 Ma (Harrison *et al.* 1979). The prominent hiatuses present between the Middle Eocene and Upper Miocene may be related to intensifications of the bottom circulation associated with the opening of the various sills between the Norwegian Basin and the North Atlantic Ocean.

Sites 405 and 406 (figure 5) were drilled just 5 miles apart at the foot of the transform fault scarp controlling the southwest margin of the Rockall Plateau. The sites provide a composite stratigraphic record of the Tertiary history of a transform margin. Within the section, prominent hiatuses were found between the Upper and Middle Miocene, between the Oligocene and Upper Eocene, and between the Upper and Lower Eocene. Diatomites of Upper Eocene, Oligocene and Miocene age, that cause several of the seismic reflectors, may reflect variations in silica and carbonate productivity perhaps associated with local upwelling against the adjacent scarp. At Site 406, the Lower Eocene beds were deposited in 100 m depths in contrast with the contemporaneous inner shelf depths of deposition at Sites 403 and 404 (Murray 1978). The difference in relief implies that a substantial part of the relief of the transform fault was developed before the separation of the trailing edge of the continents.

Observations on rifting and subsidence

One of the main objectives of passive margin drilling was to examine the relation between subsidence and rifting. Preliminary subsidence curves published by Montadert *et al.* (1977) showed the depth of the sea floor at each site as a function of age in comparison to the theoretica age versus depth curves for the Pacific ocean crust. Based on the close similarity of the curves, Montadert *et al.* (1977) suggested that margins have subsided with a time constant that may be similar to the 50 Ma time constant deduced for the ocean crust. Improved subsidence curves based on seismic reflection profiles and palaeobathymetric data (Montadert *et al.* 1979) necessitate some modification to their original suggestion.

Although it is clear that substantial subsidence of all sites has taken place, the subsidence history of each site now appears to be a function of the underlying crustal thickness and distance from the continent–ocean boundary. The subsidence history of sites closest to the continent–ocean boundary, where the continental crust is thinnest (Montadert *et al.*, this volume) bears most similarity to that of the ocean crust. Sites furthest away from the boundary appear to have subsided with a shorter time constant that is presumably a function of decreasing heat flow and increasing crustal thickness. The subsidence curve for the base Aptian illustrated in figure 6 shows these relations clearly. None the less, it is important to emphasize that the absolute depth of a point on the margin depends on its initial attitude relative to sea level, and not on its age as is the case for the ocean crust.

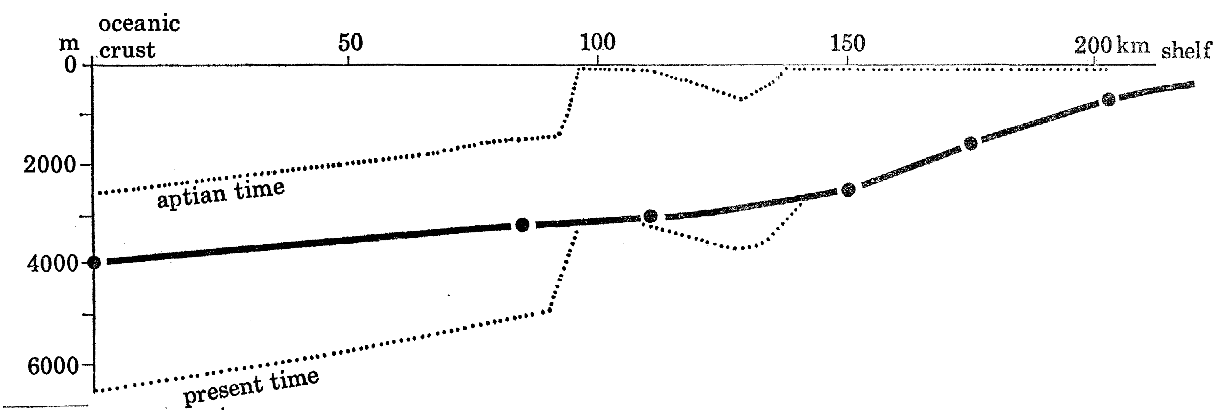

FIGURE 6. Subsidence curve for the Aptian plotted against distance from the shelf.

In understanding the significance and the application of these curves, it is important to distinguish between the thermal régimes that are operative during rifting and spreading. During rifting, the continental crust remains joined so that the heat source remains fixed beneath the rift axis. During spreading, the heat source continually migrates away from the rifted margin as new crust accretes at the rift axis, resulting in cooling which can therefore only begin at the end of rifting and the onset of spreading.

If this premise is correct, subsidence curves derived for passive margins can be used to infer the onset of spreading and the altitude of the continent at that time. In the case of the Rockall Plateau, the curve suggests initiation of cooling at about 52 Ma in close agreement with the onset of spreading at that time (Montadert *et al.* 1979; Hailwood *et al.*, this volume). In Biscay, however, the closest correspondence between the observed and theoretical curves suggests initiation of cooling at about 120 Ma with the site already in 2000 m water depth. Spreading in Biscay may therefore have begun in 2000 m water depth at 120 Ma. In both cases, the subsidence was accompanied by a gentle oceanward tilt rather than by renewed faulting.

Despite the broadly similar relation between rifting, subsidence and spreading, there are radical differences in the rift and post-rift environments of Biscay and Rockall. In the case of Rockall, rifting was associated with widespread contemporaneous volcanism and a substantial subaerial relief, since the first post-rift sediments were deposited in inner shelf conditions at the foot of a 1000 m subaerial scarp to close the continent–ocean boundary (Montadert *et al.* 1977). In this respect the environment bears many similarities to the East African rift system, and may be responsible for the similar structure of the Outer Voring Plateau (Eldholm, this volume). In Biscay, however, the inferred late Jurassic – early Cretaceous rifting was associated with only minor volcanism, but produced 2000 m of submarine relief by the time the post-rift sediments were laid down (Montadert *et al.* 1977). These differences, also reflected in the contrasting structural configuration of these margins (Montadert *et al.*, this volume), may be related to rifting of a Pre-Cambrian craton in the case of Rockall and a Mesozoic epicontinental basin in the case of Biscay.

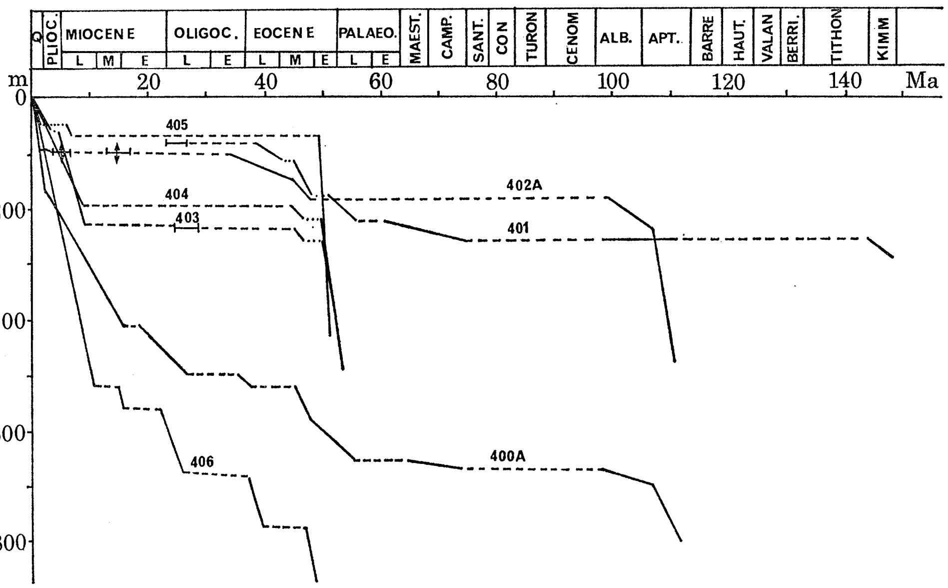

FIGURE 7. Sedimentation rate curves for Leg 48 Sites 400A–406.

UNCONFORMITIES ON PASSIVE MARGINS

A number of prominent hiatuses were found on the margins of both Biscay and Rockall. The origin and nature of such hiatuses in both the deep sea geological record and on the adjacent margins is not well understood and remains a problem common to an understanding of the oceanic palaeoenvironment and the tectonic history of the ocean basins and their margins.

There is a reasonable correlation between hiatuses and/or sedimentation rate changes at both Biscay and Rockall that must imply the importance of large scale correlative events (Figure 7). In the deep sea geological record, such events have usually been ascribed to changes in ocean circulation arising from plate reorganization and/or changes in the sill depths of the ocean basins owing to subsidence (van Andel *et al.* 1975; Kennett 1977). In both Biscay and Rockall, increased sedimentation appears to follow the spreading rate changes at 55 and 10 Ma. The Eocene–Oligocene hiatus seems to be associated with a rise in the c.c.d. and a change in water temperatures that may indicate greater exchange of waters between high and low latitudes (Grazzini *et al.* 1979). A more surprising correlation seems to exist between these events and unconformities recorded on the adjacent land and shelf that are associated with

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

uplift (Montadert *et al.* 1977). If this correlation is real and substantiated by further drilling, it is important and puzzling since it implies that continental part of a plate warps vertically in coincidence with spreading rate changes.

Albian–Aptian palaeoenvironments in the Bay of Biscay

The nature of the palaeoenvironments associated with a young and narrow ocean basin has provoked much interest, especially concerning the origin of black shales of Cretaceous age (Ryan & Cita 1977; Schlanger & Jenkyns 1976; Thiede & van Andel 1977). 'Black shales' of Albian–Aptian age were penetrated at Sites 402A and 400A during Leg 48. Contemporaneous black shales have been widely cored in the Atlantic, Pacific and Indian Oceans. Three hypotheses have been proposed to account for their widespread distribution. Reducing conditions in the narrower Cretaceous oceans have been proposed to account for the preservation of organic matter. As an alternative, the existence of a thickened oxygen minimum layer has also been proposed (Thiede & Van Andel 1977). Lastly, a detrital origin has been proposed to account for the abundance of the organic matter. The data from Sites 402A and 400A indicate contemporaneous deposition of carbonaceous limestones in water depths ranging from 100 m to 2000 m. Turbidity currents are inferred to have been the downslope transport mechanism (De Graciansky *et al.* 1979). Pyrolysis studies of the organic matter at both sites has indicated that it has a low-temperature history and is largely terrigenous. This geochemical evidence is independently supported by the presence of numerous spheres and plant fragments of terrigenous origin (Davey 1979). The black shales of Biscay are thus most directly related to periodic influxes of land-derived organic matter rather than to changes in oxygen content in the Cretaceous ocean. It is equally possible, however, that climatic controls and the development of a densely vegetated land area may have contributed significantly to the global development of black shales.

Although this paper has been presented on behalf of the Shipboard Scientific Party of Leg 48, we wish to acknowledge the studies made by shoreside colleagues which have formed an important contribution to Leg 48. D.G.R. wishes to acknowledge support from the Department of Energy for seismic surveys, well logging and his shipboard and shoreside studies.

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PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

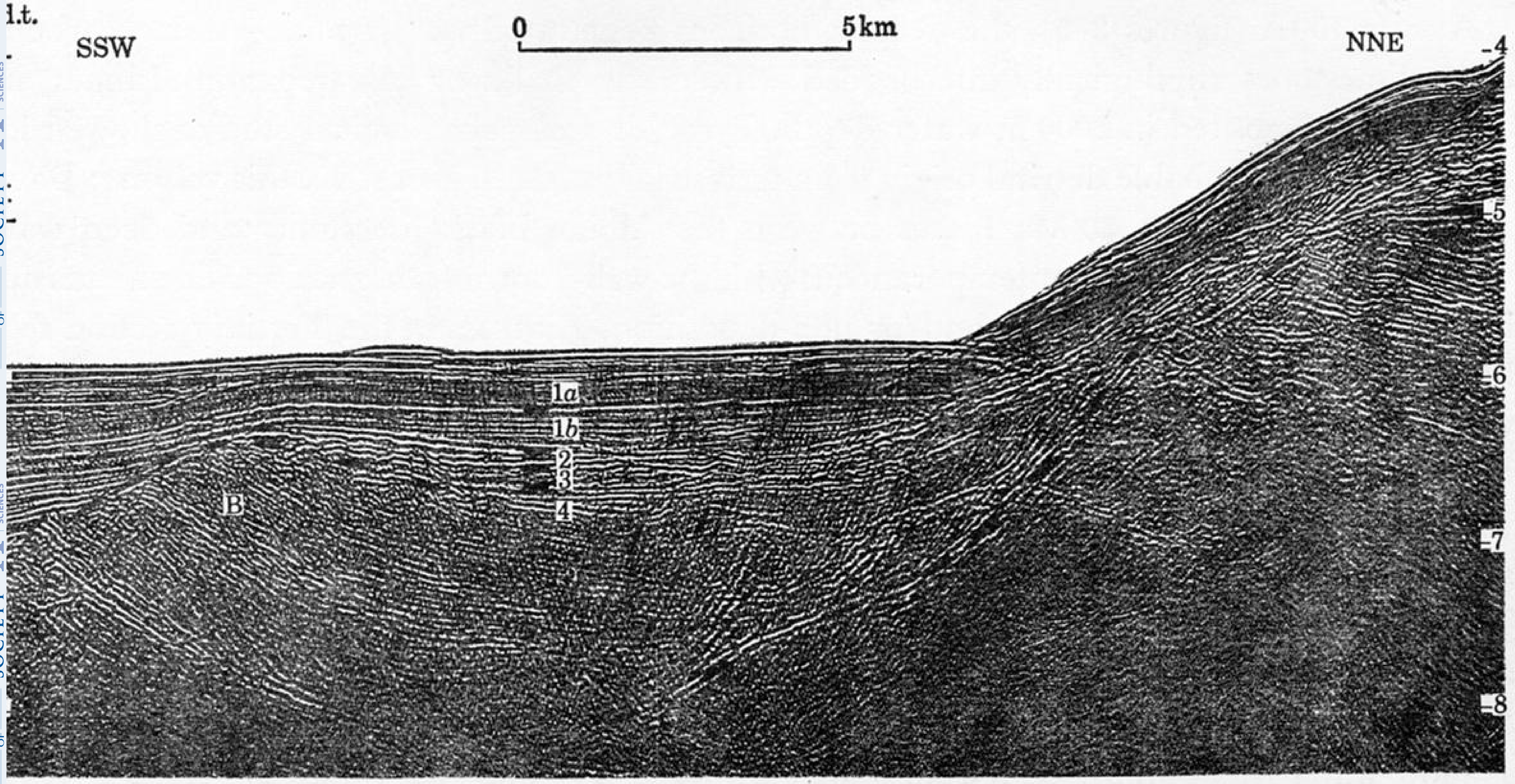

FIGURE 4. Migrated multichannel seismic profile through Site 400A.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES