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1. INTRODUCTION[1]

Shipboard Scientific Party[2]

The rifting and breakup of continental lithosphere to form passive or rifted continental margins is one of the most fundamental geological processes on Earth. This process has many physical similarities with the formation of sedimentary basins and relates directly to the onset of seafloor spreading, a process that generates mid-ocean ridges and the crust underlying the ocean basins. However, largely because of the thick to very thick (2-15 km) sediments found on many rifted margins and the consequent inaccessibility of basement rocks to scientific drilling, rifted margins have so far been studied largely by remote geophysical means or by the post-rift and synrift histories recorded in the overlying sediments at a few "sediment-starved" margins. In the northeast Atlantic Ocean, for example, nonvolcanic rifted margins were drilled off Goban Spur (de Graciansky, Poag, et al., 1985), the northern Bay of Biscay (Montadert, Roberts, et al., 1979), Galicia Bank (Boillot, Winterer, Meyer, et al., 1987), Vigo Seamount (Sibuet, Ryan, et al., 1979), and the Mazagan Escarpment (Hinz, Winterer, et al., 1984).

Quantitative models have been developed for the post-rift isostatic and thermal subsidence of margins and basins (McKenzie, 1978) and, more recently, for the critical effect of asthenospheric temperature at the time of the breakup of the lithosphere on the quantity and composition of melt, which may be underplated at the base of the crust and/or erupted as lavas at the surface (White and McKenzie, 1989). Finite-element models have also been developed for modeling the tectonic evolution of the crust and lithosphere under extensional margins (e.g., Harry and Sawyer, 1992). Nevertheless, in spite of the predictive capability of these geophysical models, some uncertainty remains about both the geological processes involved in the crust and mantle and, in particular, the location and nature of features such as the ocean/continent transition.

The North Atlantic Rifted Margins Detailed Planning Group (NARM DPG) was convened by the Planning Committee of the Ocean Drilling Program (ODP) and met in 1991 to plan a program of drilling to study the problems of the formation and evolution of rifted margins. The DPG identified two important classes of rifted margin for study: margins in which magmatism has dominated the rifting process (volcanic margins) and margins in which magmatism seems to have played a minor role in the rifting process (nonvolcanic margins). The DPG recommended that ODP focus on a transect of holes across each class of margin and that each transect include a conjugate pair of margins. The criteria for selecting the locations of the two transects included (1) the existence of high-quality geophysical data about both conjugate margins, (2) the presence of relatively thin sediment cover on the conjugate margins so that drilling into basement would be possible using the *JOIDES Resolution,* (3) the absence of salt, which might interfere with drilling, and (4) the absence of post-rift volcanism, which may have modified the divergent margin.

Leg 149 represented the first part of the program proposed by the DPG for the study of nonvolcanic margins. The total program, which was expected to require four 2-month legs, was to include drilling of multiple sites in both the Iberia Abyssal Plain and the conjugate Newfoundland Basin, and one site on the Galicia Bank margin. Drilling on each of the margins was to include sites that allowed for sampling of significant sections of basement with minimum sediment penetration, and sites having thicker and stratigraphically more complete sequences of synrift and post-rift sediments. During Leg 149, sites of the first type were drilled; a future deep hole in the Iberia Abyssal Plain will be planned to take into account the Leg 149 results. The program also was designed to allow for assessment of the degree of symmetry in the structure and evolution of the conjugate margins. Characterization of crustal type within a wide zone of thin continental or oceanic crust in the Newfoundland Basin and Iberia Abyssal Plain and the position and nature of the ocean/continent transition (OCT) on the two margins also were important scientific objectives. Geophysical data suggest that seafloor exposures of mantle peridotite on the west side of Galicia Bank, to the north of the Iberia Abyssal Plain transect, may have a counterpart in the Iberia Abyssal Plain. If such exposures were to be found during the proposed drilling, then clearly they would be a feature of more than local significance. Sites designed to sample synrift sequences will constrain the timing of rifting and breakup, the rift environment, and possibly significant anomalous elevation and/or subsidence asymmetries, which were strongly indicated by recently acquired seismic data. The subsidence histories of the conjugate margins were expected to help in determining the relative importance of lithosphere-scale, pure and simple shear mechanisms of extension.

REGIONAL BACKGROUND

The western continental margin of Iberia extends from Cape Finisterre in the north to Cape Saint Vincent in the south (Fig. 1). The continental margin has a straight narrow shelf and a steep continental slope. South of 40°N, the slope is cut by several large canyons. This simple picture is complicated by several offshore bathymetric features. The largest feature is the Galicia Bank, a 200- to 150-km area within which the seafloor shoals to a minimum water depth of about 600 m. Galicia Bank is characterized by a series of isolated seamounts on its southern edge (Vigo, Vasco da Gama, and Porto) and is separated from northwestern Iberia by a broad submarine valley underlain by the Interior Basin. At 39°N, the Estremadura Spur extends east-west about 150 km from the shelf edge and forms a barrier between the Iberia and Tagus abyssal plains. Last, the east-northeast-trending Gorringe Bank forms the southern boundary of the Tagus Abyssal Plain and marks the surface expression of the seismically active Eurasia/Africa Plate boundary.

Like many rifted or passive margins, the west Iberia margin had a long history of rifting before the separation of Iberia from the Grand Banks of North America. Three main Mesozoic rifting episodes affected the west Iberia margin. These episodes are recorded in the deposits of the Lusitanian Basin, which is probably continuous with the Interior Basin that separates Galicia Bank from northeastern Iberia (Wilson et al., 1989; Murillas et al., 1990). A Triassic to Early Jurassic (Liassic) continental rifting phase created graben and half-graben structures in which evaporites were deposited. The second rifting phase consisted of extension during the Late Jurassic. The last phase of extension occurred during the Early Cretaceous (from Valanginian to early Aptian time), which coincided with the south-to-north

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[2] Shipboard Scientific Party is as given in list of participants preceding the contents.

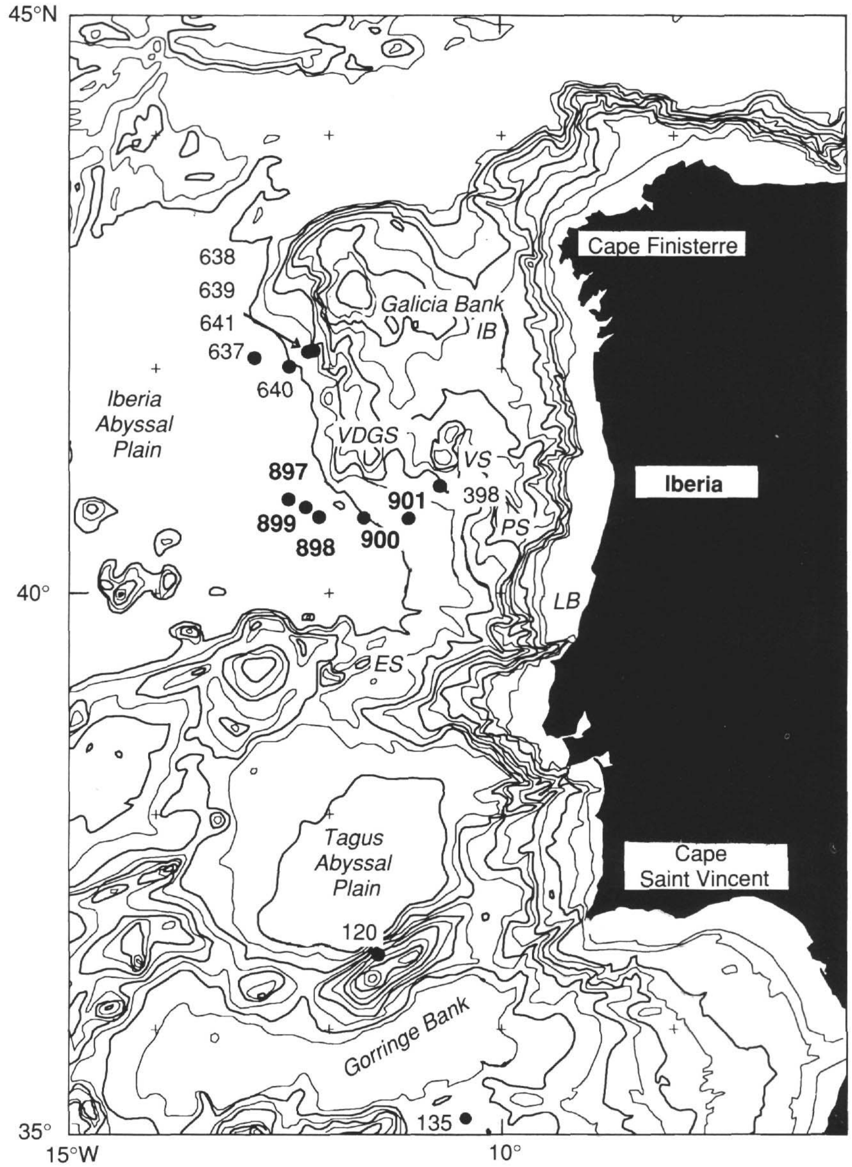

Figure 1. Regional bathymetric chart of the west Iberia margin (contours in 500-m intervals, 1000-m contours in bold). Smaller numbers refer to previous DSDP/ODP drill sites; larger numbers refer to sites drilled during Leg 149. IB = Interior Basin, VDGS = Vasco da Gama Seamount, VS = Vigo Seamount, PS = Porto Seamount, LB = Lusitanian Basin, and ES = Estremadura Spur.

breakup of Iberia from the Grand Banks and which has been well documented with offshore geological and geophysical data (Boillot, Winterer, et al., 1988; Whitmarsh, Miles, and Mauffret, 1990; Pinheiro et al., 1992).

The rifting phases were accompanied by only minor volcanism (dikes and flows) within Iberia. Two phases of pre-breakup volcanism were recognized by Ribeiro et al. (1979) and Martins (1991). A tholeiitic phase lasted from 190 to 160 Ma, coeval with Late Jurassic rifting, and a second phase occurred from 135 to 130 Ma in the Lusitanian Basin. This volcanism was relatively minor, and the west Iberia margin has the characteristics of a nonvolcanic margin. For example, tilted fault blocks and half grabens clearly can be observed off Galicia Bank (Mauffret and Montadert, 1987), and no evidence is seen of seaward-dipping reflectors or of substantial subcrustal underplating.

Parts of the west Iberia margin underwent two additional phases of deformation in the Eocene and the Miocene. The Eocene deformation was caused by the Pyrenean orogeny and the abortive subduction of the Bay of Biscay oceanic crust beneath the north Spanish margin; this deformation affected the margin adjacent to the Iberia Abyssal Plain and included the uplifting of Galicia Bank and adjacent seamounts (Boillot et al., 1979). The Miocene deformation accompanied a phase of compression in the Rif-Betic Mountains and led to the gentle folding of sediments in the Iberia and northern Tagus abyssal plains, as seen in reflection profiles (Masson et al., in press; Mauffret et al., 1989).

Several plate-tectonic reconstructions have attempted to show the original positions of North America, Iberia, and Europe (Le Pichon et al., 1977; Masson and Miles, 1984; Klitgord and Schouten, 1986; Srivastava et al., 1988; Srivastava, Roest, et al., 1990; Srivastava and Verhoef, 1992). The along-strike relative positions of the North American and European plates are not well constrained because oceanic crust that formed mostly during the Mesozoic constant-magnetic-polarity interval lies offshore the Grand Banks and Iberia, and no large fracture zones occur at this latitude. However, a useful constraint is provided by the northern termination of the J magnetic anomaly, a probable isochron slightly older than M0, which should have been contiguous with the northern end of the J anomaly in the Newfoundland Basin. The various reconstructions differ by a few tens of kilometers in the north-south direction. The situation is further complicated by intraplate deformation and "jumping" plate boundaries, which imply that Iberia was alternately attached to Africa or to Europe (Srivastava, Schouten, et al., 1990). The reconstruction by Srivastava and Verhoef (1992), which included de-stretching of the continental crust, is now generally regarded as the most closely constrained (Fig. 2).

THE OCEAN/CONTINENT TRANSITION OFF WESTERN IBERIA

The western margin of Iberia comprises three segments (the Tagus Abyssal Plain segment, the Iberia Abyssal Plain segment, from Estremadura Spur to Vasco da Gama Seamount, and the segment that lies west of Galicia Bank), which appear to have experienced progressive breakup from south to north during the Early Cretaceous (Pinheiro et al., 1992). Geological and geophysical studies of each of these segments have provided data leading to a conceptual model for the nature of the ocean/continent transition on this nonvolcanic rifted margin. These studies and the subsequent model are outlined below.

Tagus Abyssal Plain Segment

In the Tagus Abyssal Plain, Pinheiro et al. (1992) showed magnetic models that indicate seafloor spreading began about 136 Ma (Valanginian in the time scale of Harland et al., 1990). They used seismic refraction, seismic reflection, and magnetic profiles to show that the oceanic crust adjacent to the OCT is unusually thin (2 km) and that a transitional region lies between the thinned continental crust and the thin oceanic crust; this region, although not truly oceanic (for example, it has no seafloor-spreading magnetic anomalies), has a magnetization far stronger than is usually associated with continental crust. This may indicate the presence of intrusive and extrusive material within the crust of the transitional region. The thin oceanic crust is underlain by a 7.6- to 7.9-km/s layer, which is probably serpentinized peridotite.

Iberia Abyssal Plain Segment

Whitmarsh, Miles, and Mauffret (1990) and Whitmarsh et al. (1993) studied the middle segment off Iberia (between 39° and 41 °30'N) using seismic refraction and reflection profiles, gravity, and magnetics. They found that the oceanic crust adjacent to the OCT is thin (4 km) and that the OCT is underlain by a layer of about 7.6 km/s. A regional magnetic anomaly chart and modeling of a magnetic anomaly profile across the Iberia Abyssal Plain (Whitmarsh, Miles, and Mauffret, 1990), strongly suggest that seafloor spreading began about the time of anomaly M3 (130 Ma, Barremian), but that crust to the east of M3 was weakly magnetized and probably of continental origin. This analysis appears to be confirmed by a deep-towed magnetometer profile that also conclusively indicates that a transitional region exists between the thin oceanic crust and the thinned continental crust that, although not formed by seafloor spreading, has a relatively high magnetization (R.B. Whitmarsh and P.R. Miles, unpubl. data). Modeling of a single east-west gravity profile across the Iberia Abyssal Plain, which was constrained by a multichannel seismic reflection profile and by seismic refraction profiles, appears to confirm the existence of thinned continental crust adjacent to unusually thin oceanic crust, both of which are underlain by a continuous layer having a velocity of about 7.6 km/s. Two possible explanations for this unusual layer have been proposed (Whitmarsh et al., 1993). First, it may represent underplated material emplaced at the time of rifting and breakup, as in White and McKenzie's model (1989); although such material is commonplace on volcanic rifted margins, the essential absence of synrift volcanism on the west Iberia margin, the restriction of the layer to only the parts of the OCT where the crust is thinnest (unlike, for example, the more widespread occurrence of underplated material and seaward-dipping reflector sequences off the western Rockall Plateau; Fowler et al, 1989), and the relatively high velocity associated with the layer all strongly suggest that this explanation is unlikely to be the correct one. Second, the layer may represent serpentinized upper mantle peridotite; serpentinization might have occurred immediately after lithospheric breakup and during the onset of seafloor spreading because of the relatively easy access of seawater, probably thermally driven, to the upper mantle through the thin crust, in an analogous fashion to the serpentinization of the uppermost mantle, known to have occurred in oceanic fracture zones (Calvert and Potts, 1985). Last, the Iberia Abyssal Plain at this latitude also is underlain by a smooth acoustic basement in multichannel seismic reflection profiles between the apparently most-seaward tilted continental rift block to the east and a highly linear basement ridge to the west. One might speculate that this smooth basement represents volcanic rocks, thereby also providing an explanation for the high magnetic anomalies in the transitional region between the thin oceanic crust and the weakly magnetized thinned continental crust. Should tentative extrapolations of basement morphology be correct, the basement ridge represents the counterpart in the Iberia Abyssal Plain of a peridotite ridge drilled off Galicia Bank (Boillot, Winterer, Meyer, et al., 1987; Beslier et al., 1993).

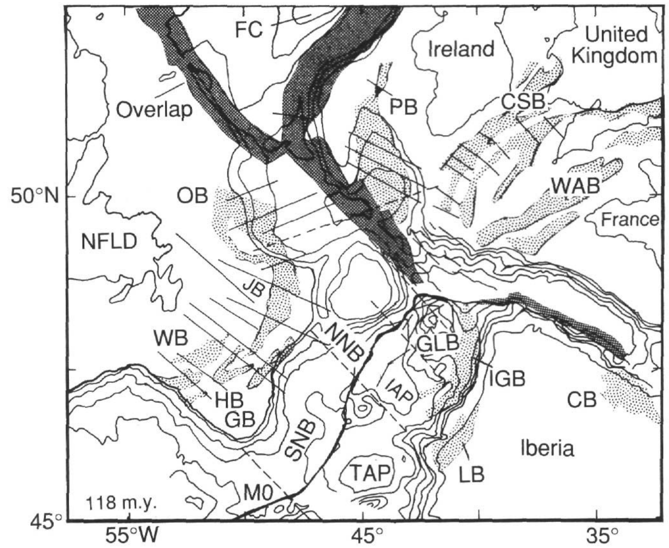

Figure 2. Plate tectonic reconstruction of Iberia and the Grand Banks at the time of anomaly M0 (from Srivastava and Verhoef, 1992) with simplified bathymetry on each plate, outlines of the sedimentary basins (shaded regions), and their tectonic features (continuous lines). Also shown are the directions of relative plate motion (dashed lines) and the resulting overlap between plate boundaries (dark stippled regions). GB = Grand Banks; JB = Jeanne d'Arc Basin; WB = Whale Basin; HB = Horseshoe Basin; OB = Orphan Basin; FC = Flemish Cap; CSB = Celtic Sea Basin; WAB = Western Approaches Basin; PB = Porcupine Basin; GLB = Galicia Bank; IGB = Interior Galicia Basin; LB = Lusitanian Basin; CB = Cantabrian Basin; NNB = North Newfoundland Basin; SNB = South Newfoundland Basin; IAP = Iberia Abyssal Plain; TAP = Tagus Abyssal Plain.

Galicia Bank Segment

The western margin of Galicia Bank, the third of the three segments, has been studied with seismic refraction and reflection profiles and also has been sampled extensively with dredges, submersibles, and by drilling (Horsefield, 1992; Mauffret and Montadert, 1987; Boillot, Winterer, Meyer, et al., 1987; Boillot et al., 1988). A seismic refraction model across the margin shows a thinned continental crust at the OCT adjacent to a moderately thinned (5-km) oceanic crust, which thickens rapidly to the west (Horsefield, 1992). A layer having a 7.2- to 7.3-km/s velocity, which underlies the thinned continental crust, may represent either crustal underplating (Horsefield, 1992) or serpentinization of the upper mantle. In August 1992, a continuous gravity profile was obtained along an east-west seismic refraction line across the whole OCT. A complete crustal-density model across the OCT, constrained by seismic velocities, has now been computed (J.C. Sibuet, pers. comm., 1992). Because crust that formed during the Cretaceous constant-magnetic-polarity interval abuts the OCT at this margin, magnetic anomalies cannot be used to date the beginning of seafloor spreading. However, the recognition of the reversed-polarity paleomagnetic interval M0 in cores from below the breakup unconformity at Site 641 (Ogg, 1988) indicates that breakup occurred about 120 Ma (Aptian). Sampling has shown unequivocally that a north-south basement ridge, which appears to coincide with an abrupt ocean/continent boundary, is composed of serpentinized peridotite.

A Conceptual Model of the OCT

The cumulative results from studies of these three segments of the west Iberia margin suggest that the following features are characteristic of the OCT in this region and may exist elsewhere in similar settings:

1. Abnormally thin oceanic crust (2-4 km) having a seafloor-spreading magnetic signature underlies part of the OCT;
2. Strongly magnetized, nonoceanic crust, capped by a smooth acoustic basement, exists immediately landward of the thin oceanic crust;
3. A subcrustal layer, which has a velocity of 7.6 km/s and is probably serpentinized peridotite, underlies much of the OCT; and
4. A peridotite basement ridge (like that found west of Galicia Bank) may separate the thin oceanic crust from the strongly magnetized nonoceanic crust.

Before Leg 149, the following working hypothesis (Whitmarsh et al., 1993) seemed to account for the abnormally thin crust. Continental rifting before breakup (i.e., before the onset of seafloor spreading) often develops over tens of millions of years, yet rarely involves extension of more than 100 to 200 km at a single margin. In this situation, the slow rate of extension results in conductive cooling of the ascending mantle diapir. Consequently, much less melt is produced than in the case of adiabatic decompression (Bottinga and Allègre, 1978). Fracture zone (FZ) seismic velocity structures and thin FZ crust have been explained by a poor magma supply, caused by the cooling effect of the adjacent older oceanic plate (Whitmarsh and Laughton, 1976; Langmuir and Bender, 1984). An analogous mechanism may explain the thin oceanic crust at the OCT, where the poor magma supply was caused by the adjacent cooler continental lithosphere. However, this situation is temporary because a spreading axis continually recedes from the two adjacent continental lithospheric plates. Hence, the "steady-state" production of melt characteristic of a slow-spreading ridge takes some time to develop once continental breakup has occurred. Were magma production a passive response to the upwelling of asthenospheric material and, indirectly, to the separation rate of the overlying plates (as in the model of White and McKenzie, 1989), then mantle melting should have increased at breakup to keep pace with plate separation at a rate that was faster than the original horizontal stretching of continental crust alone. The thin oceanic crust at the OCT appears to represent the earliest product of seafloor spreading at the west Iberia margin. The width (a few tens of kilometers) of this region thus should indicate the time needed to establish steady-state melt production (a few million years). In fact, the oceanic crust may gradually thicken oceanward.

The above conceptual model of the OCT off Iberia was developed by Whitmarsh et al. (1993; Fig. 3A). The elements of this model were derived principally from the observations summarized in this section. Independent gravity modeling of a gravity profile across the Iberia Abyssal Plain, constrained by seismic refraction and reflection structures, led to a structure that is consistent with the broad features of the model, in particular the existence of a wide zone of 7.6 km/s and 3.26 Mg/m^3 at the base of the crust (Fig. 3B). The 7.6-km/s layer might be serpentinized peridotite or, alternatively, the result of underplating. We can explain the presence of a serpentinized peridotite layer by the downward percolation of seawater through the thin, faulted oceanic or continental crust to the underlying mantle around the time of breakup, similar to what happens at fracture zones. Underplating is a

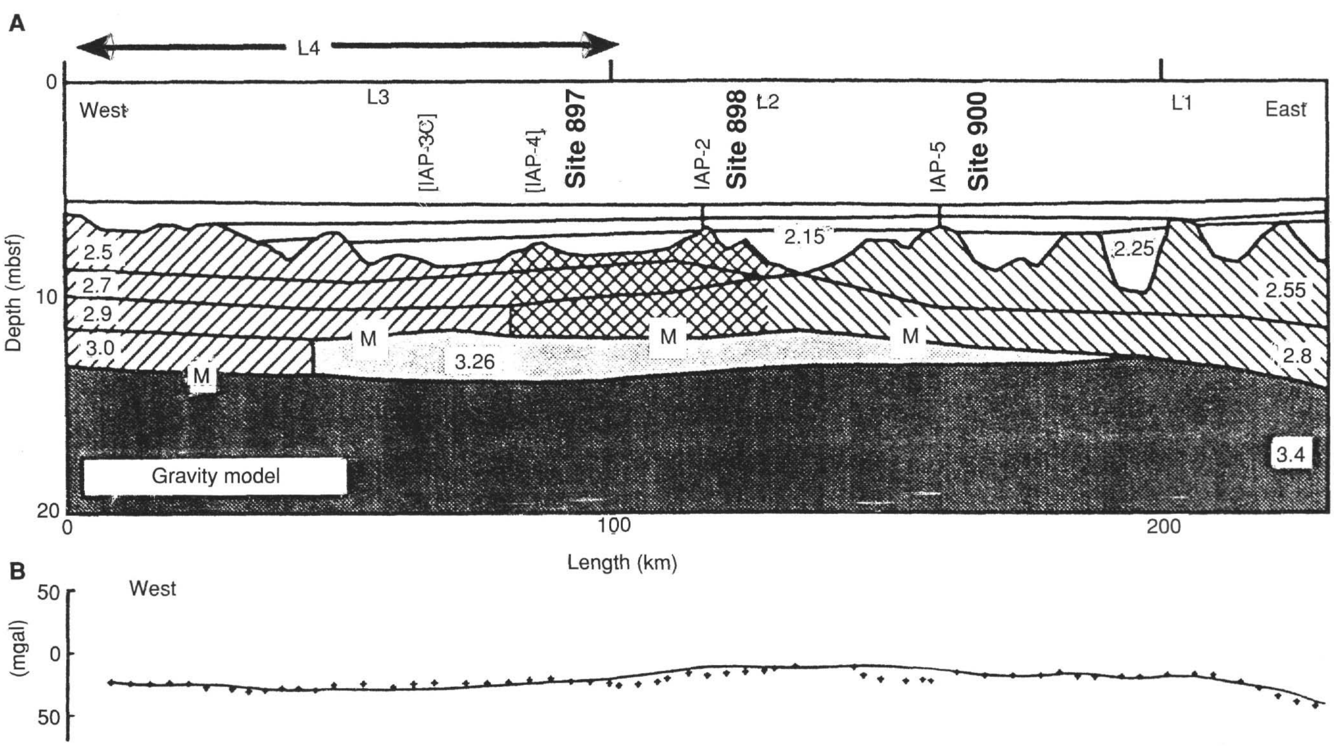

Figure 3. **A**. Conceptual model of the OCT off western Iberia. East-dipping hachured symbols indicate thinned continental crust; west-dipping hachured symbols indicate oceanic crust; the cross-hachured region indicates transitional and relatively highly magnetized, but nonoceanic, crust (see text). The light gray layer beneath the OCT represents either serpentinized peridotite or material affected by underplating. Densities ($Mg \cdot m^3$) are indicated for each layer. L1, L2, and so forth, are seismic refraction lines reported by Whitmarsh, Miles, and Mauffet (1990). IAP-2, IAP-3C, and so forth, are the proposed Leg 149 drill sites; sites in square brackets have been projected onto the east-west profile. **B**. A gravity profile (continuous line) computed with the densities and model given in (**A**). Crosses represent observations (Whitmarsh et al., 1993).

less likely explanation on this margin because synrift volcanics are absent on land and because the 7.6-km/s velocity is relatively high for underplated material and can be found only where the continental crust is thinnest.

Several aspects of our model need further elaboration and investigation. One is the existence of a basement peridotite ridge (so far, detected with certainty only off Galicia Bank) and its emplacement mechanism. Another is the fact that the seaward edge of the thinned continental crust may be densely intruded by dikes (e.g., as observed in the southern Red Sea; Voggenreiter et al., 1988) or even be covered in places by lava flows. At present, our only evidence of this off Iberia is a region of unusually strongly magnetized continental crust in magnetic models of profiles across the Tagus and Iberia abyssal plains that coincides with a smooth diffractive acoustic basement (Pinheiro et al., 1992). Nevertheless, Srivastava et al. (1988) also postulated the existence of a similar feature when modeling profiles across the northeastern Newfoundland margin.

Clarification and testing of aspects of the above model constituted the chief reason for drilling the Leg 149 sites.

SPECIFIC DRILLING OBJECTIVES

A number of specific drilling objectives related to all the drill sites of Leg 149 are presented below. The ways in which the individual sites were expected to contribute to these objectives are discussed in the site chapters of this volume.

Ocean/Continent Transition

The principal objective of Leg 149 was to sample the upper crust within the OCT of the Iberia Abyssal Plain to establish its nature and to test some of the predictions based on geophysical observations. Naturally, this bold objective had to be tempered by the accessibility of the crust, using current technology. To achieve significant progress within a single leg, four proposed sites (IAP-2, 3C, 4, and 5) were chosen (Fig. 4). These sites lie on basement highs situated at critical points within the OCT (Fig. 5). We expected to be able to drill three of these sites within the time allotted to Leg 149.

We planned to penetrate the upper acoustic basement to a depth of several hundred meters and, using cores and downhole logs, to determine its origin and history. This was to be done by petrological and chemical analysis of the cores, by microstructural examination of the cores, by examination of the mineralogy of the cores, by apatite fission track analysis and/or isotope dating of suitable core material, by velocity and magnetic measurements in cores, by analysis of geochemical logs, by interpretation of the Formation Microscanner (FMS) and other logs, and by whatever other means seemed appropriate.

The Sedimentation History

Secondary objectives related to the sediments themselves. One aim was to determine the history of turbidite sedimentation in the Iberia Abyssal Plain. Work done in the Madeira Abyssal Plain indicates that, in general, a single turbidite was deposited each time sea level changed between a glacial and an interglacial period or vice versa (Weaver and Kuijpers, 1986). We also expected to determine to what extent the age and frequency of turbidites related to past climatic change. Another objective was to date the deformation of the sediments and to relate this to the Paleogene and Miocene deformation in Europe (mentioned above). Last, we also intended to test estimates of the depth of the ooze/chalk transition made on the basis of seismic refraction measurements in the Iberia Abyssal Plain (Whitmarsh, Miles, and Pinheiro, 1990) and to relate the velocity logs to these predictions.

Heat Flow

We planned to estimate heat flow at each of the Leg 149 sites through measurements of thermal conductivities and thermal gradients. Thermal conductivity of the core samples was to be measured routinely on board the ship. The thermal gradient was to be determined by measuring in-situ temperatures in relatively shallow sediments at various depths (approximately the upper 300 mbsf) using the ADARA temperature and WSTP tools. Temperatures in open holes were to be measured as part of most logging runs. We planned to

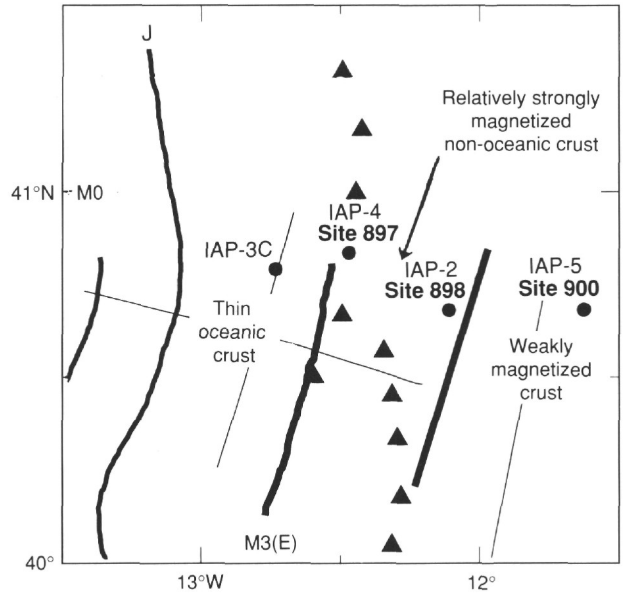

Figure 4. Sketch showing the relationship of the site locations to the various characteristic features of the OCT in the Iberia Abyssal Plain. Thick lines bind the three main types of crust identified in the OCT. Triangles mark the trend of the peridotite ridge, proposed from seismic reflection profiles by Beslier et al. (1993). Thinner bold lines mark the positions of seafloor spreading magnetic anomalies J and M0, chosen from a reduced-to-the-pole magnetic anomaly contour chart (S.R. Srivastava, pers. comm., 1993) and the eastern edge M3(E) of the magnetic block used in a two-dimensional seafloor spreading model to model anomaly M3. Thin lines are seismic refraction profiles reported by Whitmarsh, Miles, and Mauffret (1990).

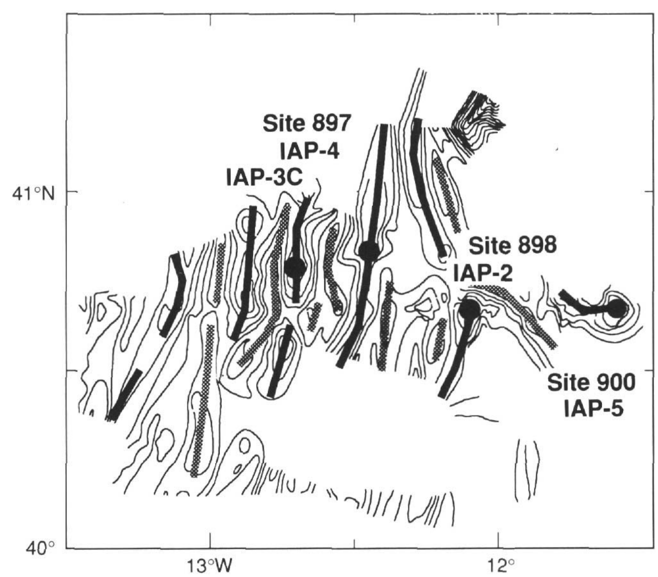

Figure 5. Preliminary basement contour map (0.25 s two-way traveltime contour interval) based on unmigrated multichannel and single-channel seismic reflection profiles with the highs and lows highlighted by black and gray lines, respectively. Numbers and dots indicate sites planned to be drilled during Leg 149.

correct temperature logs, on the basis of the results of successive runs in the same hole, for disturbances caused by drilling and circulation.

Late Post-rift Subsidence

We expected to acquire data that could be used to estimate the late post-rift subsidence history of the Iberia Abyssal Plain. We planned to observe the paleodepth, age, environment of deposition, and physical properties of each sedimentary unit. We did not expect to be able to deduce the synrift and early post-rift subsidence histories because we did not expect to encounter a continuous sequence of sediments of that age. The subsidence history was unlikely to be precise at these sites because the basin was relatively starved of sediments. Estimates of depths of deposition of continental slope sediments from paleoenvironment observations are, at best, accurate to 500 m.

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