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38. EVIDENCE FOR DETACHMENT TECTONICS ON THE IBERIA ABYSSAL PLAIN RIFTED MARGIN[1]

C.M. Krawczyk,[2,3] T.J. Reston,[2] M.-O. Beslier,[4] G. Boillot[4]

ABSTRACT

The Iberia Abyssal Plain segment of the western Iberian Atlantic margin is characterized by highly extended and thinned continental crust bounded westward by a ridge of serpentinized peridotite within the transition zone between continental and oceanic crust. To better understand the evolution of this margin, we have analyzed the margin-normal profile Lusigal 12 (LG12) between Sites 898 and 901. After optimum processing, including prestack depth migration, the seismic sections image strong reflections below the breakup unconformity in this segment of the Iberian nonvolcanic margin. We show that these intracrustal reflections are overlain by probable basement rocks (Vp > 5 km/s), whereas synrift or prerift sedimentary units exhibit generally lower velocities (Vp < 4.7 km/s). Between Site 901 (identified by drilling as probable continental crust) and Site 900 (amphibolite facies metamorphosed gabbro) to the west, basement is broken up into landward-tilted crustal blocks bound by normal faults. These block-bounding faults appear to detach onto bright intracrustal reflections, which thus mark the lower boundary of the tilted blocks. By analogy with the similar seismic image of the Galicia Bank area to the north, where continental breakup has been controlled by a detachment fault structure (the S reflector), we suggest that continental breakup in the Iberia Abyssal Plain could have been also controlled by detachment faults that were active at different times during rifting. Extension of the upper lithosphere along the detachment system may have exposed a cross-section through the entire lithosphere from the upper crust (in the east, at Site 901), through the lower crust (Site 900), to the uppermost mantle exposed at the western edge of the drilling transect (Site 897, just landward of oceanic crust).

INTRODUCTION

West of Iberia, three main structural segments make up the nonvolcanic rifted passive margin: the Galicia Banks area to the north, the south Iberia Abyssal Plain in the center, and the Tagus Abyssal Plain south of the Estremadura Spur (Fig. 1; Beslier et al., 1993). On the Iberian Margin, the rifting occurred in three phases: Triassic to Middle Jurassic, Late Jurassic, and Early Cretaceous. Early Cretaceous breakup between Iberia and the Grand Banks appears to have propagated northwards, occurring at about 137 Ma in the Tagus Abyssal Plain (Pinheiro et al., 1992), at about 130 Ma in the Iberia Abyssal Plain (Whitmarsh et al., 1990), and finally at about 114 Ma in the Galicia Banks area (Boillot, Winterer, Meyer, et al., 1988).

The northward propagation of the spreading center during the Early Cretaceous is further evidenced by the seafloor spreading magnetic anomaly pattern west of the Iberia margin. The large amplitude magnetic J-anomaly is found just westward of the presumed ocean/continent transition in the Iberia Abyssal Plain and Tagus Abyssal Plain basin, but not west of the Galicia Banks (Fig. 1). The J anomaly is the oldest oceanic magnetic anomaly positively identified west of the Iberia Abyssal Plain margin, and is thought to be slightly older than chron M0 as modeled by Whitmarsh et al. (1990), indicating that seafloor spreading off the Iberia Abyssal Plain margin started shortly prior to the J anomaly's formation in Hauterivian-Barremian time and the breakup off Galicia must have occurred later (see Pinheiro et al., this volume).

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[2]Geomar Research Centre for Marine Geoscience, Kiel University, Wischhofstraße 1-3, D-24148 Kiel, Federal Republic of Germany.

[3]Present address: GeoForschungsZentrum Potsdam, Projektbereich 3.1, Telegrafenberg C2, D-14473 Potsdam, Federal Republic of Germany, ckrawe@gfz-potsdam.de

[4]Laboratoire de Géodynamique Sous-Marine, BP 48, 06230 Villefranche-sur-Mer, France.

The Galicia Banks rifted margin had been investigated by drilling during Ocean Drilling Program (ODP) Leg 103 (Boillot, Winterer, Meyer, et al., 1987; Boillot, Winterer, et al., 1988), by diving (Boillot et al., 1988) and by the seismic reflection method (e.g., Montadert et al., 1979). There, tilted fault blocks, shown by diving and drilling to be cored by continental basement, are separated by normal faults. These appear to terminate at a bright intracrustal reflection, called the S reflector (de Charpal et al., 1978), a series of unusually bright reflections in the basement. Reston et al. (in press) and Krawczyk and Reston (in press) have verified the hypothesis of Wernicke and Burchfiel (1982) by showing that the S reflector is a tectonic contact, interpreted as a detachment fault that controlled continental breakup. To the west of S, the ocean/continent transition is marked by a ridge of serpentinized peridotite, drilled at Site 637 (Boillot, Winterer, Meyer, et al., 1987).

In the Iberia Abyssal Plain, a similar basement ridge was interpreted by Beslier et al. (1993) to be serpentinized peridotite and to mark the ocean/continent transition like the mantle outcrop west of Galicia. This hypothesis was further supported by the analysis of refraction seismic data combined with the modeling of a single east-west gravity profile (Whitmarsh et al. 1993). These authors identify a layer of extremely thinned continental crust adjacent to thin oceanic crust, both underlain by a layer with seismic velocity of 7.6 km/s, which may be interpreted in two ways. First, it may be underplated material, brought up by some kind of small-scale volcanism during rifting and/or breakup. This hypothesis seems unlikely because of the absence of volcanism on this passive margin (Sawyer, Whitmarsh, Klaus, et al., 1994), the local extent of the thin layer, and finally, the relatively high velocity compared to that found on volcanic margins for underplated material (e.g., White et al., 1987). The second possibility is that this thin layer consists of peridotitic mantle material that was partly exhumed during lithospheric extension and was serpentinized during and after breakup when penetration of water has been facilitated by the thin sediment cover and the highly fractured overlying section (Boillot et al, 1989; Beslier et al., 1993). In this hypothesis, the 7.6 km/s layer represents that portion of mantle material that was partly serpentinized at or close to breakup. Landward of the peridotite ridge the crust is about 4 km thick (Whitmarsh et al., 1993), and thickens gradually landward. Although the width of the transition from oceanic crust through serpentinized mantle to definite continental crust is four times wider on the Iberia Abyssal Plain (Beslier et al., 1993), the basic structure of the Iberia Abyssal Plain margin is similar to that of the Galicia Banks margin (Krawczyk et al., 1994).

Drilling Site 897 on ODP Leg 149 (Sawyer et al., 1993; Fig. 2) confirmed that the basement ridge comprises serpentinized mantle rocks bounding the western end of the transition zone from oceanic to continental crust. Drilling also sampled serpentinites at Site 899, in the form of a mass-flow deposit, suggesting that serpentinized peridotite must form basement close to this site. Farther east, at Site 900, metamorphosed mafic igneous rocks were sampled; these are perhaps best interpreted as either prerift or synrift lower crust. Finally, Site 901, although failing to reach basement, did sample tilted Tithonian strata, which was interpreted as either very early synrift sediments, or perhaps more likely prerift sediments. In either case, it is considered very likely that these were deposited on upper continental basement.

Leg 149 thus partly confirmed the existing geophysical model, but also left a number of questions unanswered and posed some new ones. The extent of the peridotite appears to be larger than previously supposed; the ocean/continent transition may be of wider extent than previously thought (the first unequivocally continental crust occurs at Site 901 rather than at Site 898); and previously unsuspected lower crustal rocks were found at the intervening Site 900.

Here we present the results of reprocessing and analysis of the seismic reflection data, previously interpreted by Krawczyk et al. (1994) and Beslier et al. (in press). These new results provide a framework for the interpretation of the drilling results, and thus constrain the evolution of this margin in particular and the mechanism of continental breakup in general.

Furthermore, having carried out a similar analysis in the north, we have the opportunity to compare the results from the Iberia Abyssal Plain with those of the west Galicia Bank rifted margin. There it has been shown that rifting leading to breakup was controlled by a detachment fault, the S reflector (Wernicke and Burchfiel, 1982; Boillot et al., 1989; Hoffmann and Reston, 1992; Reston et al., in press; Krawczyk and Reston, in press). Although no such detachment fault has previously been identified along the Leg 149 drilling transect, it is also possible that detachment faulting played an important role in the evolution of the Iberia Abyssal Plain margin (Beslier et al., 1993). Furthermore, the presence of peridotitic basement on the Galicia Margin (Boillot, Winterer, Meyer, et al., 1987) marking the ocean/continent transition indicates that the two margins have certain similarities, although the distance between peridotite and the first subcrop of upper continental basement is considerably greater off the Iberia Abyssal Plain.

DATA PROCESSING AND ANALYSIS

The processed multichannel reflection seismic profile Lusigal 12 discussed here was acquired during the Lusigal campaign in 1990 under the leadership of the GEMCO working group in Villefranche (chief scientist G. Boillot).

The source used for the LG series was an array of eight waterguns (shot interval 50 m). A 2.4 km, 96-channel streamer (group interval 25 m) was used, resulting in a common midpoint (CMP) interval of 12.5 m. Profile LG12 was recorded from west to east normal to the Iberia passive margin and to the main structures, and so has been successfully time- and depth-migrated.

In processing the data, we took particular care to keep steeply dipping reflections. For instance, in the time migrated section (Fig. 3), we have applied neither trace mixing nor trace summation, and used fk-filter (frequency-wavenumber) only locally. We have also applied

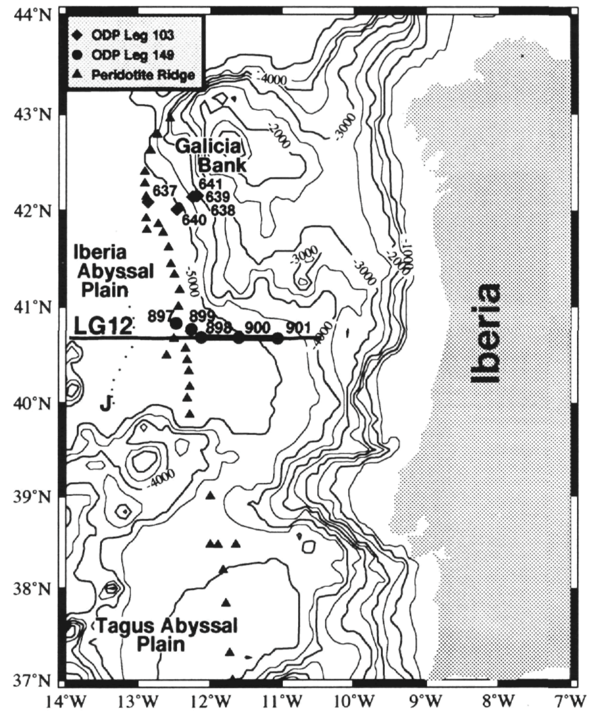

Figure 1. Bathymetric map showing the location of the analyzed multichannel reflection seismic line Lusigal 12 (LG12) west of Iberia. Triangles trace the partially drilled ridge of serpentinized peridotite at the ocean/continent transition. Depth contours are in m below sea level; contour interval is 250 m.

dip-moveout correction prior to final velocity analysis to improve the image of steep events on the stack section. As will be seen below, imaging of steep events greatly facilitates interpretation of the data.

Another aim of our processing was the depth-migration of the data, to better reveal the true geometry and geometrical relationships of key structures. As stacking velocity is not suitable for depth-migrating seismic data, we constructed a detailed velocity function by the technique of depth-focusing error analysis (Denelle et al., 1986). This analysis is a by-product of performing depth migration before stack and results from the importance of velocity both in converting a time section to depth, and in the migration of diffraction and reflection hyperbolae at different offsets to produce a final section (Fig. 4). As this technique is very expensive in terms of computer time, we have applied it only to the most important parts of the seismic profile covering the drill locations from Leg 149 at the outer and central basement highs of this section (Fig. 2). We then used the resultant velocity information to construct a velocity model across the whole transect for poststack depth-migration (Fig. 5).

Prestack depth migration has two main advantages compared to standard migration: as a migration before stack, it avoids the smearing effects of CMP-stacking (Sherwood, 1989), important in regions of complex geology (Peddy et al., 1986), and additionally as a depth migration it counts for effects like raypath bending and velocity pull-up/push-down (e.g., Yilmaz, 1987), in particular in areas with rapid lateral velocity changes as given by the complex geological structures on passive rifted margins. Thus, applying the depth migration before stack one can provide a much more constrained and accurate image of the structures with their true geometry in depth.

Using the Migpack® software (Denelle et al., 1986) we created the velocity model iteratively down from the ocean bottom to deeper levels through depth-focusing error analysis (Fig. 4), which compares apparent and focusing depth of reflected and diffracted energy with a spacing of 10 shotpoints (analysis interval of 500 m) along the profile. The model is created from top to bottom of the section, determin-

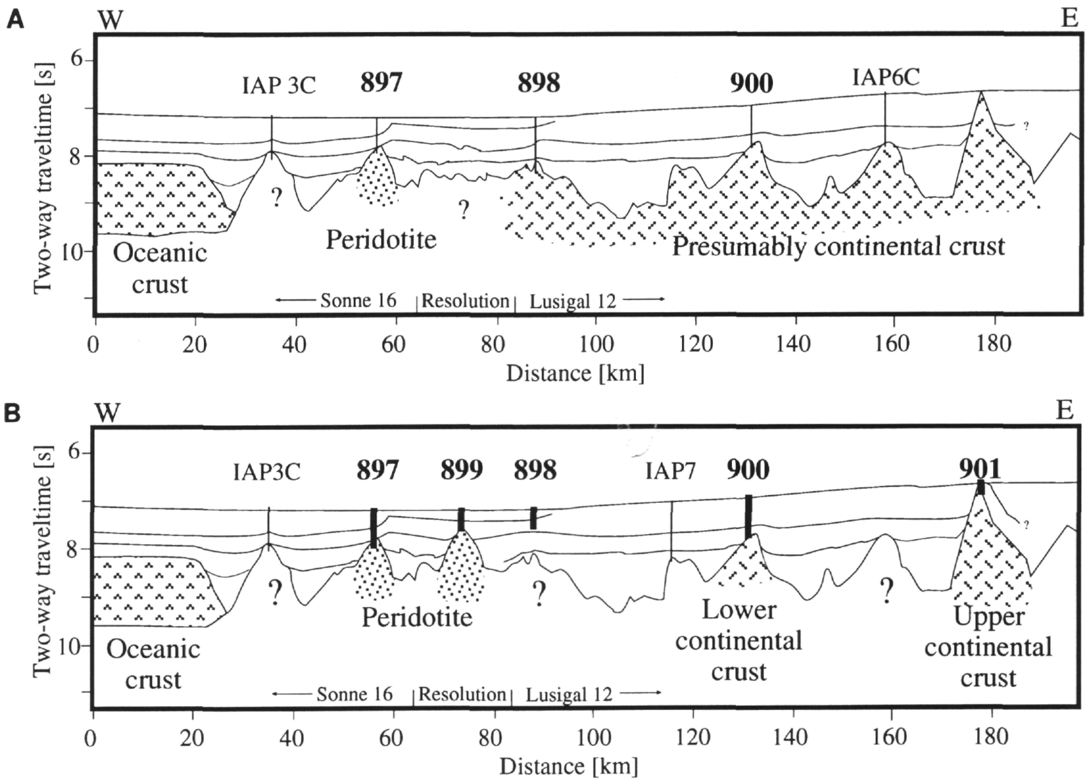

Figure 2. Predicted (**A**) and actual (**B**) drilling results from Leg 149 (after Sawyer et al., 1993) with special emphasis on basement rock type (vertical exaggeration 5). From west to east, this transect sampled in Sites 897 and 899 peridotitic basement, and lower crust in Site 900 (metamorphosed, mafic igneous rocks); Site 901 cored Tithonian sediments interpreted as prerift, so that basement here is very likely upper continental crust. Sites IAP-3C, IAP-6C, and IAP-7 are proposed drill locations.

ing velocity in one layer at a time because the velocity structure of the upper layer affects the accuracy of the velocity determination from the deeper levels.

Therefore, we first determine the correct water velocity (and in the process check on the geometry of the data), then determine the velocity in the uppermost sedimentary layer in the next iteration. These steps are repeated until the whole section and all specific layers have been analyzed through depth-focusing error analyses. As this method needs clear and strong reflections for reliable focusing of reflected and diffracted energy, it is difficult to determine different velocity layers within the basement where reflections are limited. Basement is migrated with a half-space velocity revealed by the bright reflections present within the basement (5.5-6 km/s). In contrast, the sedimentary layers above provide a clear image as long as lithological boundaries or high reflectivity interfaces are picked.

This procedure yields a depth migrated section, which images the geological structures with their true geometry, and results in a detailed velocity model. This model not only allows the correct migration of the data, but strongly constrains the lithologies present.

RESULTS

The multichannel reflection seismic profile LG12 covers part of the drilled transect across the ocean/continent transition in the Iberia Abyssal Plain (see Fig. 1 for location). The extreme ends of the analyzed section (Fig. 3) are marked by two basement highs corresponding to Sites 898 and 901, whereas the central high is at Site 900, all drilled during Leg 149 (Sawyer, Whitmarsh, Klaus, et al., 1994). Drilling results (Fig. 2) proved Site 901 to consist of prerift sediment of Tithonian age dominated by mud and clay, whereas Site 900 sampled highly sheared and fractured gabbro, which probably represents lower continental crust (Reston et al., proposal to ODP, 1994) or material underplated during rifting (see Cornen et al., this volume). Site 898 did not reach basement, but at Site 897 farther to the west, samples of serpentinized peridotite proved the existence of a mantle ridge marking the ocean/continent transition as inferred by Beslier et al. (1993; this volume); Site 899 also cored serpentinized material within three distinct breccia units, indicating the presence of peridotitic basement in the vicinity (see Comas et al., this volume; Cornen et al., this volume). Thus, drilling points to a general deepening of lithospheric level from east to west along the drilled transect and analyzed reflection seismic data.

Sediment Sequences

Between Sites 898 and 900, the postrift sequence on the western part of profile LG12 exhibits a pattern of low-angle, apparently westward-inclined reflections, attributable to a progradational sequence (Fig. 3). These are unconformably overlain by a sequence of mainly terrigeneous turbidites (Shipboard Scientific Party, 1994a). This unconformity (at Site 898 at 7.5-s two-way traveltime depth and 750 mbsf) is correlated with a 10 m.y. hiatus from middle Miocene to late Pliocene, and may be related to gentle regional deformation during the northwest-southeast compressional phase of the Rif-Betic Mountains in southern Spain and North Africa (see Wilson et al., this volume). East of Site 900, the westerly-inclined reflections are no longer imaged, and the postrift sequence shows, except for two places, a regular and subparallel bedding; thickness varies from 750 to 2500 m, and interval velocities are not higher than 3.1 km/s (Fig. 5). Two mounded units east of Site 900 may represent contourites: one is a large sediment ridge extending 14 km between shots 4600 and 4875, the other is a minor one between shots 4950 and 5025 (see Comas et al., this volume; Fig. 3). The lower boundary of a seismic more trans-

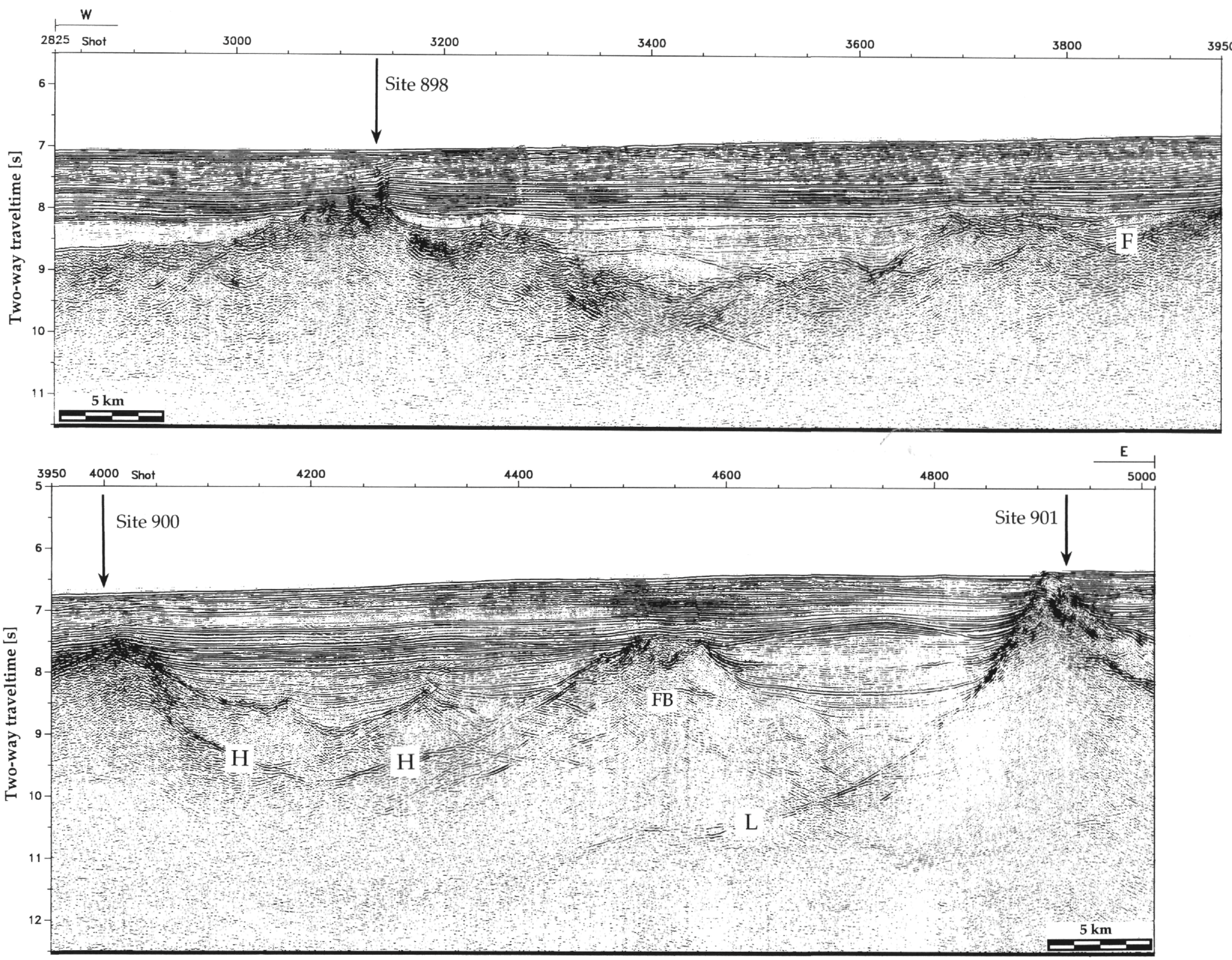

Figure 3. Time-migrated seismic section of profile LG12 covering (from west to east) Sites 898-901 (50-m shot spacing; vertical exaggeration 2). Interpretations based on the depth section in Figure 8 are presented in Figure 10. Note the detachment fault H, the listric fault structure L, and the low-angle fault F. FB = fault block.

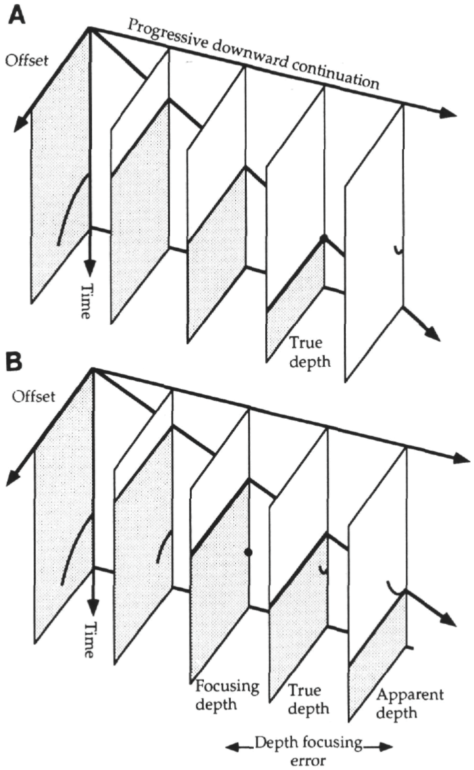

Figure 4. Principle of depth-focusing error analysis (after Denelle et al., 1986). **A.** During simultaneous migration with the correct velocity in the shot and receiver domains, maximum focusing occurs when the downward continuation operator reaches the actual depth of the reflector. **B.** An incorrect velocity yields a discrepancy between these depths.

parent sedimentary sequence is marked by a major unconformity, which we consider to represent the breakup unconformity, separating postrift from synrift sedimentary units or basement. Confirmation of this interpretation will have to await sampling of the oldest sedimentary units above and of the sediments underneath this unconformity in the deep basins between basement highs.

In the eastern part of the profile (shots 4000-4450, directly to the east of Site 900), thin sedimentary sequences of late synrift age overlie wedge-shaped layers of early synrift/prerift sediments *(Vp* = 4.1 km/s). Further synrift deposits may be interpreted on top of the basement high between Site 901 and 900 (Fig. 6) as well as east of it (Fig. 7), all characterized by interval velocities between 3.2 and 4 km/s (Figs. 6 and 7) and a maximum thickness of approximately 1750 m (Fig. 8).

The only place where presumed prerift sediments are identified, and also sampled by drilling (Shipboard Scientific Party, 1994c), is Site 901 at the eastern end of the profile. Here, the seismic section displays a more transparent layer of Tithonian strata tilted after deposition (Fig. 9).

Basement Structures

Within the basement, the profile images the most striking and relevant features for discussing the transition between continental and oceanic crust and the mechanism of lithospheric extension on this Iberia Abyssal Plain segment of the Iberian passive margin. Of particular importance are strong basement reflections imaged between Site 900 and Site 901 (Krawczyk et al., 1994; Beslier et al., in press). Other basement reflections east of Site 900 may also be important, but are less easily interpreted.

Vicinity of Site 901

The easternmost high on LG12 appears to be a tilted fault block, capped by a 450- to 750-m-thick seismically transparent layer of prerift or pretilting sediment (Fig. 9). The basement itself exhibits velocities of 5.5 to 6 km/s, whereas within the pretilting layer the velocity values between 2.8 and 3.4 km/s are relatively low compared to approximately 4.1 km/s close to Site 900 (Figs. 6, 7). One reason may be the higher degree of probable basement fragments mixed with the directly overlying sediment at Site 900 during continued extension, and the different lithology, described here by mud dominated clay and silty clay (Shipboard Scientific Party, 1994c). It is however also possible that this sequence is less compacted than the more deeply buried units to the west.

500 m west of Site 901, the seafloor is marked by a 100-m-high fault scarp (Fig. 8). This is the surface expression of a large fault structure forming the western side of the large fault block drilled at Site 901. The fault can be followed to depth as a bright reflection (L) between shotpoints 4400 and 4900; this is a distance of almost 25 km. L appears on the time section (Fig. 3) to be a listric structure, flattening beneath the fault block (labeled here FB) immediately to the west of Site 901. Thus, L is clearly a major structure, and probably controlled extension leading to breakup for this part of the transect. West of shotpoint 4400, L becomes hard to follow.

Site 900 to Site 901

The east flank of the central high (fault block FB) does not show many structures, but its central upper part appears faulted and may contain a small basin with up to 750 m of probably synrift sediment (Fig. 8). More pronounced are the reflections between Site 900 and the basement high FB. West-dipping to subhorizontal reflections (shotpoints 4075-4325) bound landward thickening wedge-shaped blocks, overlain by oceanward-thickening wedges of sediments, interpreted as synrift. These reflections end at depth at the level of another bright reflection (H), which extends between shots 4025 and 4325 in a depth ranging between 6 and 10 km. H cuts down from the central high with an oceanward dip, but flattens, turns and cuts up towards the top of the Site 900 high as a band of strong, landward-dipping reflections.

Site 898 to Site 900

An alternation of small highs and basins within the basement topography appears west of Site 900 between shotpoints 2825 and 3900, which also images some intracrustal reflections with various dips (Fig. 3). Between shotpoints 3300 and 3800, the seismic section exhibits three irregular lens-shaped features, each of them extending approximately 10 km along the profile. These are tentatively identified as basement, perhaps highly fractured, with a consistent interval velocity of 4.7 km/s, and are clearly separated from the overlying sediment sequences with a maximum velocity of 3.5 km/s (Fig. 5).

In this western part of line LG12, deep reflections of various dip directions are also apparent (Fig. 8). Cutting down from Site 900 towards the west, a reflection (labelled here F) deepens between shotpoints 3700 and 4000 from 6 km at Site 900 to at least 9 km depth, but cannot be followed clearly farther oceanward below the next basement block. The basement high next to Site 900 marks the proposed drill location IAP-7 (shotpoint 3775; Reston et al., proposal to ODP, 1994). The major reflector below the IAP-7 basement block to the west of Site 900 may be possibly the same structure as the H reflector east of it, as will be discussed further below.

Three basement reflections with eastward dip are imaged approximately 2-10 km east of Site 898 (shotpoints 3150-3300, 3250-3350 and 3300-3500), extending landward from the top of the basement down to 10 km depth (Fig. 8). These may be interpreted as extension-

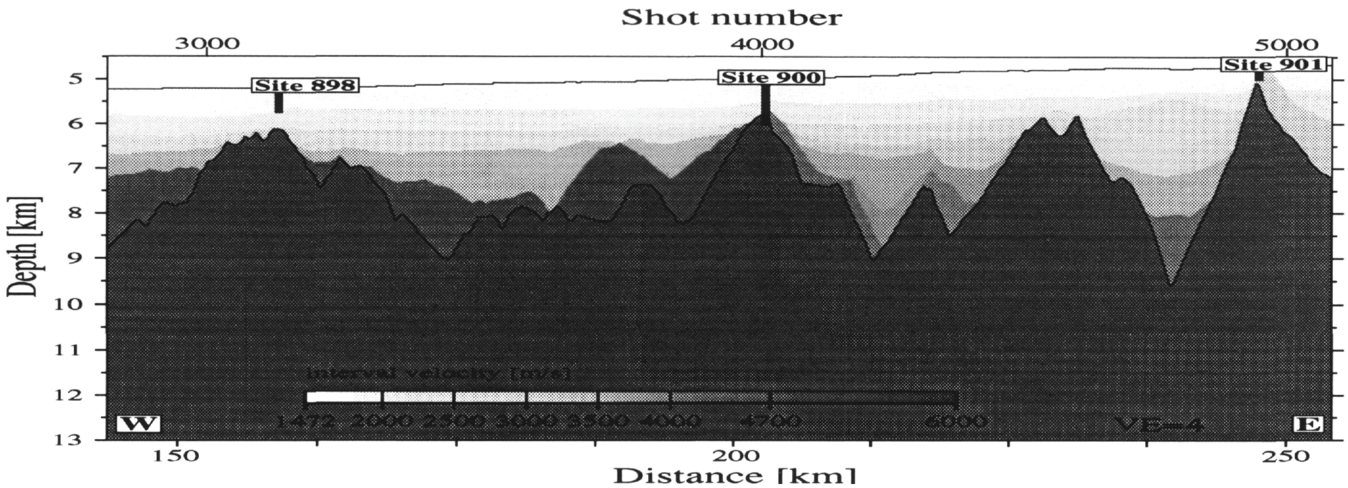

Figure 5. Velocity model of profile Lusigal 12 between Sites 898 and 901. Next to the drill sites, the model was derived from iterative prestack depth migration, and extrapolated to the whole, analyzed segment of LG12 for poststack depth migration shown here. The model allows the following units to be identified: basement *(Vp* = 5.5 km/s), postrift *(Vp* = 1.7-3.1 km/s), synrift *(Vp* = 3.2-4 km/s), and prerift *(Vp* = 4.1-4.7 km/s) sediments capping the tilted block at Site 901, where prerift sediments of Tithonian age had been drilled (Shipboard Scientific Party, 1994c), and probably east of Site 900. Figures 6 and 7 show the models derived by prestack depth-migration in more detail next to the drill sites.

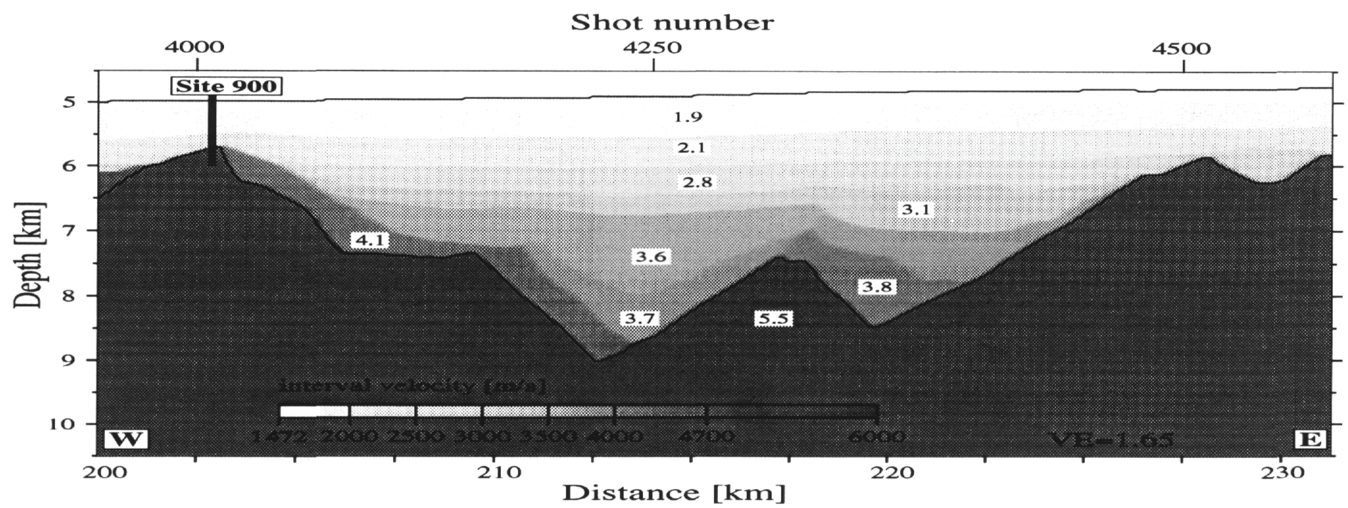

Figure 6. Interval velocities on profile LG12 east of Site 900 derived from iterative prestack depth migration. The different sedimentary sequences are clearly discernible by the velocities. The wedge-shaped sequences on top of the landward-tilted blocks are interpreted as syn- and/or prerift. Sediments show velocities between 1.7 and 4.7 km/s: *Vp* = 1.7-3.1 km/s for postrift, *Vp* = 3.2-4 km/s for synrift, and *Vp* = 4.1-4.7 km/s for prerift sediments on top of the basement (*Vp* = 5.5 km/s).

al structures accommodating top-to-the-east shear, and perhaps postdate structure H.

Site 898 and Farther West

Drilling Site 898 did not reach basement, so this location is mainly described by geophysical investigations (e.g., Pinheiro et al., this volume). The seismic image here shows an irregular surface and a series of small, oceanward-dipping fault structures cutting into the upper 750 m of this basement high (Fig. 8). From here to the western end of the investigated seismic section of profile LG12, the basement deepens in three steps farther oceanward to 9 km depth, and again, the velocity function runs from 1.9 to 3.5 km/s within the sediment sequences to 5.5 km/s within the basement (Fig. 5).

INTERPRETATIONS AND DISCUSSION

The complexity of the basement reflections allows several interpretations. Here we present two possible interpretations, both consistent with all geological and geophysical observations (e.g., Pinheiro et al., this volume).

Interpretation 1. West-dipping Detachment (CMK and TJR)

Site 900 to Site 901

From the seismic data, we infer at least two phases of rifting (Fig. 10A). First a detachment fault (H) accommodated top-to-the-west motion, accompanied by the development of the small landward-

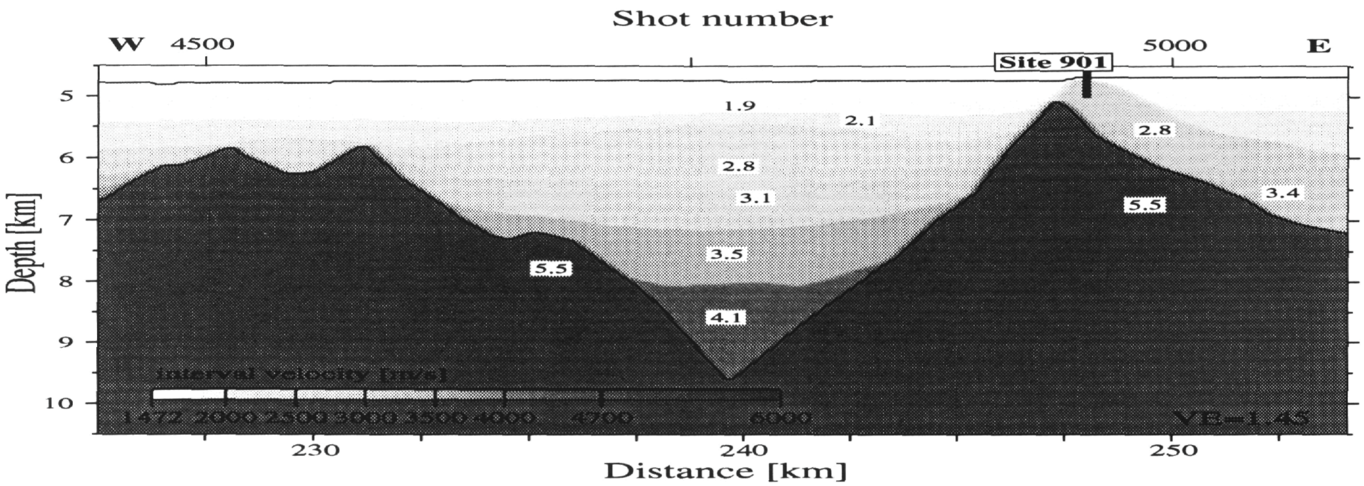

Figure 7. Enlargement of the velocity model of profile LG12 next to Site 901 derived from iterative prestack depth migration. Sediment velocities increase *(Vp* = 1.7-4.1 km/s) from shallow to deeper levels, and those sampled on top of the tilted block (*Vp* basement = 5.5 km/s) are most likely of prerift age (Shipboard Scientific Party, 1994c). In contrast, the prerift sequence near Site 900 shows higher velocity values than the layer here, which is characterized by mud-dominated ooze and clay as proved by sampling.

thickening, landward-tilted, wedge-shaped fault blocks riding on H: the wedge-shaped blocks between Site 900 and basement high FB (shots 4025-4425). These wedge-shaped blocks are bound by westward-dipping normal-fault structures that are synthetic to and detach onto H (Fig. 11). We suggest that during progressive extension and exhumation of the lower plate to H, the unloading of the lower plate to H caused this to bow up, as inferred for detachment faults in the western United States (Lister and Davis, 1989). This may have rendered at least part of H inactive.

The detailed seismic image from prestack depth migration (Fig. 12) provides evidence for the presence of lower crustal material and H itself on top of the basement high of Site 900. H can clearly be followed from 9 km depth to the top of the fault block at 6 km depth, approaching the basement surface apparently slightly east of the drilled position, so that we consider it most likely that the lower plate to H was drilled. This is also indicated by the heavily sheared and fractured structure of the analyzed samples (Shipboard Scientific Party, 1994b).

The change of dip direction of structure H from west to east is however remarkable and hard to explain within a single phase of faulting. Instead we infer that H, and the overlying wedge-shaped blocks, were rotated during a later phase of faulting and extension. The most pronounced structure interpreted to have been active during this later phase is the bright L reflection, which cuts down from the easternmost tilted block (Site 901) and probably marks the lowermost boundary of the middle basement high (FB). On the depth migrated section (Fig. 8), L appears approximately planar down to 12 km depth, where it appears to flatten into a deeper level along which the continental block east of Site 900 moved to the west (Fig. 8). This subsequent faulting along L may even be active today, expressed by the 100-m-high fault scarp at Site 901. Other structures active at this phase of faulting may include approximately planar faults bounding the western flanks of basement highs FB and 900, although these structures are less clearly imaged. Together, these faults would have formed an array of oceanward-dipping faults, dissecting the original detachment system (H), and rotating the segments of that system landward.

Thus, we identify a detachment fault, H, accommodating top-to-the-west motion, overlain by two wedge-shaped "horses" (Gibbs, 1987), and itself back-rotated both during the unloading of the footwall that accompanied extension, and also by later steeper faulting. This leads us to suggest that various phases of faulting may have controlled continental breakup in the Iberia Abyssal Plain region.

This interpretation is supported by the results of Leg 149 (Sawyer, Whitmarsh, Klaus, et al., 1994; Fig. 2). Whereas Site 897 proved the existence of a peridotite ridge between oceanic crust and the western end of the transition zone between oceanic and continental crust, Site 901 drilled prerift or pretilting sediment of Tithonian age, capping conformably the most westward tilted crustal fault block. This block is interpreted as thinned continental crust, because the overlying sediment is approximately 15 m.y. older than the onset of seafloor spreading in this area (Whitmarsh and Miles, 1995; Miles et al., this volume). The third drilling location where basement was reached, Site 900, sampled mafic rocks (meta gabbros, sensu lato) strongly deformed at about 15 km depth under granulite facies conditions (Cornen et al., this volume) at 136 Ma (Féraud et al., this volume), that is 6 m.y. before final breakup at 130 Ma (Whitmarsh and Miles, 1995). Because of the depth and grade of metamorphism, we interpret these rocks as lower crust exhumed during the rifting process.

Thus, going from east to west, the basement consists of upper crust, lower crust, and upper mantle. Therefore, we conjecture that a cross-section through the upper lithosphere was exposed during the rifting process, probably by top-to-the-west motion along detachment H, and was subsequently dismembered by steeper normal faults.

West of Site 900

The complex seismic image of the area west of Site 900 also offers different possibilities for interpretation (Fig. 13). Between lower crust (Site 900) and serpentinized mantle material (found at Site 897, 27 km west of Site 898), the major and controlling structure may be a westward dipping low-angle normal fault corresponding to the reflection F. It cuts down from Site 900 from 6 km depth towards the west below the basement high IAP-7 to 9 km depth (Fig. 13), and extends over at least 15 km along the profile. F may represent on the west flank of Site 900 the same structure as H does on the east flank. If so, the basement high at IAP-7 (see also Fig. 2) would be an upper-plate fault block to this master detachment, which accommodated extension by top-to-the-west motion.

As block-faulting or detachment structures are less pronounced, F may also have been later than H, perhaps coeval to L, in which case IAP-7 would be part of the footwall to H. Within this scope, the Moho may lie nearby, and mantle material could be found at shallow levels. Finally, the IAP-7 basement high could represent a volcanic structure formed by magmatism accompanying breakup on the Iberi-

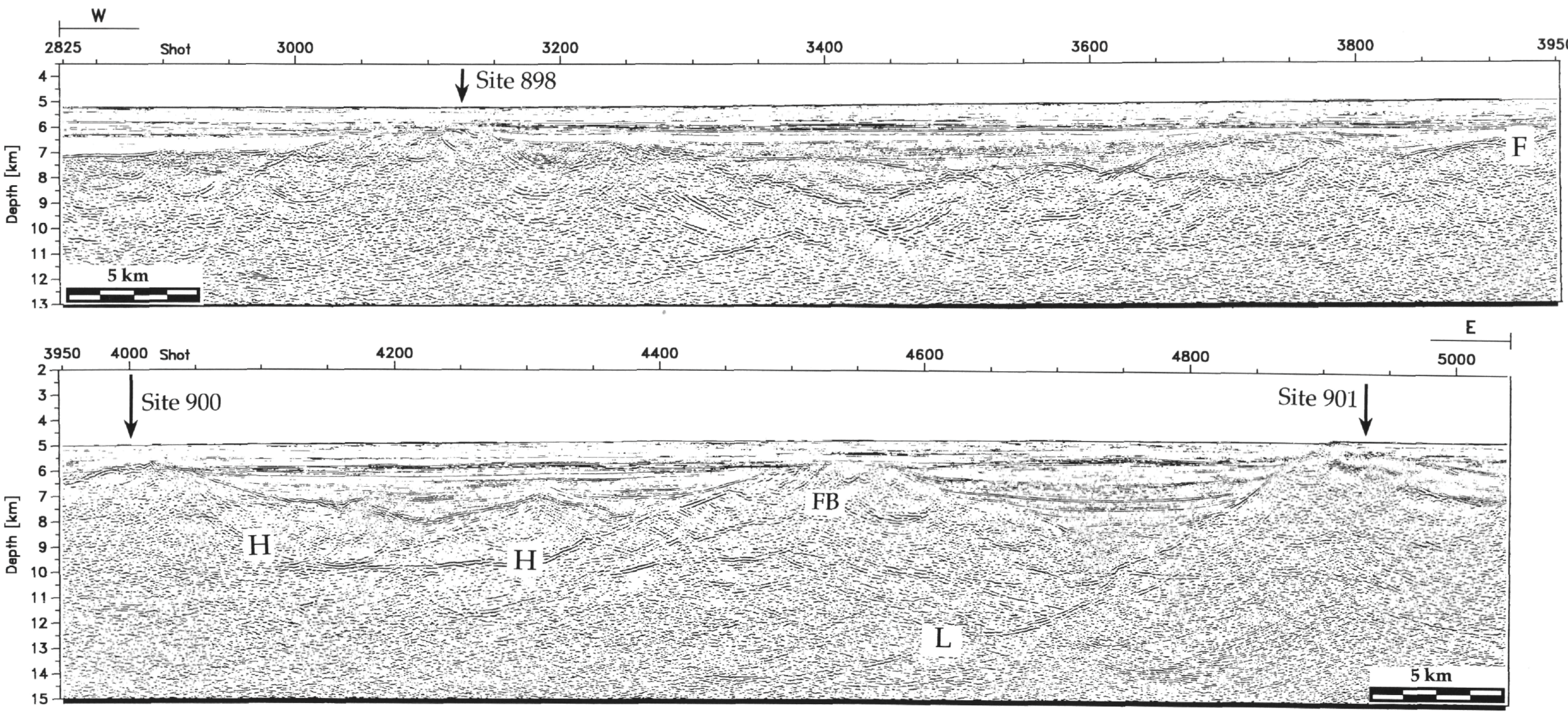

Figure 8. Depth-migrated section of profile LG12 between Sites 898 and 901 drilled during Leg 149 (50-m shot spacing; no vertical exaggeration). Strong reflections in the basement characterize this segment of the Iberian passive margin, showing different fault structures (H, L, F, FB) of various dips. For details see Figures 9, 11, and 13.

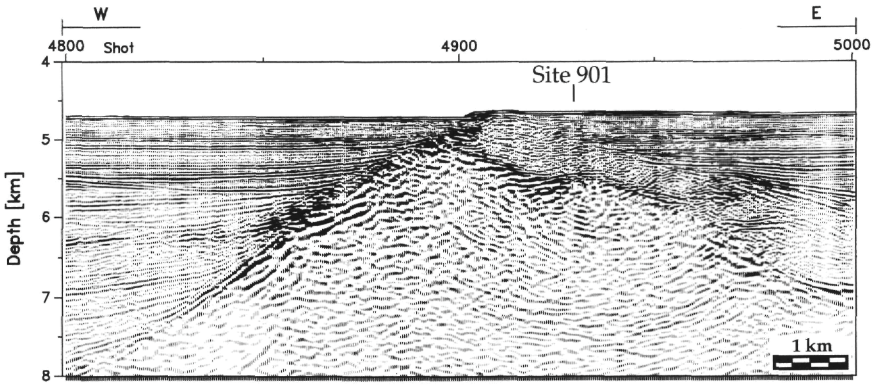

Figure 9. Enlarged seismic section adjacent to Site 901 migrated before stack. This basement high represents the most westward-tilted crustal block drilled within this transect across the transition between oceanic and continental crust off the Iberian rifted margin. It is capped conformably by prerift sediments of Tithonian age (Shipboard Scientific Party, 1994c).

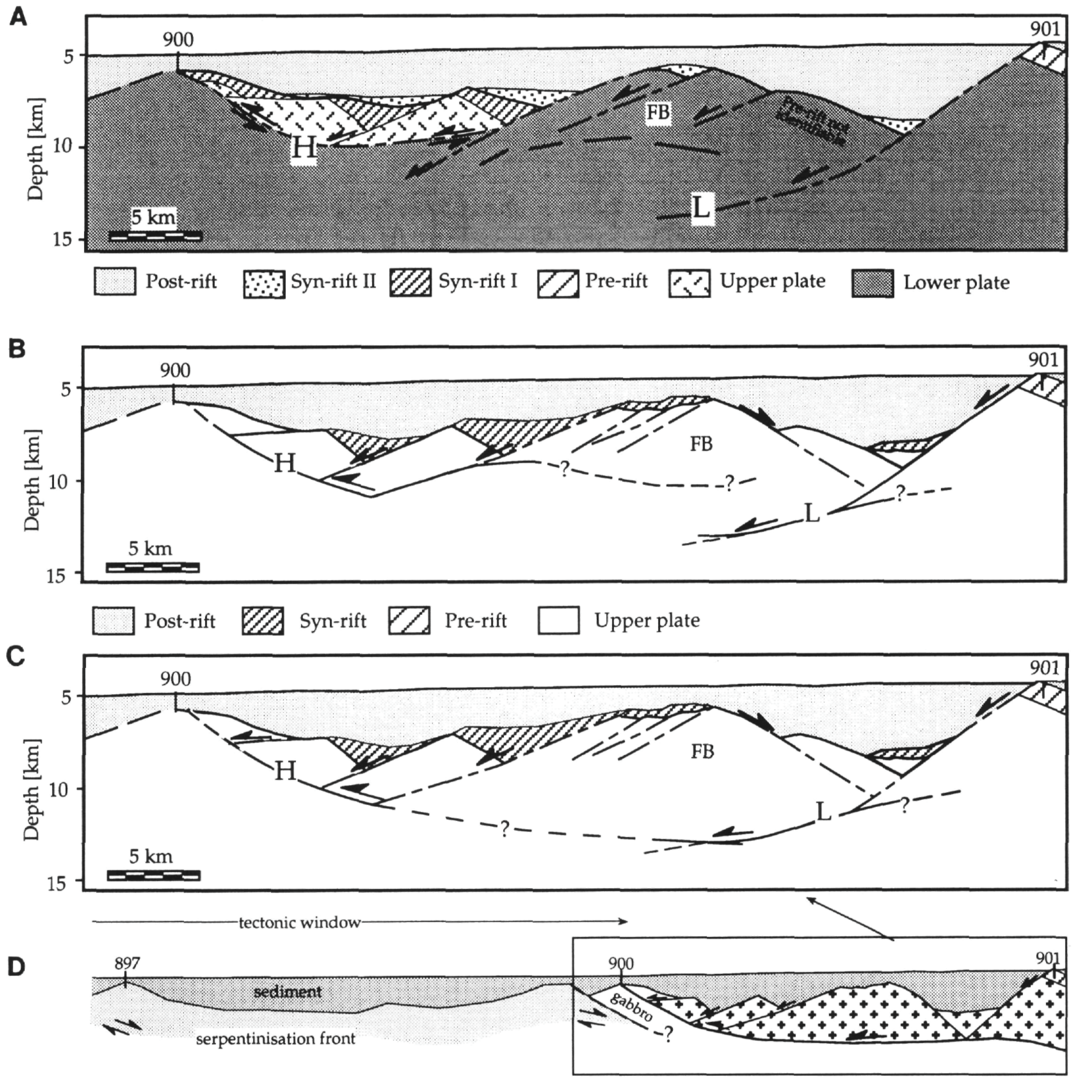

Figure 10. Interpretations of the depth section of profile LG12 between Sites 900 and 901. The eastern basement high is capped by a seismic transparent layer of prerift/pretilting sediments. Farther to the west, different tilted blocks are imaged. They are bound by fault structures (e.g., the listric structure L) and a detachment (H), which developed during different phases of rifting. **A.** H developed during the synrift I stage accommodating top-to-the-west motion, and was subsequently cut and rotated by L during the synrift II stage. Backrotation of H first during synrift I and subsequently during synrift II explains its current orientation. H terminates at the top of the basement high 500 m east of the drilled Site 900 (see also Figs. 11 and 12). Wedge-shaped sedimentary sequences are either of early synrift/prerift or of synrift II age. **B.** and **C.** Another interpretation involves H and L belonging to the same (C) or to the same family (B) of detachments, where normal faults and tilted blocks of the margin are rooted. (C) assumes the eastward-dipping part of H cutting across L at about 12 km depth by analogy to the Galicia Margin (e.g., Boillot et al., in press). **D.** This panel summarizes and extends interpretations of (B) and (C); to the west: deep lithospheric levels were tectonically unroofed as a result of conjugate, lithospheric shear zone activity during rifting (after Beslier et al., 1995).

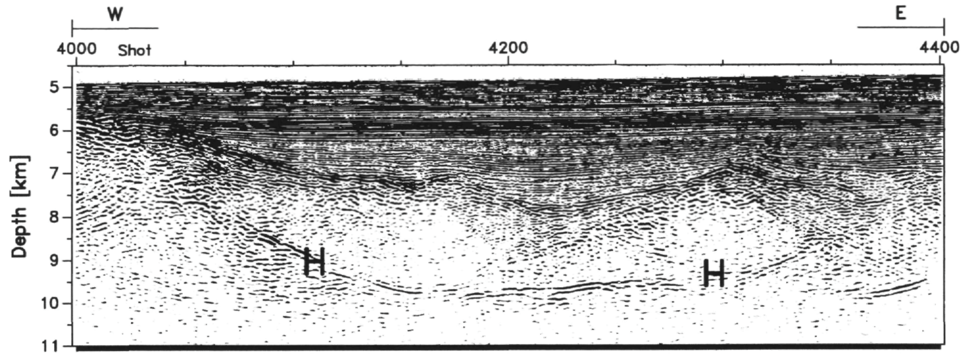

Figure 11. Prestack depth-migrated seismic section east of Site 900, converted with the velocity model shown in Figure 6. The landward-tilted blocks are separated by normal faults stopping at the underlying reflector H, which is therefore interpreted as detachment fault subcropping near Site 900. Wedge-shaped sedimentary sequences thicken towards the block-bounding faults and can clearly be identified as syn- and/or prerift sediments as also indicated by the changes in velocity. Above, the postrift sequence shows regular and subparallel bedding.

an continental margin. Nevertheless, this hypothesis seems rather unlikely because of the general absence of volcanism on this passive rifted margin and the local extent of this layer.

Model

Our results are consistent with a simple model for the evolution of the Iberia Abyssal Plain (Fig. 14). Although an oversimplification and although other models (e.g., Masson and Miles, 1994; Whitmarsh and Miles, 1995; Miles et al., this volume) may be equally valid, this model provides the simplest explanation for the apparent deepening of lithospheric level found going from east to west across the drilled transect. We thus advance this model as a basis for further work and investigations of this margin. As lithospheric extension started, Newfoundland and Iberia moved apart along a large detachment, accommodating top-to-the-west simple-shear motion in the upper lithosphere. Asthenospheric upwelling and consequent decompression melting may have led to the local intrusion of melt into the lower crust. If such melting occurred beneath highly thinned lithosphere, it may be indistinguishable from that occurring at mid-ocean ridges.

Extension of the upper lithosphere along a top-to-the-west detachment would have brought lower crustal and mantle rocks close to the surface to the west (Wernicke, 1981). After the detachment had become inactive, block-faulting may have accommodated continued extension. This faulting would have dissected the lower plate and the detachment itself, and rotation of the blocks would have tilted this back towards the continent. As the block-faulting appears to have dissected the entire detachment system, we infer that mantle thinning (and hence lithospheric weakening) may have taken place over a broad zone during detachment faulting (Fig. 14), rather than being localized down-dip of the detachment. This in turn might be taken as an indication that no single lithosphere penetrating detachment developed, but rather that extension in the lower lithosphere may have been accommodated ductilely (Fig. 14) or along a system of extensional structures.

The model in Figure 14 is consistent with the drilling results (Sawyer, Whitmarsh, Klaus, et al., 1994). The transect between Sites 901, 900, and 898 represents a transition from upper continental crust to lower crust (perhaps synrift intrusion) to mantle, as predicted by the model. It predicts additionally a significant amount of mantle material between oceanic and continental crust, locally exposed at the seafloor during the last rift stage prior to continental breakup. Site 901 sampled continental material; Site 900 drilled a lower crustal tilted block, identified by its lithology (amphibolite facies gabbro, probably synrift); Sites 897 and 899 sampled mantle rocks.

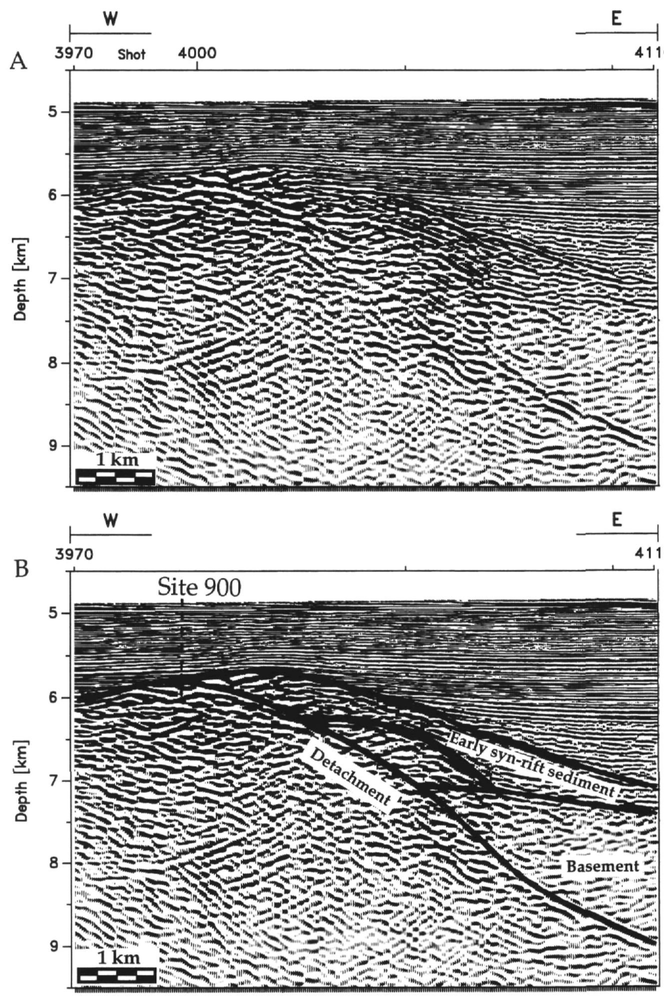

Figure 12. **A.** Detailed seismic depth section, migrated before stack, and (**B**) its interpretation at Site 900. The probable detachment fault H subcrops just east of Site 900, which sampled highly deformed, amphibolite-grade gabbro with shear structures between 10 and 40 degrees. The detachment is overlain by a small lens of crustal rocks (*Vp* > *5* km/s), which is covered by probable early synrift sediment *(Vp* = 4.1 km/s).

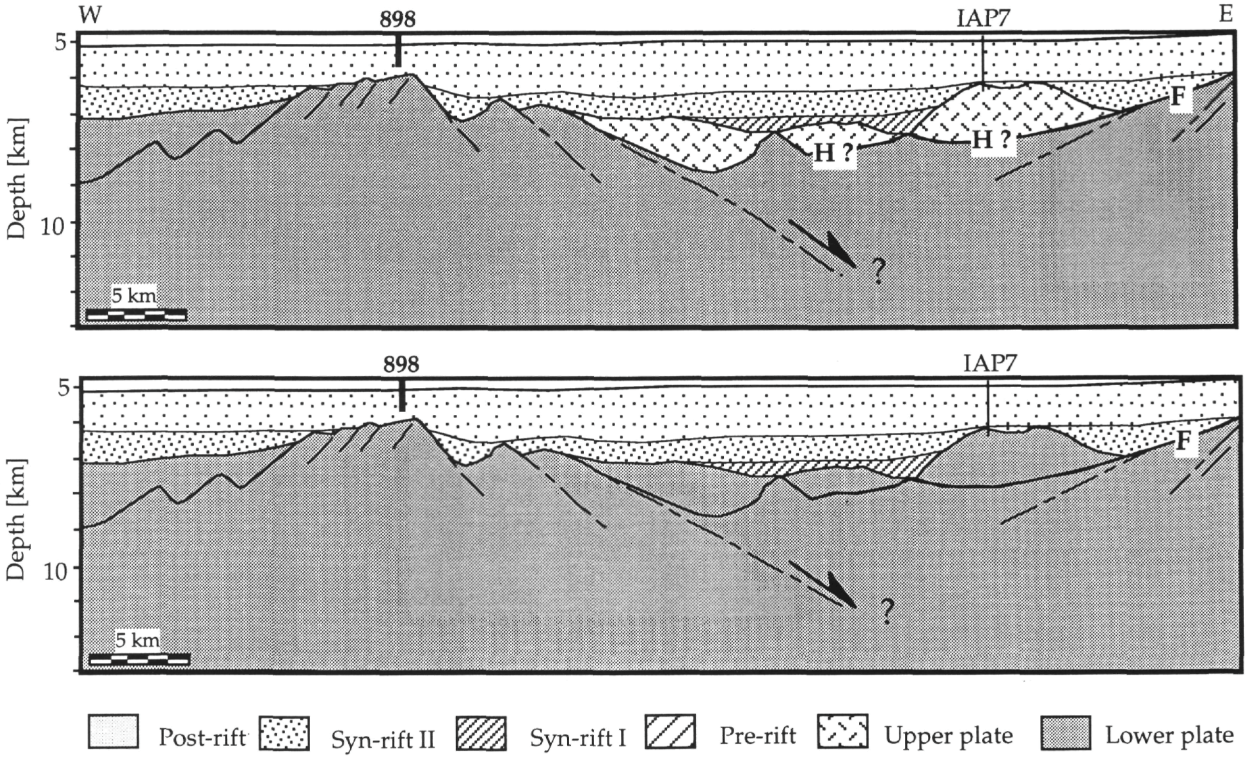

Figure 13. West of Site 900, basement topography is characterized by alternating, small-scale highs and basins between Sites 900 and 898, where the basement high is cut by a series of oceanward-dipping normal faults. Thick, lens-shaped sequences extend over a range of 40 km on top of the basement. Reflection F, cutting towards the west below the basement high of the proposed drill location IAP-7, may be a low-angle normal fault. F may either represent on the west flank of Site 900 the same structure as H east of it, or it may be a separate feature, different from H. Therefore, the crustal block at IAP-7 may either be an upper-plate or a lower-plate fault block to the master detachment H.

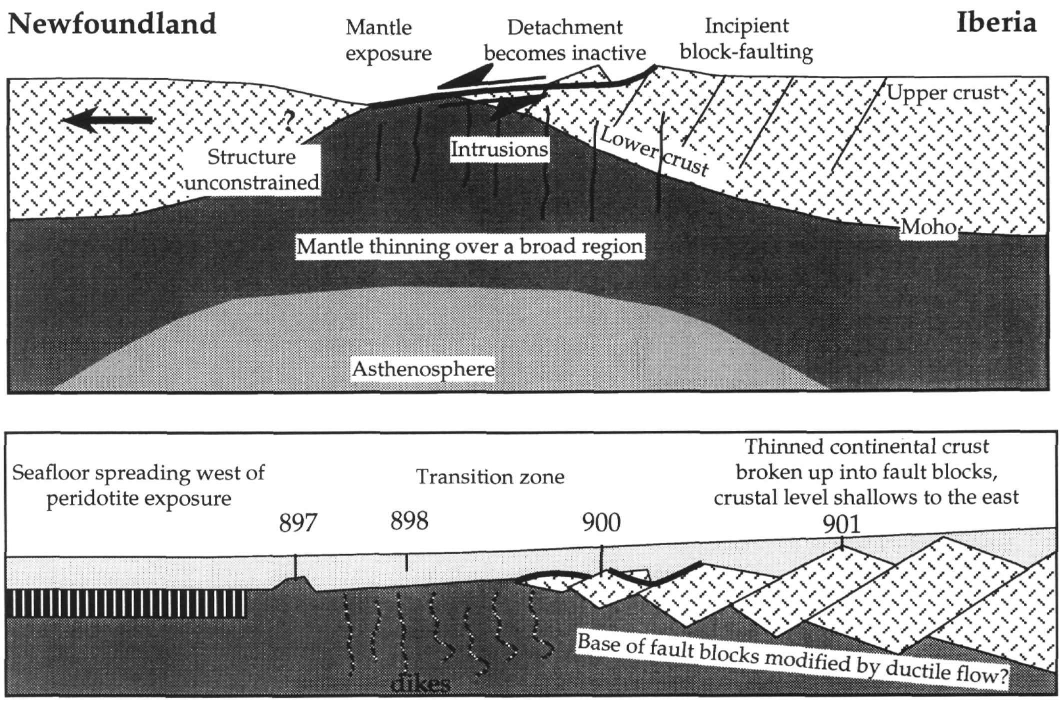

Figure 14. Cartoon, illustrating an initial, simplified model for the extension of the lithosphere controlled by detachment faulting during rifting on the Iberia Abyssal Plain margin. During synrift I, lithospheric extension may have been accommodated by detachment faulting and accompanied by consequent upwelling, melting, and intrusion of gabbro into the lower crust at about l36 Ma (see Féraud et al., this volume). Subsequently, during synrift II, block-faulting cuts the upper plate into tilted blocks, dismembering the detachment system and the lower plate. The resulting crustal cross section shows an oceanward deepening of lithospheric level, consistent with the results of Leg 149.

The model (Fig. 14) is also broadly consistent with the structure of the Newfoundland Basin margin. Although Reid and Keen (1990) describe large east-cutting normal faults on this conjugate margin, these do not appear to cut down into the mantle, but rather detach at lower crustal levels. Furthermore, we note that the reported (Reid, 1994) crustal structure of the conjugate Newfoundland Basin margin (reconstruction of Malod and Mauffret, 1990) is consistent with a west-cutting detachment: landward of the Newfoundland Basin, the lower crust appears to be truncated by a west-dipping Moho beneath the top of the continental slope, and is absent beneath most of the continental slope and rise, as in an upper plate margin (Fig. 14). Thus the structure of the conjugate margin is also compatible with a west-cutting master detachment fault that exposed mantle rocks at the seafloor on the Iberian side.

Interpretation 2. Conjugate Shear Zones (MOB and GB)

As in the previous interpretation, H and L are considered to be features similar to the S reflector imaged on the Galicia Margin, i.e., as the seismic signature of tectonic contacts formed during extension. However, the seismic data do not fully constrain the relationship between H and L, thus allowing the two interpretations presented in Figures 10B and C. It is however clear that H cuts up to top basement just east of Site 900, implying that the whole area located between Site 900 and the oceanic crust (accreted more than 100 km to the west) is a tectonic window opened on deep lithospheric levels (mantle rocks now partially serpentinized and gabbros probably underplated during continental rifting). This interpretation is in good agreement with the petrostructural evolution of serpentinized peridotites and gabbros, both of which underwent a ductile shear deformation at high and decreasing temperature followed by a complex deformation in subsurface conditions (Beslier et al., 1994; this volume). This evolution likely occurred in extensional lithospheric shear zones which led to tectonic denudation and exposure of deep lithospheric levels at the seafloor.

However, in contrast to interpretation 1 (Fig. 10A), this second interpretation (Figs. 10B, C) postulates that the Iberia Abyssal Plain margin belongs entirely to the upper plate, the main detachment being rooted beneath Iberia (Fig. 10D; for more detailed discussion see Beslier and Brun, 1991; Boillot et al., in press; Beslier et al., in press). However, although the structure of the ocean/continent transition of the two margin segments (Galicia Bank and Iberia Abyssal Plain) is comparable, the ocean/continent transition is much wider beneath the Iberia Abyssal Plain (150 km) than on the western Galicia Margin (30 km). The complex late deformation and structure of the ocean/continent transition beneath the Iberia Abyssal Plain suggest that the mantle and associated mafic rocks can be stretched over a wide region after the breakup of continental crust is completed and before oceanic accretion has started.

CONCLUSIONS

The results of the reprocessing and prestack depth migration analyses of a reflection seismic profile across the Iberia Abyssal Plain margin show deep reflections within the basement, which are associated with block faulting. The overlying sediments, deposited during different phases of rifting, are discernible by their interval velocities. Combined with the present knowledge of the mechanism of lithospheric extension in the area of the Galicia Bank, this profile supports the idea that the Iberia Abyssal Plain continental extension leading to breakup may also have been controlled by detachment fault systems active during different phases of rifting. As a consequence of exhumation during repeated extension, a crustal cross-section is exposed, where one can identify upper crust, lower crust, and finally mantle material from east to west along this transect across the ocean/continent transition.

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