Beslier, M.-O., Whitmarsh, R.B., Wallace, P.J., and Girardeau, J. (Eds.)
Proceedings of the Ocean Drilling Program, Scientific Results Volume 173

The Rift-to-Drift Development of the West Iberia Nonvolcanic Continental Margin: A Summary and Review of the Contribution of Ocean Drilling Program Leg 173[1]

R.B. Whitmarsh[2] and P.J. Wallace[3]

ABSTRACT

During Ocean Drilling Program Leg 173 (and earlier Leg 149), a transect of 10 sites was drilled across the southern Iberia Abyssal Plain to investigate the rift-to-drift evolution of the central part of the west Iberia nonvolcanic rifted continental margin. Many drill holes penetrated the sediments immediately overlying acoustic basement and the basement itself. The main result of Leg 173 was the discovery that late Hercynian lower crustal rocks were exhumed where the continental crust has been tectonically thinned to almost zero thickness. The results from the cores have been combined with interpretations of geophysical data in the vicinity of the transect to arrive at a greatly improved understanding of the processes involved in the extension and breakup of continental crust leading to the onset of seafloor spreading. Isotope geochronology and pressure-temperature-time histories of some of the cores have also provided constraints on the rates of extension and exhumation. The principal conclusions from the results of Leg 173, when combined with independently acquired geophysical data, are as follows:

1. All fault blocks imaged on seismic reflection profiles are blocks of thinned continental (and not oceanic) crust. At least one block (Site 1065) was tilted during rifting.

[1] Whitmarsh, R.B., and Wallace, P.J., 2001. The rift-to-drift development of the west Iberia nonvolcanic continental margin: a summary and review of the contribution of Ocean Drilling Program Leg 173. *In* Beslier, M.-O., Whitmarsh, R.B., Wallace, P.J., and Girardeau, J. (Eds.), *Proc. ODP, Sci. Results,* 173, 1–36 [Online]. Available from World Wide Web: <http://www-odp.tamu.edu/publications/173_SR/SYNTH/SR173SYN.PDF>. [Cited YYYY-MM-DD]
[2] Challenger Division, Southampton Oceanography Centre, University of Southampton, European Way, Southampton SO14 3ZH, United Kingdom. **rbw@soc.soton.ac.uk**
[3] Texas A&M University, 1000 Discovery Drive, College Station TX 77845-9547, USA.

Initial receipt: 10 July 2000
Acceptance: 18 January 2001
Web publication: 22 May 2001
Ms 173SR-017

2. The continental crust thins dramatically seaward (practically to zero) and is broken into blocks by low-angle detachment faults. These blocks are probably underlain by a tectonic crust/mantle boundary, which in the center of the transect, on a basement ridge called Hobby High, has been uplifted to within a few hundred meters of the top of acoustic basement.
3. All the mafic cores from Sites 900, 1067, and 1068 on Hobby High are of late Hercynian (270 Ma; early Permian) age and were emplaced in the lower continental crust or at the base of thinned crust. These mafic magmas were derived from melting of heterogeneous mantle sources during a late Hercynian extensional phase. The mafic magmas crystallized to form both cumulate and noncumulate gabbros, followed by ductile shearing at middle to lower continental crustal depths.
4. At the Hobby High sites, exhumation of lower crustal rocks proceeded over tens of millions of years and preceded the onset of seafloor spreading.
5. The Site 1068 and 1070 peridotites are not as depleted as typical abyssal (oceanic) peridotites and are more likely to be derived from the suprasubduction zone or subcontinental mantle. The mantle rocks show geochemical and mineralogical evidence of heterogeneous partial melting (probably <10% melting). They were also locally and intensely percolated by melts during the last stage of high-temperature deformation that generated a porphyroclastic foliation. Available data indicate a range of compositions for these percolating melts from depleted mid-ocean ridge basalt-like trace element values to more enriched compositions that crystallized kaersutite and phlogopite.
6. The basement cores at Site 1070 show gabbro pegmatite overlying serpentinized peridotite veined by gabbro. On the other hand, geophysical observations indicate the presence of oceanic crust at this site, but, remarkably, no rocks from the upper oceanic crust (neither basalt nor sheeted dikes) were encountered. The cores may indicate oceanic crust formed at a time when tectonism was more important than magmatism, but we cannot be sure that Site 1070 is representative of the surrounding crust.
7. The basement rocks at Site 1070 were exhumed at the seafloor at least 14 m.y. later than the crustal age computed from seafloor-spreading magnetic anomalies. Either this exhumation was more rapid than at Hobby High, or more likely, the 250°–500°C isotherms were much closer together at Site 1070.
8. The surprising lack of synrift melt products in the basement cores from five sites over thinned continental crust or the ocean-continent transition (OCT) zone can be explained qualitatively by the gradual post-breakup evolution of the margin towards steady-state seafloor spreading. Some indirect evidence exists for intrusive bodies within the top 6 km of the acoustic basement of the OCT, but their age of intrusion is unknown.
9. Strong and informative parallels were noted between the character and history of the Leg 173 (and Leg 149) cores and the character and history of the rifted margins and transition zones exposed today in the Alps.

INTRODUCTION

For many years, rifted continental margins have been classified as volcanic or nonvolcanic based on the presence or absence of seaward-dipping reflector sequences (lavas) on reflection profiles and on whether the crust underlying the margin has been thickened by 7.0–7.4 km/s (gabbroic) material underplated to the base of the crust at the time of rifting. In spite of subsequent recognition that these two types of margin lie at opposite ends of a spectrum of margins, this has remained a useful and relatively robust classification scheme. Volcanic margins attracted attention because it proved possible to calculate the temperature of the asthenosphere around the time of breakup from the seismically estimated volume (thickness) of melt produced at volcanic margins (McKenzie and Bickle, 1988; Pedersen and Ro, 1992; White and McKenzie, 1989), just as similar calculations attempted to relate the variation in thickness of oceanic crust to asthenosphere temperature and seafloor-spreading rates (Bown and White, 1994). However, the effusive magmatism of volcanic margins carries with it the disadvantage that the lavas represented by the seaward-dipping reflections probably obscure potential seismic images of underlying fault blocks indicative of the tectonism that undoubtedly accompanied the rifting. Therefore, nonvolcanic margins have recently received renewed attention, because it was realized that the study of their tectonism, as evidenced by seismic images of faults and fault blocks, could complement that of magmatism at volcanic margins. Such studies sought to differentiate between hypotheses that predicted that simple shear, pure shear, or even combinations of the two, dominated lithospheric extension (e.g., Lister et al., 1991; McKenzie, 1978; Sibuet, 1992a; Wernicke, 1985; Wernicke and Burchfiel, 1982). Numerical modeling was also used to attempt to relate lithospheric extension to asthenospheric temperature, strain rate, and other factors (e.g., Bassi, 1995; England, 1983). An additional impetus was the discovery off Galicia Bank, on the nonvolcanic west Iberia margin, of an extensive margin-parallel basement peridotite ridge (Beslier et al., 1993), because it appeared that mantle could be tectonically "unroofed" or exhumed during the final rifting process itself (Boillot et al., 1989). Lately it has become apparent that there is yet another, more fundamental, problem to be addressed at nonvolcanic margins. The question is, how do the effectively nonvolcanic (and even apparently amagmatic) processes of continental rifting and breakup evolve into the onset of seafloor spreading, which is unquestionably a magmatic process (Whitmarsh et al., in press)?

Concurrently, discoveries were being made in the Alps that certain nappes, created during Alpine mountain building, contained the largely undisturbed history of the tectonic and sedimentary development of Mesozoic Tethyan rifted margins (e.g., Florineth and Froitzheim, 1994; Froitzheim and Eberli, 1990). Subhorizontal detachment faults were recognized that had allowed many kilometers of relative motion during the process of continental extension, and even exposures of synrift tectonically exhumed mantle were found. Careful mapping on the ground, essentially (but not entirely!) in the horizontal plane, came to complement the one- or two-dimensional, in the vertical plane, drilling and geophysical results from the west Iberia margin.

The above events largely took place in the mid-1980s to 1990s at a time when Ocean Drilling Program (ODP) Leg 173 (and earlier Legs 103 [Boillot, Winterer, et al., 1988] and 149 [Whitmarsh, Sawyer, Klaus, and

Masson, 1996] to the west Iberia margin) were being planned, executed, or worked up. Here, an attempt is made to report the principal current results from Leg 173 and to document their contribution to the development of the above ideas.

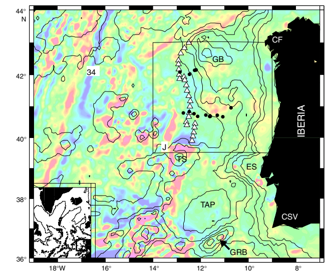
BACKGROUND AND LEG OBJECTIVES

Leg 173 had its roots in the report of a North Atlantic Rifted Margins Detailed Planning Group (DPG) convened by the Planning Committee of the ODP in 1991. The DPG recommended that a transect of holes be drilled across a conjugate pair of nonvolcanic margins, which were chosen to be the west Iberia and Newfoundland margins in the North Atlantic Ocean. Leg 149 ensued in 1993, and five sites off west Iberia located over basement highs that were expected to allow relatively easy access to the acoustic basement rocks were drilled (Sawyer, Whitmarsh, Klaus, et al., 1994; Whitmarsh, Sawyer, Klaus, and Masson, 1996) (Figs. F1, F2, F3). The results of Leg 149 confirmed the existence of the peridotite ridge already drilled farther north during Leg 103 at Site 637 (Boillot, Winterer, Meyer, et al., 1987) and that at least one of the landward fault blocks seen on seismic reflection profiles represented a block of thinned continental crust covered by synrift or late prerift Late Jurassic sediments (Site 901). At Site 900, highly sheared mafic rocks appeared to represent synrift melt products. This very important discovery indicated that even nonvolcanic margins might be accompanied by some early synrift magmatism (Cornen et al., 1999), although an alternative view developed that these rocks had mid-ocean ridge basalt-like properties and therefore indicated active seafloor spreading (Seifert et al., 1997). Lastly, at Site 899, an acoustic basement of brecciated serpentinite over a mass-flow deposit of unbrecciated serpentinized peridotite lent some credence to the notion that there was a broad transitional zone of exhumed mantle basement between thinned continental crust to the east and normal oceanic crust to the west.

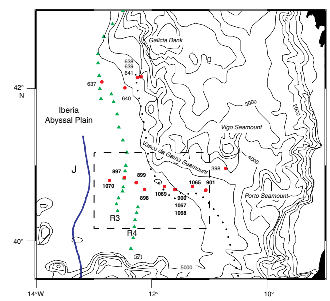
However, Leg 149 left many questions unanswered and a further leg was proposed, which became Leg 173. Leg 173 took place in April–June 1997, and we drilled five sites (ODP Leg 173 Shipboard Scientific Party, 1998; Whitmarsh, Beslier, Wallace, et al., 1998) (Figs. F1, F2, F3). The overall objective was to refine knowledge of the nature and evolution of the basement rocks and their relationships within the ocean-continent transition (OCT) zone (defined here as the region between the seaward edge of fault blocks of thinned continental crust and the landward edge of normal oceanic crust), both for its intrinsic relevance to the general problem of rift-to-drift processes and to test aspects of the working models of the tectonic and magmatic processes involved. Subsidiary objectives, with the sites at which they were eventually addressed during the leg, were as follows:

1. To sample acoustic basement, principally within the OCT, to characterize those tectonic and magmatic processes that dominate the transition from continental to oceanic crust in space and time (Sites 1065, 1067, 1068, 1069, and 1070).
2. To determine the role of simple shear deformation in the evolution of the margin. This was to be done by drilling through a major synrift tectonic contact on the east side of the high on which Site 900 had already been drilled. Figure F4, in which a possible detachment fault represented by a major reflector (H), seen far-

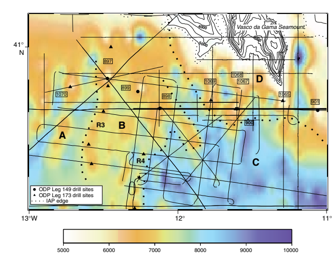
F1. Magnetic anomaly chart of the west Iberia continental margin, p. 29.



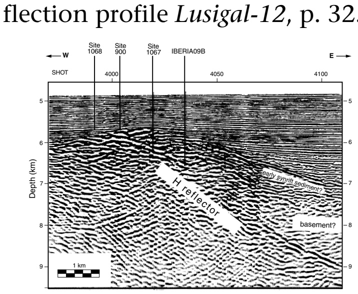
F2. Bathymetry of the Galicia Bank and southern Iberia Abyssal Plain margins of west Iberia, p. 30.



F3. A contoured basement chart based on reflection profiles acquired up to 1997, p. 31.



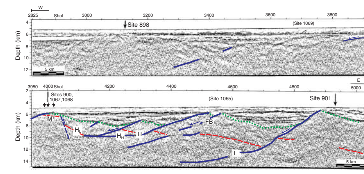
F4. Part of the prestack depth migrated multichannel seismic reflection profile *Lusigal-12*, p. 32.



ther east (Fig. F5), that can be traced almost continuously to the top of the fault block, shows this possibility particularly clearly. The seismic image at Site 900 suggests that site could be located very close to the place where the detachment intersects the acoustic basement surface. By offsetting some hundreds of meters to the east of Site 900, however, the possibility existed to drill through the complete shear zone/detachment at Site 1067. Unfortunately, once at Site 1067, this was judged to be impractical if not impossible in the time available when cores of acoustic basement revealed that it consisted of relatively high velocity (5.1–6.4 km/s) amphibolite/metagabbro/tonalite gneiss instead of the predicted relatively low-velocity (4.0 km/s) and more rapidly drillable synrift sediment, thereby significantly increasing not only the predicted target depth but also the time required to reach it (Shipboard Scientific Party, 1998b). Site 1067, as originally planned, was also expected to enable the mode and kinematics of the deformation along the tectonic contact to be determined and the lateral extent of the Site 900 mafic rocks to be assessed. Eventually, as an alternative strategy, Site 1068 was drilled 600 m west of Site 900 to sample the basement beneath Reflector H. Another site (1069) was drilled on the next basement high to the west shown in Figure F3, associated on reflection profiles with a westward-dipping normal fault, to test the prediction that continental breakup led to the exposure of progressively deeper lithospheric levels (low-level crust or even uppermost mantle) westward in the OCT (Sites 1067, 1068, and 1069).

3. To determine the role and extent of synrift magmatism in the OCT basement, which was inferred to exist from new interpretations of magnetic anomalies (Russell, 1999) and from Site 900 basement cores, using isotopes to determine the petrogenetic origin and dates of original crystallization and subsequent metamorphism of igneous rocks (Sites 1065, 1067, 1068, and 1069).
4. To sample basement beneath Site 1065 to confirm predictions of the existence of continental crust there, to determine the approximate level in the crust from which it came, and thereby to set an unequivocal landward limit to the OCT (Site 1065).
5. To sample the probably atypical early formed oceanic crust. This remained unsampled in the Iberia Abyssal Plain, other than 170 km west of Site 1070 (Matthews, 1961, 1962), and its presence and location were inferred only by geophysical observations. Samples from this site were expected to provide definitive evidence of the oceanic nature of the crust 20 km west of the peridotite ridge, and by biostratigraphic and/or isotopic dating, to enable the seafloor-spreading model to be verified. Samples were also expected to yield the possibly unusual chemistry of the thin crust formed by the earliest magma-starved seafloor spreading and to provide valuable petrological information about initial melt production following continental breakup at a nonvolcanic margin (Site 1070).

F5. A new tectonic interpretation of profile *Lusigal-12*, p. 33.



GEOLOGICAL AND GEOPHYSICAL CONTEXT OF LEG 173

Rifting between Iberia and the Grand Banks of North America proceeded intermittently during the late Paleozoic and Mesozoic, culminating in a final phase and eventual continental breakup in the Early Cretaceous. The western margin of the Iberian peninsula, like the conjugate Grand Banks margin, presents the characteristics of a nonvolcanic continental margin. Tilted fault blocks (bounded by seaward-dipping normal faults) are frequently seen on reflection profiles (Groupe Galice, 1979; Krawczyk et al., 1996; Pickup et al., 1996). The final phase of breakup took place far from an active plume or hot spot, and onshore (and as we shall see, offshore) evidence of synrift volcanism is essentially absent. Final breakup appears to have developed from south to north, as evidenced by the northward younging of the oldest seafloor-spreading magnetic anomalies starting with M11 (133 Ma) (the timescale of Gradstein et al. [1994] is used here) in the Tagus Abyssal Plain (Fig. F1) (Pinheiro et al., 1992; Whitmarsh and Miles, 1995), particularly the northward termination of magnetic anomaly J (approximately seafloor-spreading isochron M0) around 41.5°N, isotopic dating of basement rocks (Féraud et al., 1996; Féraud et al., 1988; Féraud et al., 1986; Schärer et al., 2000; Schärer et al., 1995), the identification of an Aptian/Albian (~112 Ma) unconformity separating prerift and postrift sediments off Galicia Bank (Boillot, Winterer, Meyer, et al., 1987), and the subsidence history of onshore wells (Stapel et al., 1996). Further details of the development of the margin and its relationship to onshore geology can be found in Pinheiro et al. (1996).

There appears to be a broad consensus that in the immediate vicinity of the Legs 149 and 173 drilling transect in the southern Iberia Abyssal Plain (Fig. F2), rifting and breakup of continental crust and the subsequent onset of seafloor spreading have produced several characteristic features. First, a segmented but otherwise continuous margin-parallel acoustic basement ridge has been recognized for over 300 km around 12°30′W on every multichannel seismic (MCS) reflection profile that crosses that longitude (Fig. F1) (Beslier et al., 1993; R. Whitmarsh, unpubl. data); this ridge has been shown by drilling and other sampling to consist of serpentinized peridotite (e.g., Boillot et al., 1995a, 1980; Boillot, Winterer, Meyer, et al., 1987; Sawyer, Whitmarsh, Klaus, et al., 1994). It appears to some workers to mark the landward edge of oceanic crust, although its precise origin remains enigmatic (Sibuet et al., 1995; Whitmarsh and Miles, 1995). Second, three types of acoustic basement have been recognized in the southern Iberia Abyssal Plain (Russell, 1999); they are thinned continental crust (Region D in Fig. F3), probable (but as yet unsampled) serpentinized peridotite (Region C in Fig. F3), and thin oceanic crust (Region A in Fig. F3). The thinned continental crust is recognized by fault blocks bounded by seaward-dipping normal faults on MCS profiles (e.g., Fig. F5), a characteristically high top-basement velocity (5.2–5.3 km/s), and relatively weak magnetization; the probable serpentinized peridotite basement is recognized by a distinctive velocity/depth structure, the absence of normal incidence and wide-angle Moho reflections, an unreflective zone in the uppermost basement, deep and low relief, a very weak magnetization, and magnetization sources situated down to 6 km below top basement; the oceanic crust is recognized by its typical basement relief of isochron-parallel ridges and valleys (Fig. F3), the presence of seafloor-spreading magnetic anomalies, relatively high magnetization, and a typical velocity/depth structure (albeit slightly thin), including seismic Layer 3. Locally, in the region between two overlapping and en échelon offset segments of the peridotite ridge that includes Sites 897 and 899, peridotite basement occupies an area of elevated and irregular relief, which may represent a fourth type of basement (Region B in Fig. F3). These results are based not only on remote geophysical observations (i.e., MCS profiles, wide-angle seismic velocity models, and inversion and modeling of surface and deep-towed magnetometer profiles) (Chian et al., 1999; Dean et al., 2000; Discovery 215 Working Group, 1998; Krawczyk et al., 1996; Pickup et al., 1996; Russell, 1999; Sibuet et al., 1995; Whitmarsh and Miles, 1994; Whitmarsh et al., 1990, 1996, in press) but also on the nature and spatial distribution of acoustic basement cores (Sawyer, Whitmarsh, Klaus, et al., 1994; Whitmarsh, Beslier, Wallace, et al., 1998) obtained by direct ODP sampling or strong inferences drawn from such sampling. For example, although in situ continental crust has been sampled only on Hobby High (Sites 900 and 1067), the presence of Upper Jurassic shallow-water sediments at several other sites all now in water depths >4700 m (Sites 901, 1065, and 1069) (Concheryo and Wise, Chap. 7, this volume) clearly indicates the sites must have been underlain by continental crust just before or at the onset of the last phase of rifting and subsidence.

The results from the Leg 173 drill sites will now be discussed briefly in the context of the above distribution of basement type and with reference to Leg 149 results, where appropriate. Emphasis is placed on the nature of the acoustic basement cores; sediment cores are mentioned only when they contribute to the development of understanding of the margin up to the onset of seafloor spreading. More details can be found in Sawyer, Whitmarsh, Klaus, et al. (1994) and Whitmarsh, Sawyer, Klaus, and Masson (1996) for Leg 149 and in Whitmarsh, Beslier, Wallace, et al. (1998), ODP Leg 173 Shipboard Scientific Party (1998) and elsewhere in this volume for Leg 173. Further reviews of Leg 173 results will be published in Wilson et al. (in press b).

INDIRECT EVIDENCE OF CONTINENTAL CRUST

Even though many dredge hauls and rock cores from over Galicia Bank (sensu latu) and its flanks have collected continental metamorphic and plutonic igneous rocks (Capdevila and Mougenot, 1988; Mougenot et al., 1986), only at Sites 900 and 1067 along the drilling transect have in situ continental basement rocks been cored. Such rocks are expected on several grounds, one being that a new basement relief chart (Fig. F3) clearly shows continuity between the roughly north-south ridges of, and adjacent to, Vasco da Gama Seamount and the three buried ridges on which Sites 1069, 900, 1067, 1068, and 1065 are located. Site 901 may also lie on a fourth similar ridge.

The cores from Sites 901, 1065, and 1069 all have features indicative of underlying continental crust. Sites 901 and 1065 are 21 km apart on two different tilted fault blocks, each flanked by a normal fault on its western (seaward) side. At both sites, Upper Jurassic (Tithonian) sediments contain clasts of metasediments, which indicate exposure and erosion of nearby Hercynian basement rocks (similar lithologies have been dredged from Vasco da Gama Seamount) (Capdevila and Mougenot, 1988; Mougenot et al., 1986) (Fig. F2). Clasts of shallow-water carbonates are similar to Tithonian limestones recovered from the Galicia Bank margin during Leg 103 (Boillot, Winterer, Meyer, et al., 1987). Tithonian sedimentation in a restricted basin, which was only briefly and intermittently connected to the open ocean, is indicated by the paucity of calcareous nannofossils, the general lack of bioturbation (indicating, together with common nannofossil coccospheres, anaerobic conditions), and the relatively high amounts of organic carbon (Concheryo and Wise, **Chap. 7,** this volume). Benthic foraminifer assemblages from Site 901 indicate a similar environment (Collins et al., 1996). Sedimentary features at both sites suggest deposition below wavebase by turbidites, with clays transported by low-density currents and sandstones by higher density flows, which carried clasts of metasediments and possibly coeval shallow-water carbonate grains from nearby basement highs. Thus, evidence suggests that during the Late Jurassic, deposition at Sites 901 and 1065 occurred at depths of only a few hundred meters. Assuming Airy isostasy and in the complete absence of any evidence of excessive volcanism or thermal uplift from plume activity, this indicates the sites were underlain by only slightly thinned continental crust at that time.

Site 1069 is located farther west over the southern extension of the ridge that lies immediately west of Vasco da Gama Seamount and dies out southward (Fig. **F3**). Several tens of pieces of hard low-grade metasediment were recovered from the lowermost 86 m. Micas in this sediment have been $^{40}Ar/^{39}Ar$ dated at 348 Ma (Manatschal et al., in press). At least three pieces appear to be rounded pebbles. Despite the very hard lithologies recovered, each core was drilled quickly. This suggests a very friable matrix, a conclusion supported by the clay mineral–rich nature of a few small samples that were retained in the cores. Above this equivocal sequence, a thin bed of reworked shallow-water limestone clasts is capped by 10 cm of dark clay with a thin band of latest Tithonian nannofossil ooze, analogous to that encountered at Sites 901 and 1065 (Concheryo and Wise, **Chap. 7,** this volume). The clay is overlain by lowermost Cretaceous (upper Berriasian–lower Valanginian) slumped nannofossil chalk of an outer shelf-slope, open-marine facies. The chalk is separated by a 50-m.y. hiatus from an overlying deep-water uppermost Cretaceous (uppermost Campanian) turbidite/hemipelagite sequence. Hence, here too, the evidence suggests the site originally lay in water depths of at most a few hundred meters, which again indicates the underlying crust is almost certainly continental, before it subsided during the Cretaceous.

The mafic basement cores from Sites 1067 and 900 are also considered to represent lower continental crust. The evidence for this is described in the next section.

CONTINENTAL BASEMENT CORES

Direct evidence of continental basement rocks comes from three sites (Sites 900, 1067, and 1068) drilled within 1400 m of each other along the east-west *Lusigal-12* seismic profile (Fig. **F4**) and from scattered clasts in the breccias and mass-flow deposit at Site 899. The first three sites lie on a north-south trending, elongate basement high (called Hobby High by Leg 173 scientists) now known to form part of a ridge that forms the western half of Vasco da Gama Seamount (Fig. **F3**). The two Leg 173 sites were drilled using an offset strategy designed to sample above and below a 15° east-dipping strong intrabasement reflector (M) that is offset downward by a steep east-dipping normal fault (Whitmarsh et al., 2000) to join a deeper reflector (H_L, H_H, and H in Fig. F5) identified as a major synrift detachment (Beslier et al., 1995; Krawczyk et al., 1996) or décollement (Brun and Beslier, 1996) at the base of tilted continental blocks. Reflectors M and H_L (immediately adjacent to Hobby High) probably represent a tectonic crust/mantle boundary (Whitmarsh, Beslier, Wallace, et al., 1998; Whitmarsh et al., 2000).

At Site 1067, amphibolite with minor tonalite gneiss and meta-anorthosite was cored. Relict textures indicate that the amphibolite protolith may have been either hornblende gabbro or retrometamorphosed pyroxene gabbro. A heterogeneous ductile shear deformation developed a clear locally folded foliation at the top and bottom of the cored section. The foliation is overprinted by mainly static retrometamorphism and heterogeneous fracturing, which locally grades into brecciation in the middle part of the cored section. R. Rubenach, N. Froitzheim, P. Wallace, M. Fanning, and R. Wyzsoczanski (unpubl. data) dated magmatic zircons, which were separated from a metagabbro, at 270 ± 3 Ma; this most likely represents the gabbro intrusion age and is coeval with many other late Hercynian rocks from Western Europe. Further support for this conclusion was obtained from hornblende geobarometry on igneous amphiboles included in plagioclase porphyroclasts in a metatonalite clast from Site 1068 and a tonalite vein from Site 1067; this technique yielded intrusion pressures of 0.73 and 0.60 GPa, respectively. Therefore, they concluded that the metagabbros and metatonalites encountered at Sites 1067 and 1068 intruded and were metamorphosed at lower to mid-crustal depths in the late Hercynian and do not represent igneous or metamorphic rocks contemporaneous with continental breakup. It is interesting to note that the Iberian Basin in Spain was undergoing extension at this time (Arche and Lopez, 1996).

Clasts of amphibolite, metagabbro, and meta-anorthosite were encountered at Site 1068 within a sequence of poorly sorted sedimentary and tectonic breccias. The lower breccias show evidence of cataclasis and hydrothermal metasomatism. The breccias are separated by a tectonized zone from an underlying commonly weakly foliated peridotite, which, although up to 99% serpentinized, contains relict primary textures suggesting the protolith was foliated spinel- and plagioclase-bearing peridotite. Clasts of basalt, microgabbro, diabase, and chlorite-bearing mylonite were also found in the breccias and mass-flow deposits of Site 899.

Metagabbros cored at Site 900 during Leg 149 were metamorphosed under amphibolite to granulite grade conditions (Cornen et al., 1996b) and have trace element and rare-earth element (REE) concentrations that are similar to transitional mid-ocean ridge basalt (MORB) (Seifert et al., 1996, 1997). Based on these geochemical characteristics and MORB-like ε_{Nd} values (+6 to +11), the metagabbros have been interpreted as cumulates that formed at a spreading center active during the opening of the Iberia Abyssal Plain OCT (Seifert et al., 1997). However, the late Hercynian ages of zircons from metagabbros at Site 1067, on the same basement high as Site 900, are not consistent with the spreading center interpretation. Alternatively, the metagabbros may be cumulates that were emplaced and sheared at the base of slightly thinned continental crust at pressures of <0.8 GPa (Cornen et al., 1999). $^{40}Ar/^{39}Ar$ dating of plagioclase from Site 900 metagabbros yielded a date of 136.4 ± 0.3 Ma (Féraud et al., 1996), but given that the closure temperature of plagioclase is 200°–250°C (McDougall and Harrison, 1988), this date may simply indicate the time when these rocks were tectonically uplifted and cooled through the 200°–250°C isotherm during the last phase of rifting.

Despite their proximity to Site 900, amphibolites and metagabbros from Sites 1067 and 1068 have higher trace element and REE abundances (Smith Nagihara and Casey, **Chap. 10,** this volume). The Site 1067 and 1068 rocks also differ from Site 900 metagabbros in lacking certain geochemical traits that are diagnostic of gabbroic cumulates, such as strongly positive Eu/Eu* and Sr/Sr* anomalies that result from plagioclase accumulation. On this basis, Smith Nagihara and Casey (**Chap. 10,** this volume) interpreted the protoliths for Site 1067 and 1068 amphibolites and metagabbros to have originally formed by direct crystallization of basaltic magmas without significant crystal accumulation. In support of this interpretation, these authors note that the Site 1067 and 1068 rocks have similar trace element compositions to metabasalt and diabase clasts, respectively, recovered at Site 899, located ~60 km to the west. The evidence from Site 1067 and 1068 rocks for the existence of incompatible trace element–enriched melts suggests a simple genetic relationship with the more incompatible element-depleted metagabbros at Site 900, because crystal accumulation generally results in cumulate gabbros that are more depleted than the melt from which the crystals precipitate. The large range in trace element and REE abundances in Site 1067 and 1068 amphibolites and metagabbros, as well as the variations in ε_{Nd} values of Site 900 cumulate gabbros, indicate that mantle source regions for the original melts were heterogeneous in both trace element and isotopic compositions.

In conclusion, therefore, current evidence points to the gabbros, amphibolites, and tonalite gneisses encountered at Hobby High (Sites 900 and 1067 and the equivalent clasts at Site 1068) having undergone a long history. A late Hercynian (270 Ma) extensional phase was accompanied by the generation of melts from heterogeneous mantle sources, emplacement and crystallization of the melts to form cumulate and noncumulate gabbros in the lower continental crust or at the base of slightly thinned continental crust, followed by ductile shearing at middle to lower continental crustal depths. There is no direct evidence at the Hobby High sites of magmatism that accompanied the last phase of rifting and eventual continental breakup (i.e., 130–140 Ma).

MANTLE PETROGENESIS AND MAGMATISM

Serpentinized peridotite cores were obtained from the acoustic basement at Sites 897, 899, 1068, and 1070. Comparable rocks have been dredged, sampled by submersible, and drilled both off Galicia Bank and from Gorringe Bank (e.g., Cornen et al., 1999; Girardeau et al., 1998). Sites 897 and 899 lie within the region of uplifted basement (Region B in Fig. **F3**) of the OCT, which has been suggested to consist of exhumed upper mantle (Brun and Beslier, 1996; Dean et al., 2000; Discovery 215 Working Group, 1998; Krawczyk et al., 1996; Pickup et al., 1996). Site 1068, on the west flank of Hobby High, lies between two continental basement ridges (Fig. **F3**) and adjacent to the deep part of the OCT (Region C in Fig. **F3**), of which it may be representative. Site 1070 lies in a very different geophysical situation within Region A (Fig. **F3**) of oceanic crust. Questions of the subcontinental or suboceanic origin of the mantle rocks, the degree of depletion (partial melting) that they have undergone, and the nature and origin of the 300-km-long, margin-parallel peridotite ridge are very relevant to models of the development of this nonvolcanic margin. The serpentinization history is treated later.

Serpentinized peridotites that were recovered at Sites 897 and 899 have been described by Cornen et al. (1996a), Sawyer, Whitmarsh, Klaus, et al. (1994), and Seifert and Brunotte (1996). The peridotites are spinel- and plagioclase-bearing harzburgite and lherzolite with minor pyroxenite and dunite. No in situ serpentinized peridotite was cored at Site 899, only a serpentinite breccia and serpentinized peridotite unit resulting from mass wasting that also includes clasts of high K_2O basalt (altered or non-MORB), diabase, and microgabbro. Cornen et al. (1996a) describe the cores as coarse-grained websterites (Site 897 only) and depleted peridotites with minor plagioclase-rich lherzolites. Variations in the modal abundance and composition of primary phases provide evidence of heterogeneous partial melting of the peridotites. However, the extent of partial melting was probably relatively low (<10%) based on the modal composition of the peridotites and the abundance of lherzolite (Site 899) and websterite (Site 897) relative to more depleted harzburgite and dunite (Cornen et al., 1996a).

Some of the peridotites contain locally pervasive patches or veinlets of plagioclase, suggesting that the rocks underwent impregnation by mafic melts at pressures below 1 GPa (i.e., in the plagioclase stability field). This impregnation probably occurred at the end of the high-temperature deformation stage, because, in many samples, the plagioclase framework parallels the main porphyroclastic foliation observed in adjacent rocks (Cornen et al., 1996a). These authors further suggest that impregnation was caused by percolation of undersaturated alkaline melts based on local enrichments of Fe, Ti, and Na in olivine and pyroxene and, in one peridotite, the presence of Na-Ti-rich phases such as kaersutite, phlogopite, rutile, and ilmenite. However, Seifert and Brunotte (1996) showed that some lherzolites from Site 897 have flat REE patterns with near chondritic abundances, whereas others have light REE–depleted patterns similar to normal mid-ocean ridge basalts (N-MORB). They interpreted the latter as evidence that melt impregnation of the lherzolites involved melts with N-MORB-like composition. Thus, there is no evidence from the REE data for pervasive infiltration of undersaturated alkaline melts, which would be much more highly enriched in incompatible trace elements and probably have light REE–enriched patterns.

As mentioned already, serpentinized peridotite was cored at Site 1068 beneath a seaward-dipping normal fault zone represented by breccias, flanking the west side of Hobby High. Site 1070 lay on the crest of a north-south basement high 20 km west of the peridotite ridge and 30 km east of the crest of magnetic anomaly J, which, together with magnetic anomaly modeling, a probably normal oceanic velocity structure, and the presence of elongate, isochron-parallel basement highs and lows, is a definitive indicator of oceanic crust. Basement cores from Site 1070 consist of matrix-supported serpentinized peridotite breccias separated by a tectonic contact from an underlying pegmatitic gabbro, which in turn has an intrusive contact with the underlying peridotite.

Hébert et al. (in press) studied the peridotites from Sites 1068 and 1070. The peridotites differ in that those of Site 1068 are fine grained with a well defined high-temperature foliation, whereas those of Site 1070 are coarse grained with little evidence of high-temperature foliation. From visual descriptions, the Site 1068 peridotites were originally mostly plagioclase bearing, whereas at Site 1070 plagioclase was absent. However, in terms of mineral chemistry, peridotites from both sites show many common features. In particular, the wide range in pyroxene composition at both sites suggests a range of primary peridotite compositions from aluminous lherzolite to more aluminum-poor harzburgite. Gabbroic intrusions within Site 1070 peridotites contain primary kaersutite and biotite, providing evidence for relatively K- and H_2O-rich magmas. Because the most Ti-rich spinels in peridotite at Site 1070 are near gabbroic veins, Hébert et al. (in press) suggest that much of the variation in spinel compositions at both Site 1070 and nearby Site 1068 may be due to intrusion and percolation of such incompatible element-enriched melts into mantle peridotite. The abundance of platinum group elements is very low in peridotites from both Sites 1068 and 1070, on the basis of which Hébert et al. (in press) suggest that the peridotites were derived from subcontinental mantle.

Abe (in press) presents major and trace element data for primary mantle minerals in the Site 1068 and Site 1070 peridotites. These data show that the trace element concentrations in clinopyroxene are intermediate between values typical of abyssal (oceanic) peridotites and peridotites from continental regions, and are most closely similar to mantle peridotite xenoliths from suprasubduction zone volcanic arcs. It should be noted, however, that there is significant overlap between the different fields on most trace element discrimination diagrams, especially between the arc and subcontinental mantle fields. Abe also found that the REE patterns for clinopyroxenes are light-REE depleted, similar to the pattern observed for whole-rock samples of some lherzolites from Site 897 mentioned above. Given the compositional similarities of pyroxenes to those in mantle xenoliths from arcs, it is possible that Site 1068 and Site 1070 sampled Proterozoic Ossa-Morena Zone mantle that experienced suprasubduction zone processes within the ancient Precambrian Ibero-Armorican Arc, which exists adjacent to the Iberia margin (Abalos and Cusi, 1995, fig. 12A; Silva et al., 2000).

It is too early to draw detailed petrogenetic comparisons between all the peridotites cored in the southern Iberia Abyssal Plain. However, Abe's results clearly indicate that Site 1068 and 1070 peridotites are not as depleted as typical abyssal peridotites and are more likely to be derived from suprasubduction zone or subcontinental mantle. Whitmarsh, Beslier, Wallace, et al. (1998) have noted that although the Site 1070 peridotites differ from those at Sites 897 and 1068 in the lower initial plagioclase mode, in the smaller proportion of coarser grained spinel, in the coarser grain size, and in the near lack of high-temperature foliation, preliminary shipboard geochemical analyses indicate that these peridotites are compositionally close to the less plagioclase-rich peridotites of Sites 897 and 1068. At present, it is thus not possible to find any petrological or geochemical difference between peridotites drawn from sites that it is suspected lie in at least two geophysically different domains.

TECTONO-METAMORPHIC PROCESSES

The tectono-metamorphic development of the southern Iberia Abyssal Plain segment of the west Iberia margin has been investigated at three distinct scales: in thin section, in hand specimen, and at the scale of individual seismic reflection profiles. Similar studies have been carried out off Galicia Bank (e.g., M. Beslier, unpubl. data; Boillot et al., 1995b; Brun and Beslier, 1996; Reston et al., 1996).

The development of the mantle section at the microscopic and hand-specimen scales is revealed mostly by the study of the peridotite cores from Sites 897, 1068, and 1070. The tectono-metamorphic evolution of the Site 897 peridotites was described by Beslier et al. (1996). Here, four stages were recognized, high-temperature (900°–1000°C) ductile shearing, limited partial melting, subsolidus reequilibration in the plagioclase field at <1 GPa, and mylonitic shearing at 700°C under high deviatoric stress and low pressure. The rocks appear to have undergone a continuum of deformation at decreasing temperature under coeval increasing deviatoric stress and decreasing pressure. Shear deformation was a major mechanism of stretching and thinning of the lithosphere. At the present time, only preliminary results from Sites 1068 and 1070 are available. At Site 1068, the Subunit 1B serpentinized peridotites are foliated but commonly only weakly so. The average dip of the foliation is 43° in a northwest to west-southwest direction. The foliation is suggested to have formed under high-temperature conditions (Shipboard Scientific Party, 1998c). At Site 1070, the serpentinized peridotites are locally weakly foliated with discrete layers of pyroxenite or unfoliated. Olivine relicts show dislocation lamellae and some kink bands, indicating a high-temperature upper mantle deformation. Pyroxenes are mostly undeformed. The serpentinization operated, at least in part, after intrusion of the igneous mafic phase. In thin section, high-temperature deformation features are rarely seen. The high-temperature foliation is moderately inclined in the peridotites. The gabbroic veins are moderately to weakly inclined. The apparent absence of high-temperature deformation suggests that these mantle rocks did not undergo intense deformation during their exhumation.

The absence of significant mylonitic deformation in the mantle rocks at Sites 1068 and 1070 and the presence of ultramylonitic shear bands only locally at Site 897 contrast with the intense ductile deformation observed in the Site 900 metagabbro and in the upper amphibolites of Site 1067. Nevertheless, the mafic cores from Hobby High exhibit a similar metamorphic history from granulite to amphibolite to greenschist facies. The Site 1067 and 1068 gabbros and tonalite veins were intruded and experienced granulite to amphibolite facies metamorphism at ~270 Ma (late Hercynian) (R. Rubenach, N. Froitzheim, P. Wallace, M. Fanning, and R. Wyzsoczanski, unpubl. data). This was followed by greenschist facies metamorphism and then very low-grade metamorphism (fig. 35 in Shipboard Scientific Party, 1998b). The Site 1067 metatonalite lenses or veins exhibit mylonitic microstructures indicative of deformation under greenschist facies conditions (Manatschal et al., in press). Consistent shear-sense indicators and crystallographic preferred orientation in dynamically recrystallized quartz layers provide evidence for strongly noncoaxial (simple shear) deformation. The Site 1067 amphibolites similarly experienced retrograde metamorphism under amphibolite to greenschist facies conditions dominated by hydration reactions (Gardien et al., in press). The Site 900 metagabbros were strongly sheared in granulite to high-amphibolite facies conditions that were followed by intense fluid-assisted extension under greenschist facies conditions (Cornen et al., 1996b).

All basement cores exhibit late stage low-temperature brittle deformation accompanied by veining, and in the case of the peridotite cores, intense serpentinization that, at least at Site 1070, appears to decrease with depth. Using stable isotope chronology of flow and deformation, two episodes of fluid infiltration through serpentinized peridotite have been distinguished (Skelton and Valley, 2000). The first episode, at temperatures above 175°C, was pervasive and coeval with the serpentinization; the second episode occurred at 50°–150°C, was "structurally focused," and accompanied mantle exhumation. These authors therefore conclude that upper mantle serpentinization occurred before exhumation. The serpentinized peridotite may have formed weaknesses exploited by faulting and because of its low permeability (and density?), may have inhibited melt migration to the top of basement.

The effects of low-temperature hydrothermal fluids, especially their association with the fault at Site 1068, have been extensively studied by Beard and Hopkinson (2000), Beard (**Chap. 2,** this volume), and Hopkinson and Dee (in press). Beard and Hopkinson (2000) showed that the Site 1068 fault was host to a hydrothermal system rooted in serpentinization reactions at depth. The serpentinites and breccias exhibit a zonation, which reflects the mixing of seawater with a fluid whose composition is controlled by serpentinization reactions. Hopkinson and Dee (in press) also studied the complex multistage hydrothermal mineralization associated with the fault and showed how very late stage aragonite clusters replace serpentinite (both fractally and nonfractally). The clusters are thought to result from incursions of reactive seawater in and around the fault in response to pressure gradients. The latter may have been short-lived high-flowrate events most likely generated by tectonism. It has even been suggested that the basal sediments and basement(?) at Sites 897 and 1070 remain overpressured today (Ask, **[N1];** Karig, 1996).

Studies of the low-temperature alteration of Leg 149 cores were carried out by Agrinier et al. (1996) and Gibson et al. (1996a).

A persistent feature of most of the cores that sampled the sediment/igneous-metamorphic basement interface was the presence of mass-flow deposits (olistostromes and breccias) at the base of the sedimentary section (Sites 897, 899, 1068, and 1070), slumped and fractured deposits (Site 1069), and tectonic breccias within the igneous-metamorphic basement, sometimes localized as narrow shear zones (Sites 897, 900, 1067, 1068, and 1070). These phenomena are a clear sign of brittle failure of the upper basement rocks at a late stage in the rifting process; the sediments involved are Late Jurassic(?) to Early Cretaceous in age. The mass flow deposits of Site 897 and Site 1068 have been studied in detail by Comas et al. (1996) and Gibson et al. (1996b) and by St. John (**Chap. 1,** this volume), respectively.

Many authors have made tectonic interpretations of seismic reflection profiles, aided by other geophysical and ODP results, to infer how rifting of the west Iberia margin developed and to propose more general models. This has been done either off Galicia Bank (e.g. Boillot et al., 1995b, 1989; Hoffmann and Reston, 1992; Krawczyk and Reston, 1995; Manatschal and Bernoulli, 1999a; Pickup, 1997; Reston et al., 1995, 1996; Sibuet, 1992b; Sibuet et al., 1995) or in the southern Iberia Abyssal Plain (e.g., Krawczyk et al., 1996; Manatschal et al., in press; Whitmarsh et al., 2000). Another model was developed from analogue modeling (Brun and Beslier, 1996). Wilson et al. (1996, in press a) studied the distribution of synrift sediments off Galicia Bank and in the southern Iberia Abyssal Plain. Wilson et al. (in press a) emphasize that published identifications of synrift intervals have not demonstrated thickening of sedimentary units or divergence of seismic reflections toward footwalls. They therefore conclude that rifting lasted <5 m.y. (probably from the late Berriasian to early Valanginian). Although this conclusion has important implications for, among others, models that attempt to estimate the amount of synrift melting, it is important to realize that it is not conclusive because it is based on negative evidence (i.e., the lack of seismic observations of synrift sediment packages). This lack could be explained, for example, by the inability of seismic profiles to resolve any thin synrift sediments that resulted from a relatively low rate of sedimentation or by the collapse and resedimentation of unstable synrift sediments and the resulting destruction of the original characteristic seismostratigraphic geometry (Wilson et al., in press a).

Here, we consider just the southern Iberia Abyssal Plain segment of the margin. Recently, new seismic refraction results have been published that indicate the thickness and extent of thinned continental crust there (Chian et al., 1999; Dean et al., 2000). This enabled Whitmarsh et al. (2000) to revisit the interpretation of the depth section of profile *Lusigal-12* by Krawczyk et al. (1996). Several important new conclusions were reached. First, the ODP cores indicate that all tilted fault blocks on reflection profiles consist of thinned continental (and not oceanic) crust. Second, it is now apparent that the thinned continental crust under Site 901 is only ~6 km thick and that this crust thins westward to ~3 km immediately east of Hobby High. Third, in detail, it appears that reflector H, just east of Hobby High, and the corresponding fault-offset reflector M on the crest of the High represent a tectonic crust/mantle boundary as argued by Brun and Beslier (1996). It is also apparent that several reflections interpreted as low-angle normal faults cut down into the uppermost mantle, thereby indicating that the mantle lay in the brittle regime toward the end of the rifting process. Direct evidence of the tilting of a continental fault block was obtained at Site 1065. Here, downhole Formation MicroScanner logs show that the site was tilted 15° to the southeast in the Middle to Late Jurassic and then 15° to the east in post–Late Jurassic (Early Cretaceous?) time (Basile, 2000).

Although the initial stages of rifting may well be considered to have been dominated by pure shear of the whole lithosphere, it is also clear that in the final stages of rifting leading to breakup, a series of low-angle normal or detachment faults dominated crustal deformation. The model of Brun and Beslier (1996) suggests that initially the ductile lower crust acts as a decoupling (décollement) zone between brittle upper crust and strong upper mantle. As extension proceeds, the original ductile lower crust is preferentially thinned (Brun and Beslier, 1996) and/or the brittle–ductile transition descends because the original upper crust has become thinner, causing the ductile zone between brittle crust and strong mantle to thin also (T.J. Reston, pers. comm., 2000). Eventually, however, the model of Whitmarsh et al. (2000) suggests that the thinned crust and uppermost mantle together lie within the brittle domain because low-angle, and even high-angle, faults are seen on seismic profiles to penetrate the uppermost mantle.

EARLY OCEANIC ACCRETION

Site 1070 lies on the crest of a north-south basement high 20 km west of the peridotite ridge and 30 km east of the crest of magnetic anomaly J, which is a definitive indicator of oceanic crust. The magnetic anomaly modeling near the site suggests that it is underlain by oceanic crust (Whitmarsh and Miles, 1995), as does recent seismic velocity modeling ~40 km further south (Dean et al., 2000), although a less well-resolved seismic velocity structure over the site, which was published earlier, is less convincingly oceanic (Whitmarsh et al., 1990);

the presence of elongate, isochron-parallel basement highs and lows is consistent with the presence of oceanic crust. The spreading rate used in the magnetic anomaly models also implies that the crust formed within ~2 m.y. of the onset of continuous seafloor spreading. Basement cores consist of matrix-supported serpentinized peridotite breccias separated by a tectonic contact from an underlying pegmatitic gabbro. The original igneous mineralogy suggests that the gabbro crystallized from a differentiated mafic magma. The pegmatite is intruded into weakly deformed serpentinized peridotite, as are gabbroic veinlets. The peridotite protolith, which was highly heterogeneous, included lherzolites, harzburgites, and dunites and graded locally into pyroxenite (Shipboard Scientific Party, 1998d).

Remarkably, no rocks from the upper oceanic crust (neither basalts nor sheeted dikes) were encountered at Site 1070. The oldest sediments are upper Lower Cretaceous (upper Aptian) claystones that were deposited near or below the calcium carbonate compensation depth and contain abyssal microfossils, traces of manganese and hematite, and grains of volcaniclastic sediment.

Thus, the cores suggest the site is underlain by serpentinized upper mantle with minor intrusive bodies of gabbro and lacks extrusive material. Such a structure, close to that described at some slow-spreading ridges (Cannat, 1993), implies a lack of melt generation in the upwelling asthenosphere, possibly because of vertical and lateral loss of heat (perhaps accentuated by hydrothermal circulation) at the onset of seafloor spreading. After its intrusion, the gabbro was tectonically exposed at the seafloor. Such tectonism might also explain the lack of lavas at Site 1070. Given the geophysical interpretation that this site lies over or very close to crust with oceanic affinities, we cannot be certain that cores from this single site are representative of the surrounding crust.

PRESSURE-TEMPERATURE HISTORY, ISOTOPE GEOCHRONOLOGY, AND SEAFLOOR SPREADING

Quantitative estimates of the pressure-temperature (PT) history of the cores have been made by several authors using geobarometric and geothermometric methods (Table T1) (Cornen et al., 1999; Gardien et al., in press; R. Rubenach, N. Froitzheim, P. Wallace, M. Fanning, and R. Wyzsoczanski, unpubl. data). When combined with the results of isotope geochronology (Table T2) (Féraud et al., 1996; Manatschal et al., in press; Rubenach and Wysoczanski, 1998), a relatively precise understanding begins to emerge of the evolution of the margin.

The in situ mafic rocks encountered at Sites 900, 1067, and 1068 were emplaced in late Hercynian time in a pressure range of 0.6–0.8 MPa and at temperatures between 600° and 740°C. Assuming that pressures were purely lithostatic, the pressure estimates imply depths of 21–29 km (given a continental crust density of 2.8 Mg/m^3) and (assuming continental crust thermal gradients of 25°–30°C/km) the temperature estimates imply depths of 20–30 km. Therefore, these rocks were emplaced either near the base of a slightly thinned crust (as suggested by their apparent association with the Moho) (Whitmarsh et al., 2000) or within the crust at lower/middle crustal levels.

T1. Pressure-temperature estimates for cores, Legs 149 and 173, p. 34.

T2. Isotopic ages of acoustic basement cores, p. 35.

The three-stage metamorphic history of the Site 1067 amphibole-plagioclase samples investigated by Gardien et al. (in press) (Table T1) reveals that they experienced a systematic elevation toward the surface, but the metamorphic stages have not been dated.

Dates are available for other hornblendes and plagioclases from Sites 900 and 1067 (Table T2), which indicate passage through the hornblende closure temperature (~500°C) around 161 Ma and through the plagioclase closure temperature (200°–250°C) around 137 Ma (Féraud et al., 1996; Manatschal et al., in press). The final date of exhumation at the seafloor is unknown. Apatite fission-track ages obtained by Gardien et al. (in press) are hard to interpret, but if exhumation continued at the same rate as between the hornblende and plagioclase closure temperatures, then exhumation would be expected around 117 Ma, which is some 7–17 m.y. earlier than predicted by Gardien et al. (in press). Active tectonic exhumation of Hobby High, tentatively during Valanginian–Barremian time (121–137 Ma), is probably indicated by the oldest fossiliferous mass-wasting deposits encountered on its west flank at Site 1068. It can be concluded, therefore, that exhumation of the Hobby High basement rocks continued over several tens of millions of years as they were brought to the surface from depths of at least 20 km.

Seafloor spreading in the southern Iberia Abyssal Plain is estimated to have been under way at a rate of ~10 mm/yr in the vicinity of the peridotite ridge by the time of anomaly M3, ~126.5 Ma (Whitmarsh and Miles, 1995; Whitmarsh et al., 1996). The hornblende gabbro pegmatite at Site 1070, situated 20 km west of the peridotite ridge, passed through the hornblende closure temperature at 119 ± 0.7 Ma and the plagioclase closure temperature at 110.3 ± 1.1 Ma (Table T2). Even allowing for ~2 m.y. (20 km) of seafloor spreading between the peridotite ridge and Site 1070, the pegmatite was clearly exhumed at least 14 m.y. after the magnetic isochron age of the subjacent oceanic crust. Active tectonic exhumation of Site 1070 is probably indicated by a late Aptian (112.2–119.0 Ma) (W. Wise, pers. comm., 2000) mass-wasting deposit that overlies the igneous basement. It is difficult at present to reconcile the >14-m.y. difference between the predicted ~124.5-Ma age of the oceanic crust and the later exhumation of basement rocks (<110.3 Ma) at Site 1070. It might appear that magmatism and tectonism, perhaps when associated with the onset of seafloor spreading, are distributed over a broad region many tens of kilometers wide.

It is also evident that, given a constant geotherm during exhumation, exhumation of the pegmatite at Site 1070 proceeded either almost three times faster than the exhumation of continental crustal rocks at Hobby High or that more likely the geotherm between 250° and 500°C was three times steeper under Site 1070 or that a combination of these factors was present. The second explanation is consistent with the ascent of an asthenospheric diapir, which lay close to the surface once seafloor spreading had begun.

THE ALPINE DIMENSION

An important part of Leg 173 was the participation of geologists familiar with the Tethyan margins exposed in the Alps. During the 1990s, important new insights and supporting evidence for marine-based hypotheses of margin development were obtained by fieldwork on Alpine nappes. The sedimentary contacts of synrift or earliest postrift sediments overlying both continental (granite and gneiss) and oceanic (serpentinized peridotite) basements were recognized on the southern Briançonnais continental margin of the Early Cretaceous Valais ocean (Tasna nappe) (Florineth and Froitzheim, 1994; Froitzheim and Rubatto, 1998). Similar contacts of deep-water marine sediments overlying peridotite were recognized on the eastern Apulian continental margin of the Jurassic Piemont-Liguria ocean (Err, Malenco, and Platta nappes) (Froitzheim and Manatschal, 1996; Manatschal and Nievergelt, 1997). This work established the important contribution of low-angle normal and detachment faults to the process of continental extension and mantle exhumation at nonvolcanic rifted margins and allowed palinspastic reconstructions to be attempted. In one location, it was even possible to recognize remnants of the lower continental crust and crust/mantle boundary (Hermann et al., 1997). Later studies included the effects of channelized fluid flow along rift-related detachment faults (Manatschal, 1999; Manatschal et al., 2000). Finally, comparisons have recently been made of geological observations in the Alpine ocean-continent transition zones with geological and geophysical observations of rifted margins at sea (Manatschal and Bernoulli, 1999a, 1999b; Manatschal et al., in press; Wilson et al., in press a). The observed similarity of the sedimentary and tectonic relationships in the two cases is providing a very fruitful means of furthering our understanding of continental rifting processes.

DISCUSSION

This paper has briefly reviewed the results of Leg 173 with allusions to results of Leg 149, where appropriate and for completeness, that also relate to the development of the west Iberia continental margin before the onset of seafloor spreading. Further details can be found in the references that accompany the text. Other references refer to geophysical observations off west Iberia and to comparable work done in the rifted margin and transition zone fragments now exposed in the Alps. In spite of the importance of considering both members of a conjugate pair of margins when discussing their development, this has not been done here because of the lack of comparable ODP or other borehole data from beyond the shelf edge off the Newfoundland margin. Aspects of the postrift history, which was not a specific objective of Leg 173 drilling, are also omitted and are discussed elsewhere (Kuhnt and Urquhart, 2001; Whitmarsh, Sawyer, Klaus, and Masson, 1996) and in this volume (Roessig and Wise, **Chap. 4;** Urquhart, **Chap. 9;** Wallrabe-Adams, **Chap. 6;** Zhao et al., **Chap. 8**).

One as-yet unresolved problem on the west Iberia margin is the apparently almost complete lack of synrift melt products in the ODP cores, although a synrift (122.1 ± 0.3 Ma) chlorite schist derived from a Fe-Ti-rich gabbro protolith has been sampled northwest of Galicia Bank (Schärer et al., 1995). It has also been suggested, from analysis of mostly deep-towed magnetometer profiles, that scattered gabbroic bodies may exist within the serpentinized peridotite basement of the OCT (Russell, 1999; Whitmarsh et al., in press). The lack of melt is a problem for melting models (Bown and White, 1995), given the relatively short minimum periods of continental lithosphere extension suggested by Wilson et al. (in press a) (5 m.y.) and Dean et al. (2000) (7 m.y.); for $\beta = 10$ stretching of a 125-km lithosphere overlying a 1300°–1350°C potential temperature asthenosphere, Bown and White's model predicts 3–6 km of melt. Harry and Bowling (1999) and Bowling and Harry (in press) presented a finite element model of nonvolcanic rifted margins that predicts that melting begins only after lithospheric necking has become focused and results in a short period of magmatism confined to the end of the rift episode just before continental breakup. Unfortunately, the problem off west Iberia is a lack of evidence for significant melt, not only in the thinned continental crust prior to breakup but also in the broad OCT, for some time immediately after breakup. Minshull et al. (in press) considered and rejected the effects of lateral heat conduction, anomalously low mantle potential temperature, and depth-dependent stretching to explain totally the lack of melt products at the time of continental breakup and subsequently in the OCT. Instead, they proposed qualitative arguments that, even for OCT extension lasting only 10 m.y., melting was inhibited while asthenospheric upwelling remained relatively unfocused as the thermal structure of the lithosphere evolved from that of a rifting margin to that of a steady-state spreading ridge. In this context, it is salutary to recognize that radiometric dates from Site 1067 suggest that exhumation, and therefore extension, at the seaward edge of thinned continental crust lasted at least 24 m.y. (Table T2), far longer than suggested by Wilson et al. (in press a).

It is clear that the combined efforts of scientific drilling and geophysical observations off west Iberia, and particularly in the southern Iberia Abyssal Plain, have provided a valuable set of data with which to investigate the development of this nonvolcanic rifted margin. Even so, several problems remain. The significance and continental or oceanic origin of the peridotite ridge remains obscure. The OCT is ≤15 km wide off Galicia Bank and is up to 170 km wide in the southern Iberia Abyssal Plain, but there is insufficient evidence at present to estimate its width in the Tagus Abyssal Plain with confidence. How and why does the width of the OCT vary along the margin? Does the so-far unsampled deep OCT (Region C in Fig. F3) really consist of serpentinized peridotite, as inferred from indirect evidence? A deep drill hole in this region would test this inference and also provide a very valuable and potentially complete postrift sedimentary record (and subsidence history), which is currently lacking. Lastly, scientific drilling on the deep conjugate Newfoundland margin has the potential to make a very significant contribution to our understanding of the development and eventual lithospheric reconstruction of the west Iberia-Newfoundland conjugate pair of margins.

CONCLUSIONS

The principal conclusions from the results of Leg 173, combined with independently acquired geophysical data, are as follows:

1. All fault blocks imaged on seismic reflection profiles are blocks of thinned continental (and not oceanic) crust. At least one block (Site 1065) was tilted during rifting.
2. The continental crust thins dramatically seaward (practically to zero) and is broken into blocks by low-angle detachment faults. These blocks are probably underlain by a tectonic crust/mantle boundary, which in the center of the transect on a basement ridge called Hobby High has been uplifted to within a few hundred meters of the top of acoustic basement.
3. All the mafic cores from Sites 900, 1067, and 1068 on Hobby High are of late Hercynian (270 Ma; early Permian) age and were

emplaced in the lower continental crust or at the base of thinned crust. These mafic magmas were derived from melting of heterogeneous mantle sources during a late Hercynian extensional phase. The mafic magmas crystallized to form both cumulate and noncumulate gabbros, followed by ductile shearing at middle to lower continental crustal depths.

4. At the Hobby High sites, exhumation of lower crustal rocks proceeded over tens of millions of years and preceded the onset of seafloor spreading.
5. The Site 1068 and 1070 peridotites are not as depleted as typical abyssal (oceanic) peridotites and are more likely to be derived from suprasubduction zone or subcontinental mantle. The mantle rocks show geochemical and mineralogical evidence of heterogeneous partial melting (probably <10% melting). They were also locally and intensely percolated by melts during the last stage of high-temperature deformation that generated a porphyroclastic foliation. Available data indicate a range of compositions for these percolating melts, from depleted MORB-like trace element values to more enriched compositions that crystallized kaersutite and phlogopite.
6. The basement cores at Site 1070 show gabbro pegmatite overlying serpentinized peridotite veined by gabbro. On the other hand, geophysical observations indicate the presence of oceanic crust at this site but, remarkably, no rocks from the upper oceanic crust (neither basalt nor sheeted dikes) were encountered. The cores may indicate oceanic crust formed at a time when tectonism was more important than magmatism, but we cannot be sure that Site 1070 is representative of the surrounding crust.
7. The basement rocks at Site 1070 were exhumed at the seafloor at least 14 m.y. after the crustal age computed from seafloor-spreading magnetic anomalies. Either this exhumation was more rapid than at Hobby High, or more likely, the 250°–500°C isotherms were much closer together at Site 1070.
8. The surprising lack of synrift melt products in the basement cores from sites over thinned continental crust or the OCT zone can be explained qualitatively by the gradual post-breakup evolution of the margin toward steady-state seafloor spreading. Some indirect evidence exists for intrusive bodies within the top 6 km of the acoustic basement of the OCT, but their age of intrusion is unknown.
9. Strong and informative parallels were noted between the character and history of the Leg 173 (and Leg 149) cores and the character and history of the rifted margins and transition zones exposed today in the Alps.

ACKNOWLEDGMENTS

We thank reviewers Gilbert Boillot and Niko Froitzheim for their comments and geological insight, which helped us to improve this review. This overview of the results from the Leg 149 and 173 transect of holes off west Iberia has drawn on the work of about 100 shipboard and shore-based scientists in many countries. The work could not have been done without the efforts of the other two Co-Chief Scientists, Dale Sawyer and Marie-Odile Beslier, ODP Staff Scientist Adam Klaus, and ODP Operations Superintendents Gene Pollard and Mike Storms. We thank them and all the other shipboard scientists and ODP and drilling staff for their assistance and support during the two legs drilled off west Iberia. We also thank several authors for preprints in advance of publication. Gilbert Boillot, Karl Hinz, and Dale Sawyer generously provided copies of *Lusigal* (*Suroît*), *Sonne,* and *Maurice Ewing* seismic reflection profiles, respectively, used in the construction of Figure **F3.**

REFERENCES

Abalos, B., and Cusi, J.D., 1995. Correlation between seismic anisotropy and major geological structures in SW Iberia: a case study on continental lithosphere deformation. *Tectonics,* 14:1021–1040.

Abe, N., in press. Petrochemistry of serpentinized peridotite from the Iberia Abyssal Plain (ODP Leg 173): its character intermediate between sub-oceanic to sub-continental upper mantle. *In* Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., and Froitzheim, N. (Eds.), *Non-volcanic Rifting of Continental Margins: Evidence From Land and Sea.* Geol. Soc. Spec. Publ. London.

Agrinier, P., Cornen, G., and Beslier, M.-O., 1996. Mineralogical and oxygen isotopic features of serpentinites recovered from the ocean/continent transition in the Iberia Abyssal Plain. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 541–552.

Arche, A., and Lopez, G.J., 1996. Origin of the Permian-Triassic Iberian Basin, central-eastern Spain in "Dynamics of extensional basins and inversion tectonics." *Tectonophysics,* 266:443–464.

Basile, C., 2000. Late Jurassic sedimentation and deformation in the west Iberia continental margin: insights from FMS data, ODP Leg 173. *Mar. Pet. Geol.,* 17:709–721.

Bassi, G., 1995. Relative importance of strain rate and rheology for the mode of continental extension. *Geophys. J. Int.,* 122:195–210.

Beard, J.S., and Hopkinson, L., 2000. A fossil serpentinization-related hydrothermal system, ODP Leg 173, Site 1068 (Iberia Abyssal Plain): some aspects of mineral and fluid chemistry. *J. Geophys. Res.,* 105:16527–16540.

Beslier, M.O., Ask, M., and Boillot, G., 1993. Ocean-continent boundary in the Iberia abyssal plain from multichannel seismic data. *Tectonophysics,* 218:383–393.

Beslier, M.O., Bitri, A., and Boillot, G., 1995. Structure de la transition continent-océan d'une marge passive: sismique réflexion multitrace dans la Plaine Abyssale Ibérique (Portugal). *C. R. Acad. Sci. Ser. 2,* 320:969–976.

Beslier, M.-O., Cornen, G., and Girardeau, J., 1996. Tectono-metamorphic evolution of peridotites from the ocean/continent transition of the Iberia Abyssal Plain margin. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 397–412.

Boillot, G., Agrinier, P., Beslier, M.-O., Cornen, G., Froitzheim, N., Gardien, V., Girardeau, J., Gil-Ibarguchi, J.-I., Kornprobst, J., Moullade, M., Schaerer, U., and Vanney, J.-R., 1995a. A lithospheric syn-rift shear zone at the ocean-continent transition: preliminary results of the GALINAUTE II cruise (Nautile dives on the Galicia Bank, Spain). *C. R. Acad. Sci. Ser 2a,* 321:1171–1178.

Boillot, G., Beslier, M.O., Krawczyk, C.M., Rappin, D., and Reston, T.J., 1995b. The formation of passive margins: constraints from the crustal structure and segmentation of the deep Galicia margin (Spain). *In* Scrutton, R.A., Stocker, M.S., Shimmield, G.B., and Tudhope, A.W. (Eds.), *The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region.* Geol. Soc. Spec. Publ. London, 90:71–91.

Boillot, G., Féraud, G., Recq, M., and Girardeau, J., 1989. "Undercrusting" by serpentinite beneath rifted margins: the example of the west Galicia margin (Spain). *Nature,* 341:523–525.

Boillot, G., Grimaud, S., Mauffret, A., Mougenot, D., Kornprobst, J., Mergoil-Daniel, J., and Torrent, G., 1980. Ocean-continent boundary off the Iberian margin: a serpentinite diapir west of the Galicia Bank. *Earth Planet. Sci. Lett.,* 48:23–34.

Boillot, G., Winterer, E.L., et al., 1988. *Proc. ODP, Sci. Results,* 103: College Station, TX (Ocean Drilling Program).

Boillot, G., Winterer, E.L., Meyer, A.W., et al., 1987. *Proc. ODP, Init. Repts.,* 103: College Station, TX (Ocean Drilling Program).

Bowling, J.C., and Harry, D.L., in press. Geodynamic models of continental extension and the formation of non-volcanic rifted continental margins. *In* Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., and Froitzheim, N. (Eds.), *Non-volcanic Rifting of Continental Margins: Evidence From Land and Sea.* Geol. Soc. Spec. Publ. London.

Bown, J.W., and White, R.S., 1994. Variation with spreading rate of oceanic crustal thickness and geochemistry. *Earth Planet. Sci. Lett.,* 121:435–449.

————, 1995. The effect of finite extension rate on melt generation at continental rifts. *J. Geophys. Res.,* 100:18011–18030.

Brun, J.P., and Beslier, M.-O., 1996. Mantle exhumation at passive margins. *Earth Planet. Sci. Lett.,* 142:161–173.

Cannat, M., 1993. Emplacement of mantle rocks in the seafloor at mid-ocean ridges. *J. Geophys. Res.,* 98:4163–4172.

Capdevila, R., and Mougenot, D., 1988. Pre-Mesozoic basement of the western Iberian continental margin and its place in the Variscan Belt. *In* Boillot, G., Winterer, E.L., et al., *Proc. ODP, Sci. Results,* 103: College Station, TX (Ocean Drilling Program), 3–12.

Chian, D., Louden, K.E., Minshull, T.A., and Whitmarsh, R.B., 1999. Deep structure of the ocean-continent transition in the southern Iberia Abyssal Plain from seismic refraction profiles: Ocean Drilling Program (Legs 149 and 173) transect. *J. Geophys. Res.,* 104:7443–7462.

Collins, E.S., Kuhnt, W., and Scott, D.B., 1996. Tithonian benthic foraminifers from Hole 901A. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 193–201.

Comas, M.C., Sánchez-Gómez, M., Cornen, G., and de Kaenel, E., 1996. Serpentinized peridotite breccia and olistostrome on basement highs of the Iberia Abyssal Plain: implications for tectonic margin evolution. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 577–591.

Cornen, G., Beslier M.-O., and Girardeau, J., 1996a. Petrologic characteristics of the ultramafic rocks from the ocean/continent transition in the Iberia Abyssal Plain. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 377–395.

————, 1996b. Petrology of the mafic rocks cored in the Iberia Abyssal Plain. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 449–469.

Cornen, G., Girardeau, J., and Monnier, C., 1999. Basalts, underplated gabbros and pyroxenites record the rifting process of the West Iberian margin. *Mineral. Pet.,* 67:111–142.

Dean, S.M., Minshull, T.A., Whitmarsh, R.B., and Louden, K.E., 2000. Deep structure of the ocean-continent transition in the southern Iberia abyssal plain from seismic refraction profiles: the IAM-9 transect at 40 degrees 20′N. *J. Geophys. Res.,* 105:5859–5886.

Discovery 215 Working Group, 1998. Deep structure in the vicinity of the ocean-continent transition zone under the southern Iberia Abyssal Plain. *Geology,* 8:743–746.

England, P., 1983. Constraints on extension of continental lithosphere. *J. Geophys. Res.,* 88:1145–1152.

Féraud, G., Beslier, M.-O., and Cornen, G., 1996. $^{40}Ar/^{39}Ar$ dating of gabbros from the ocean/continent transition of the western Iberia Margin: preliminary results. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 489–495.

Féraud, G., Girardeau, J., Beslier, M.O., and Boillot, G., 1988. Datation $^{39}Ar/^{40}Ar$ de la mise en place des péridotites bordant la marge de la Galice (Espagne). *C. R. Acad. Sci. Ser. 2,* 307:49–55.

Féraud, G., York, D., Mével, C., Cornen, G., Hall, C.M., and Auzende, J.M., 1986. Additional ^{40}Ar-^{39}Ar dating of the basement and the alkaline volcanism of the Gorringe Bank (Atlantic Ocean). *Earth Planet. Sci. Lett.,* 79:255–269.

Florineth, D., and Froitzheim, N., 1994. Transition from continental to oceanic basement in the Tasna nappe (Engadine window, Graubunden, Switzerland): evidence for Early Cretaceous opening of the Valais ocean. *Schweiz. Mineral. Petrogr. Mitt.,* 74:437–448.

Froitzheim, N., and Eberli, G.P., 1990. Extensional detachment faulting in the evolution of a Tethys passive continental margin, Eastern Alps, Switzerland. *Geol. Soc. Am. Bull.,* 102:1297–1308.

Froitzheim, N., and Manatschal, G., 1996. Kinematics of Jurassic rifting, mantle exhumation, and passive margin formation in the Austroalpine and Penninic nappes (eastern Switzerland). *Geol. Soc. Am. Bull.,* 108:1120–1133.

Froitzheim, N., and Rubatto, D., 1998. Continental breakup by detachment faulting: field evidence and geochronological constraints (Tasna nappe, Switzerland). *Terra Nova,* 10:171–176.

Gardien, V., Poupeau, G., Hebert, R., Muceku, B., Beslier, M.-O., and Labrin, E., in press. P-T-t evolution of the drilling site 1067 amphibolites, ODP Leg 173 (Iberia Abyssal Plain). *In* Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., and Froitzheim, N. (Eds.), *Non-volcanic Rifting of Continental Margins: Evidence From Land and Sea.* Geol. Soc. Spec. Publ. London.

Gibson, I.L., Beslier, M.-O., Cornen, G., Milliken, K.L., and Seifert, K.E., 1996a. Major- and trace-element seawater alteration profiles in serpentinite formed during the development of the Iberia Margin, Site 897. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 519–527.

Gibson, I.L., Milliken, K.L., and Morgan, J.K., 1996b. Serpentinite-breccia landslide deposits generated during crustal extension at the Iberia Margin. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 571–575.

Girardeau, J., Cornen, G., Beslier, M.O., Le Gall, B., Monnier, C., Agrinier, P., Dubuisson, G., Pinheiro, L., Ribeiro, A., and Whitechurch, H., 1998. Extensional tectonics in the Gorringe Bank rocks, eastern Atlantic ocean: evidence of an oceanic ultra-slow mantellic accreting centre. *Terra Nova,* 10:330–336.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., van Veen, P., Thierry, J., and Huang, Z., 1994. A Mesozoic time scale. *J. Geophys. Res.,* 99:24051–24074.

Groupe Galice, 1979. The continental margin off Galicia and Portugal: acoustical stratigraphy, dredge stratigraphy, and structural evolution. *In* Sibuet, J.-C., Ryan, W.B.F., et al., *Init. Repts. DSDP,* 47 (Pt. 2): Washington (U.S. Govt. Printing Office), 633–662.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., and Smith, D.G., 1990. *A Geologic Time Scale 1989:* Cambridge (Cambridge Univ. Press).

Harry, D.L., and Bowling, J.C., 1999. Inhibiting magmatism on nonvolcanic rifted margins. *Geology,* 27:895–898.

Hébert, R., Gueddari, K., Lafleche, M.R., Beslier, M.-O., and Gardien, V., in press. Petrology and geochemistry of exhumed peridotites and gabbros at non-volcanic margins: ODP Leg 173 West Iberia ocean-continent transition zone. *In* Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., and Froitzheim, N. (Eds.), *Non-volcanic Rifting of Continental Margins: Evidence From Land and Sea.* Geol. Soc. Spec. Publ. London.

Hermann, J., Muentener, O., Trommsdorff, V., Hansmann, W., and Piccardo, G.B., 1997. Fossil crust-to-mantle transition, Val Malenco (Italian Alps). *J. Geophys. Res.,* 102:20123–20132.

Hoffmann, H.J., and Reston, T.J., 1992. The nature of the S reflector beneath the Galicia Bank rifted margin: preliminary results from pre-stack depth migration. *Geology,* 20:1091–1094.

Hopkinson, L., and Dee, S., in press. Moving reactive interfaces and fractal carbonate replacement patterns in serpentinites: evidence from the southern Iberia Abyssal Plain. *Mineral. Mag.*

Karig, D.E., 1996. Uniaxial reconsolidation tests on porous sediments: mudstones from Site 897. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 363–373.

Krawczyk, C.M., and Reston, T.J., 1995. Detachment faulting and continental break-up: the S reflector offshore Galicia. *In* Banda, E., Torne, M., and Talwani, M. (Eds.), *Rifted Ocean-Continent Boundaries:* Dordrecht (Kluwer), 231–246.

Krawczyk, C.M., Reston, T.J., Beslier, M.-O., and Boillot, G., 1996. Evidence for detachment tectonics on the Iberia Abyssal Plain rifted margin. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 603–615.

Kuhnt, W., and Urquhart, E., in press. Tethyan flysch-type benthic foraminiferal assemblage in the North Atlantic: Cretaceous to Paleogene deep-water agglutinated foraminifers from the Iberia Abyssal Plain (ODP Leg 173). *Rev. Micropaleontol.*

Lister, G.S., Etheridge, M.A., and Symonds, P.A., 1991. Detachment models for the formation of passive continental margins. *Tectonics,* 10:1038–1064.

Manatschal, G., 1999. Fluid- and reaction-assisted low-angle normal faulting: evidence from rift-related brittle fault rocks in the Alps (Err Nappe, eastern Switzerland). *J. Struct. Geol.,* 21:777–793.

Manatschal, G., and Bernoulli, D., 1999a. Architecture and tectonic evolution of non-volcanic margins: present-day Galicia and ancient Adria. *Tectonics,* 18:1099–1199.

————, 1999b. Rifting and early evolution of ancient ocean basins: the record of the Mesozoic Tethys and of the Galicia-Newfoundland margins. *Mar. Geophys. Res.,* 20:371–381.

Manatschal, G., Froitzheim, N., Rubenach, M.J., and Turrin, B., in press. The role of detachment faulting in the formation of an ocean-continent transition: insights from the Iberia Abyssal Plain. *In* Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., and Froitzheim, N. (Eds.), *Non-volcanic Rifting of Continental Margins: Evidence From Land and Sea.* Geol. Soc. Spec. Publ. London.

Manatschal, G., Marquer, D., and Fruh-Green, G.L., 2000. Channelised fluid flow and mass transfer along a rift-related detachment fault (Eastern Alps, southeast Switzerland). *Geol. Soc. Am. Bull.,* 112:21–33.

Manatschal, G., and Nievergelt, P., 1997. A continent-ocean transition recorded in the Err and Platta nappes (Eastern Switzerland). *Eclogae Geol. Helv.,* 90:3–27.

Matthews, D.H., 1961. Lavas from an abyssal hill on the floor of the North Atlantic Ocean. *Nature,* 190:158–159.

————, 1962. Altered lavas from the floor of the eastern North Atlantic. *Nature,* 194:368–369.

McDougall, I., and Harrison, T.M., 1988. *Geochronology and Thermochronology by the ^{40}Ar/^{39}Ar Method:* New York (Oxford Univ. Press).

McKenzie, D., 1978. Some remarks on the development of sedimentary basins. *Earth Planet. Sci. Lett.,* 40:25–32.

McKenzie, D., and Bickle, M.J., 1988. The volume and composition of melt generated by extension of the lithosphere. *J. Petrol.,* 29:625–679.

Miles, P.R., Verhoef, J., and Macnab, R., 1996. Compilation of magnetic anomaly chart west of Iberia. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 659–663.

Minshull, T.A., Dean, S.M., White, R.S., and Whitmarsh, R.B., in press. Anomalous melt production after continental break-up in the southern Iberia Abyssal Plain. *In* Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., and Froitzheim, N. (Eds.), *Non-volcanic Rifting of Continental Margins: Evidence From Land and Sea.* Geol. Soc. Spec. Publ. London.

Mougenot, D., Vanney, J.R., Mauffret, A., and Kidd, R.B., 1986. Les montagnes sous-marines de la marge continentale nord-portugaise: morphologie et evolution structurale. *Bull. Soc. Geol. Fr.,* 3:401–412.

ODP Leg 173 Shipboard Scientific Party, 1998. Drilling reveals transition from continental breakup to early magmatic crust. *Eos,* 79:173.

Pedersen, T., and Ro, H.E., 1992. Finite duration extension and decompression melting. *Earth Planet. Sci. Lett.,* 113:15–22.

Pickup, S.L.B., Whitmarsh, R.B., Fowler, C.M.R., and Reston, T.J., 1996. Insight into the nature of the ocean-continent transition off West Iberia from a deep multichannel seismic reflection profile. *Geology,* 24:1079–1082.

Pickup, S.M.R., 1997. Rifted margin development off West Iberia from deep seismic reflection profiles [Ph.D. thesis]. Univ. of London.

Pinheiro, L.M., Whitmarsh, R.B., and Miles, P.R., 1992. The ocean-continent boundary off the western continental margin of Iberia, II. Crustal structure in the Tagus Abyssal Plain. *Geophys. J.,* 109:106–124.

Pinheiro, L.M., Wilson, R.C.L., Pena dos Reis, R., Whitmarsh, R.B., and Ribeiro, A., 1996. The western Iberia Margin: a geophysical and geological overview. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 3–23.

Reston, T.J., Krawczyk, C.M., and Hoffmann, H.J., 1995. Detachment tectonics during Atlantic rifting: analysis and interpretation of the S reflection, the west Galicia margin. *In* Scrutton, R.A., Stoker, M.S., Shimmield, G.B., Tudhope, A.W. (Eds.), *Tectonics of the North Atlantic Region.* Geol. Soc. Spec. Publ. London.

Reston, T.J., Krawczyk, C.M., and Klaeschen, D., 1996. The S reflector west of Galicia (Spain): evidence for detachment faulting during continental breakup from prestack depth migration. *J. Geophys. Res.,* 101:8075–8091.

Rubenach, M.J., and Wysoczanski, R., 1998. Metagabbros and metatonalites from the ocean-continent transition, Iberia Abyssal Plain: syn-rift or Hercynian basement? *14th Aust. Geol. Conv., Geol. Soc. Aust., Abstr.,* 49:386.

Russell, S.M., 1999. A magnetic study of the West Iberia and conjugate rifted continental margins: constraints on rift-to-drift processes [Ph.D. thesis]. Univ. of Durham.

Sawyer, D.S., Whitmarsh, R.B., Klaus, A., et al., 1994. *Proc. ODP, Init. Repts.,* 149: College Station, TX (Ocean Drilling Program).

Schärer, U., Girardeau, J., Cornen, G., and Boillot, G., 2000. 138–121 Ma asthenospheric magmatism prior to continental break-up in the North Atlantic and geodynamic implications. *Earth Planet. Sci. Lett.,* 181:555–572.

Schärer, U., Kornprobst, J., Beslier, M.O., Boillot, G., and Girardeau, J., 1995. Gabbro and related rock emplacement beneath rifting continental crust: U-Pb geochronological and geochemical constraints for the Galicia passive margin (Spain). *Earth Planet. Sci. Lett.,* 130:187–200.

Seifert, K., and Brunotte, D., 1996. Geochemistry of serpentinized mantle peridotite from Site 897 in the Iberia Abyssal Plain. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 413–424.

Seifert, K., Gibson, I., Weis, D., and Brunotte, D., 1996. Geochemistry of metamorphosed cumulate gabbros from Hole 900A, Iberia Abyssal Plain. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 471–488.

Seifert, K.E., Cheng-Wen, C., and Brunotte, D.A., 1997. Evidence from ODP Leg 149 mafic igneous rocks for oceanic crust in the Iberia Abyssal Plain ocean-continent transition zone. *J. Geophys. Res.,* 102:7915–7928.

Shipboard Scientific Party, 1998a. Leg 173 introduction. *In* Whitmarsh, R.B., Beslier, M.-O., Wallace, P.J., et al., *Proc. ODP, Init. Repts.,* 173: College Station, TX (Ocean Drilling Program), 7–23.

————, 1998b. Site 1067. *In* Whitmarsh, R.B., Beslier, M.-O., Wallace, P.J., et al., Proc. ODP, Init. Repts., 173: College Station, TX (Ocean Drilling Program), 107–161.

———, 1998c. Site 1068. *In* Whitmarsh, R.B., Beslier, M.-O., Wallace, P.J., et al., *Proc. ODP, Init. Repts.,* 173: College Station, TX (Ocean Drilling Program), 163–218.

———, 1998d. Site 1070. *In* Whitmarsh, R.B., Beslier, M.-O., Wallace, P.J., et al., *Proc. ODP, Init. Repts.,* 173: College Station, TX (Ocean Drilling Program), 265–294.

Sibuet, J.-C., 1992a. Formation of non-volcanic passive margins: a composite model applies to the conjugate Galicia and southeastern Flemish Cap margins. *Geophys. Res. Lett.,* 19:769–772.

———, 1992b. New constraints on the formation of the non-volcanic continental Galicia-Flemish Cap conjugate margins. *J. Geol. Soc. London,* 149:829–840.

Sibuet, J.-C., Louvel, V., Whitmarsh, R.B., White, R.S., Horsefield, S.J., Sichler, B., Leon, P., and Recq, M., 1995. Constraints on rifting processes from refraction and deep-tow magnetic data: the example of the Galicia continental margin (West Iberia). *In* Banda, E., Torné, M., and Talwani, M. (Eds.), *Rifted Ocean-Continent Boundaries:* Amsterdam (Kluwer), 197–218.

Silva, E.A., Miranda, J.M., Luis, J.F., and Galdeano, A., 2000. Correlation between the Palaeozoic structures from West Iberian and Grand Banks margins using inversion of magnetic anomalies. *Tectonophysics,* 321:57–71.

Skelton, A.D.L., and Valley, J.W., 2000. The relative timing of serpentinization and mantle exhumation at the ocean-continent transition, Iberia: constraints from oxygen isotopes. *Earth Planet. Sci. Lett.,* 178:327–338.

Stapel, G., Cloetingh, S., and Pronk, B., 1996. Quantitative subsidence analysis of the Mesozoic evolution of the Lusitanian Basin (western Iberian margin). *In* Cloetingh, S., Ben-Avraham, Z., Sassi, W., and Horvath, F. (Eds.), *Dynamics of Extensional Basins and Inversion Tectonics. Tectonophysics,* 266:493–507.

Wernicke, B., 1985. Uniform sense normal simple shear of the continental crust. *Can. J. Earth Sci.,* 22:108–125.

Wernicke, B., and Burchfiel, B.C., 1982. Modes of extensional tectonics. *J. Struct. Geol.,* 4:105–115.

White, R.S., and McKenzie, D., 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *J. Geophys. Res.,* 94:7685–7729.

Whitmarsh, R.B., Beslier, M.-O., Wallace, P.J., et al., 1998. *Proc. ODP, Init. Repts.,* 173: College Station, TX (Ocean Drilling Program).

Whitmarsh, R.B., Dean, S.M., Minshull, T.A., and Tompkins, M., 2000. Tectonic implications of exposure of lower continental crust beneath the Iberia Abyssal Plain, northeast Atlantic Ocean: geophysical evidence. *Tectonics,* 19:919–942.

Whitmarsh, R.B., and Miles, P.R., 1994. Propagating rift model for the West Iberia rifted margin based on magnetic anomalies and ODP drilling. *Eos,* 75:616.

———, 1995. Models of the development of the West Iberia rifted continental margin at 40°30′N deduced from surface and deep-tow magnetic anomalies. *J. Geophys. Res.,* 100:3789–3806.

Whitmarsh, R.B., Miles, P.R., and Mauffret, A., 1990. The ocean-continent boundary off the western continental margin of Iberia, I. Crustal structure at 40°30′N. *Geophys. J. Int.,* 103:509–531.

Whitmarsh, R.B., Miles, P.R., Sibuet, J.-C., and Louvel, V., 1996. Geological and geophysical implications of deep-tow magnetometer observations near Sites 897, 898, 899, 900, and 901 on the west Iberia continental margin. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 665–674.

Whitmarsh, R.B., Minshull, T.A., Louden, K.E., Russell, S.M., Dean, S.M., and Chian, D., in press. The role of syn-rift magmatism in the rift-to-drift evolution of the West Iberia continental margin: geophysical observations. *In* Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., and Froitzheim, N. (Eds.), *Non-volcanic Rifting of Continental Margins: a Comparison of Evidence From Land and Sea.* Spec. Publ. Geol. Soc. London.

Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), 1996. *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program).

Wilson, R.C.L., Manatschal, G., and Wise, S., in press a. Rifting along non-volcanic passive margins: stratigraphic and seismic evidence from the Mesozoic of the Alps and Western Iberia. *In* Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., and Froitzheim, N. (Eds.), *Non–volcanic Rifting of Continental Margins: a Comparison of Evidence From Land and Sea*. Geol. Soc. Spec. Publ. London.

Wilson, R.C.L., Sawyer, D.S., Whitmarsh, R.B., Zerong, J., and Carbonell, J., 1996. Seismic stratigraphy and tectonic history of the Iberia Abyssal Plain. *In* Whitmarsh, R.B., Sawyer, D.S., Klaus, A., and Masson, D.G. (Eds.), *Proc. ODP, Sci. Results,* 149: College Station, TX (Ocean Drilling Program), 617–633.

Wilson, R.C.L., Whitmarsh, R.B., Taylor, B., and Froitzheim, N., in press b. *Non-volcanic Rifting of Continental Margins: a Comparison of Evidence From Land and Sea*. Geol. Soc. Spec. Publ. London.

Figure F1. Magnetic anomaly chart of the west Iberia continental margin from Miles et al. (1996) overlain by 1000-m bathymetric contours. Triangles = peridotite ridge, solid circles = ODP/DSDP drill sites on the margin. Seafloor-spreading magnetic anomalies J (approximately M0) and 34 are shown. Box denotes area of Figure F2, p. 30. Inset relates Iberia to the rest of the North Atlantic Ocean. CF = Finisterre, CSV = Cape St. Vincent, GB = Galicia Bank, TS = Tore Seamount, ES = Estremadura Spur, TAP = Tagus Abyssal Plain, GRB = Gorringe Bank.

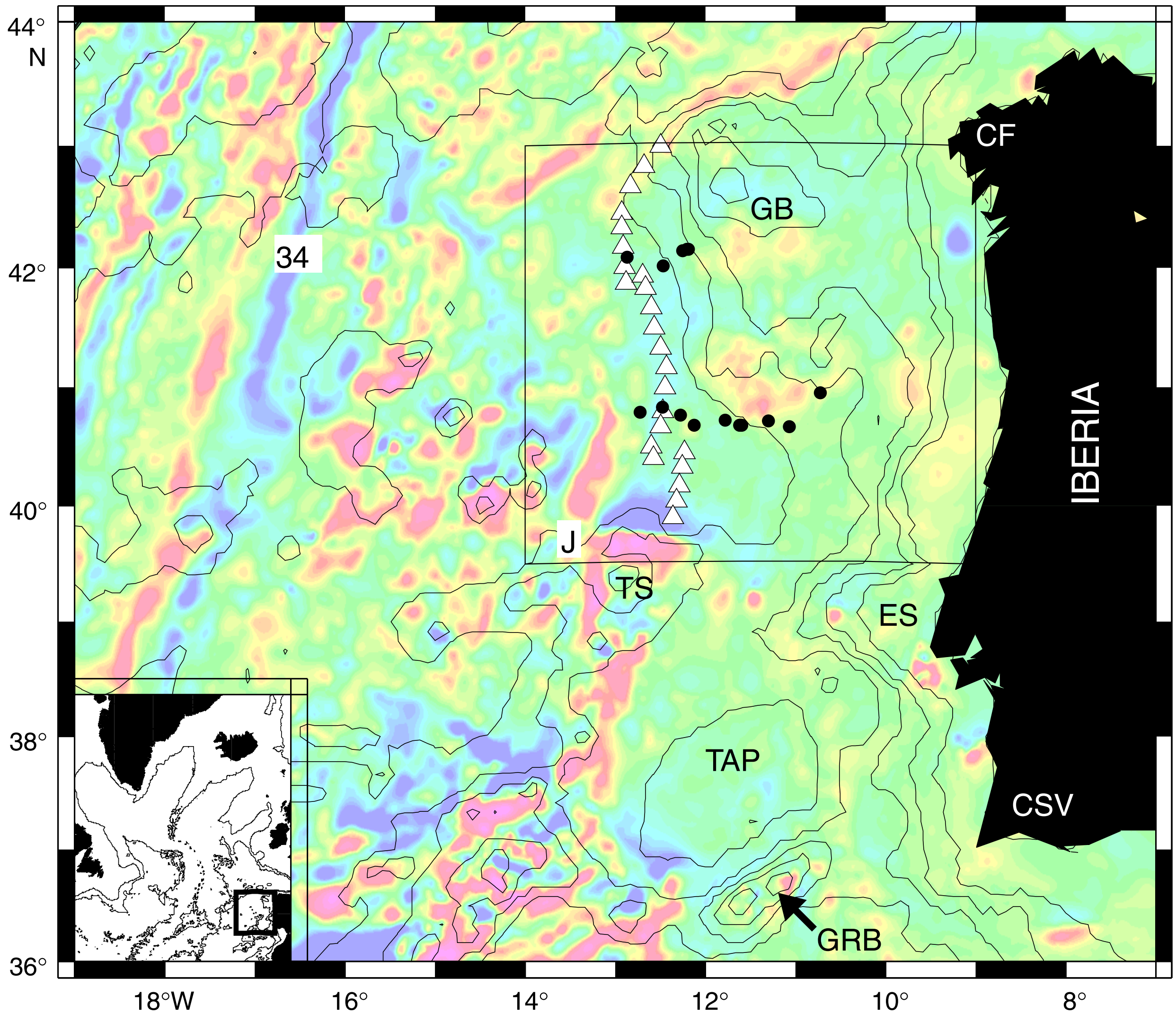


Figure F2. Bathymetry of the Galicia Bank and southern Iberia Abyssal Plain margins of west Iberia (contours in meters). DSDP and ODP sites appear as numbered circles and squares. The dotted line indicates the approximate and smoothed oceanward edge of thinned continental crust. The thick solid line denotes the trend of magnetic anomaly J. Triangles denote the peridotite ridge; segments R3 and R4 are indicated. Box denotes area of Figure F3, p. 31.

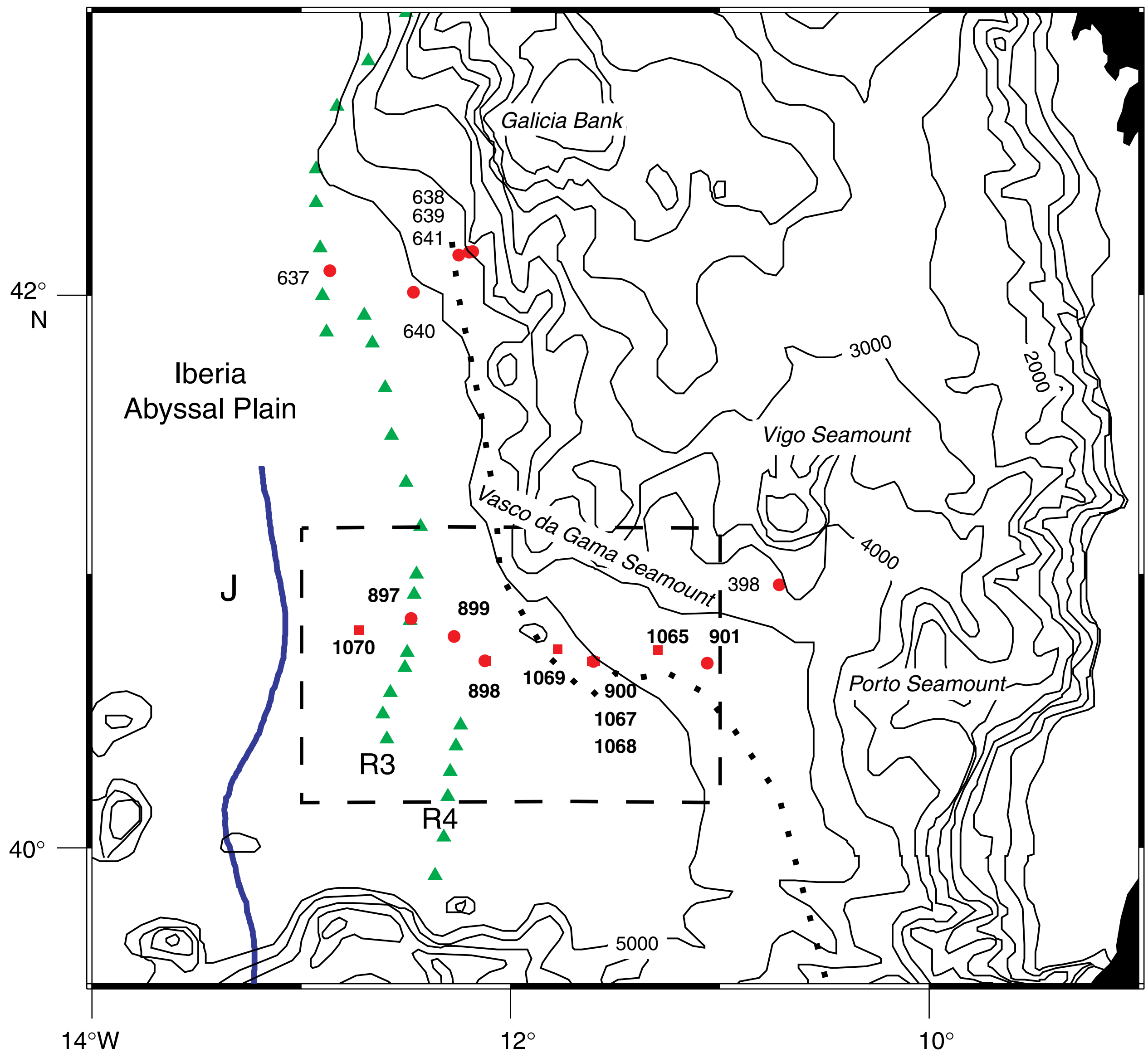


Figure F3. A contoured basement chart (0.25-s two-way traveltime contour interval) based on reflection profiles acquired up to 1997, from Whitmarsh et al. (in press) after Russell (1999). Tracks of multichannel seismic reflection profiles (thin lines) used to construct the chart and locations of ODP drill sites are also shown. Seafloor bathymetry (contoured in meters) is shown north of the edge (fine dotted line) of the Iberia Abyssal Plain. The thick line is the part of profile *Lusigal-12* shown in Figure F5, p. 33. Regions A, B, C, and D are discussed in the text.

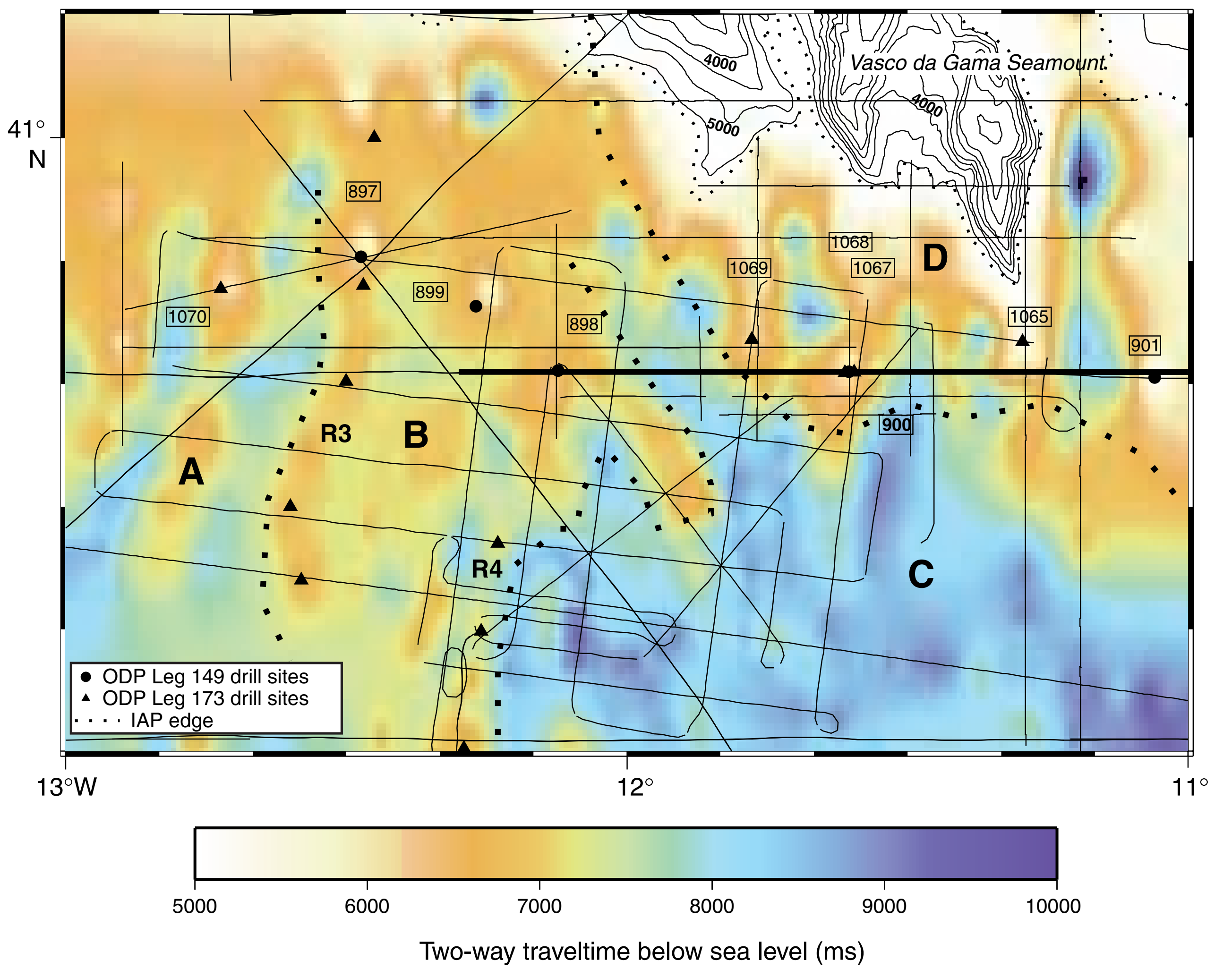


Figure F4. Part of the prestack depth-migrated multichannel seismic reflection profile *Lusigal-12* of Krawczyk et al. (1996) across Hobby High showing the detachment fault (H reflector) proposed by them and Sites 900, 1067, and 1068 (from fig. 10, Shipboard Scientific Party, 1998a). Site IBERIA09B was not drilled.

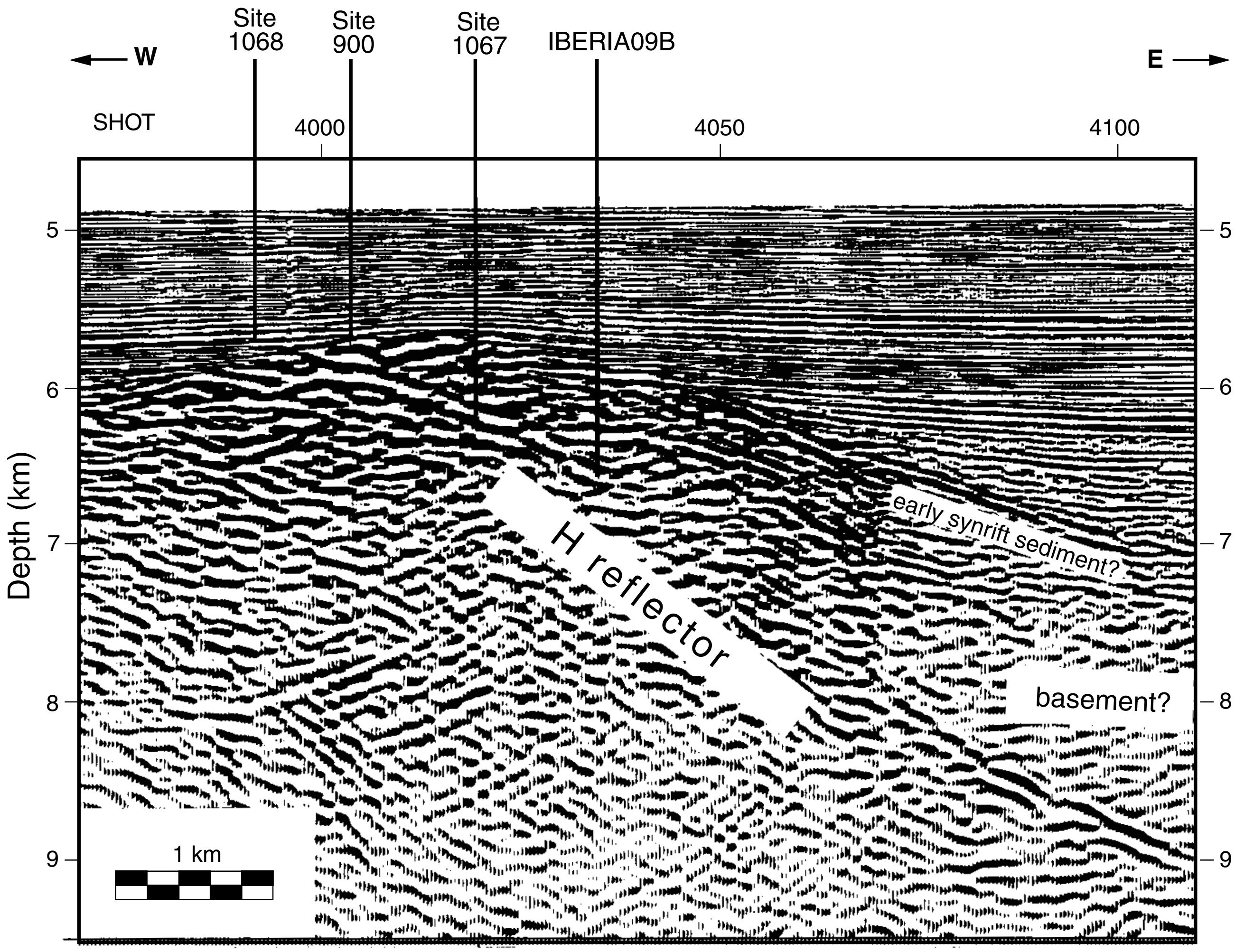


Figure F5. A new tectonic interpretation of profile *Lusigal-12* from Whitmarsh et al. (2000); the profile was originally published by Krawczyk et al. (1996). See Figure **F3,** p. 31, for location. L, M, F, H_L, H_H, and H are reflectors referred to in the text; reflector FB is interpreted as a low-angle normal fault. Dotted lines = top of acoustic basement, dashed lines = crust/mantle boundary, solid lines = major detachment faults, dashed line = normal fault. Sites refer to ODP drill sites coincident with (arrows), or close to (in parentheses), the profile.

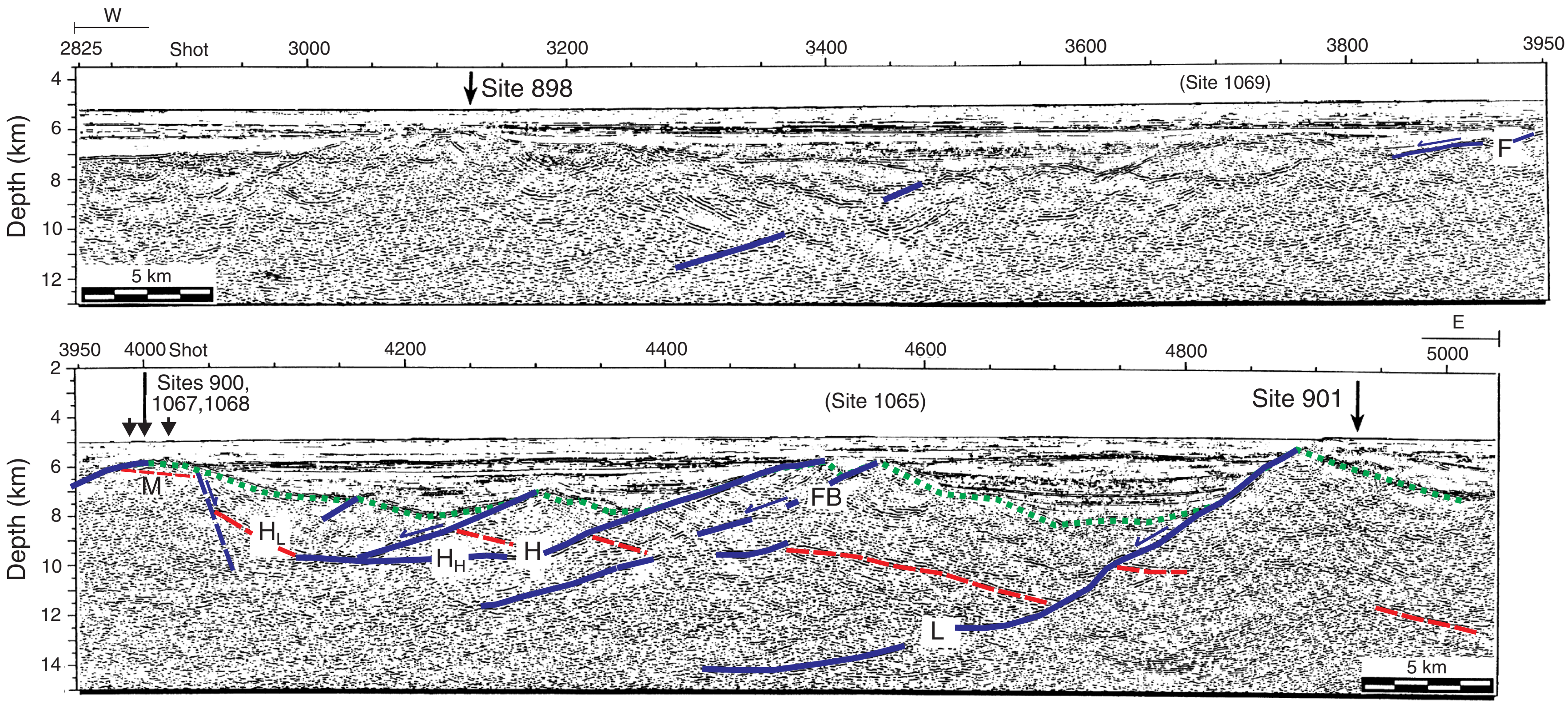


Table T1. Pressure-temperature estimates for in situ material in Legs 149 and 173 basement cores.

Site	Mineral	Pressure (GPa)	Approximate temperature (°C)	Remarks	Source
897	Pyroxenite	0.8-1.0	970	End of high-temperature deformation	Cornen et al., 1999
			730	Subsolidus reequilibration	Cornen et al., 1999
900	Green spinel in gabbro	<0.8	Unknown		Cornen et al., 1999
1067	Hornblende	0.6			Unpublished data*
1068	Hornblende	0.73			Unpublished data*
1068	Spinel-amphibole-clinopyroxene	0.4	600, 740	Metagabbro clast	Unpublished data*
1067	Amphibole-plagioclase	0.7 ± 0.1	670 ± 40	Three-stage retrograde metamorphism to greenschist facies	Gardien et al., in press
		0.55 ± 0.1	550 ± 60		
		>0.22	200-400		

Note: * = R. Rubenach, N. Froitzheim, P. Wallace, M. Fanning, and R. Wyzsoczanski.

Table T2. Isotopic ages of acoustic basement cores from the southern Iberia Abyssal Plain.

Site	Mineral	Rock	Method	Age (Ma)	Stage	Source
900	Plagioclase	Metagabbro	$^{40}Ar/^{39}Ar$	136.4 ± 0.3	lower Valanginian	Féraud et al., 1996
1067	Magmatic zircon	Metagabbro	U/Pb	270 ± 3	lower Permian (late Hercynian)	Unpublished data*
1067	Hornblende	Metagabbro	$^{40}Ar/^{39}Ar$	161 ± 1	middle/upper Callovian	Manatschal et al., in press
1067	Plagioclase	Metagabbro	$^{40}Ar/^{39}Ar$	137.2 ± 0.5	upper Berriasian	Manatschal et al., in press
1069	Mica	Meta-arkosic wacke	$^{40}Ar/^{39}Ar$	348 ± 0.8	Visean	Manatschal et al., in press
1070	Hornblende	Hornblende gabbro pegmatite	$^{40}Ar/^{39}Ar$	119 ± 0.7	lower Aptian	Manatschal et al., in press
1070	Plagioclase	Hornblende gabbro pegmatite	$^{40}Ar/^{39}Ar$	110.3 ± 1.1	lower Albian	Manatschal et al., in press

Notes: Stages are taken from Gradstein et al. (1994) and Harland et al. (1990). * = R. Rubenach, N. Froitzheim, P. Wallace, M. Fanning, and R. Wyzsoczanski.

CHAPTER NOTE*

N1. Ask, M., submitted. Elevated pore-fluid pressure in basal sediments within the ocean-continent transition zone of the West Iberia margin, East Atlantic Ocean: results from mechanical tests on claystones from ODP Hole 1070A. *Mar. Geol.*

*Dates reflect file corrections or revisions.