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43. GEOLOGICAL AND GEOPHYSICAL IMPLICATIONS OF DEEP-TOW MAGNETOMETER OBSERVATIONS NEAR SITES 897, 898, 899, 900, AND 901 ON THE WEST IBERIA CONTINENTAL MARGIN[1]

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ABSTRACT

We present new magnetic measurements from deep-towed magnetometers, operated within a few hundred meters of the seabed of the Iberia Abyssal Plain, over oceanic crust and within the ocean-continent transition itself. In December 1991, the *Charles Darwin* towed a three-component fluxgate magnetometer, mounted on the Institute of Oceanographic Sciences' towed ocean-bottom instrument (TOBI), along 40°40'N in the Iberia Abyssal Plain. In July 1993, *Le Suroît* towed a similar magnetometer fitted to Ifremer's Système Acoustique Remorqué (SAR) deep-tow vehicle over Ocean Drilling Program (ODP) Sites 897, 898, and 899. The observed TOBI profile shows not only a steep gradient on the east flank of the J anomaly, but also anomalies of hundreds of nT over the oceanic crust. Immediately east of the peridotite ridge sampled at Site 897 there are two strong peaks, but further east the anomalies become more subdued. The SAR profile similarly shows a large broad anomaly of hundreds of nT over the oceanic crust and a very strong peak over Site 899 within the ocean-continent transition. Both profiles exhibit the broad trough identified on surface anomalies immediately west of the peridotite ridge. We present two-dimensional models constrained by seismic refraction and reflection profiles and loosely constrained by the magnetic properties of the ODP cores. The common mismatch in amplitude and phase, between the observations and the anomalies resulting from basement relief alone, indicates that magnetization contrasts must exist within the ocean-continent transition crust itself. The results presented here do not at present help us to distinguish definitively between a number of alternative hypotheses for the formation of the ocean-continent transition. However, the unexpectedly low amplitude of some of the relatively short (a few kilometers) wavelength anomalies in the observations may indicate that no significant magnetization contrasts exist on scales of less than 10 km along the profiles near the top of basement. Nevertheless, such contrasts may still exist a few kilometers below the top of basement.

INTRODUCTION

The rifting and break-up of a continent to form an ocean basin is accompanied by important tectonic and magmatic processes. These processes strongly influence the way in which the continental crust merges, temporally and spatially, into oceanic crust formed by seafloor spreading. At a volcanic rifted margin the continent-to-ocean transition is characterized by a carapace of lavas and by underplated mafic rocks, often at least several kilometers thick, at the base of the crust. All this igneous material tends to obscure evidence of the tectonic history and to hinder efforts to distinguish continental crust from oceanic crust. On the other hand, a nonvolcanic margin, such as was drilled during Ocean Drilling Program (ODP) Leg 149, appears to be associated with a broad region, tens of kilometers wide, which, in a geophysical and geological sense, is transitional between continental and oceanic crust. Here, neither tectonism nor magmatism clearly dominate. Off western Iberia, tectonism is expressed on seismic profiles by the presence of tilted fault blocks and likely low-angle detachments. The effects of magmatism are less obvious but synrift magmatism has been inferred by the presence of linear magnetic anomalies, apparently not produced by seafloor spreading, within the ocean-continent transition (Whitmarsh and Miles, 1995). As seafloor spreading itself is a magmatic process its onset immediately west of the ocean-continent transition implies either an abrupt onset of magmatism there or a possibly more gradual build up during the rifting process which would involve synrift magmatism.

Geophysical cruises to the ocean-continent transition off western Iberia have collected seismic reflection, seismic refraction, gravity, and magnetic profiles (e.g., Mauffret et al., 1989; Whitmarsh et al., 1990, 1993; Boillot et al., 1992; Pinheiro et al., 1992; Beslier et al, 1993; Banda et al., 1995; Whitmarsh and Miles, 1995). Whereas sea-surface magnetic observations have been useful off Iberia in detecting the relatively long-wavelength M-series seafloor-spreading anomalies, and other linear anomalies further east of less certain origin, such studies are hampered by the fact that the top of the crust lies about 7 km below sea level. This common situation has meant that, in general, over the outer parts of nonvolcanic rifted continental margins sea-surface magnetic anomalies are often subdued, and for that reason they are rarely mapped. Nevertheless, because the amplitude of a linear magnetic anomaly depends on the square of the depth to the source layer, there is some advantage in using a near-bottom magnetometer over such margins, although this may be at the expense of increased spatially random noise (McKenzie and Sclater, 1971). The advantage is particularly great when the margin has been relatively starved of sediment. For example, off western Iberia about 2 km of sediment overlies basement beneath about 5 km of water so that a seabed magnetometer might be expected to detect anomalies at least 12 times smaller than would be detectable at the surface and, in addition, to resolve anomalies of shorter wavelength.

Here we present new magnetic measurements from deep-towed magnetometers operated within a few hundred meters of the seabed of the Iberia Abyssal Plain over oceanic crust and within the ocean-continent transition itself. These observations have the potential to provide a much higher resolution "view" of the ocean-continent transition crust and to be more easily related directly to the nature of

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basement rocks sampled by drilling. Such magnetic measurements are also expected to be useful to detect the contrasts that will exist between relatively strongly magnetized magmatic material and relatively weakly magnetized continental crust of sedimentary or metamorphic origin (Carmichael, 1982), and they also may lead to new discoveries about the nature of the ocean-continent transition crust.

BACKGROUND

Seismic refraction lines and surface magnetic anomaly profiles collected off western Iberia in 1986 suggested that the ocean-continent transition can be differentiated from oceanic crust on the basis of its nonoceanic seismic velocity structure and by the recognition of the onset of M-series seafloor-spreading magnetic anomalies immediately west of the ocean-continent transition (Whitmarsh et al., 1990). However, the possibly ambiguous evidence of the seismic velocities (crust lacking the typical structure of oceanic crust might not be simply thinned continental crust but represent some form of mixed crust) and the rather narrow strip of oceanic crust produced before the Cretaceous constant polarity interval, which hindered definitive identification of the M-anomalies, suggested the need for other approaches to the problem of locating, and identifying the nature of, the ocean-continent transition. Therefore, in December 1991, *Charles Darwin* towed a three-component fluxgate magnetometer mounted on the Institute of Oceanographic Sciences' towed ocean-bottom instrument (TOBI, Murton et al., 1992) along 40°40'N in the Iberia Abyssal Plain (Figs. 1, 2). This profile followed the track of a multichannel seismic line, Lusigal 12, shot by G. Boillot in 1990 (pers. comm.; see Fig. 1, back pocket, of Beslier, this volume) and also crossed some of the proposed ODP sites in that area. The success of this technique, and the promise of the preliminary results, led one of us (JCS) also to fit a three-component fluxgate magnetometer to Ifremer's Systeme Acoustique Remorqué (SAR) deep-tow vehicle (Sibuet et al., 1995). This instrument was towed over ODP Sites 897, 898, and 899 immediately following the completion of ODP Leg 149 during the Fluigal cruise on board *Le Suroît* in July 1993 (Figs. 1, 2).

As will be shown, modeling of the magnetic anomalies can be constrained only loosely by the magnetic properties of the basement cores. During Leg 149 basement was sampled at Sites 897, 899, and 900 (Figs. 1, 2; Sawyer, Whitmarsh, Klaus, et al., 1994). At Site 897, we encountered 143 m of serpentinized peridotite. At Site 899, acoustic basement consists of a sequence of locally derived serpentinized peridotite breccia units up to 95 m thick underlain by unbrecciated serpentinized peridotite and other igneous material (probably a series of mass-flow deposits). At Site 900, we drilled 56 m of retrograde metamorphosed gabbro. The cores from the first site are probably representative of a peridotite basement ridge also detected, drilled, and sampled off Galicia Bank (Boillot, Winterer, Meyer, et al., 1987), which appears in both locations to mark the landward edge of oceanic crust (Whitmarsh et al., 1990; Sibuet et al., 1995) and may extend, with en echelon offsets, along the margin for about 300 km (Beslier et al., 1993). The basement rocks from Site 899 were unexpected and are also rather unusual. It is possible that the site location is atypical of the ocean-continent transition as a whole. This suggestion is based on a new reduced-to-the-pole magnetic anomaly chart of the west Iberia Margin (Miles et al., 1994, and Fig. 1 of Miles et al., this volume, back-pocket foldout) whose contours show an atypical isolated large positive anomaly enclosing the locations of Sites 898 and 899 (Fig. 2) in contrast to the linear low-amplitude magnetic anomalies seen elsewhere in the ocean-continent transition. Site 900 lay within the western part of the ocean-continent transition (that region immediately landward of the peridotite ridge that is characterized by linear isochron-parallel magnetic anomalies; Whitmarsh and Miles, 1995) over a basement high which is probably lower crust exposed by low-angle detachment faults (Krawczyk et al., this volume).

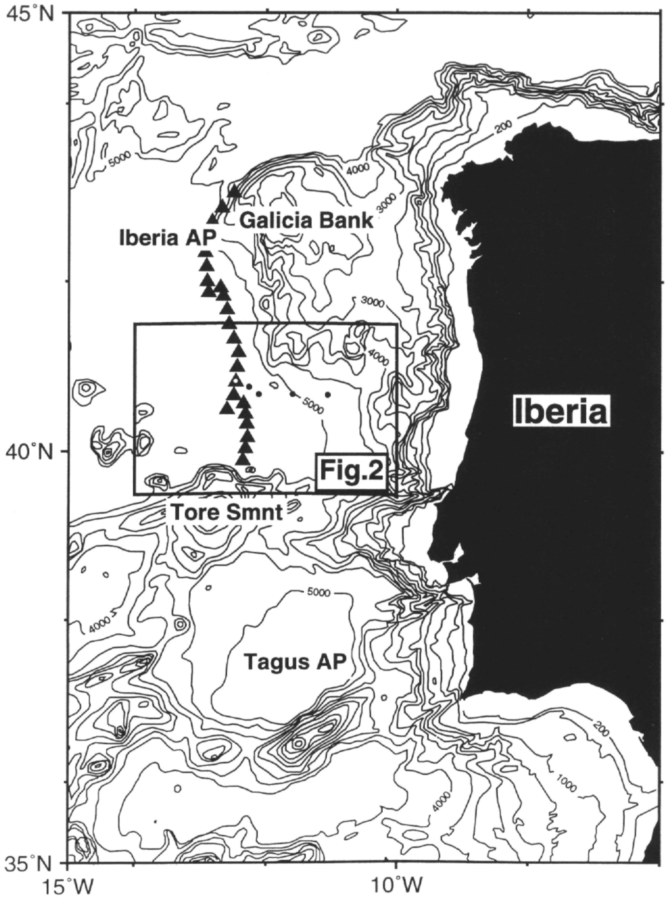

Figure 1. Location of the area off Western Iberia discussed here. Open and solid circles mark Leg 149 sites; triangles mark the observed and postulated trend of the peridotite basement ridge (Beslier et al., 1993). Bathymetric contours in meters. The box indicates the area shown in Figure 2.

DATA ACQUISITION AND PROCESSING

The TOBI track in the Iberia Abyssal Plain extended 150 km from the east flank of the J anomaly to 11 °08'W (Figs. 1, 2). The towed vehicle, kept at an average height of 400 ± 200 m above the seabed, was navigated with respect to the *Charles Darwin* by knowing the length of the tow cable and the depth of TOBI below sea level; the *Charles Darwin* was navigated by the Global Positioning System (GPS). The vehicle pitch and heading (from a magnetic compass) were recorded as well as the three orthogonal magnetic components, which were logged twice per second with a resolution of 10 nT. The raw data contained a number of short-wavelength perturbations which we attributed to the pitching motion of the weakly magnetic TOBI vehicle in Earth's field. An empirical correction for the pitch was derived from the formulae of Bullard and Mason (1961) for the magnetic field astern of a ship. The variation in magnetic heading was ±10° about a mean of about 095°. The heading variations had a disproportionately strong effect on the X (tow direction) component because the vehicle was towed along an easterly course. Although the east component of Earth's field off Iberia is relatively small the proportional change in X with heading tends to become very large because it depends on the tangent of the heading, i.e., ~ tan[π/2]. As a result, and lacking a heading correction curve for TOBI, it proved not possible to satisfactorily correct X for this effect. Consequently, the remaining discussion will concern just the total-field anomaly computed with respect to the IGRF 1990 for epoch 1992.0 (IAGA Working Group 8, 1992).

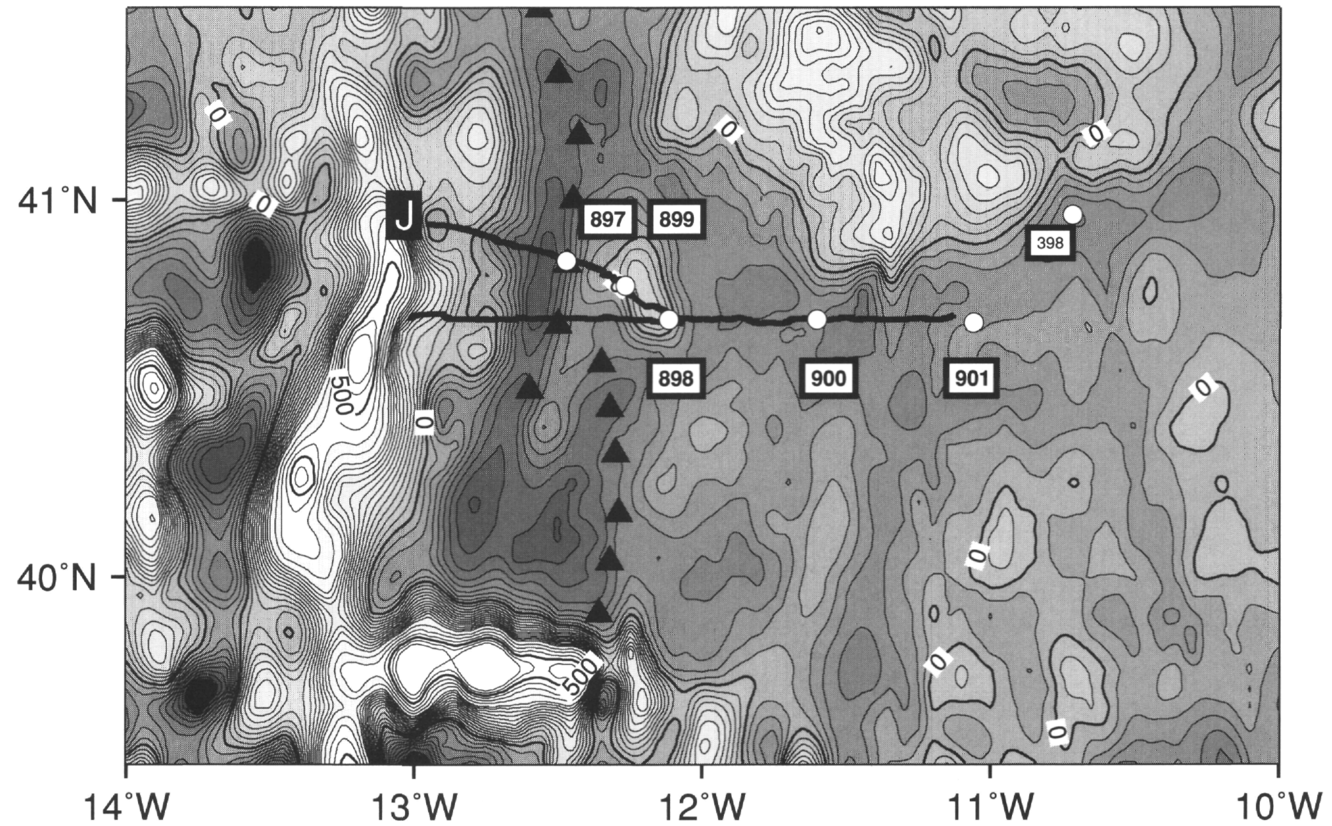

Figure 2. Part of a new reduced-to-the-pole total-field magnetic anomaly chart of the west Iberia Margin (see Fig. 1 [back-pocket foldout] of Miles et al., this volume). Contour interval 25 nT (for ± 350 nT contours) and 50 nT (>350 nT). ODP sites are shown by open circles and deep-towed magnetometer tracks by bold lines; J indicates the large positive J magnetic anomaly. The triangles indicate the postulated location of the peridotite basement ridge (Beslier et al., 1993).

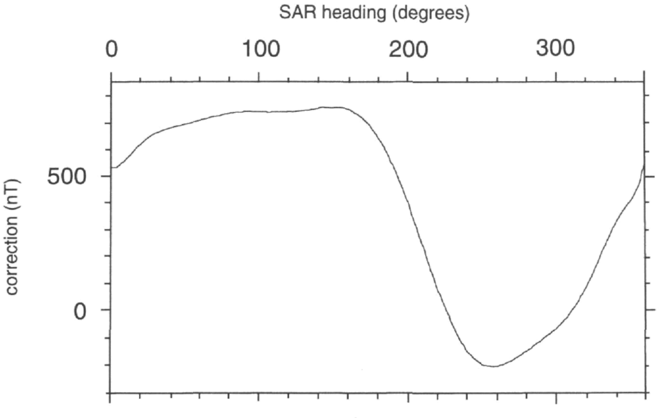

Figure 3. Total-field heading correction curve for the magnetometer mounted on the SAR vehicle. The curve was obtained by towing the vehicle in a loop in midwater (see text). SAR heading is in units of degrees east of geographic north.

An 80-km-long SAR profile, which crossed ODP Sites 897, 898, and 899, was also recorded in the Iberia Abyssal Plain (Figs. 1, 2). The SAR was towed at a mean elevation of 80 ± 30 m above the seabed. *Le Suroît* was navigated by GPS. All navigation parameters of the SAR (pitch, roll, heading, depth below sea level, and distance to the ship) were recorded every 1.5 s and were used to compute the position of the SAR. An analogue computer gave the amplitude of the total magnetic field, from the three recorded orthogonal components of the magnetic field, with a precision of 5 nT. The noise was 0.3 nT in the 0-1 kHz band. The analogue signals of the three orthogonal components and of the total magnetic field were digitized and integrated into the SAR real time system of data transmission to the ship. The magnetic values were also recorded every 1.5 s (Sibuet et al., 1995). As a result of bad weather conditions, the SAR profile was obtained during two consecutive runs. To correct the observed magnetic field for the magnetic effects of the SAR itself, a heading correction curve was established before the acquisition of the profile by steaming in a loop with the SAR located at a water depth of 1000 m, deep enough to be unaffected by the magnetic effects of the ship (Fig. 3). The SAR heading correction varies by about 800 nT as a function of the SAR heading. The curve differs slightly from a sinusoid, especially for headings between 020° and 160°. Magnetic anomalies were computed by taking into account both the heading correction curve and the IGRF 1990 for epoch 1993.5 (Fig. 3). As a result of the bad weather a surface magnetic profile was recorded later along a nearly coincident track.

The TOBI and SAR total-field anomaly profiles, after subtraction of their mean values, were projected onto straight lines with origins at 40.694°N, 13.000°W and at 40.936°N, 12.963°W and with trends of 090° and 102°, respectively (Figs. 4, 5). Because the J anomaly, which locally approximates an isochron, trends normal to 102°, the error in assuming infinite two-dimensional north-south prismatic blocks along the TOBI profile, for the purposes of two-dimensional modeling, will be small.

The observed TOBI profile shows not only a steep gradient on the east flank of the J anomaly, but also anomalies of hundreds of nT over the oceanic crust (Fig. 4B). Immediately east of the peridotite ridge are two strong peaks, but further east the anomalies become more subdued. The SAR profile similarly shows a large broad anomaly of hundreds of nT over oceanic crust and a very strong peak over Site 899 within the ocean-continent transition (Fig. 5B). Both profiles exhibit the broad trough identified on surface anomalies (Fig. 2) immediately west of the peridotite ridge.

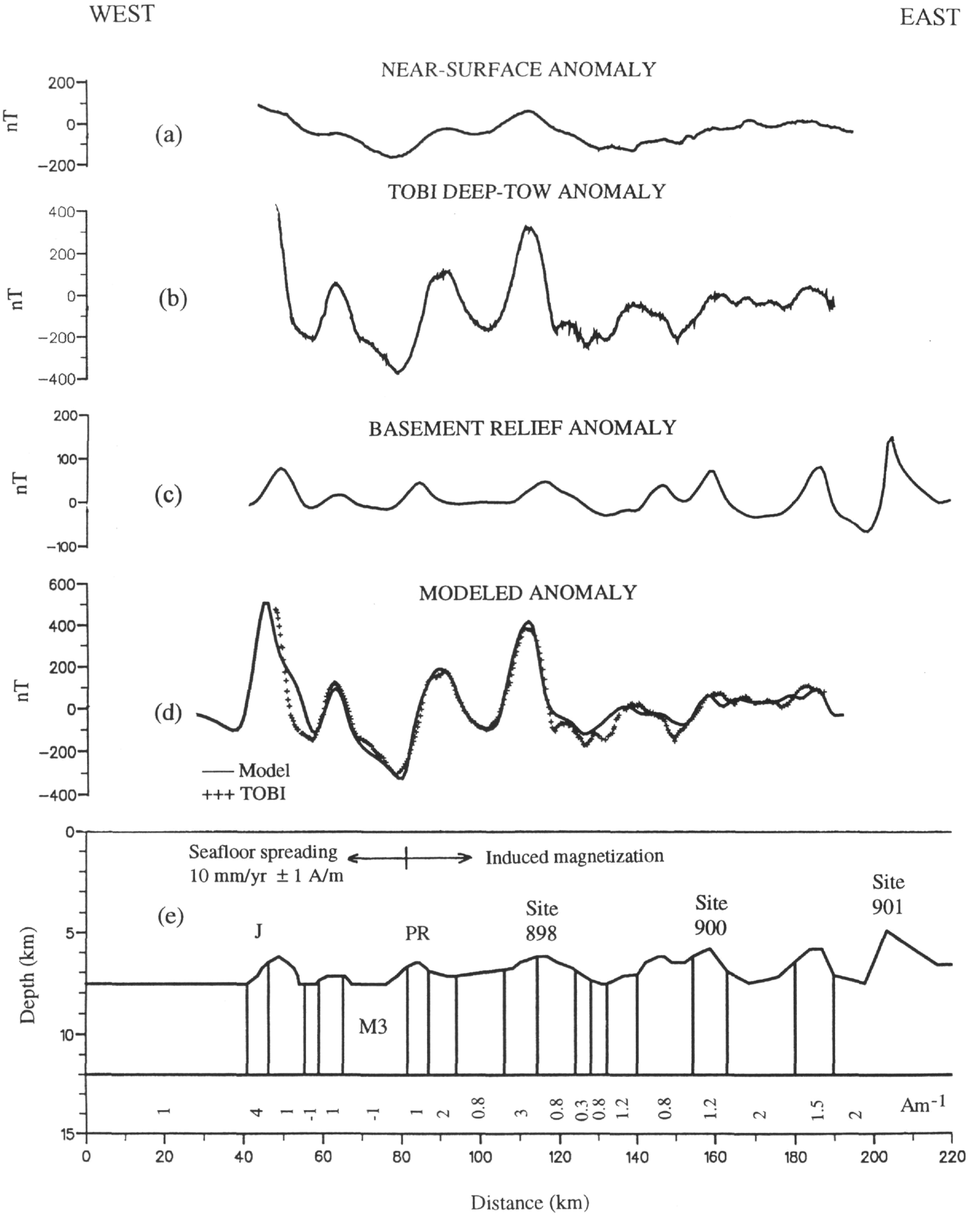

Figure 4. Profiles related to the TOBI deep-tow magnetometer profile. **A**. Total-field magnetic anomaly recorded by a near-surface magnetometer. **B**. Total-field magnetic anomaly recorded by the TOBI magnetometer. The noise on the profile east of 120 km is principally instrumental in origin. **C**. Computed total-field magnetic anomaly caused by relief at the top of two-dimensional basement uniformly magnetized (1 A/m) in the direction of the present field. Relief was obtained from a coincident multichannel seismic reflection profile (see text and Fig. 4E). Note different vertical scale from the rest of the figure. **D**. Computed total-field magnetic anomaly based on the two-dimensional model shown below. **E**. Two-dimensional model used to compute the profile in Figure 4D. Seafloor spreading was assumed west of the peridotite ridge (PR) with intensities of magnetization of ±1 A/m, except for the J anomaly block (4 A/m); direction of remanent magnetization was I = +58°, D = -43° (after Galdeano et al., 1989); induced magnetization was assumed east of the peridotite ridge (values in A/m). Sites 898, 900, and 901 are indicated.

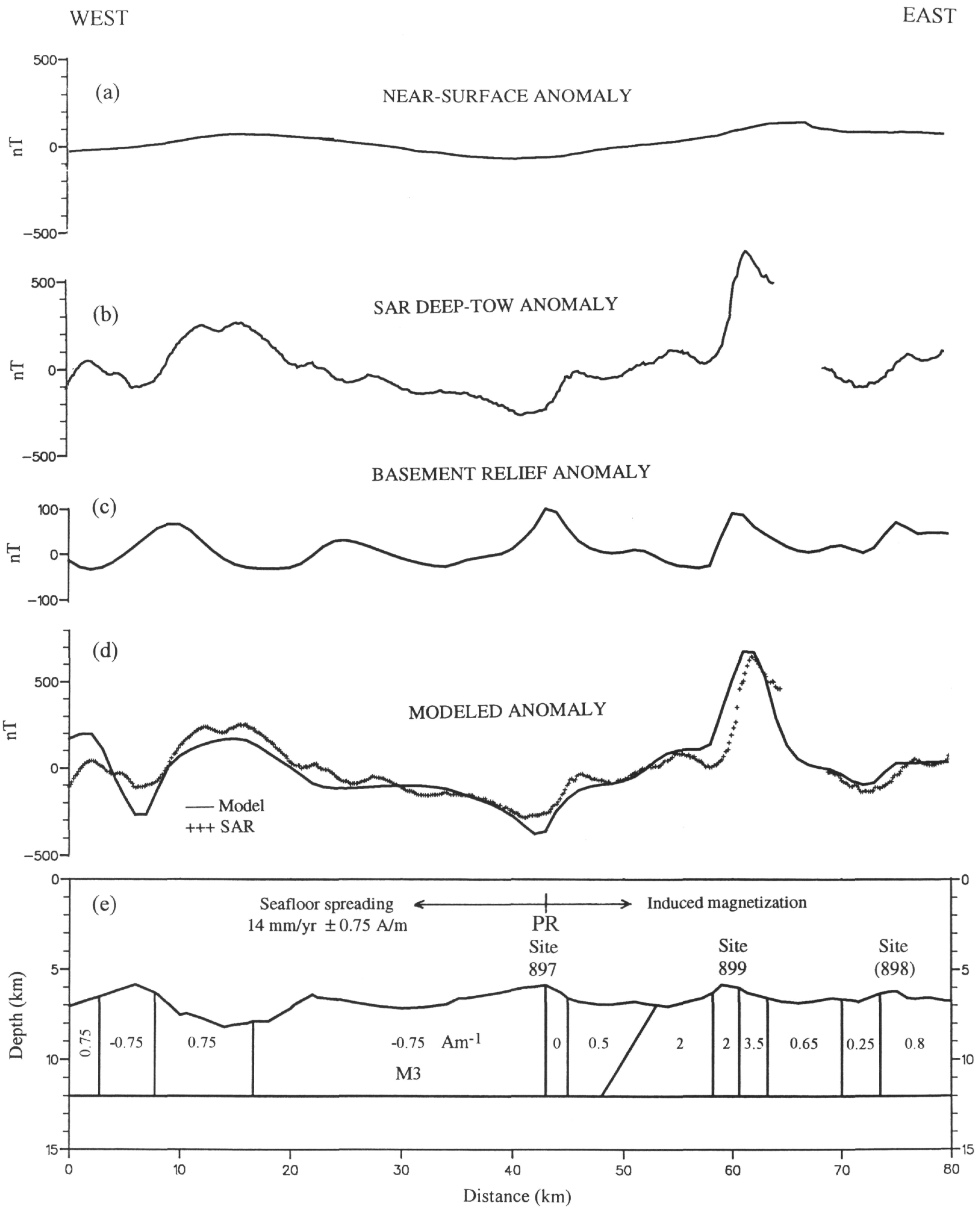

Figure 5. Profiles related to the SAR deep-tow magnetometer profile. **A**. Total-field magnetic anomaly recorded by a near-surface magnetometer. **B**. Total-field magnetic anomaly recorded by the SAR magnetometer. **C**. Computed total-field magnetic anomaly caused by relief at the top of two-dimensional basement uniformly magnetized (1 A/m) in the direction of the present field. Relief was obtained from the contoured basement chart but is poorly constrained west of 40 km (see Figs. 5E, 6). Note different vertical scale from the rest of the figure. **D**. Computed total-field magnetic anomaly based on the two-dimensional model shown below. **E**. Two-dimensional model used to compute the profile in Figure 4D. Seafloor spreading was assumed west of the peridotite ridge (PR) with intensities of magnetization of ±0.75 A/m; direction of remanent magnetization was I = +58°, D = -43° (after Galdeano et al., 1989); induced magnetization was assumed east of the peridotite ridge (values in A/m). Sites 897 and 899 and closest approach (5 km) to Site 898 are indicated.

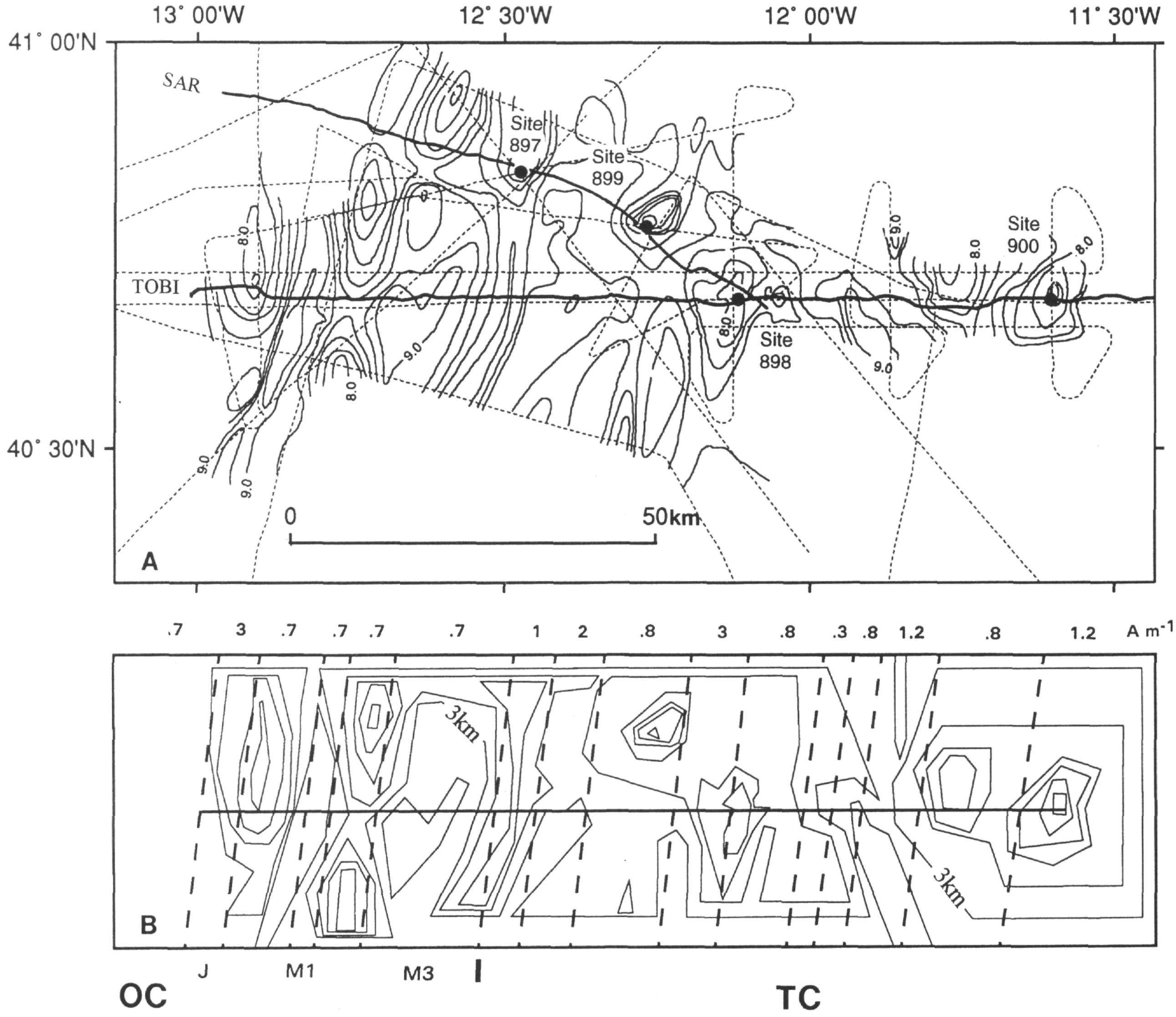

Figure 6. **A**. Basement relief in the Iberia Abyssal Plain contoured in seconds of two-way traveltime from all available seismic reflection profiles (dotted lines; from C. Krawczyk, P.R. Miles, L.M. Pinheiro, R.B. Whitmarsh, unpubl. data). The SAR and TOBI tracks are shown by the bold east-west and west-northwest-east-southeast lines, respectively. ODP sites are indicated by solid circles. **B**. Simplified contoured basement relief in km (the contour interval, derived from two-way traveltime, ranges from 0.23 to 0.33 km) from Figure 6A in a 40-km-wide rectangle centered on the TOBI track (Fig. 6A) used as input to a three-dimensional magnetic modeling program. The dashed lines trending 012° represent the vertical boundaries between the blocks; effective magnetizations in A/m are given at the top of the figure (note that the three-dimensional basement relief requires a smaller magnetization (0.7 A/m) in the best model of the oceanic crust than in the two-dimensional model). A seafloor-spreading model was assumed west of the vertical bar at the bottom of the figure. The base of the model was assumed to be flat at 7.5 km below the TOBI vehicle. OC = oceanic crust; TC = transitional crust of the ocean-continent transition.

The striking difference between subjacent surface and deep-tow magnetic anomaly profiles is evident from comparing parts A and B of Figures 4 and 5. Both sets of profiles show the same longer wavelength features but the deep-tow profiles, as expected, resolve shorter wavelength features undetectable at the surface. For the longer wavelength anomalies the ratio of the amplitudes of deep-tow to surface anomalies is about 4:1. On the other hand, the relatively short wavelength (a few kilometers) observed anomalies, that are uncorrelated with the basement relief, have unexpectedly small amplitudes; pending a more detailed investigation, this may indicate that no significant magnetization contrasts, on scales of less than 10 km along the profiles, exist near the top of basement. Nevertheless, such contrasts must exist at a greater depth and may be present a few kilometers below the top of basement.

MODELING CONSTRAINTS

The models we shall present are constrained by several factors. First, given the results of previous modeling of seafloor-spreading magnetic anomalies in the Iberia Abyssal Plain at 40°40'N (Whitmarsh et al., 1990; Whitmarsh and Miles, 1995) and the strong suggestion, here and off Galicia Bank, that the peridotite ridge represents the landward edge of normal but unusually thin oceanic crust (Boillot et al, 1992; Horsefield, 1992; Whitmarsh et al., 1993; Sibuet et al., 1995; R.B. Whitmarsh et al., unpubl. data), we shall assume the presence of oceanic crust west of the ridge. We also assume a 4.5-km-thick oceanic crustal source layer in accord with seismic refraction results of Whitmarsh et al. (1990) and with the work of Pariso and Johnson (1993), which showed that gabbros in the lower oceanic

Table 1. Average magnetic properties of acoustic basement based on Leg 149 samples from Sites 897, 899, and 900.*

Site	Rock type	NRM (A/m)	Susceptibility (10^{-3} SI units)	Q	Effective magnetization
897	Serpentinized peridotite	0.3	21	0.4	0.74
899	Polymict breccia (serpentinite, peridotite)	1.5	42	1	1.47
900	Mafic rock	0.005	0.6	0.25	0.02

Notes: *after Zhao, this volume and pers. comm., 1994. NRM = natural remanent magnetization. Koenigsberger ratio (Q) is a linear function of NRM/induced magnetization. Effective magnetization is based on an Earth's field of 44,000 nT.

crust are likely to make an important contribution to oceanic magnetic anomalies. Seismic refraction results also suggest a similar crustal thickness within the ocean-continent transition (Whitmarsh et al., 1990). Second, we shall assume that the enigmatic J anomaly, which is found 40 km west of the ridge at 40°40'N but which does not mark an isochron and hence will not be fixed in time in the magnetic reversal sequence used in our seafloor-spreading models, was formed at about the time of anomaly M0 (Rabinowitz et al., 1978; ca. 124 Ma on the time scale of Harland et al., 1990). Third, the average spreading rate at this latitude in the North Atlantic between the J anomaly (ca. 124 Ma) and anomaly 34 (83 Ma), two unambiguously clear anomalies created about 41 Ma apart, is approximately 9 mm/yr. Because the J anomaly elsewhere in the north and central Atlantic is not associated with a change in spreading rate (Rabinowitz et al., 1978), we may therefore expect the pre-J-anomaly spreading rate to be similar. Fourth, we have available a multichannel seismic reflection profile along the TOBI line and a synthetic basement relief profile along the SAR line which has been created from a contoured chart based on all seismic profiles in the area (Fig. 6A; C. Krawczyk, P.R. Miles, L.M. Pinheiro, and R.B. Whitmarsh, unpubl. data). These two profiles therefore provide the topography of the upper surface of what is probably the magnetic source layer. Last, a flat base to the models was assumed; the difference between the computed profiles for a flat-based model 12 km below sea level (bsl) and one with a constant crustal thickness is not significant (less than 10% for all anomalies). We shall attempt to incorporate magnetic measurements made on the basement cores from Sites 897, 899, and 900. These results are summarized in Table 1 (X. Zhao, pers. comm., 1994; Zhao, this volume). The important conclusion that can be reached from Table 1 is that, except at Site 899, the effective magnetization resulting from the susceptibility of the cores exceeds their remanent magnetization. Even so, this magnetization is very weak at Site 900. At Site 899, induced and remanent magnetizations are similar and here, for the model block underlying the site, we have used the resultant of a normally magnetized paleomagnetic remanent vector and the present-day induced vector. The evidence for the relative influences of the remanent and induced magnetizations at the different sites are probably more significant than their absolute values; the absolute values from the relatively thin drilled section (at most 143 m thick) are unlikely to be representative of the whole underlying crustal source layer because of the effects of near surface alteration, submarine "weathering" and other depth dependent and lateral inhomogeneities in the crust.

MODELING RESULTS

Basement relief is about 2200 m in the area of the contoured map (Fig. 6A) and at its shallowest point basement reaches within 400 m of the seabed. The expectation that basement relief can contribute significantly to the deep-tow magnetic observations is confirmed by simple two-dimensional models. Because of the magnetization contrast between basement and the relatively very weakly magnetized overlying sediments, profiles computed along the deep-tow tracks, assuming a uniformly magnetized (1 A/m) two-dimensional basement, give rise to peak-to-trough anomalies of 200 nT, about 20%-25% of the total observed anomaly (Figs. 4C, 5C). These profiles also show that the anomalies caused by uniformly magnetized relief commonly do not match the observed profiles in amplitude or phase. This leads to the important conclusion that magnetization contrasts must exist within the underlying crust of the ocean-continent transition.

The track-spacing on the basement relief map shows that the relief beneath the TOBI line is well constrained, particularly west of 12°30'W, whereas the relief beneath the SAR line is generally less well determined. Therefore, we decided to forward-model the TOBI line first to investigate the importance of including three-dimensional basement relief in the magnetic models. A simple numerical test indicated that the largest realistic relief more distant than 20 km would not affect the TOBI observations. Accordingly, the basement contours were simplified and then digitized over a corridor extending 20 km either side of the TOBI track. The two-way time contours were used to define the upper surfaces of horizontal, vertically sided slabs of basement, each about 230-330 m thick, which were used as input to the algorithm of Talwani (1965; Fig. 6B). When the profile computed from this three-dimensional model is compared with a profile computed from a two-dimensional model, with prismatic blocks oriented at 012° (parallel to the J anomaly) and extending to infinity, the difference is not significant (Fig. 7). This indicates that, except in cases of extreme basement relief with, for example, slopes with trends approaching east-west in the vicinity of the TOBI profile (halfway between Sites 898 and 900; Figs. 6, 7), the assumption of two-dimensional basement relief is reasonable. This is not a surprising result, because the top of basement lay 1.6 to 3.0 km beneath the TOBI vehicle, which is much less than the spacing of the tracks used to produce the basement contours. Therefore, we decided to continue with two-dimensional models for the remainder of the modeling.

Working from the assumptions outlined above, we computed magnetic profiles at the depths of the deep-tow magnetometers (TOBI at 4500 mbsl and SAR at 5200 mbsl), based on two-dimensional models with isolated crustal blocks oriented normal to the projected deep-tow tracks; the computed profiles are shown in Figures 4D and 5D.

The computed anomaly along the TOBI profile fits the observations within 100 nT, and often better than 50 nT (Fig. 4D). The J anomaly was modeled with a block of 4A/m but the TOBI profile crossed only the east flank of this anomaly (Fig. 2). A seafloor-spreading rate of 10 mm/yr gave the best fit, a rate similar to that obtained from modeling surface magnetic profiles (Whitmarsh et al., 1990; Whitmarsh and Miles, 1995). Because basement relief contributes only a small proportion of the total observed anomaly, blocks with significant magnetization contrasts were required to match the observed TOBI profile east of the peridotite ridge. The large anomalies at 90 and 110 km required relatively strongly magnetized blocks (2 and 3 A/m); further east block-to-block magnetization contrasts of less than 0.8 A/m, mostly 0.5 A/m or less, were sufficient to match the observations.

The assumption of seafloor spreading at 10 mm/yr did not enable the computed anomalies on the SAR profile to match the observations west of the peridotite ridge. This profile is at a latitude where the J anomaly begins to die out and where its characteristic broad eastern slope is locally steep and narrow (Fig. 2). An apparently good fit can be obtained with a spreading rate of 14.2 mm/yr (Fig. 5D) which is perhaps attributable to a local perturbation in the regional spreading rate (possibly reflected in the curvature of the J anomaly at 41 °N, Fig. 2). However, little reliance should be put on this figure considering the short segment of the polarity reversal time scale involved and the lack of firm information on basement relief along the SAR profile. Even though the computed profile fits the SAR profile east of the peridotite ridge to within 100 nT the fit is not satisfactory around 45 and 60 km. It proved difficult to model the rather smooth rounded trough and peak at 45 km and to match the western slope of the peak at 60 km. The latter feature is situated over the Site 899 base-

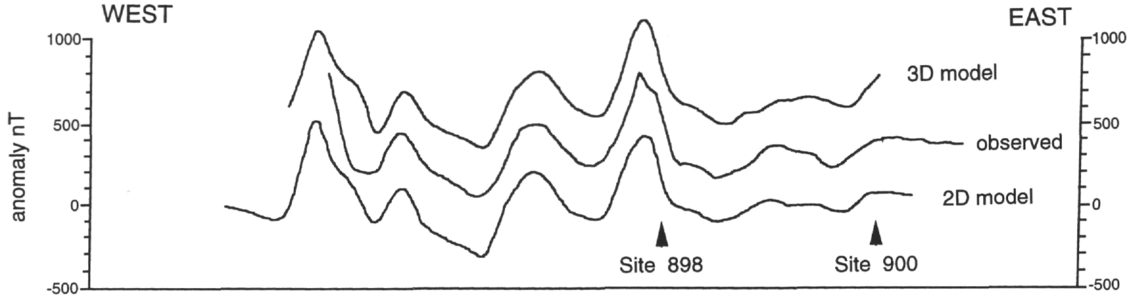

Figure 7. Computed magnetic anomalies based on two-dimensional and three-dimensional models compared with the observed TOBI profile. The two-dimensional model is shown in Figure 4 and the three-dimensional model in Figure 6B.

ment high; the high has a shape that may violate the assumption of two-dimensionality on its southern flank (Fig. 6). The sloping block interface was used to model the general trend observed between 45 and 55 km; models with a vertical interface were significantly less successful.

On the southwest Greenland margin it has been suggested that a zone of linear isochron-parallel magnetic anomalies, which are observed between firmly identified seafloor spreading anomalies and continental fault blocks, is caused by unusually slow (5.8 mm/yr) seafloor spreading (Srivastava and Roest, 1995). Using the longer TOBI profile we investigated whether this scenario might also be applied to the Iberia Abyssal Plain (Fig. 8). Profiles incorporating the topography of acoustic basement at the top of the magnetic source layer were computed for spreading rates of 4, 6 and 8 mm/yr in the period before the M3 onset of spreading at 10 mm/yr. It is evident from the computed profiles that, even ignoring the large peak at Site 898, which is part of the atypical large positive anomaly mentioned earlier, their shape does not approach a good fit to the observations and that generally their wavelengths are shorter than those of the observed anomalies. Although the latter observation might be construed to indicate a deeper source for these anomalies, than was assumed in the models, such a conclusion leaves open the explanation for the weakly magnetic overlying oceanic crust. The amplitudes of the anomalies are approximately correct and might be reduced to fit better using Srivastava and Roest's (1995) arguments for a weaker remanent magnetization of fragmented ultra-slow crust. Nevertheless the profiles in Figure 8 clearly indicate that, superficially at least, models of ultra-slow, but constant, seafloor spreading in the Early Cretaceous are unlikely to match the TOBI observations. On the other hand, the process of crustal accretion at such slow mean spreading rates is less likely to be spatially continuous and therefore two-dimensional models in which the local rate of spreading is quite variable, and the region of crustal accretion is rather wide, may fit the observations better. However, this approach is less satisfactory because of the lack of objective constraints available for such models and is not pursued here.

DISCUSSION

In the oceanic region west of the peridotite ridge the deep-tow profiles are short (less than 40 km) and only along the TOBI profile is the basement surface well known. Assuming that the magnetic source layer extends throughout the whole oceanic crust a mean magnetization of 0.75 or 1.00 A/m applies.

In the vicinity of the ODP sites the peridotite ridge lies immediately to the east of a distinctive magnetic anomaly low. This low has an amplitude, with respect to the peridotite ridge high, of 500 nT on the TOBI profile and 250 nT on the SAR profile. The cause of this anomaly is the contrast between the reversely magnetized M3 block and the induced magnetization of the peridotite ridge itself. The amplitude variation between profiles seems to be caused more by the variable magnetization of the peridotite ridge than by changes in the oceanic crust. There is a striking difference between the effective magnetization of 0.74 A/m for serpentinized peridotite core samples from Site 897 (Table 1) and the nonmagnetic model block in Figure 5 which underlies the site, although the adjacent block 2 km to the east has a similar magnetization (0.5 A/m).

We modeled magnetic anomalies within the ocean-continent transition by assuming the crustal blocks each had a uniform induced magnetization (except in the vicinity of Site 899 where core measurements indicate the presence of a mixture of NRM and induced magnetization). This assumption is consistent with the core measurements at Site 900 and also with the common hypothesis that the ocean-continent transition contains at least some continental crust. Other sorts of models, including ones with normally and reversely polarized blocks, are conceivable and may even be more valid if significant synrift magmatism affected the ocean-continent transition crust as has been suggested or implied by some authors (Sawyer, 1994; Whitmarsh and Miles, 1995; Srivastava and Roest, 1995). We present models of the first type here because they are simpler and because, at present, it is probably possible to create models of the second type only by assuming some sort of stochastic distribution of magnetic sources.

In the region to the east of the peridotite ridge the deep-tow (and surface) magnetic anomalies are relatively subdued, except in the vicinity of Sites 898 (TOBI) and 899 (SAR). Basement was not sampled at Site 898 but, at Site 899, a polymict breccia, including significant amounts of serpentinite and peridotite clasts, was cored. This material has not only a relatively high average NRM (1.5 A/m) but also a very strong average susceptibility (42×10^{-3} SI units). The peculiar nature of the breccia and the fact that it is underlain by a mass flow deposit leaves room for doubt as to whether it is representative of the underlying crust. However, the requirement for the SAR magnetic model to have a 2 A/m block beneath Site 899 is at least consistent with the core measurements. It is tempting, but unsupported by any direct evidence, to conclude that the even more strongly magnetized block under Site 898 on the TOBI profile has a similar origin. Nevertheless, the source of this large anomaly on the TOBI profile must be quite localized; the anomaly is not observed on the SAR profile less than 5 km away. Last, at Site 900 there is a discrepancy between the requirement for a relatively high average crustal magnetization (Fig. 4D) and the very weak susceptibility of the Site 900 basement cores (Table 1). This suggests that the cores from Site 900 are, at least magnetically, unrepresentative of the whole crust and may be a minor constituent of basement at that point.

CONCLUSIONS

1. We have demonstrated that deep-tow magnetometer profiles can usefully contribute to investigations of the nature of the ocean-continent transition at a nonvolcanic rifted continental margin. The deep-tow magnetic anomalies presented here are

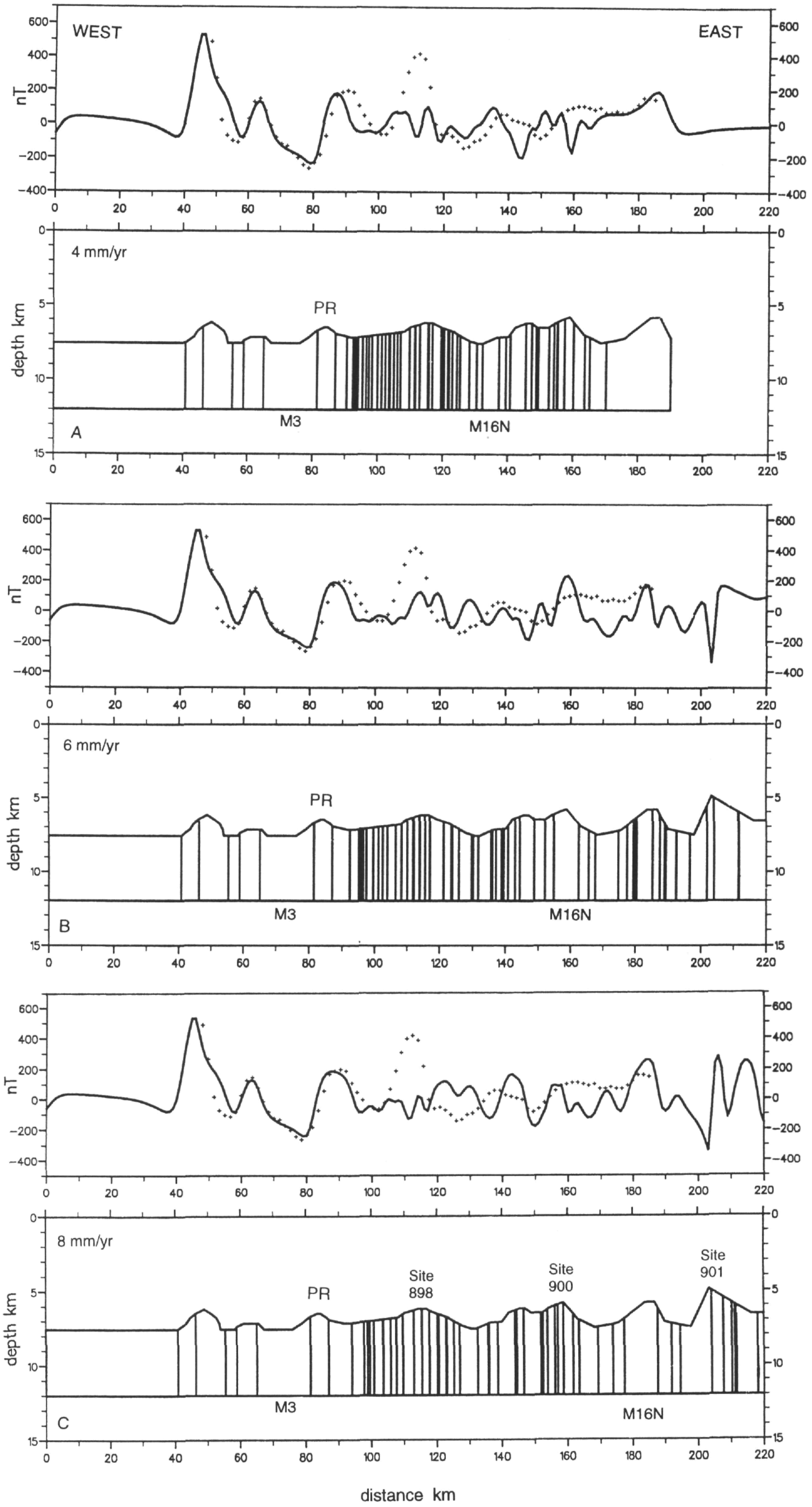

Figure 8. Magnetic anomaly profiles computed on the assumption of three different slow seafloor-spreading rates east of the peridotite ridge (PR) with a crustal magnetization of 1 A/m. The same model was used west of the peridotite ridge as in Figure 4. Crosses indicate the observed deep-tow profile measured by TOBI.

about four times greater in amplitude and exhibit some shorter wavelength anomalies than those that are seen at the sea surface.

2. The magnetization contrast at the top of acoustic basement means that the relief of acoustic basement makes an important contribution to the anomalies observed near the seabed. Therefore it is important, when modeling such observations, to use coincident seismic reflection profiles. On the other hand the common mismatch (in amplitude and phase) between the observations and the anomalies caused by the basement relief alone indicates that magnetization contrasts must also exist within the ocean-continent transition crust itself.
3. Usually the deep-tow magnetic anomalies we observed are adequately modeled by a two-dimensional model (prisms extending to infinity normal to the profile) based on a coincident reflection profile and it was unnecessary to employ a three-dimensional representation of the basement relief. The rather simple two-dimensional models presented here often match the observations within 50 nT.
4. The results presented here do not at present help us to definitively distinguish between a number of alternative hypotheses for the formation of the ocean-continent transition. However, the unexpectedly low amplitude of the relatively short wavelength (a few kilometers) observed anomalies, that cannot be correlated with basement relief, may indicate that no significant magnetization contrasts exist on scales of less than 10 km along the profiles near the top of basement. Nevertheless, such contrasts must exist at a greater depth and may be present a few kilometers below the top of basement.
5. Magnetic measurements on cores from Sites 897, 899, and 900 can probably provide only loose constraints on the two-dimensional modeling. There is a relatively weak correlation between the core properties and the average crustal magnetization in models that generate profiles to match the deep-tow observations.
6. The use of deep-tow magnetic observations to study the ocean-continent transition is a new technique. Its potential has been only touched upon here and we intend to make new observations, and to apply more sophisticated techniques to analyze the data, in the near future.

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