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Evidence for asymmetric nonvolcanic rifting and slow incipient oceanic accretion from seismic reflection data on the Newfoundland margin

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[1]   Prestack depth migrations of seismic reflection data collected around the Ocean Drilling Program (ODP) Leg 210 transect on the Newfoundland nonvolcanic margin delineate three domains: (1) extended continental crust, (2) transitional basement, and (3) apparent slow spreading oceanic basement beyond anomaly M3 and indicate first-order differences between this margin and its well-studied conjugate, the Iberia margin. Extended continental crust thins abruptly with few observed faults, in stark contrast with the system of seaward dipping normal faults and detachments imaged within continental crust off Iberia. Transition zone basement typically appears featureless in seismic reflection profiles, but where its character can be discerned, it does not resemble most images of exhumed peridotite off Iberia. Seismic observations allow three explanations for transitional basement: (1) slow spreading oceanic basement produced by unstable early seafloor spreading, (2) exhumed, serpentinized mantle with different properties from that off Iberia, and (3) thinned continental crust, likely emplaced by one or more detachment or rolling-hinge faults. Although we cannot definitively discriminate between these possibilities, seismic reflection profiles together with coincident wide-angle seismic refraction data tentatively suggest that the majority of transitional basement is thinned continental crust emplaced during the late stages of rifting. Finally, seismic profiles image abundant faults and significant basement topography in apparent oceanic basement. These observations, together with magnetic anomaly interpretations and the recovery of mantle peridotites at ODP Site 1277, appear to be best explained by the interplay of extension and magmatism during the transition from nonvolcanic rifting to a slow spreading oceanic accretion system.

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1.   Introduction

[2]   Two end-member models illustrate how continental crust extends and ultimately fails: pure shear [*McKenzie*, 1978] and simple shear [*Wernicke*, 1985; *Lister et al.*, 1986]. Each of these models carries specific predictions regarding the symmetry of the resulting conjugate margins; margins formed by pure shear extension are likely to be largely symmetric with respect to their conjugates [*McKenzie*, 1978], and margins formed by simple shear will be asymmetric, with one margin comprising the ''upper plate'' of the shear zone and the other the ''lower plate'' [*Wernicke*, 1985; *Lister et al.*, 1986]. While these two extremes are a useful way to couch the debate on the mechanisms of continental rifting, it is likely that some combination of pure and simple shear occurs, either spatially (e.g., simple shear in the upper crust and pure shear in the lower crust) or temporally (e.g., pure shear necking followed by simple shear) [*Keen et al.*, 1987; *Kusznir et al.*, 1991;
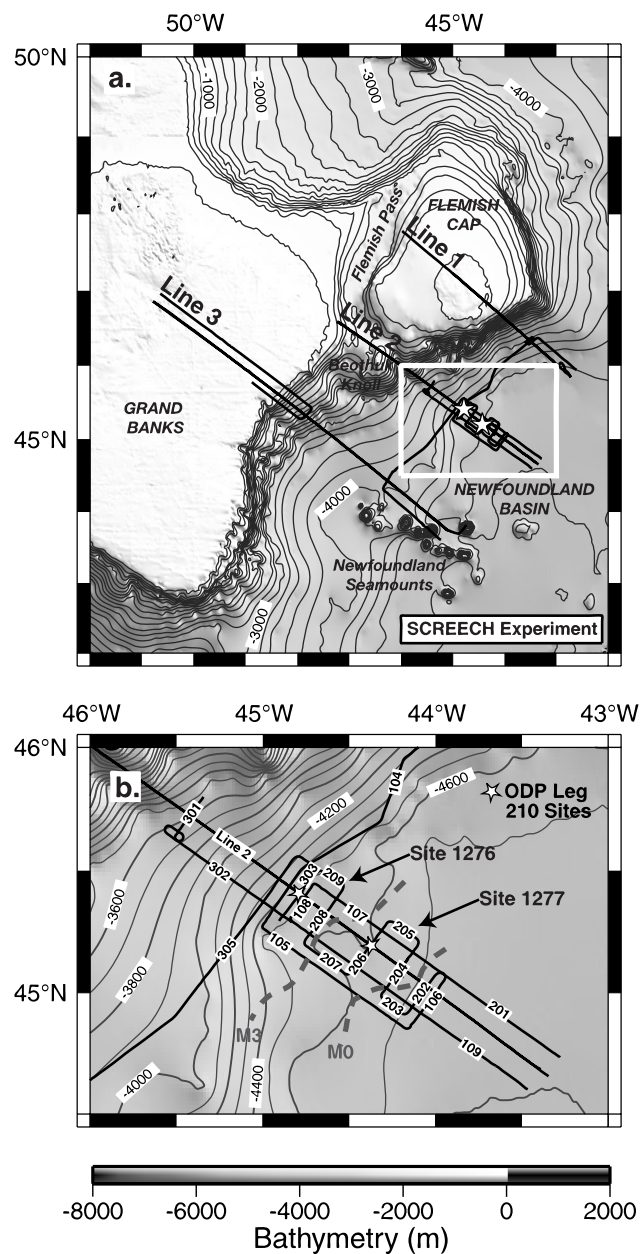
Figure 1. (a) Bathymetric map of the Newfoundland margin extracted from the GEBCO Digital Atlas [*British Oceanographic Data Centre*, 2003]. The contour interval is 200 m. Black lines show the tracks of the SCREECH survey, and white stars mark the locations of ODP sites 1276 and 1277. Coincident multichannel seismic (MCS) reflection, wide-angle seismic reflection/refraction, magnetic, gravity, and multibeam bathymetric data were acquired on SCREECH lines 1, 2, and 3. MCS, magnetic, gravity, and multibeam bathymetric data were acquired on other grid lines. (b) Bathymetric map of the area around the seaward part of SCREECH line 2 from GEBCO [*British Oceanographic Data Centre*, 2003]. The contour interval is 100 m. MCS lines are indicated with black lines and labeled by line number. The portion of SCREECH line 2 discussed in this paper lies exactly within this map (and the white box in Figure 1a). White stars mark the locations of ODP sites 1276 and 1277. Black dashed lines indicate the locations of magnetic anomalies M3 and M0 from *Shillington et al.* [2004].

Brun and Beslier, 1996; *Manatschal and Bernoulli*, 1999; *Whitmarsh et al.*, 2001a]. Additionally, other forms of depth-dependent stretching besides simple shear have been documented [*Davis and Kusznir*, 2004; *Lavier and Manatschal*, 2006]. The complexities described above make a host of complicated architectures possible.

[3] Another poorly understood part of continental breakup is the transition from late stage continental rifting to initial oceanic accretion. Recent studies of regions undergoing active rifting suggest that there can be significant temporal overlap between the final stages of breakup and the onset of seafloor spreading [e.g., *Cochran and Martinez*, 1988; *Taylor et al.*, 1999; *Fletcher and Munguía*, 2000; *Ebinger and Casey*, 2001]. This overlap might have a profound influence on the formation of new oceanic crust. For example, if new oceanic basement is accreted in a region still experiencing extension, it might be deformed by faulting away from the spreading axis [*Taylor et al.*, 1999; *Fletcher and Munguía*, 2000], and this could create unusual structural fabrics [*Taylor et al.*, 1995]. This overlap also implies that incipient oceanic accretion might modify the most seaward extended continental or transitional basement by magmatic intrusions [e.g., *Russell and Whitmarsh*, 2003]. Thus studies of oceanic material emplaced immediately adjacent to continental margins are significant to understanding the implications of overlapping rifting and drifting during the formation of a new spreading system.

[4] Nonvolcanic margins are useful places to image the structures associated with continental rupture and initial oceanic accretion due to the lack of synrift magmatism, which can mask extensional structures [e.g., *Louden and Chian*, 1999]. Limited magmatism on nonvolcanic margins is often attributed to very slow and cold rifting, where conductive heat loss suppresses melt generation [e.g., *Bown and White*, 1995], although alternative theories call for rapid strain localization and continental rupture [*Harry and Bowling*, 1999] or "cool" subcontinental geothermal gradients prior to rifting [*Reston and Phipps Morgan*, 2004]. Because of the lack of magmatism, features common on volcanic passive margins, such as seaward dipping reflections [*Mutter et al.*, 1982] and extensive igneous underplating [*Mutter et al.*, 1984; *White et al.*, 1987] are notably absent on nonvolcanic margins. Instead, seismic and drilling investigations of the Iberia rifted margin (including the Galicia Bank and the Iberia Abyssal Plain), arguably the best studied nonvolcanic margin in the world, have identified zones of exhumed continental mantle (ZECM) between thinned continental crust and "normal" oceanic crust [*Boillot et al.*, 1980, 1987; *Pickup et al.*, 1996; *Dean et al.*, 2000].

[5] Although studies of the Iberia margin have advanced our understanding of both this conjugate margin system and continental rupture in general, many questions remain concerning the symmetry of rifting processes, the manner in which altered mantle found on the Iberia margin was denuded [*Boillot et al.*, 1988; *Sibuet*, 1992; *Krawczyk and Reston*, 1995; *Reston et al.*, 1995; *Whitmarsh et al.*, 2001a], and the style of initial oceanic accretion [*Malod et al.*, 1993; *Whitmarsh et al.*, 2001a]. Some of these questions can be addressed by investigating the conjugate Newfoundland nonvolcanic margin. Previous studies of this margin have identified a section of basement of uncertain affinity between
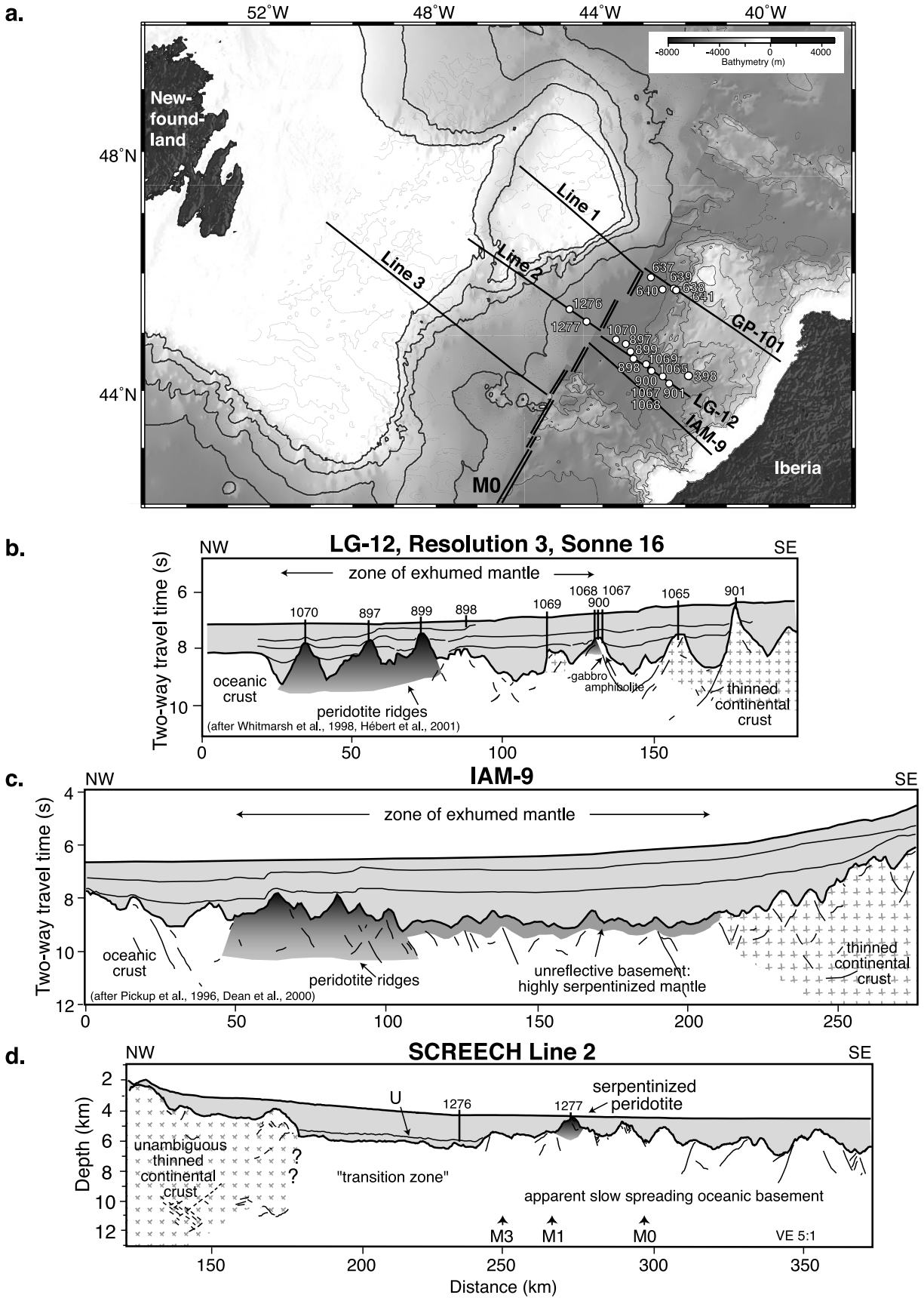
a.

b.

LG-12, Resolution 3, Sonne 16

c.

IAM-9

d.

SCREECH Line 2

Figure 2

continental and oceanic basement (i.e., "transitional" basement) [e.g., *Sullivan and Keen*, 1978; *Keen and de Voogd*, 1988; *Tucholke et al.*, 1989; *Srivastava et al.*, 2000], and determining the origin of this basement is critical to understanding the evolution of the rift.

[6] In this paper, we present new results from the SCREECH study (Studies of Continental Rifting and Extension on the Eastern Canadian Shelf), a seismic experiment consisting of three major transects across the Newfoundland nonvolcanic margin (Figure 1). We focus on multichannel seismic (MCS) reflection data from SCREECH line 2, which crosses Ocean Drilling Program (ODP) Leg 210 sites 1276 and 1277 [*Tucholke et al.*, 2004] (Figure 1) and is conjugate to the ODP Leg 149/173 transect on the Iberia margin [*Srivastava et al.*, 2000] (Figure 2). Prestack depth migrations of MCS reflection data from SCREECH line 2 and the surrounding gridlines constrain the evolution of the Newfoundland-Iberia margin pair in the following ways:

[7] 1. Unambiguous extended continental crust on Newfoundland includes very few crustal-scale normal faults in contrast to the Iberia margin, suggesting an element of depth-dependent stretching during the late stages of extension.

[8] 2. Transitional basement off Newfoundland also has different seismic reflection characteristics from much of the ZECM off Iberia, implying further asymmetry between the two margins. The coincident velocity model created from wide-angle data tentatively implies that the landward ∼55 km of transitional basement is thinned continental crust, and the seaward ∼25 km is serpentinized peridotite [*Van Avendonk et al.*, 2006].

[9] 3. Amagmatic rifting was followed by slow seafloor spreading, resulting in significantly faulted, high-topography (1–1.5 km) oceanic basement. In the remainder of this paper, we will refer to basement seaward of the last unambiguous continental block and landward of magnetic anomaly M3 as the "transition zone" or transitional basement; we discuss various interpretations for transitional basement in sections 5.4 and 6.2. Basement seaward of M3 will be referred to as "apparent oceanic basement;" however, where it has been drilled at ODP Site 1277, mantle peridotites were recovered [*Shipboard Scientific Party*, 2004b]. Petrology and geochemical analyses will ultimately determine the origin of these peridotites (subcontinental vs. oceanic) [*Müntener et al.*, 2005]; we discuss the implications of mantle rocks for the incipient oceanic accretion system in section 6.3. Ages associated with magnetic anomalies are taken from the geologic timescale of *Gradstein et al.* [2004].

2. Geologic Background and Previous Work

2.1. Opening of the North Atlantic Ocean

[10] The Eastern Canadian passive margin, including the Grand Banks and the Flemish Cap, consists of a series of terranes accreted to the Paleozoic margin of North America during the closure of the Iapetus Sea [*Haworth and Lefort*, 1979; *Williams*, 1984, 1995]. Newfoundland and Iberia underwent two primary stages of continental stretching prior to separation. The first of these occurred in the Late Triassic to Early Jurassic and resulted in the formation of rift basins throughout the Grand Banks (e.g., Carson-Bonnition, Jeanne d'Arc, Orphan, Flemish Pass) and along the corresponding European margins [*Tankard and Welsink*, 1989; *Murillas et al.*, 1990]. On the Grand Banks, these basins are typically half grabens bound by seaward dipping listric faults. Many of these basins contain a stratigraphic record of events since the first phase of rifting in the Triassic, and thus provide valuable insights into the extensional history of the area [*Enachescu*, 1988].

[11] A second Late Jurassic to Early Cretaceous phase of continental rifting is thought to have culminated in the initial accretion of oceanic crust sometime between the Valanginian (∼140 Ma) and Aptian (∼125 Ma) [*Tankard and Welsink*, 1989; *Tucholke et al.*, 1989; *Louden and Chian*, 1999; *Srivastava et al.*, 2000]. The earliest, generally accepted magnetic anomaly identifications in the vicinity of the conjugate data sets discussed in this paper are M5–M3 (∼131–127 Ma) off Iberia [*Whitmarsh and Miles*, 1995; *Russell and Whitmarsh*, 2003] and M3 or M1–M0 (∼130–125 Ma) off Newfoundland [*Tucholke and Ludwig*, 1982; *Sullivan*, 1983], although alternative interpretations suggest that the earliest spreading anomalies might be as old as ∼M15 (∼141 Ma) at the latitude of our study area [*Srivastava et al.*, 2000]. Estimating the timing of breakup using magnetic data is complicated by the low amplitudes of anomalies in this region and difficulty in their correlation along strike [*Srivastava et al.*, 2000; *Russell and Whitmarsh*, 2003]. The calculations of *Srivastava et al.* [2000] yield initial spreading half rates of 6.7 mm/yr, slower than the spreading half rates currently seen on the Mid-Atlantic Ridge (10–15 mm/yr) [e.g., *Tucholke et al.*, 1997] and sufficiently slow that the amount of igneous crust would be reduced or absent compared with fast spreading oceanic crust [e.g., *Bown and White*, 1994].

Figure 2. (a) Reconstruction of the Newfoundland-Iberia rift at magnetic anomaly M0 based on the rotation poles of *Srivastava et al.* [2000] and modified from *Hopper et al.* [2006]. White dots and text mark the locations of drill sites from Deep Sea Drilling Program Leg 47 and ODP legs 103, 149, 173 and 210. Black lines mark the locations of seismic profiles on each margin discussed in the text, including SCREECH lines 1, 2, and 3 (Newfoundland); line IAM-9; and line LG-12 (Iberia). Bathymetry taken from GEBCO [*British Oceanographic Data Centre*, 2003]. (b) Cartoon of structure along the ODP 149/173 transect based on drilling and seismic lines LG-12, Resolution 3 and Sonne 16, modified after *Whitmarsh et al.* [1998] and *Hébert et al.* [2001]. (c) Cartoon of structure along IAM-9 based on *Pickup et al.* [1996] and *Dean et al.* [2000]. (d) Cartoon of major structures along SCREECH line 2 based on drilling results and the prestack depth migration shown in Foldout 1. In all cartoons, dark grey-black shading indicates serpentinized peridotite associated with drilled basement highs; depths and extents are diagrammatic. Small crosses indicate drilled or interpreted continental crust, and light grey shading corresponds to unreflective upper 0.5 s of basement in the ZECM on IAM-9.

2.2. Previous Work on the Iberia Margin

[12] The Iberia margin is undoubtedly the best studied nonvolcanic margin in the world. Three ODP legs (103, 149, 173) have drilled the Iberia Abyssal Plain and Galicia Bank, and numerous geophysical and diving studies have also been conducted in this area (e.g., Figure 2). These studies have consistently revealed serpentinized mantle between continental and oceanic crust [*Boillot et al.*, 1987], although the width of this zone varies along the margin, decreasing significantly from south to north. The petrology and geochemistry of mantle rocks from the ZECM recovered by drilling or submersible diving demonstrate a "less depleted" signature in the landward section with an increasing "depleted" or asthenospheric component farther seaward [*Beslier et al.*, 1990; *Beard and Hopkinson*, 2000; *Skelton and Valley*, 2000; *Abe*, 2001; *Hébert et al.*, 2001]. Additionally, exposed peridotite includes minor gabbros that are likely derived from the lower continental crust [e.g., *Cornen et al.*, 1999; *Hébert et al.*, 2001]. Mylonitic structures in these peridotites appear to have developed under lithospheric conditions and indicate normal sense movement in an E-W direction, which is consistent with the denudation of peridotites at the rift axis during extension [e.g., *Beslier et al.*, 1990]. The emplacement of subcontinental peridotites may have occurred along low-angle detachment faults [e.g., *Krawczyk et al.*, 1996] or concave-down rolling-hinge faults [e.g., *Whitmarsh et al.*, 2001a]. Landward of the ZECM, large normal faults dissect thinned continental crust; at the seaward limit of continental crust, some high-angle normal faults appear to terminate at low-angle surfaces interpreted as either rolling-hinge or detachment faults [*Whitmarsh et al.*, 2001a].

2.3. Previous Work on the Newfoundland Margin

[13] The detection of denuded subcontinental mantle and possible detachment and/or rolling-hinge faults on the Iberia margin immediately raises the question of the origin and characteristics of transition zone basement on the Newfoundland margin. Previous geophysical studies recognized a section of basement of uncertain affinity between apparent oceanic and continental basement on the Newfoundland margin [*Keen et al.*, 1989; *Tucholke et al.*, 1989; *Reid*, 1994; *Srivastava et al.*, 2000]. The absence of well-defined magnetic anomalies, the unusual appearance of this basement in MCS sections, and limited seismic refraction data have allowed three possibilities for the origin of the transition zone to persist: (1) thinned, possibly intruded, continental crust [*Tucholke and Ludwig*, 1982; *Enachescu*, 1988; *Tucholke et al.*, 1989; *Enachescu*, 1992], (2) oceanic crust [*Sullivan and Keen*, 1978; *Keen and de Voogd*, 1988; *Srivastava et al.*, 2000], and (3) subcontinental, serpentinized mantle [*Reid*, 1994; *Tucholke et al.*, 2006].

[14] Interpretations of a continental origin of this basement rely largely on the correlation of strata from the continental shelf out into the basin and the relationship of these strata to the underlying basement. Of particular interest is the "U" reflection, which has been correlated to the prominent mid-Cretaceous Avalon unconformity observed in rift basins on the Grand Banks, including the Jeanne d'Arc basin [e.g., *Tucholke et al.*, 1989]. Some interpretations of MCS reflection data collected in the Newfoundland Basin

suggest that U locally truncates the underlying basement, implying a period of subaerial erosion [*Tucholke and Ludwig*, 1982; *Tucholke et al.*, 1989]. The close temporal association of the Avalon unconformity and the estimated timing of breakup made U a candidate for the breakup unconformity [*Tucholke and Ludwig*, 1982; *Tucholke et al.*, 1989]. Breakup unconformities are traditionally thought to result from subaerial erosion associated with the uplift of rift boundaries during continental rupture [*Braun and Beaumont*, 1989]. Further support for a continental origin is supplied by plate reconstructions, some of which do not allow closure of the margins beyond anomaly $\sim$M3–M1 [*Vink*, 1982; *Enachescu*, 1988; *Tucholke et al.*, 1989].

[15] Evidence for oceanic crust immediately seaward of unambiguous continental crust is derived from the interpretation of magnetic data [*Sullivan and Keen*, 1978; *Srivastava et al.*, 2000] and the interpretation of a continent-ocean boundary at the base of the continental slope in seismic reflection data [*Sullivan and Keen*, 1978; *Keen and de Voogd*, 1988]. Seismic reflection data collected during LITHOPROBE imaged landward dipping intracrustal features at the base of the continental slope, which *Keen and de Voogd* [1988] attributed to magmatic underplating at the continent-ocean boundary. The identification of some lineations in magnetic data have led some workers to interpret crust seaward of the base of the continental slope as oceanic [*Srivastava et al.*, 1988, 2000], although the low amplitudes of these anomalies make their interpretation controversial.

[16] The discovery of serpentinized subcontinental mantle by drilling on the Iberia margin led some workers to suggest that exhumed subcontinental, serpentinized peridotite is also present on the Newfoundland margin [*Reid*, 1994]. *Reid* [1994] detected a 50-km-wide zone of $\sim$3- to 4-km-thick crust with velocities of $\sim$7.2–7.6 km/s overlain by a thin layer ($\sim$1 km) with lower velocities (4.5–5.0 km/s) in the southern Newfoundland Basin, which he interpreted as serpentinized peridotite overlain by a basaltic carapace. More recently, *Tucholke et al.* [2006] interpreted seismic stratigraphy and structure together with results from drilling to suggest that "true" seafloor spreading did not begin until near the end of the Aptian ($\sim$112 Ma) and that much of the transition zone (and apparent oceanic basement) is exhumed mantle. Uncertainties concerning the affinity of crust on Newfoundland discussed above clearly bear on the evolution of the Newfoundland-Iberia conjugate margin pair and can be addressed by new seismic data collected during the SCREECH experiment, part of which is presented in this paper, and by new drilling results from ODP Leg 210.

3. SCREECH Experiment

[17] In July–August 2000, more than 3000 km of multichannel seismic (MCS) reflection data, magnetic, gravity and multibeam bathymetric data and 1000 km of wide-angle refraction data were acquired off the coast of Newfoundland during the SCREECH experiment (Figure 1). This was a two-ship program, with MCS, magnetic, gravity and bathymetric data acquired by the R/V *Maurice Ewing* (Cruise 00-07), and wide-angle reflection/refraction data acquired by ocean bottom seismometers/hydrophones (OBS/H) deployed and retrieved by the R/V *Oceanus* (Cruise 359-2). Coincident MCS reflection and wide-angle seismic reflection/refraction
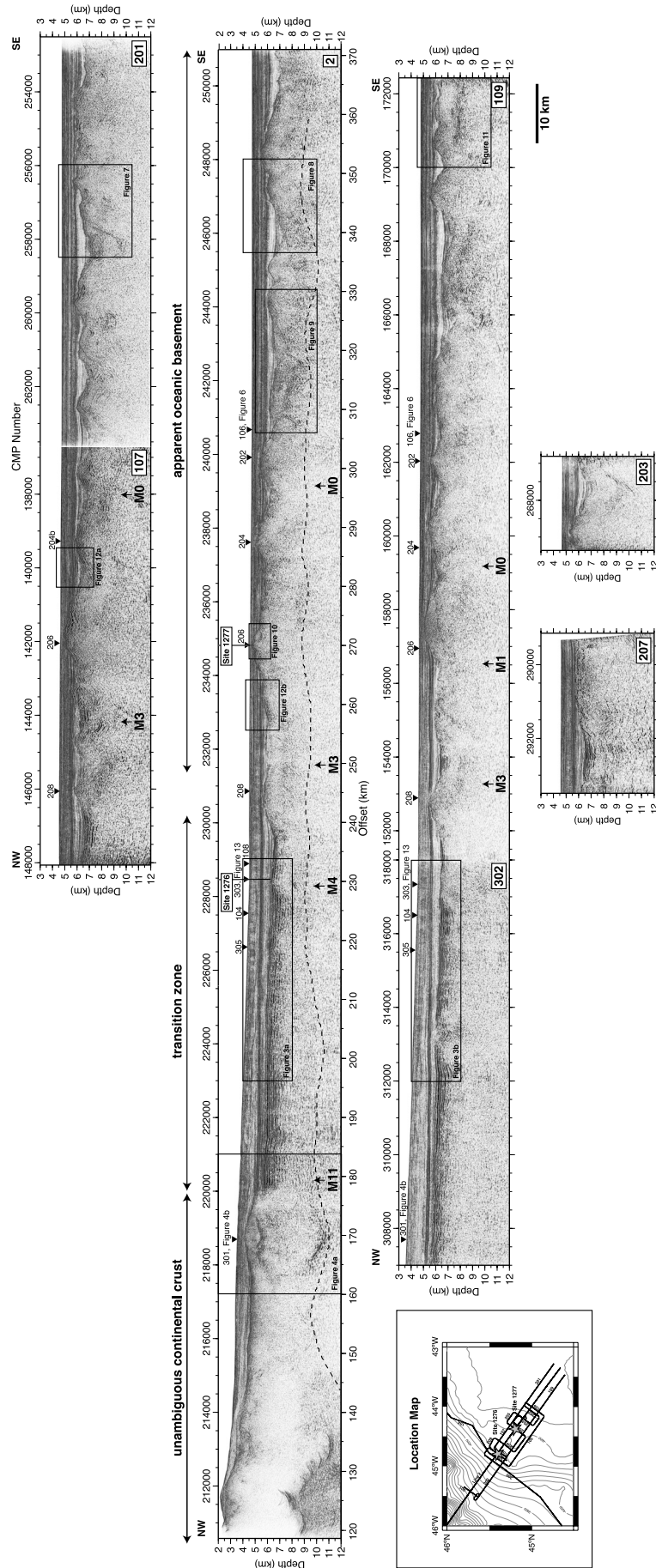
Foldout 1. Prestack depth migrations of SCREECH lines 107/201, 2, 302/109, 203, and 207 (locations shown in inset and in Figure 1b). Profiles are arranged from northeast (top) to southwest (bottom). The dotted black line on line 2 indicates the depth to the Moho derived from velocity modeling of wide-angle reflection/refraction data [*Van Avendonk et al.*, 2003]. The distance scale at the base of SCREECH line 2 is the same as the scale used to present a coincident wide-angle velocity model by *Van Avendonk et al.* [2006]. Magnetic anomalies identified by *Srivastava et al.* [2000] are shown with black arrows. Black triangles show intersections with strike lines. The locations of later seismic figures taken from dip lines are indicated with black boxes and labels. The locations of seismic figures taken from strike lines are indicated by labels where they cross dip lines.

data were collected along three primary transects off the coast of Newfoundland (Figure 1). Additional MCS data were also collected around each of the primary transects, including at the locations of both ODP Leg 210 drill sites. MCS data were recorded on the 6-km, 480-channel streamer of the R/V *Maurice Ewing*; these data have a sampling interval of 4 ms, a shot spacing of 50 m, a fold of 60, a recording length of ∼16 s, and a common midpoint (CMP) spacing of 6.25 m. The tuned, 8540 in³ 20-gun array of the R/V *Maurice Ewing* provided a seismic source for both wide-angle and MCS seismic data.

[18] SCREECH lines 1 and 2 were collected in positions conjugate to seismic and drilling transects on the Iberia margin (ODP Leg 103 and ODP legs 149/173, respectively) based on the plate reconstruction of *Srivastava et al.* [2000] (Figure 2). Taken together, the geophysical data sets collected on the Newfoundland and Iberia margins constitute the most complete information available for conjugate margins of a nonvolcanic rift.

[19] SCREECH line 2 and the attending gridlines are the subject of this paper. Line 2 reaches across the edge of the Grand Banks, Flemish Pass, Beothuk Knoll, the transition zone, and continues seaward of magnetic anomalies M3 and M0 (∼130–125 Ma). We discuss the seaward ∼250 km of SCREECH line 2 together with the accompanying the MCS gridlines that lie in this region.

4. Prestack Depth Migration Method

[20] To characterize sediments and basement structures, prestack depth migrations (PSDM) of line 2 and all surrounding lines were completed. We chose prestack migration to avoid smearing of data associated with common midpoint (CMP) sorting and stacking, which assumes reflections are generated by horizontal layering. Depth migration also yields accurate dips of in-line structural features. Initial processing was completed using Paradigm's FOCUS 5.0. Minimum phase band-pass filters limited the data to 10–100 Hz. Almost no other refinements to prestack data were required because the air gun array of the R/V *Maurice Ewing* was well tuned. Velocity model building and prestack depth migration were completed in Paradigm Geophysical's prestack migration tool, Geodepth. The initial velocity model is built by ray tracing and image focusing of CMP gathers along user-selected horizons. Predicted curves for various interval velocities, determined by ray tracing, are compared to seismic data, and semblance is computed. Because the shape of a reflection from a given interface depends on variations in thickness and velocity of all overlying layers, the velocity model is created from the top down. Interval velocities are then smoothed, and the resulting velocity section is used to create depth-migrated gathers by employing a migration based on the Kirchoff summation formula, where traveltimes to each subsurface point are based on a numerical solution of the Eikonal equation. These depth-migrated common reflection point (CRP) gathers are stacked to generate an initial depth section. Interval velocities are refined by picking the residual moveout of reflections chosen for analysis. The velocity model is updated by tomographic inversion of RMS picks, and Kirchoff depth migration is repeated. Finally, mutes are applied to depth-migrated gathers to remove data at far offsets that are affected by stretching during migration,

and the muted gathers are stacked to produce final prestack depth-migrated images (e.g., Foldout 1).

[21] Velocity model building is the most critical step in prestack depth migration. In our study, the sedimentary section was subdivided into three layers on nearly all lines, except those that have higher basement topography and do not contain a full sedimentary section. The average velocities of each of these layers are ∼1.8 km/s (above A^u), ∼2.1 km/s (below A^u) and ∼2.7 km/s (below U) (Figure 3). Velocities in the uppermost basement (0.5 km) are usually between 3–5 km/s. Below this depth, velocities were largely taken from the wide-angle velocity models of *Nunes* [2002] and *Van Avendonk et al.* [2003] because few intracrustal reflections are present, and the limited aperture of the MCS data renders velocities at this depth inaccurate. However, where intracrustal reflections were identified, velocities from PSDM agree well with those from wide-angle data [*Nunes*, 2002; *Van Avendonk et al.*, 2006].

5. Results of PSDM

[22] This section presents a description and interpretation of sedimentary and basement features observed in prestack depth migrations of SCREECH line 2 and gridlines. Selected, margin-normal, seismic sections are shown in Foldout 1. Basement features are described in three zones: (1) unambiguous extended continental crust, (2) transition zone, and (3) apparent oceanic basement. We first discuss features in the continental and oceanic domains; the transition zone is considered last because its characteristics are compared to those of apparent oceanic basement and continental crust. The extent of each of these crustal domains is indicated above the seismic section of SCREECH line 2 in Foldout 1.

5.1. Sedimentary Reflections

[23] Several prominent reflections extend across the entire region covered by SCREECH line 2 and the surrounding gridlines and throughout the remainder of the Newfoundland Basin (e.g., Foldout 1 and Figure 3). Some of these horizons have been recognized in previous seismic investigations, and they have been correlated to strata on the continental shelf, in the North Atlantic Basin to the south, and to seismic stratigraphic units on the Iberia margin [*Tucholke et al.*, 1989, 2004]. Laterally continuous horizons, particularly those from deeper levels where the conjugate margins were closer together and experienced similar depositional histories, are important because they constrain on the style and relative timing of the emplacement of the underlying basement.

[24] The uppermost reflection within the bright package of reflections at ∼5.25 km depth has been correlated to the A^u unconformity, which has been mapped in the western North Atlantic south of the Newfoundland Basin [*Tucholke and Mountain*, 1979] (Figure 3). The reflection can be traced throughout the seaward portion of this data set, over both transitional and oceanic basement. Seismic core correlation at ODP Leg 210 Site 1276 indicates that A^u and the underlying collection of bright reflections correspond to interlayered mudstones and carbonate-cemented sandstones that are Eocene to Paleocene in age [*Shipboard Scientific Party*, 2004a; *Shillington et al.*, 2006].
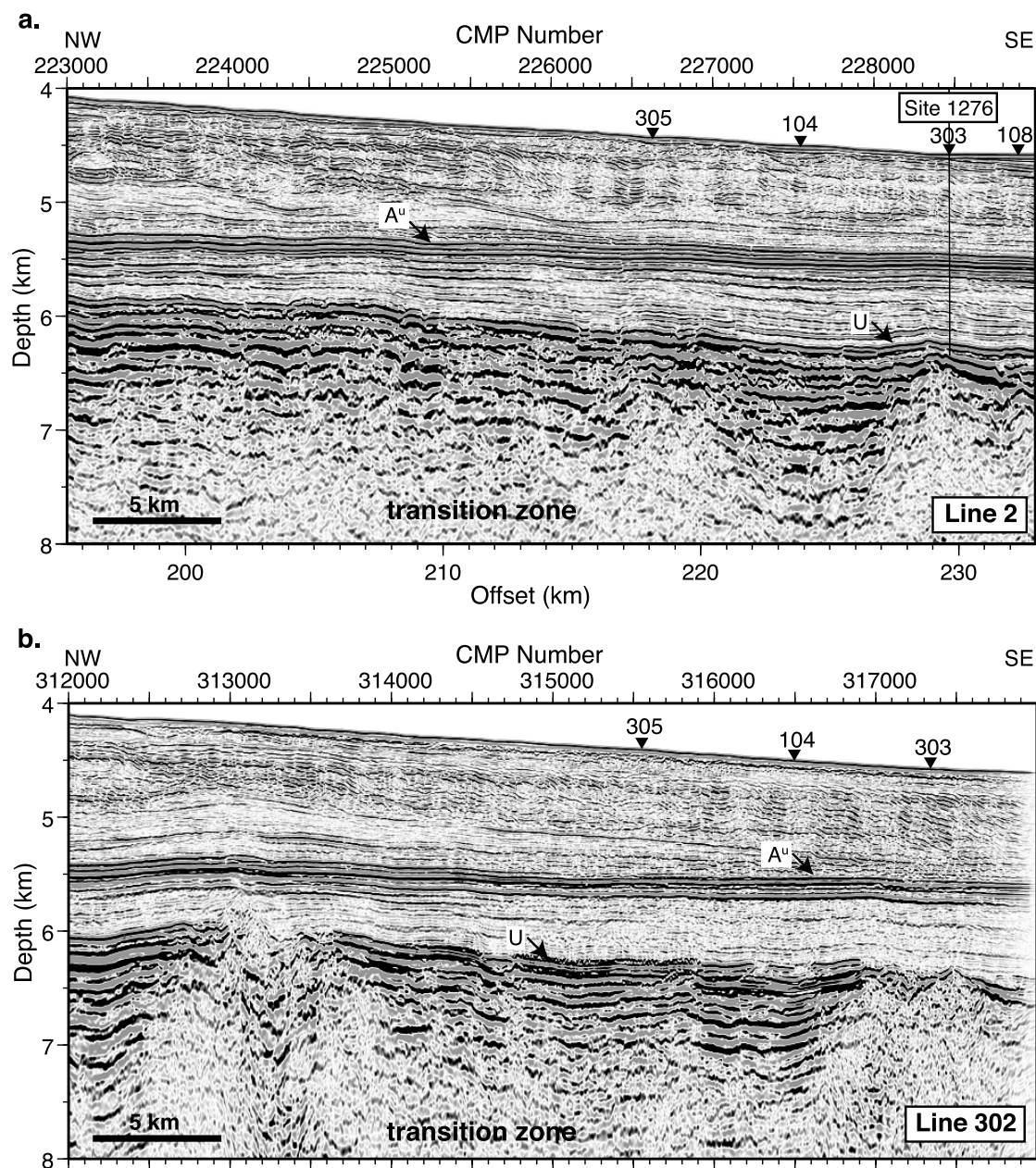
Figure 3. Prestack depth migrations (a) of line 2 across Site 1276 and (b) of parallel line 302 to the southwest. See Figure 1b and Foldout 1 for location. The locations of prominent sedimentary reflections A^u and U [*Tucholke et al.*, 2004] are labeled. The offset scale at the base of Figure 3a is the same as that used to present the coincident velocity model of *Van Avendonk et al.* [2006].

[25] Beneath these bright reflections, a 0.5- to 0.9-km-thick sedimentary unit with comparatively low amplitude reflections is observed. This unit corresponds to Albian to Turonian (~110–90 Ma) mudstones with high deposition rates interspersed with occasional turbidites where it was drilled at Site 1276 [*Shipboard Scientific Party*, 2004a; *Shillington et al.*, 2006]. The thickness of this unit appears to increase seaward, from ~0.5 km (~CMP 221000, Foldout 1) to ~0.9 km (~CMP 229500, Foldout 1). This sedimentary package is interrupted by basement highs seaward of magnetic anomaly M3.

[26] Another package of bright reflections including the U reflection is observed beneath this relatively transparent unit. Previous work identified U as a candidate for the breakup unconformity because its estimated age was close to the timing of assumed breakup (Aptian), it can be traced over a large region, and it appears to locally truncate basement features in earlier seismic data sets [*Tucholke and Ludwig*, 1982; *Tucholke et al.*, 1989]. In this data set, it is not observed to truncate basement; instead, U laps onto basement highs (e.g., Figure 3). On the seaward end of the SCREECH lines, a reflection with depth and reflection characteristics similar to U is observed in some deep basins between basement highs (e.g., CMPs 242000–243000 and CMPs 245500–246500, Foldout 1); this may be U, although it cannot be tied directly to U above transitional basement

farther landward. Drilling at Site 1276 did not penetrate to transitional basement, but the interval corresponding to U and an underlying bright reflection was cored (1613–1723 m below seafloor (mbsf)), and two diabase sills, separated by early Albian sediments, were encountered (Figure 3) [*Shipboard Scientific Party*, 2004a; *Shillington et al.*, 2006]. No unconformities or hiatuses were identified in this interval; instead, deep-water sediments as old as ~112 Ma constitute this sedimentary section.

[27] Beneath U and associated bright reflections in the transition zone, it is difficult to identify the top of basement and thus to define the character of immediately overlying sediments. However, observed reflections do not appear to include rotated or splayed horizons that might indicate the presence of prerift or synrift sediments over transitional basement. Basement troughs at the seaward end of the SCREECH lines appear to contain locally thicker (and thus possibly older) sediments beneath U, although this may be an artifact caused by increased accommodation space in the rough basement topography or a function of better imaging. Splayed and rotated horizons indicative of synrift sediment deposition are also not observed in these troughs.

5.2. Extended Continental Crust

[28] Only a small portion of the reflection data that crosses unambiguous continental crust is presented here. This section of SCREECH line 2 displays landward and seaward dipping middle and lower crustal reflectivity (~CMPs 213250–220000, line 2; ~CMPs 301000–303000, line 301; Foldout 1 and Figure 4) similar to that observed in previous investigations of Precambrian and Paleozoic rocks in the Avalon Zone of the Appalachian Orogen [*Keen et al.*, 1987; *Keen and de Voogd*, 1988; *Hall et al.*, 1998, 2002] and on adjacent SCREECH transects [*Hopper et al.*, 2004; *Hopper et al.*, 2006; *Lau et al.*, 2006a, 2006b]. Tilted sediments, most likely prerift, are observed atop blocks of continental crust, particularly on the most seaward continental crustal block (Figure 4); velocity analysis conducted for prestack depth migration yields velocities of 3.5–4 km/s for sediments in this interval. Another notable characteristic of unambiguous continental crust on line 2 is the near absence of obvious extensional structures that might have accommodated thinning, such as crustal-scale normal faults. This stands in direct contrast to the plethora of seaward dipping normal faults imaged on the Iberia margin on conjugate seismic line LG-12 [*Krawczyk et al.*, 1996; *Pickup et al.*, 1996; *Whitmarsh et al.*, 1996].

[29] The pattern of sedimentary, intracrustal and Moho reflections in the continental block at CMPs 217500–220000 (Figure 4) makes this one of the most complicated sections of crust on line 2. The brightest Moho reflections within the line 2 grid occur here; high amplitudes extend laterally over ~15 km on line 2 and over the entire length of line 301. The Moho also appears to have complicated topography in this section, with dips of ~10° on both strike and dip lines. On line 2, the Moho dips seaward in some sections (CMPs 217500–218500, Figure 4a) and landward elsewhere (CMPs ~218500–219500). These features are consistent with the trend of Moho topography observed in the coincident velocity model created from wide-angle seismic data [*Van Avendonk et al.*, 2003] (dotted lines, Foldout 1 and Figure 4). The depth discrepancy between
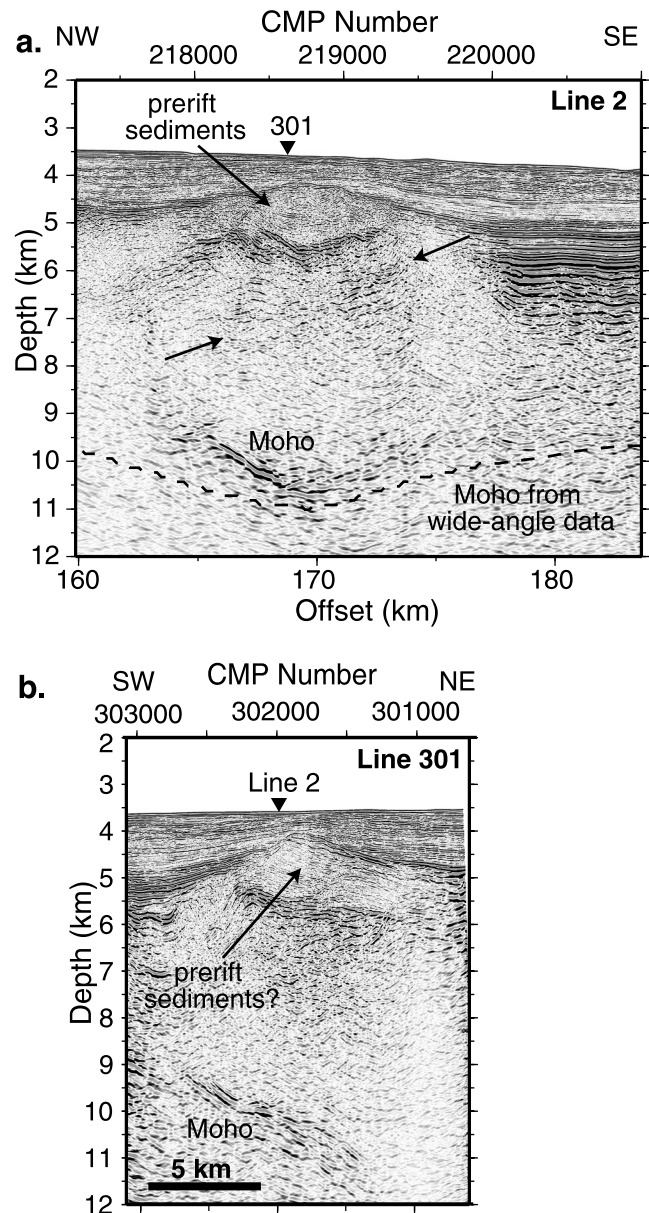
Figure 4. Prestack depth migrations of lines 2 and 301 where they cross the most seaward block of unambiguous continental crust. See Figure 1b and Foldout 1 for locations. Note the bright Moho with complex topography on both lines at a depth of ~10 km. Also note the reflections capping this block, which are likely prerift sediments. Seismic sections are plotted with a vertical exaggeration of 2:1. (a) Section of prestack depth migration of line 2. Arrows within the crust indicate possible landward dipping reflections discussed in the text. The Moho topography observed in the prestack depth migration is similar to that derived independently from velocity modeling of wide-angle reflection/refraction data by *Van Avendonk et al.* [2003], which is indicated with a dashed black line. The offset scale at the base of the figure is the same as that used to present the coincident velocity model of *Van Avendonk et al.* [2006]. (b) Prestack depth migration of line 301.
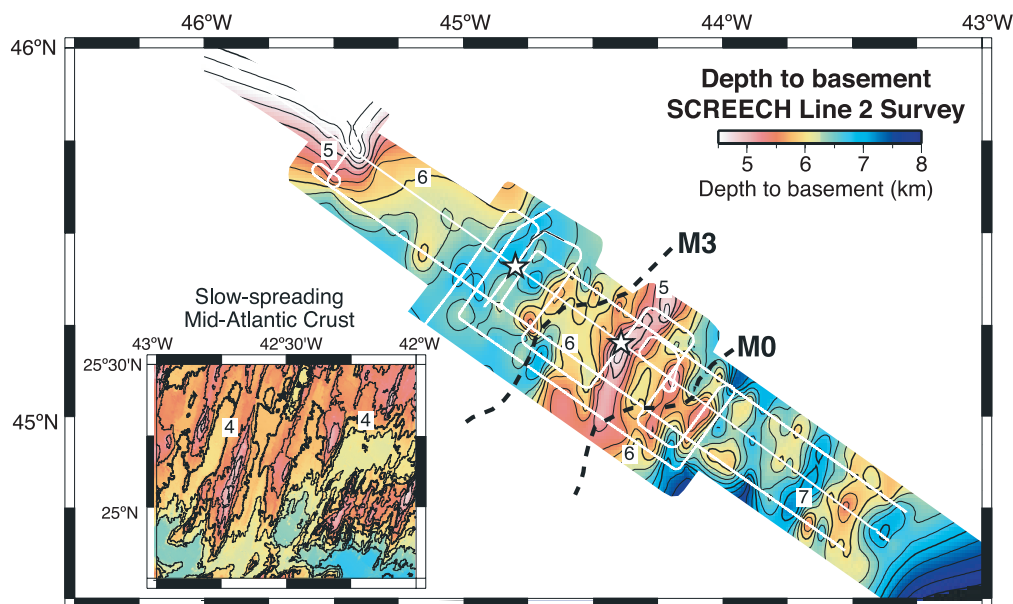
Figure 5. Contour map of basement depth in kilometers below sea level from interpretations of prestack depth migrations of the SCREECH line 2 survey. Note the margin-parallel basement ridges in the most seaward section of the survey. Inset shows contoured bathymetry from young, slow spreading oceanic crust produced at the Mid-Atlantic Ridge between the Kane and Atlantis fracture zones for comparison. The color scale is the same as that used to plot depth to basement around the line 2 survey but is shifted up by 1.75 km, and the map scale is the same. Note the similar amplitude and wavelength of basement ridges between the two data sets. Black dashed lines indicate locations of magnetic anomalies M3 and M0 from *Shillington et al.* [2004].

the wide-angle Moho and reflection Moho likely results from differences in the crustal velocities used in this location; *Van Avendonk et al.* [2003] have a small section of high velocities in the lower crust here that were not included in the PSDM velocity model, and thus the wide-angle Moho is deeper.

[30] This crustal block might also be interpreted as a synrift magmatic intrusion or a serpentinite ridge, but we do not favor these interpretations for several reasons. First, there is not a significant structural boundary between this block of crust and adjacent continental crust, as would be expected if it corresponded to a magmatic or peridotite ridge. Second, the interpreted occurrence of prerift sediments precludes the interpretation of this block as a magmatic edifice or peridotite ridge (e.g., Figure 4b). Finally, the coincident wide-angle data also show consistent lateral crustal velocity structure between this block and adjacent crust to the west (~5.5–7.5 km/s). We therefore conclude that this block is continental.

[31] The occurrence of a bright Moho reflection in this location is consistent with observations by *Keen and de Voogd* [1988], who also identified bright Moho reflections at the same approximate two-way traveltime beneath the base of the continental slope on nearby line 85-4. They attributed the high amplitude of the Moho reflection to magmatic underplating that preceded the initiation of seafloor spreading and interpret it as marking the continent-ocean boundary. An alternative interpretation is that the reflection corresponds to a tectonic boundary (e.g., shear zone), which might produce a strong impedance contrast. A tectonic interpretation is supported by the presence of shallower, landward dipping reflections within the block, which are discernable at depths of ~6–7 km (Figure 4a, ~CMPs 218500–219500).

5.3. Apparent Oceanic Basement

[32] The outer end of the SCREECH line 2 grid reaches east of magnetic Anomaly M3 (~130 Ma) and thus is presumed to cross onto "oceanic" basement [*Tucholke and Ludwig*, 1982; *Srivastava et al.*, 2000; *Russell and Whitmarsh*, 2003]. Aside from the identified magnetic anomalies, two features of this crust are consistent with an oceanic origin. First, the high-amplitude basement topography and dipping intrabasement reflections interpreted as faults resemble those of slow spreading ocean crust (e.g., Figure 5). Second, even though peridotite basement was drilled near anomaly M1 at ODP Site 1277 [*Shipboard Scientific Party*, 2004b], very slow spreading rates could account for the mantle exposure and the lack of significant magmatism [*Bown and White*, 1994]. However, petrology and geochemical analyses of Site 1277 peridotites suggest that they may have "inherited" characteristics [*Müntener et al.*, 2005], implying that not all material seaward of M3 can be considered purely "oceanic," particularly between M3 and M1 (e.g., CMPs 230000–235000, 240–270 km, Foldout 1). The implications of work on Site 1277 are discussed further in section 6.3.

[33] Several different styles of accretion processes might explain the high-amplitude basement topography and faulting observed within apparent oceanic basement in this data

set: (1) intermittent magmatic addition; (2) the accommodation of plate separation by extensional faulting in the absence of magmatism; or (3) a combination of the two [*Cannat et al.*, 2003]. Each of these carries specific predictions for the relationship between basement and Moho topography, faulting, and other observations that can be gleaned from seismic reflection profiles. To further characterize the style of initial accretion, we describe basement topography, intrabasement reflections, reflectivity in the upper 0.5 km of basement, and seismic Moho, and we compare those characteristics to observations from geophysical surveys of slow spreading oceanic crust, Iberia and to initial results from drilling at Site 1277 during ODP Leg 210 [*Shipboard Scientific Party*, 2004b].

5.3.1. Basement Topography

[34] Prestack depth migrations of gridlines around SCREECH line 2 reveal a pattern of basement topography that is characterized by high-amplitude (~1 km) margin-parallel ridges (Figure 5). Individual basement highs can be correlated between lines 2, 105, 107, 109, and 201 over along-strike distances of ~30 km (Foldout 1 and Figure 5). For example, a continuous basement ridge can be seen on lines 107 (~CMP 142000), 2 (~CMP 234800) and 109 (~CMP 157600) (Foldout 1). Considerably less topography (~200 m) exists on margin-parallel cross lines (e.g., Figure 6). Figure 5 shows the results of gridding and contouring picks of the top of basement from prestack depth migrations in the SCREECH line 2 survey; the resulting image clearly illustrates the existence margin-parallel ridges. The amplitude and wavelength of these basement ridges are similar to ridge-parallel basement topography observed in slow spreading oceanic crust [*Malinverno*, 1991; *Ranero et al.*, 1997] (Figure 5). Spreading rate is thought to exert a primary control on basement morphology, with oceanic crust produced by fast spreading ridges having a smoother basement surface than crust produced by slow spreading ridges [e.g., *Malinverno*, 1991; *Malinverno and Cowie*, 1993]. Basement morphology in slow spreading oceanic crust is typically attributed to either faulting, intermittent volcanic construction, or an interplay of both processes [*Smith and Cann*, 1993; *Macdonald et al.*, 1996]. If intermittent volcanic construction is the primary process controlling basement topography, Moho and basement topography should be anticorrelated and basement ridges should be fairly symmetric [*Cannat et al.*, 2003], because they would represent magmatic addition that results in a thicker crust. However, if plate separation is more often accommodated by faulting, Moho and basement topography should be correlated and basement ridges should be asymmetric [*Thatcher and Hill*, 1995; *Macdonald et al.*, 1996; *Cannat et al.*, 2003].

[35] The observed relationship between basement and Moho topography varies within this data set. Because we do not observe a continuous Moho reflection in seismic reflection data acquired over apparent oceanic basement, we compare the Moho derived from velocity modeling of wide-angle seismic refraction data [*Van Avendonk et al.*, 2003] (shown in Foldout 1) with basement topography in the depth migration of SCREECH line 2. This comparison shows that basement topography correlates with Moho topography between ridges at 230–300 km (CMPs ~228000–240000) but is anticorrelated with the basement topography between 310 and 340 km (CMPs ~241000–246000). Seaward of
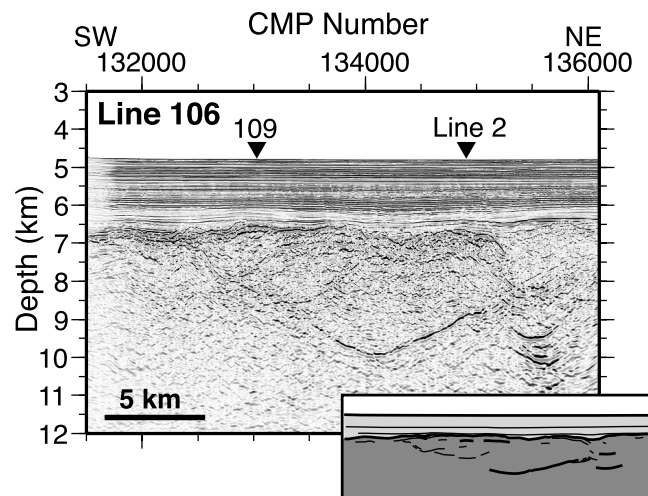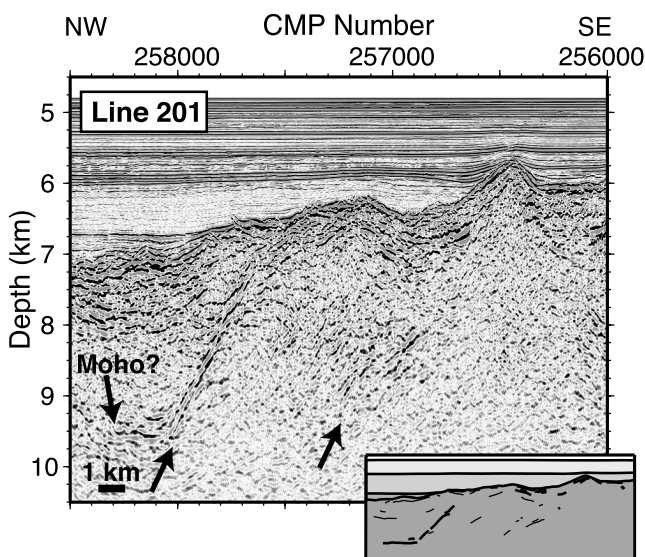

Figure 6. Prestack depth migration of margin-parallel line 106. See Figure 1b and Foldout 1 for location. Note the low basement relief on this line compared to margin-normal lines in Foldout 1. The seismic section is plotted with a vertical exaggeration of 2:1. The simplified interpretation in lower right-hand corner of the seismic section shows major features and is plotted without vertical exaggeration.

340 km, a correlation is again suggested, although much of the Moho structure in this portion of the line is unreversed, and thus poorly constrained. Basement ridges are often slightly asymmetric. For example, the seaward sides of the three basement ridges on line 2 between CMPs 234000–240500 in Foldout 1 have dips that are 2–4 degrees steeper on the seaward side than the landward side. This asymmetry is also consistent along strike; basement ridges on adjacent lines exhibit the same sense of asymmetry.

[36] Although topographic features observed on line 2 can be traced to adjacent dip lines around line 2 over distances of 20–30 km, basement roughness on SCREECH lines 1 and 3 to the north and south (Figure 1) is less pronounced [*Hopper et al.*, 2004; *Lau et al.*, 2006b]. The differences in basement topography between these lines might be explained by crustal segmentation. Previous studies indicate that the amplitude of topography and the magnitude of extension at the ends of oceanic spreading segments are stronger than at segment centers [*Goff*, 1991; *Wolfe et al.*, 1995; *Escartin et al.*, 1997; *Tucholke et al.*, 1997], possibly because magma supply is comparatively limited at segment ends. *Sibuet et al.* [2006] have suggested that a fracture zone is present ~20–30 km north of SCREECH line 2 based on a new compilation of magnetic data.

5.3.2. Intrabasement Reflections

[37] Intrabasement reflections observed in the seaward portion of the SCREECH line 2 grid exhibit a range of dips (landward and seaward at angles between 15° and 45°) and relationships to basement topography. These relationships can also be used to assess the contributions of magmatism and faulting. Most of the large-scale (>1 km) dipping features that are likely to be faults are observed on margin-normal rather than margin-parallel lines, particularly in the middle and lower crust. Many of the reflections appear to span the entire crust and terminate at Moho depths as defined by wide-

Figure 7. Close-up of prestack depth migration of part of line 201, which parallels the seaward portion of line 2. See Figure 1b and Foldout 1 for location. Landward dipping faults cross the entire crust in this section and appear to terminate at the seismic Moho. In this example, a weak, discontinuous Moho reflection can be observed, which is labeled with an arrow. Note the different topographic expression of basement where two faults (marked with black arrows) intersect the basement surface. The fault to the NW (left) accommodates little displacement at the basement surface, but the fault to the SE (right) is associated with high-amplitude basement topography. The seismic section is plotted with a vertical exaggeration of 2:1. The simplified interpretation in the lower right-hand corner of the seismic section shows major features and is plotted without vertical exaggeration.

angle data [*Van Avendonk et al.*, 2003, 2006] (Foldout 1); occasionally, these reflections can be seen to reach the Moho where its visible in reflection profiles, but do not cross it (Figure 7). This is similar to dipping reflections observed in seismic reflection profiles over Mesozoic oceanic crust around the Blake Spur Fracture Zone [*White et al.*, 1990; *Morris et al.*, 1993] and in the Canary Basin [*Ranero et al.*, 1997].

[38] The apparent orientation of intrabasement reflections varies throughout the grid of profiles around SCREECH line 2, although landward dipping features appear to be more abundant (e.g., Figures 7, 8, and 9). This is surprising given the manner in which this crust was likely emplaced. Seismic experiments over Mesozoic oceanic crust and bathymetric studies at mid-ocean ridges show that the majority of intracrustal faults dip toward the spreading axis [*Carbotte and Macdonald*, 1990; *Morris et al.*, 1993; *Carbotte and Macdonald*, 1994; *Srivastava and Keen*, 1995; *Ranero et al.*, 1997]. The variable dips observed in our data set may be explained by the continuing influence of continental extension during the emplacement of the basement or by diverse fault geometries associated with weakly magmatic accretion of slow spreading crust [*Cannat et al.*, 2003]. Notably, dipping reflections observed in apparent

oceanic basement on line IAM-9 off Iberia also commonly dip landward, as do faults that bound the peridotite ridges [*Pickup et al.*, 1996].

[39] Like the basement ridges described above, dipping intrabasement reflections can often be observed on adjacent dip lines, implying that these features might be continuous over distances of ~10 km. For example, a prominent landward dipping reflection can been seen on line 201 (CMPs 257500–258500) and to the south on line 2 (CMPs 246000–247000) at depths of ~6–9 km (Foldout 1 and Figures 7 and 8). Likewise, other dipping reflections appear to continue along strike from ~CMP 262500 on line 201 to ~CMP 241000 on line 2, and from ~CMP 261250 on line 201 to ~CMP 242750 on line 2 (Foldout 1).

[40] It is widely thought that strong basement topography in slow spreading crust is generated by faulting [e.g., *Malinverno*, 1991; *Thatcher and Hill*, 1995]. In our data set, we observe four different relationships between intrabasement reflections and basement topography: (1) dipping reflections that bound and possibly account for basement topography (Figures 7 and 8), (2) dipping reflections that intersect the basement surface within basement highs, but do not produce any offset (Figure 9), (3) dipping reflections that roughly parallel basement topography or appear to pass through it at a shallow angle (Figure 10), and (4) flat-lying reflections that do not have any apparent relationship to basement and might represent a compositional boundary (Figure 11).

[41] Topography-bounding reflections in the first category are observed (Figures 7 and 8) but are not as common as might be expected. Instead, most dipping intracrustal reflections fall into category 2. They appear to span the entire
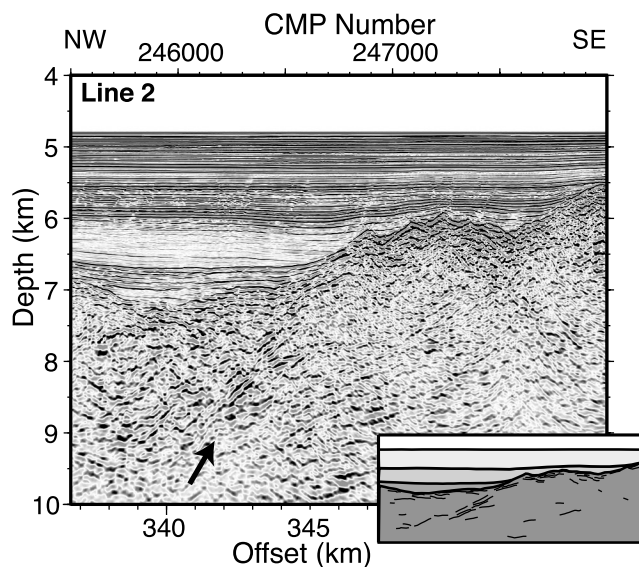
Figure 8. Close-up of prestack depth migration of the seaward end of line 2 showing an example of an interpreted fault that offsets the basement surface, indicated with a black arrow. See Figure 1b and Foldout 1 for location. The seismic section is plotted with a vertical exaggeration of 2:1. The simplified interpretation in the lower right-hand corner of the seismic section shows major features and is plotted without vertical exaggeration.
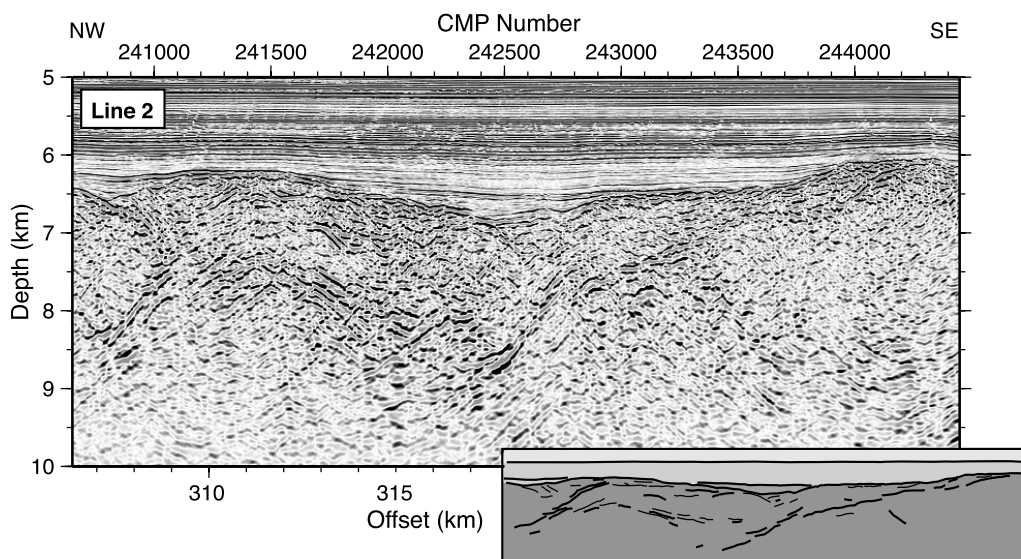
Figure 9. Close-up of prestack depth migration from the seaward end of line 2. See Figure 1b and Foldout 1 for location. At the left, a west dipping intracrustal feature appears to span the entire crust, but it does not cause offset of the basement surface. Another such dipping reflection can be observed to the right. Between these two features, a shallowly SE dipping reflection nearly parallels the basement surface and appears to be tilted and offset by the faults on either side. The seismic section is plotted with a vertical exaggeration of 2:1. The simplified interpretation in the lower right-hand corner of the seismic section shows major features and is plotted without vertical exaggeration.

"crust" as defined by wide-angle data [*Van Avendonk et al.*, 2003, 2006], and they intersect the basement surface, but do not appear to accommodate a significant amount of movement. This has also been observed in other MCS studies of oceanic crust [*Morris et al.*, 1993] and might be explained as either (1) the youngest of multiple generations of faults, which did not remain active for long enough to significantly displace the basement surface, (2) an older generation of faults that were rotated and cut by newer faults, or (3) a compositional boundary (e.g., between basalts and gabbros, or gabbros and serpentinites). The relative simplicity of these features suggests a structural (rather than compositional) origin [*Reston*, 1996].

[42] The third category of intrabasement reflection is important because it includes the structures in the basement ridge where ODP Site 1277 was drilled and serpentinized peridotites were recovered. Here, two shallow, seaward dipping intrabasement reflections are observed on the seaward side of Mauzy Ridge (Figure 10). Similar reflections that are subparallel to basement topography or lie at small angles to the basement surface can be seen on other basement highs in the SCREECH line 2 grid. These features resemble reflections observed in seismic profiles of the Mid-Atlantic Ridge on the Atlantis Megamullion [*Canales et al.*, 2004], which were interpreted as either paleodetachment faults, where the most active detachment fault corresponds to the basement surface, or as serpentinization fronts [*Canales et al.*, 2004].

[43] Finally, the fourth category encompasses other features that do not have a specific relationship to basement. For example, a few subhorizontal reflections that are too shallow to correspond to the crust-mantle boundary are observed. The character of these reflections is variable; on line 109, a comparatively thick zone of horizontal reflectivity can be observed (Figure 11). Because this feature occurs as a package of reflections rather than a simple reflection, which might be expected to result from a sharp contact such as a fault surface [*Reston*, 1996], we interpret bright horizontal packages of reflectivity to represent compositional features, such as a series of horizontal sills.

5.3.3. Reflectivity Within the Upper 0.5 km of the Basement Surface

[44] Most basement along the seaward part of line 2 is very reflective in its upper 0.5 km and relatively transparent beneath 0.5 km. Strong reflectivity in upper oceanic crust is often ascribed to variable porosity and hydrothermal alteration within basalt flows and sills [*Purdy*, 1987; *Wilkens et al.*, 1991; *Minshull and Singh*, 1993]. However, at ODP Site 1277, only 30 m of basalt and mixed debris containing clasts of basalt, gabbro and peridotite were recovered above a serpentinized peridotite basement [*Shipboard Scientific Party*, 2004b]. Because Site 1277 is located above a basement high exhibiting strong reflectivity in its upper part, the blanket interpretation of bright reflectivity within the upper 0.5 km of basement as being indicative of volcanic and intrusive rocks typical of upper oceanic crust on SCREECH line 2 is precluded.

[45] We can identify two varieties of reflectivity in the upper 0.5 km of basement: (1) layered reflectivity, occasionally crosscut and offset by apparent faults (Figure 12) and (2) relatively incoherent reflectivity. Figure 12 shows examples of layered reflectivity, which is more often found in the basement troughs. This layering may represent material shed from adjacent basement highs or be igneous layering (e.g., basalt flows) similar to that observed by *Salisbury and Keen* [1992], *Srivastava and Keen* [1995],
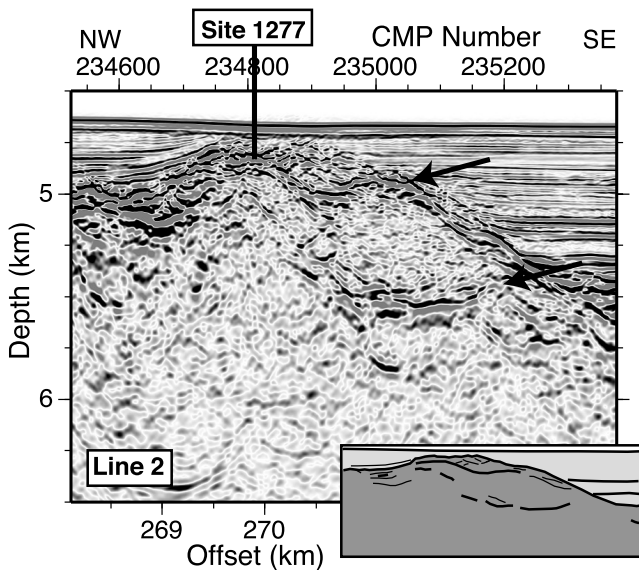
Figure 10. Close-up of prestack depth migration of line 2 around Mauzy High where ODP Site 1277 was drilled. See Figure 1b and Foldout 1 for location. This shows an example of crustal reflections that roughly parallel the basement surface (top arrow) or are subhorizontal (lower arrow) and might be detachment faults. Also note the semidisorganized reflectivity at Site 1277. Just to the southeast of the drill site (around CMP 234877), small, rotated, and stratified blocks can be observed in what may be the hanging wall of a detachment. The seismic section is plotted with a vertical exaggeration of 2:1. The simplified interpretation in lower right-hand corner of the seismic section shows major features and is plotted without vertical exaggeration.

and *Hopper et al.* [2004]. The variations in physical properties created by such flows can result in a layered character in seismic reflection profiles [*Purdy*, 1987]. Debris flows would also be expected to result in a layered seismic character (e.g., ODP Site 1277, Figure 10). The causes of the comparatively disorganized reflectivity that is often associated with basement highs is less clear but might be symptomatic of irregular fracturing or intrusions in exposed lower crustal and upper mantle rocks.

5.3.4. Moho Reflections

[46] Moho reflections are rare in the seaward 200 km of the region around line 2, although discontinuous reflections are occasionally observed at the depth predicted by the wide-angle velocity model (e.g., Foldout 1 and Figure 7) [*Van Avendonk et al.*, 2003]. The scarcity of Moho reflections in the MCS data in this domain is consistent with the weakness or absence of PmP reflections in the wide-angle data set. The velocity model shows a gradational velocity change at the crust-mantle boundary rather than a velocity discontinuity capable of producing reflections [*Nunes*, 2002; *Van Avendonk et al.*, 2003, 2006]. The recovery of upper mantle rocks at Site 1277 [*Shipboard Scientific Party*, 2004b] implies that basement in at least some parts of the SCREECH line 2 grid might be composed primarily of serpentinized peridotites, and therefore a bright Moho reflection would not be anticipated. Although a Moho reflection is weak or absent, the depth at which velocities

increase to 8 km/s appears to exert control on intrabasement reflections. Faults observed in seismic profiles terminate at the seismic Moho determined from wide-angle data [*Van Avendonk et al.*, 2003, 2006] (Foldout 1 and Figure 7).

[47] Taken together, the characteristics described above indicate the interplay of magmatic construction and extension in the incipient oceanic accretion system off New-foundland. The slight asymmetry of basement ridges and the mixed relationship between basement and Moho topography suggest that both extension and magmatic accretion were important during initial "spreading." Notably, Moho and basement topography appear to correlate beneath the Mauzy Ridge (Foldout 1), where mantle rocks were recovered at Site 1277 [*Shipboard Scientific Party*, 2004b], and the adjacent ridges (Foldout 1, CMPs 228000–240000, 230–300 km), but are anticorrelated further seaward (Foldout 1, CMPs >241000, >310 km). This may suggest a seaward increase in magmatism associated with the early oceanic accretion system.

5.4. Transitional Basement

[48] Basement immediately seaward of unambiguous continental crust on SCREECH line 2 (and covered by gridlines 108, 209, 302, 303, and 304; Foldout 1 and Figures 1 and 3) is difficult to characterize because it is essentially featureless in seismic reflection data. Very little
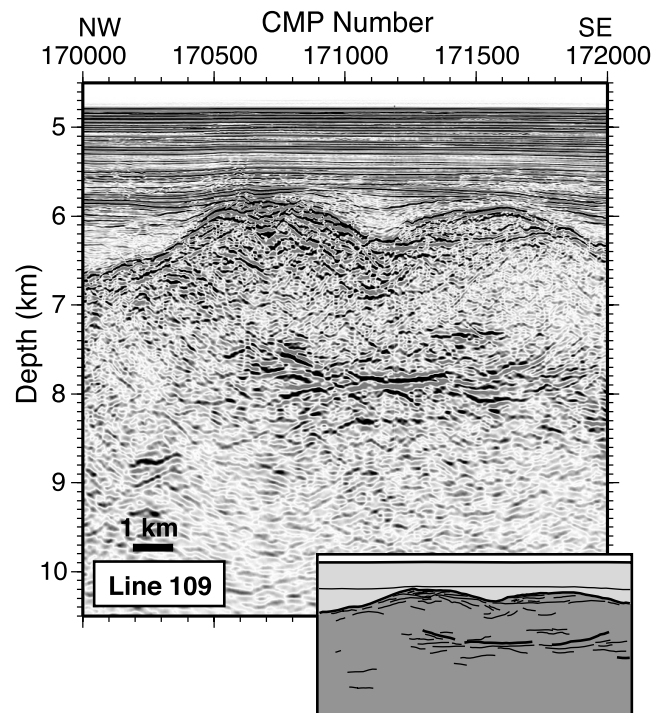
Figure 11. Close-up of prestack depth migration from the seaward portion of line 109, which shows an example of a bright, flat, midcrustal package of reflections at a depth of ~8 km that appears to have no relationship to the overlying basement topography. See Figure 1b and Foldout 1 for location. The seismic section is plotted with a vertical exaggeration of 2:1. The simplified interpretation in the lower right-hand corner of the seismic section shows major features and is plotted without vertical exaggeration.
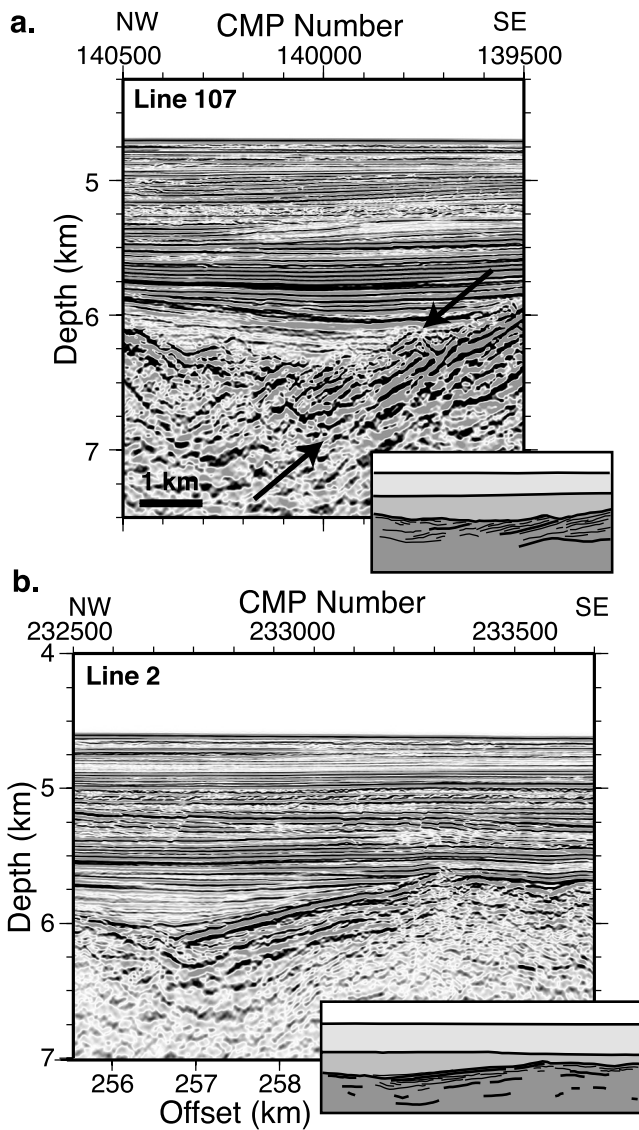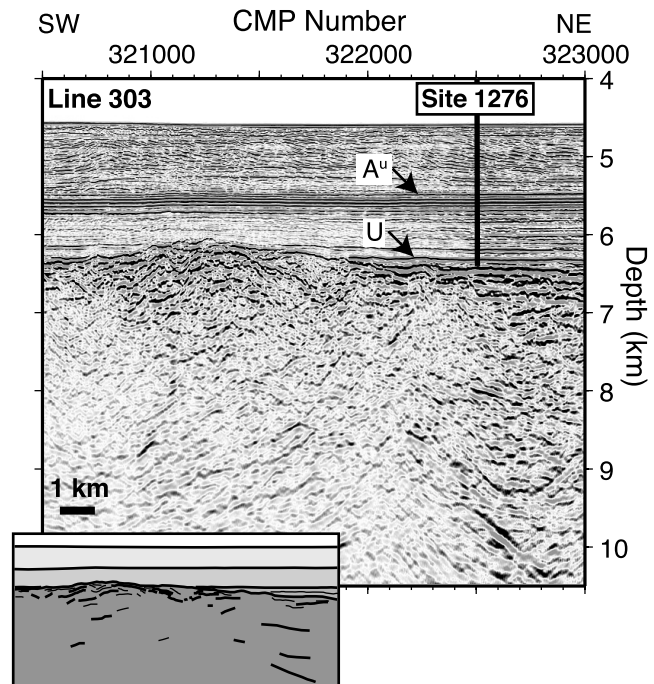
Figure 12. Close-ups of prestack depth migrations showing strong layering within the upper crust in basement swales. (a) Basement swale on line 107. Note the prominent NW dipping layers indicated with black arrows. This layering can also be observed in margin-parallel line 204 that crosses line 107 near this location. (b) Close-up of apparent intracrustal layering just seaward of magnetic anomaly M3 on line 2. Note the shallowly NW dipping layers. The simplified interpretations in the lower right-hand corners of the seismic sections show major features and are plotted without vertical exaggeration. See Figure 1b and Foldout 1 for locations.

[*Shipboard Scientific Party*, 2004a] (Figure 3), and they would be expected to reflect much of the seismic energy, particularly for the vertically incident seismic waves recorded in the MCS data.

[49] However, there are a few locations where transitional basement protrudes through bright reflections in the lowermost section, thus allowing the seismic reflection characteristics of this basement to be discerned. In these instances, transitional basement is characterized primarily by strong reflectivity in the upper ∼0.5 km and weak reflectivity below (e.g., Figures 3, 13, and 14). Notably, these basement highs do not resemble seismic images of basement in much of the ZECM (Figure 14). *Pickup et al.* [1996] described ZECM basement along IAM-9 as markedly unreflective in its upper part with an underlying, highly reflective layer riddled by faults (e.g., Figure 14d). These two layers correspond to a low-velocity carapace (4–4.5 km/s) and a 3- to 4-km-thick high-velocity layer (7–7.5 km/s) in the coincident velocity model constructed from wide-angle seismic refraction data [*Dean et al.*, 2000]. Elsewhere in the ZECM, peridotite basement exhibits very different characteristics. For example, it sometimes occurs as fault-bound basement highs with a reflective upper 0.5 s [*Beslier et al.*, 1995; *Krawczyk et al.*, 1996; *Pickup et al.*, 1996]. These observations illustrate the varying seismic characteristics that can be associated with serpentinized peridotite, and the inability of reflection data, alone, to identify such basement.

Figure 13. Prestack depth migration of margin-parallel seismic line 303 from the transition zone, which crosses Site 1276. See Figure 1b and Foldout 1 for location. Note the reflective character of basement where it protrudes above bright reflections in the lowermost sedimentary section, including U. The seismic section is plotted with a vertical exaggeration of 2:1. The simplified interpretation in lower left-hand corner of the seismic section shows major features and is plotted without vertical exaggeration.
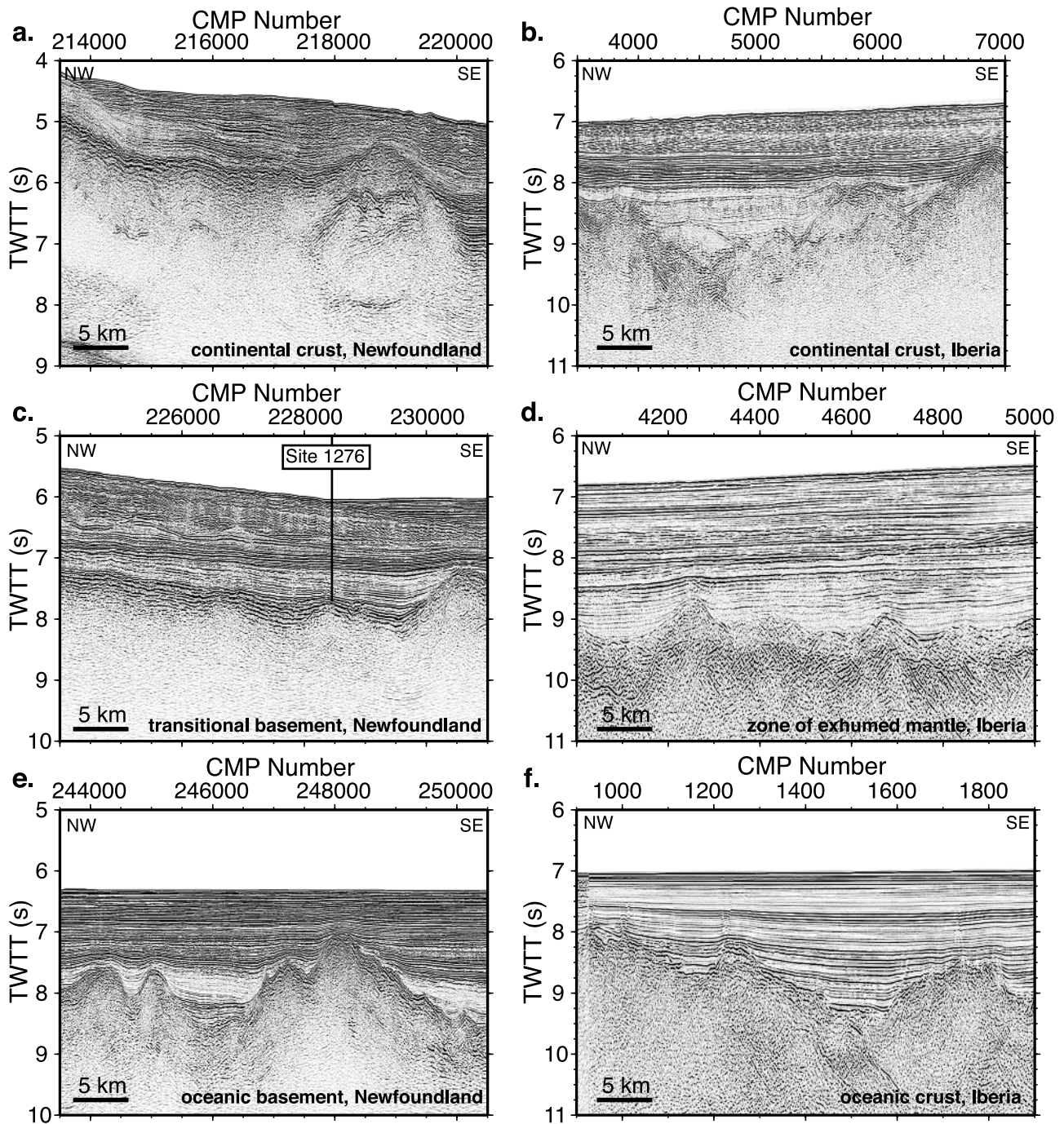
structure is visible below U and other bright reflections in the lowermost sedimentary section. This low reflectivity might be explained by a lack of seismic transmission through the overlying, high impedance contrasts, by weak reflectivity of the basement, or both. Postrift (Albian-Cenomanian) diabase sills interlayered with sediments recovered at ODP Site 1276 in the vicinity of the U reflection have highly variable seismic velocities and densities

Figure 14. Comparison of sedimentary and crustal features in seismic reflection profiles from different crustal domains off Newfoundland and Iberia. Prestack time migrations are shown from Newfoundland (left) [*Shillington et al.*, 2004] because depth-migrated images were not available for all Iberia lines (right). (a) Extended continental crust on SCREECH line 2 off Newfoundland. (b) Extended continental crust on conjugate profile LG-12 off Iberia [*Krawczyk et al.*, 1996]. (c) Transitional basement on SCREECH line 2 off Newfoundland. (d) Zone of denuded mantle on line IAM-9 off Iberia [*Pickup et al.*, 1996]. Note the unreflective character of the upper 0.5 s of basement, which is underlain by bright, dipping reflections. (e) Apparent oceanic basement from the seaward end of SCREECH line 2 off Newfoundland. (f) Interpreted oceanic crust on line IAM-9 off Iberia [*Pickup et al.*, 1996].

Nonetheless, reflection data from the low-topography transition zone off Newfoundland do not resemble seismic images of low-topography ZECM from the conjugate margin on IAM-9, and this observation implies that some differences might exist in the composition, emplacement history or evolution of these two conjugate domains through time.

[50]   The boundaries at the edges of the transition zone in the SCREECH line 2 survey also provide clues concerning

the relationships between transitional basement and adjacent crustal domains. The boundary between unambiguous continental crust and the transition zone is abrupt and marked by a large step in basement topography from the continental block (4.25 km depth) to the transitional basement seaward, which lies at least 1.5 km deeper (~CMP 220000, 180 km, Foldout 1 and Figure 4). This location also hosts the brightest occurrence of Moho and the presence of landward dipping intracrustal reflections (Figure 4). Conversely, the boundary between the transition zone and apparent oceanic basement appears more gradual. Completely featureless crust, within which no basement morphology can be observed, is present in the landward portion of the transition zone. Farther seaward, subdued basement topography is apparent (Foldout 1 and Figure 3). These smaller basement topographic features gradually give way to the greater relief apparent within basement seaward of M3.

[51] Results from Site 1276 tentatively indicate that transitional basement was emplaced in a deep-water setting. Sediments recovered from the deepest levels of Site 1276 (1723 mbsf, latest Aptian/earliest Albian) did not include hiatuses or evidence for a shallow water depositional environment [*Shipboard Scientific Party*, 2004a]. However, this hole did not penetrate the entire sedimentary section to basement, and the age and depositional environment of sediments immediately overlying this basement remain unknown.

[52] Finally, modeling of coincident wide-angle reflection/refraction data produces a different velocity structure from that observed in the ZECM on the Iberia margin [*Nunes*, 2002; *Van Avendonk et al.*, 2006]. Crust in the Newfoundland transition zone thins oceanward from 6 km to 2 km with velocities of 5.5–6.5 km/s between 180 and 235 km (Foldout 1), and the underlying crust-mantle boundary is marked by an increase in velocities to >8 km/s over much of this domain [*Van Avendonk et al.*, 2006]. The seaward part of the transition zone (235–260 km, Foldout 1) shows velocities of 6.3 km/s at the top, increasing to 7.7 km/s at 5 km below basement. Most notably, Newfoundland transitional basement, with the exception of the outer ~25 km, does not contain the thick (4–5 km) 7.× km/s layer that has consistently been associated with tracts of serpentinized peridotite basement off Iberia [*Chian et al.*, 1999; *Dean et al.*, 2000].

[53] The observations presented above place the following constraints on the emplacement of transitional basement: (1) the boundary between continental and transitional basement is tectonic, while the boundary between transitional and apparent oceanic basement is more gradual; (2) this domain does not resemble the ZECM on Iberia in terms of reflective character or seismic velocity structure [*Van Avendonk et al.*, 2006], and is therefore not exactly analogous, and (3) Newfoundland transitional basement was most likely emplaced during the late stages of rifting in a "deep-water" setting after significant thinning of the lithosphere and associated subsidence had occurred. Although none of these observations definitively determine the nature of transitional basement, they can be used to constrain the margin evolution for each of the three cases, which are described in section 6.2. However, the interpretation of most of the transitional basement as thinned continental crust denuded during the late stages of rifting and possibly modified by magmatic intru-

sions and/or mantle exhumation/initial oceanic accretion best fits the available observations. *Van Avendonk et al.* [2006] interpret crustal velocities of 5.5–6.5 km/s and regular seaward thinning of this crust from 6 to 2 km observed in velocity model created from wide-angle data (180–235 km, Foldout 1) as a sliver of continental crust. The apparently flat topography associated with transitional basement could be explained if this surface corresponded to a rolling hinge or detachment fault [*Lavier et al.*, 1999]. Bright Moho reflections and other dipping features within the last block of unambiguous continental crust (Figure 4) might then be related to the emplacement of continental crust in the transition zone. *Van Avendonk et al.* [2006] explain high velocities between 235 and 260 km as a section of exhumed, serpentinized mantle. *Lau et al.* [2006a, 2006b] make similar interpretations of transitional basement to the south on SCREECH line 3.

6. Discussion

[54] We first discuss unambiguous extended continental crust on both the Newfoundland and Iberia margins and evaluate different models for the initial stages of continental stretching. We then discuss three models for the emplacement of transitional basement off Newfoundland. Finally, we consider how the transition from final rifting to initial seafloor spreading may have developed.

6.1. Continental Stretching

[55] The fault geometries and thinning profiles of the Newfoundland and Iberia margins can be compared with idealized models for margin evolution to investigate the processes responsible for their formation. In this section, we compare structures in unambiguous continental crust on SCREECH line 2 to conjugate line LG-12 in the Iberia Abyssal Plain [*Krawczyk et al.*, 1996; *Whitmarsh et al.*, 2000] and to line IAM-9, which lies ~50 km to the south of LG-12 [*Pickup et al.*, 1996; *Dean et al.*, 2000] (Figure 2). The depth-uniform (pure shear) stretching model would predict that margins will be symmetric in both their fault patterns and thinning profiles [*McKenzie*, 1978]. Strain would be evenly distributed through depth, so that the magnitude of brittle extension in the upper crust would coincide laterally with that of deformation in the lower crust and mantle lithosphere. In contrast, more complicated and less symmetric margins would arise for different forms of depth-dependent stretching [*Lister et al.*, 1986; *Lavier et al.*, 1999; *Manatschal et al.*, 2001; *Lavier and Manatschal*, 2006].

[56] The symmetry of the bulk thinning profiles of the Newfoundland and Iberia margins observed in velocity models created from wide-angle data [*Dean et al.*, 2000; *Van Avendonk et al.*, 2006] imply that depth-uniform stretching was important during the early stages of extension, as has been suggested by previous work [*Manatschal and Bernoulli*, 1999; *Whitmarsh et al.*, 2000, 2001a]. However, the fault patterns observed within the most extended continental crust in seismic reflection profiles on either margin are significantly different. On the Iberia margin, a series of prominent seaward dipping faults are apparent in seismic reflection sections (LG-12 and IAM-9), although faulting patterns change significantly between

these two lines (Figure 2) [*Krawczyk et al.*, 1996; *Pickup et al.*, 1996; *Dean et al.*, 2000; *Whitmarsh et al.*, 2000]. The zone of faulted continental crust spans an along-strike distance of more than ∼60 km. On the near-margin parts of these profiles, seaward dipping, listric normal faults penetrate the entire crust and appear to offset the crust-mantle boundary, while farther seaward, normal faults typically terminate near the Moho or at interpreted intra-crustal detachments (e.g., the H reflection [*Whitmarsh et al.*, 2000]). Conversely, the most seaward portion of unambig-uous continental crust on the Newfoundland margin thins abruptly with very few evident normal faults. A bright Moho reflection is imaged beneath the most seaward block of unambiguous continental crust on SCREECH line 2, which we hypothesized might correspond a structural fea-ture, such as a shear zone (Figure 4). These asymmetries might be explained if extension on the Newfoundland margin was accommodated partially by the exposure of deeper levels of the crust and lithosphere now observed in the Newfoundland transition zone and Iberia ZECM [*Driscoll and Karner*, 1998; *Lavier and Manatschal*, 2006; *Van Avendonk et al.*, 2006], as described in following section.

6.2.   Emplacement of Transitional Basement

[57]   There are three possible origins for transitional basement: (1) oceanic basement similar to apparent oceanic basement further seaward off Newfoundland, (2) exhumed, moderately to highly serpentinized mantle, and (3) thinned, possibly intruded continental crust. For each of these possible interpretations of the transition zone, we describe a model for its emplacement based on existing constraints (Figure 15).

6.2.1.   Model 1: Slow Spreading Oceanic Basement, Ridge Jump(s)

[58]   In this case (Figure 15a), incipient seafloor spreading began between unambiguous continental crust off of New-foundland and the zone of serpentinized peridotite on the Iberia margin. If all of the Newfoundland transitional basement is oceanic, approximately 70 km of oceanic basement would be present off Newfoundland (∼M15 to M3) that would not be mirrored off Iberia. The simplest explanation for this discrepancy would be for oceanic accretion to have continued in the original location until ∼chron M3 time, when spreading jumped eastward, isolat-ing pre-M3 oceanic basement on the Newfoundland side. It is also possible that more than one ridge jump occurred, that there was more than one locus of magmatism (i.e., disor-ganized spreading), or that extremely asymmetric accretion took place at the ridge axis [*Allerton et al.*, 2000]. Studies of regions undergoing late stage rifting and initial seafloor spreading (e.g., Woodlark Basin) suggest that ridge jumps are common due to unstable magmatic dynamics [*Yamazaki et al.*, 1993; *Benes et al.*, 1997; *Taylor et al.*, 1999]. In many locations, magmatism initiates as a series of unrelated, discrete cells that later coalesce to form an organized spread-ing center [*Cochran and Martinez*, 1988], which could produce asymmetries in early oceanic basement. This model implies that the transition zone on the Newfoundland margin was emplaced in a deep-water environment following the exposure of ZECM crust on the Iberia margin (Figure 15a).

[59]   Existing data provide some support for this model. The abrupt contact between continental crust and

transitional basement is manifested by a 1.5-km step in basement depth, the brightest occurrence of Moho and a change in reflection attributes (Figure 4). *Keen and de Voogd* [1988] interpreted such features on a nearby LITHOPROBE reflection line to represent the continent-ocean boundary. In contrast to this abrupt contact, a gradational boundary con-nects transitional basement and apparent oceanic basement to the east, which may suggest that these domains have a common or related origin. The apparent absence of prerift or synrift sediments and the deep-water setting of the oldest sediments recovered from the base of Site 1276 might also be explained by the presence of oceanic basement in the transition zone.

[60]   However, the seismic reflection and refraction data also signal significant differences between transitional and apparent oceanic basement. Transitional basement appears to contain little to no topography compared with apparent oceanic basement farther seaward, and wide-angle seismic data indicate that most transitional crust thins regularly seaward in contrast to more variable crustal structure within apparent oceanic basement [*Van Avendonk et al.*, 2006]. Consequently, if transitional basement is oceanic, either its emplacement or later modifications must explain differences between this domain and apparent oceanic crust farther seaward.

6.2.2.   Model 2: Serpentinized, Exhumed Subcontinental Mantle

[61]   In this model (Figure 15b), the transition zone off Newfoundland is highly serpentinized, subcontinental, mantle. Observed basement velocities of ∼5.5–6.5 km/s in the landward portion (180–235 km) of the transition zone allow the interpretation of moderately to highly serpentinized peridotite (∼50–75%) [*Escartin et al.*, 1999; *Christensen*, 2004]. However, a prominent 7.× km/s layer appears to be conspicuously absent over much of this domain (180–235 km), with the exception of the outer 25 km of the transition zone (235–260 km) [*Van Avendonk et al.*, 2006]. In contrast, a ∼4-km-thick, 7.× km/s layer (indicating <25% serpentinization) overlain by a thin, low-velocity layer (indicating >75% serpentinization) is detected over the entirety of the ZECM on the Iberia margin [*Dean et al.*, 2000]. Furthermore, seismic reflection data off New-foundland do not reveal characteristics similar to those observed in seismic reflection sections across the ZECM in line IAM-9 [*Pickup et al.*, 1996] (Figure 14). Therefore some mechanism would be required to juxtapose a layer of mod-erately to highly serpentinized mantle (5.5–6.5 km/s) over relatively unaltered mantle (∼8.0 km/s) off Newfoundland and to explain the differences in seismic properties between this domain and the ZECM off Iberia. Possible explanations include (1) late stage alteration that changed the velocity structure of exhumed mantle on one or both margins, (2) the exhumation of mantle with variable properties in the New-foundland transition zone and Iberia ZECM, or (3) the alteration of exhumed mantle off Newfoundland by a later stage of faulting.

[62]   In the first case, exhumed mantle would have been emplaced in both the Newfoundland transition zone and Iberia ZECM, with eventual seafloor spreading beginning in the center of the rift. Subsequent alteration of the Newfound-land transition zone might have been caused by the intrusion of melts, for example [*Tucholke and Whitmarsh*, 2006]. In the
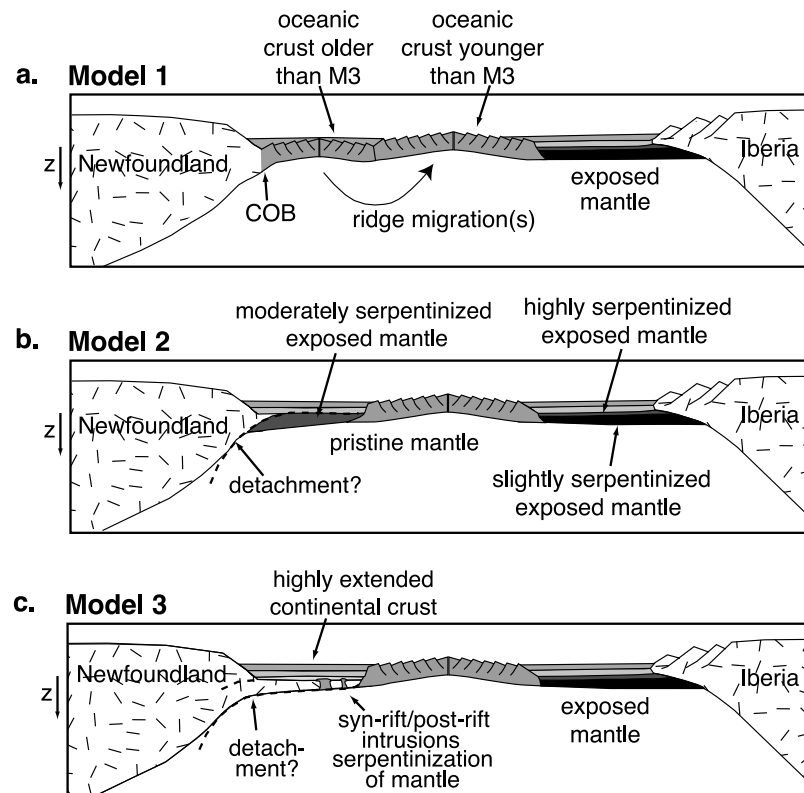
Figure 15. Schematic models of Newfoundland-Iberia margin formation. Black lines and shading within the sedimentary section are intended to show expected large-scale stratigraphic patterns; darker grays indicate younger sediments and lighter grays indicate older sediments. Shading within mantle indicates the degree of serpentinization; black shading indicates low degrees of serpentinization (<25%); and dark grey indicates moderately to highly serpentinized mantle (>50%). All models assume initial pure shear extension between Newfoundland and Iberia. (a) In model 1, continued extension is accommodated by exhumation of continental mantle. In the simplest case, spreading initiates between unambiguous continental crust off Newfoundland and the ZECM off Iberia, and jumps eastward at chron ~M3, abandoning the original spreading center on the Newfoundland side of the rift. Alternatively, additional ridge jumps, extremely asymmetric accretion, or unstable initial magmatism (multiple loci of magmatism) could explain this section. COB marks continent-ocean boundary. (b) In model 2, exhumed serpentinized mantle is emplaced off both Newfoundland and Iberia by one or more detachment or rolling-hinge faults. Differences in seismic character between the Newfoundland transition zone and Iberia ZECM are then explained by (1) late stage alteration that changed the velocity structure of exhumed mantle on one or both margins, (2) the exhumation of mantle with variable properties in the Newfoundland transition zone and Iberia ZECM, or (3) the alteration of exhumed mantle off Newfoundland by a later stage of faulting. (c) In model 3, most of the transition zone is composed of thinned continental crust. This continental sliver of continent would have emplaced during the final stages of rifting by one or more detachment or rolling-hinge faults and possibly modified by intrusions and/or serpentinization at its seaward end. Initial seafloor spreading would have occurred between the thin continental crust/mantle off Newfoundland and exhumed subcontinental mantle off Iberia.

second case, mantle exposed in the Newfoundland transition zone and the Iberia ZECM might have variable properties across the rift, leading to differences in the seismic expression of this mantle. In the third case, high-velocity, slightly serpentinized (<25%) mantle might have been removed tectonically from Newfoundland by one or more rolling-hinge or detachment faults. This could be accomplished by exhumation of a section of mantle roughly equivalent in width to either the Newfoundland transition zone or Iberia ZECM by either one detachment or rolling-hinge fault or by a conjugate set of faults [*Lavier and Manatschal*, 2006]. A second-generation fault would have formed later within the exposed mantle between moderately to highly serpentinized (>50–75%) peridotite and underlying slightly (<25%) serpentinized peridotite, removing the higher-velocity, seismically reflective material from beneath the transition zone on Newfoundland. This would juxtapose moderately to highly serpentinized peridotite against relatively pristine (8 km/s) mantle, which would be too hot to undergo significant serpentinization, in the Newfoundland transition zone. Following second-stage faulting, the upper part of the Iberia ZECM would become extensively serpentinized, thus ac-

counting for its low velocities [*Pickup et al.*, 1996; *Dean et al.*, 2000] (Figure 15b).

[63] The apparently gradational change from transitional to apparent oceanic basement observed in seismic reflection profiles might be produced by similar phenomena to those proposed for Iberia [*Whitmarsh et al.*, 2001b], whereby melt derived from upwelling asthenospheric mantle might have increasingly intruded and altered exhumed mantle in a seaward direction until organized spreading was initiated. This model is also consistent with the apparent absence of prerift and synrift sediments and with the recovery of deep water sediments (~112 Ma) at the base of Site 1276; if exhumed subcontinental mantle is present in Newfoundland's transition zone, it would most likely have been emplaced during the late stages of rifting after significant thinning and subsidence occurred. In addition, in all the cases described above, it is possible that the bright Moho reflection observed beneath continental crust off Newfoundland (Figure 4) might have been involved in the exhumation of the Newfoundland transition zone.

6.2.3. Model 3: Thinned Continental Crust

[64] If transitional basement on the Newfoundland margin is thinned continental crust, it would most likely have been emplaced during the late stages of extension and mantle denudation by one or more detachment or rolling-hinge faults (Figure 15c). As displacement on these faults increased, the sliver of continental crust would have been increasingly thinned and possibly subjected to magmatic intrusion and/or mantle serpentinization at its seaward end. In this model, final separation would have occurred between fragmented, intruded continental crust and exhumed mantle on the Newfoundland margin and exposed mantle on the Iberia margin.

[65] This model is consistent with seismic reflection data. The subdued basement topography present in this domain might be explained by extensive faulting. Where transitional basement is visible, it does not resemble unambiguous thinned continental crust on SCREECH line 2 or LG-12 (e.g., Figures 14a and 14b). However, if continental crust were modified by significant extension, subsequent magmatic intrusions or serpentinization of the underlying mantle, it could have a different seismic expression. The gradual transition between transitional and apparent oceanic basement might be explained by an oceanward increase in either synrift intrusions or precursors to seafloor spreading, or by a transition from continental crust to serpentinized peridotite. Such effects, particularly if they resulted in lavas or serpentinites emplaced at the surface, might cause the most oceanward transitional basement to increasingly resemble apparent oceanic basement further seaward; *Van Avendonk et al.* [2006] interpret high velocities (6.3–7.5 km/s) at the seaward end of the transition zone (235–260 km) to represent serpentinized mantle. In this model, the bright Moho and dipping reflections observed in the most seaward block of unambiguous crust might represent a westward dipping detachment or rolling-hinge fault that would have been involved in the emplacement of a thin sliver of continental crust in the transition zone (Figure 4). Results from Site 1276 suggest that this crust would have been emplaced in a deepwater environment during the late stages of rifting. As described in section 5.4, the observations from both seismic reflection data presented here and coincident wide-angle refraction data tentatively favor this model.

6.3. Initiation of Seafloor Spreading

[66] Although basement seaward of anomaly M3 has been assumed to be oceanic in origin, consistent with identifications of magnetic anomalies [*Whitmarsh and Miles*, 1995; *Srivastava et al.*, 2000] and the seismic reflection characteristics described above, there are several reasons to believe that not all of this basement is purely oceanic. During ODP Leg 210, drilling at Site 1277 recovered serpentinized peridotites overlain by breccias with clasts of peridotite and gabbro and minor basalts [*Shipboard Scientific Party*, 2004b]. Shipboard work tentatively identified this assemblage as oceanic, although geochemical analyses of magmatic and mantle rocks are required to definitively classify these mantle rocks. Initial geochemical results imply that peridotites from Site 1277 may record an earlier melting event that was unrelated to rifting [*Müntener et al.*, 2005]. Furthermore, *Van Avendonk et al.* [2006] interpret high crustal velocities between 235 and 260 km (Foldout 1) to represent a section of serpentinized peridotite exposed during the late stage rifting prior to the onset of seafloor spreading following M1 (~127 Ma).

[67] The possibility that a section of subcontinental mantle has been recovered in the midst of widely recognized magnetic anomalies on both the Iberia and Newfoundland margins (e.g., sites 1070 and 1277) indicates that a simple, purely oceanic spreading system had not developed by this time. The geochemistry of mantle rocks recovered on Iberia suggests a rough seaward trend from less depleted (e.g., sites 1067 and 1068) to more depleted or "asthenospheric" (e.g., Site 1070) peridotites [*Beard and Hopkinson*, 2000; *Skelton and Valley*, 2000; *Abe*, 2001; *Hébert et al.*, 2001]. If a similar trend is present off Newfoundland, both margins may be recording a progressive shift from nonvolcanic rifting to slow oceanic accretion. Calculated half spreading rates of ~6.7 mm/yr [*Srivastava et al.*, 2000] and the observation of high basement relief and faulting within this domain from seismic reflection profiles indicate slow initial spreading. Early melts in this system might be generated at depth and percolate up through the overlying "cold" lithosphere, suggesting that lithospheric mantle exposed at the surface might not be genetically related to limited melts; this has been suggested for subcontinental mantle rocks exposed in the Alps [*Müntener et al.*, 2004]. *Russell and Whitmarsh* [2003] modeled magnetic anomalies in the ZECM and peridotite ridges as arising from magmatic intrusions at depth in the early stages of seafloor spreading. Finally, the apparent shift from correlation to anticorrelation of basement topography with Moho topography might signal the increasing importance of magmatic addition in the seaward portion of SCREECH line 2. Therefore the transition to spreading on nonvolcanic margins might be manifested by trends in mantle petrology and geochemistry, and the progressive modification and intrusion of subcontinental mantle by melts produced at depth during incipient spreading [*Whitmarsh et al.*, 2001a]. Further work on magmatic and mantle rocks recovered at Site 1277 will clarify the form of this transition on Newfoundland [*Müntener et al.*, 2005].

7. Conclusions

[68] Prestack depth migrations of seismic reflection profiles around the ODP Leg 210 drilling transect delineate three

crustal domains on the Newfoundland margin: (1) unambiguous thinned continental crust, (2) transitional basement, and (3) apparent oceanic basement seaward of M3. These profiles demonstrate significant asymmetries in the outer parts of the Newfoundland and Iberia conjugate margins, implying that depth-dependent extension operated during the late stages of rifting. The apparent absence of normal faults on Newfoundland stands in stark contrast to plethora of normal faults imaged off Iberia. Our data also reveal clear differences in the seismic reflection characteristics of the transition zone on the Newfoundland margin and the ZECM on the Iberia margin. Where it can be imaged on SCREECH line 2 and adjacent lines, transitional basement contains a seismically reflective upper ~0.5 km and is relatively transparent beneath. These characteristics are unlike those in the section of low-topography exhumed mantle on the Iberia margin observed on line IAM-9. We propose three possible origins for the Newfoundland transition zone based on reflection data and coincident refraction data [*Van Avendonk et al.*, 2006]: (1) slow spreading oceanic basement, similar to basement further seaward, (2) denuded mantle that was later modified by alteration, intrusion or second generation faulting, and (3) highly thinned continental crust that shows a seaward increase in the influence of intrusions or mantle serpentinization. These data tentatively favor a continental affinity for most of the transitional basement (~180–235 km). Finally, the variable appearance and fault geometries within apparent oceanic basement on the Newfoundland margin suggest extension and an intermittent magma supply during the transition from nonvolcanic rifting to slow incipient oceanic accretion, similar to what is observed on adjacent SCREECH transects (transect 695 [*Funck et al.*, 2003], transect 156 [*Hopper et al.*, 2004], and transects 1006 and 1007 [*Lau et al.*, 2006a, 2006b]).

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