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Case History

Seismic signal penetration beneath post-rift sills on the Newfoundland rifted margin

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ABSTRACT

Analysis of averaged, smoothed instantaneous frequency and amplitude of seismic-reflection data collected on the Newfoundland magma-starved rifted margin along the Ocean Drilling Program (ODP) leg 210 transect demonstrate that the transparency of "transitional" crust arises from poor signal penetration. In principle, the high-frequency spectral content and amplitude of seismic reflection data should decrease with increasing traveltime as a result of absorption, geometric spreading, and scattering so long as seismic energy continues to return from deeper levels of the subsurface. As a result, if average frequency and amplitude cease to decrease with depth, background noise, rather than returning seismic energy, likely dominates the record. Average frequency increases and average amplitude remains comparatively constant below bright reflections overlying transitional crust on the Newfoundland margin. Similar patterns are not observed at the sediment-basement contact farther seaward in oceanic crust where intracrustal reflections are apparent. In those records, both amplitude and frequency continue to decrease steadily for at least 2–3 s below the top of basement. We interpret these observations as evidence that signal penetration is comparatively poor beneath bright reflections overlying transitional basement. Consequently, the featureless appearance of transitional crust on the Newfoundland margin in seismic-reflection profiles cannot be used to make inferences about its physical properties; instead, only seismic characteristics observed in rare basement highs that rise above bright reflections in the lowermost sedimentary section can provide meaningful information. Weak signal penetration in this crustal domain is consistent with the results from site 1276 during ODP leg 210, where interlayered diabase sills and sediments were recovered above basement, which would be expected to result in high reflection coefficients and low signal penetration. The apparent lack of seismic penetration throughout the transition zone off Newfoundland also implies interlayered sills and sediments might be widespread over this crustal domain.

INTRODUCTION

Rifted continental margins serve as lasting records of the events that facilitate continental rupture and incipient seafloor spreading. Thus, the study of conjugate rifted-margin pairs offers the opportunity to assess the processes associated with continental rifting. Two end-member types of passive margins have been recognized: magma-rich and magma-starved (White et al., 1987; Boillot et al., 1988). The crustal structure of magma-starved rifted margins commonly includes a section of highly thinned continental crust and altered mantle seaward of oceanic crust (termed *transitional crust* or the *transition zone;* Louden and Chian, 1999). Drilling legs conducted by the Ocean Drilling Program (ODP) and seismic investigations haveshown that transitional basement on the Iberia margin (Figure 1a), the best-studied magma-poor margin in the world, is composed primarily of serpentinized subcontinental mantle (Boillot et al., 1988; Pickup et al., 1996; Shipboard Scientific Party, 1998; Dean et al., 2000; Whitmarsh et al., 2001). It has been hypothesized that the mantle exposed on the Iberia margin was exhumed during the final stages of continental rupture prior to the onset of seafloor spreading (e.g., Whitmarsh et al., 2001).

One of the distinguishing characteristics of this zone of exhumed mantle on Iberia is its appearance in some multichannel seismic (MCS) reflection profiles. Large tracts of low-relief exhumed mantle

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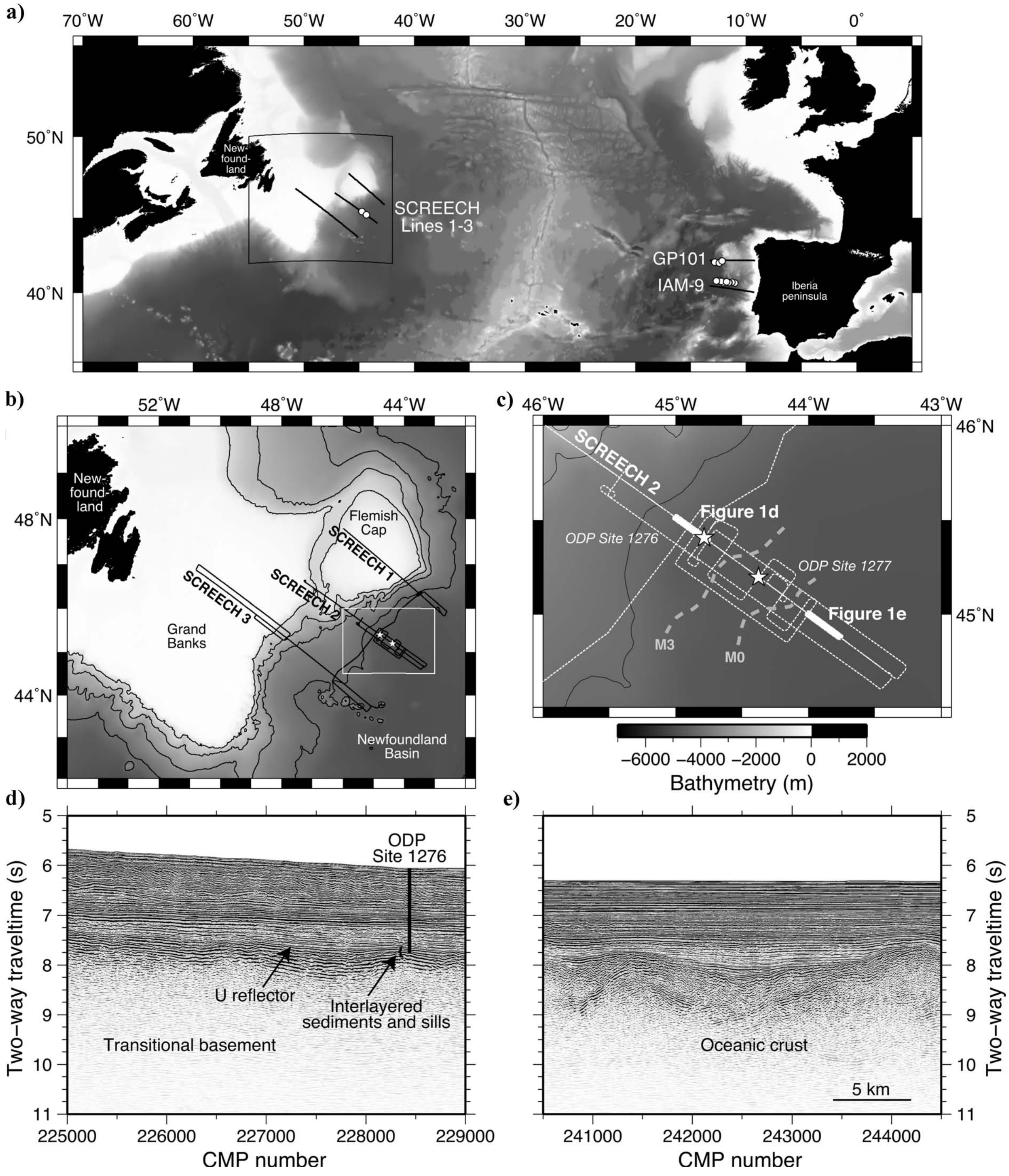

Figure 1. (a) Bathymetric map of the northern Atlantic Ocean showing the conjugate Newfoundland-Iberia margins extracted from the GEBCO Digital Atlas published by the British Oceanographic Data Centre on behalf of IOC and IHO (IOC IHO BODC, 2003). Black lines show the locations of seismic profiles discussed in the text. White dots indicate the locations of ODP drill sites from legs 103, 149, 173 (off Iberia), and 210 (off Newfoundland) (b) Bathymetric map of the Newfoundland margin extracted from the GEBCO Digital Atlas (IOC IHO BODC, 2003). The contour interval is 1000 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 lines 1, 2, and 3. MCS, magnetic, gravity, and multibeam bathymetric data were acquired on other lines. (c) Bathymetric map of the area around the seaward part of SCREECH line 2 from GEBCO (IOC IHO BODC, 2003). The contour interval is 1000 m. White stars mark the locations of sites 1276 and 1277. Dotted gray lines with text show the locations of magnetic anomalies M3 and M0 as interpreted by Srivastava et al. (2000). Thin white lines indicate the locations of seismic reflection profiles. Thick white lines and text show locations of data extracts shown in Figure 1d and e. (d) Example of prestack time migration of seismic data from flat transitional crust. Note bright reflections at the base of the sedimentary section and the apparent transparency of basement. (e) Example of prestack time migration of seismic data from oceanic crust. Note the intracrustal reflections.

along seismic-reflection profile IAM-9 (Figure 1a) often appear notably unreflective in the upper 0.5 s of crust, though the underlying middle and lower crust are riddled with landward- and seaward-dipping reflections (Pickup et al., 1996). The unreflective layer within this basement has been explained by the lack of an impedance contrast between the lowermost sedimentary section and the highly serpentinized (75–100%) peridotites ($V_p = \sim 4.0$ km/s) that are interpreted to comprise the upper 0.5 km of basement (Pickup et al., 1996; Dean et al., 2000). Elsewhere, serpentinized mantle in basement ridges is associated with a relatively reflective sediment-basement contact (Henning et al., 2004), implying the physical properties of exposed mantle vary significantly.

A section of transitional crust has also been recognized between unambiguous continental and oceanic crust on the Newfoundland margin, which is conjugate to Iberia. Three hypotheses have been proposed for the origin of this crust: (1) thinned, possibly intruded continental crust (Tucholke et al., 1989; Lau et al., 2006b; Van Avendonk et al., 2006); (2) slow-spreading oceanic crust (Keen and de Voogd, 1988; Srivastava et al., 2000); and (3) serpentinized mantle (Reid, 1994; Tucholke et al., 2007). Van Avendonk et al., 2006 and Lau et al., 2006b interpret much of the landward part of this domain as thinned continental crust based on its seismic-velocity structure from wide-angle seismic data.

Nonetheless, the affinity of transitional basement on Newfoundland has remained controversial largely because velocities of 5.5–6.5 km/s found in this basement can be interpreted in multiple ways and because of the transparent appearance of this crust in seismic-reflection sections (Figure 1; Lau et al., 2006a; Shillington et al., 2006). It is difficult to identify the top of basement in seismic-reflection profiles or to recognize any features within it. There are two possible explanations for this featureless appearance. The nonreflective nature of transitional basement on the Newfoundland margin can result either from its physical properties, such as internal homogeneity or the lack of an impedance contrast between transitional basement and the overlying sediments, as interpreted on some sections of the Iberia margin, or from poor signal penetration beneath interfaces representing high impedance contrasts in the lowermost sedimentary section overlying transitional basement. The recovery of interlayered sediments and postrift sills above transitional basement on the Newfoundland margin at ODP site 1276 suggests the latter is a realistic possibility (Shipboard Scientific Party, 2004a).

Because the seismic reflection characteristics of crust on magma-poor rifted margins have been critical in delineating the extent and affinity of various crustal domains, it is important to determine which of these scenarios for the cause of seismic transparency applies to transitional basement on the Newfoundland margin. In this contribution, we analyze the averaged instantaneous frequency and amplitude characteristics of seismic-reflection data collected along a profile in the Newfoundland Basin that crosses ODP leg 210, sites 1276 and 1277 to distinguish between competing hypotheses for the featureless appearance of transitional basement.

PREVIOUS WORK: GEOPHYSICAL AND DRILLING DATA

In July–August 2000, more than 3000 km of 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 (Studies of Continental Rifting and Extension on the Eastern Canadian shelf) experiment (Figure 1a and b). The survey was located conjugate to seismic and drilling transects on Newfoundland's conjugate margin, off Iberia (ODP legs 103, 149, and 173; Srivastava et al., 2000; Figure 1a). Taken together, the geophysical data sets collected on the Newfoundland and Iberia margins constitute the most complete information available for the conjugate margins of a magma-starved rift. The purpose of this study was to delineate the sedimentary and crustal structure of the Newfoundland margin, compare this structure to that of the conjugate Iberia margin to learn more about the evolution of the rift system, and to select possible ODP drill sites in the Newfoundland Basin.

During this study, we collected coincident MCS-reflection data on the 480-channel, 6-km streamer of the R/V *Maurice Ewing* and wide-angle seismic reflection/refraction data on 29 ocean-bottom seismometers/hydrophones (OBS/H) deployed and recovered by the R/V *Oceanus* along three primary transects (Figure 1b). MCS data were also collected on lines parallel and perpendicular to all transects, including at the locations of all leg 210 targets (Figure 1b and c). The MCS data discussed here have a sampling interval of 4 ms, a shot spacing of 50 m, a fold of 60, a recording length of ~16 s, a CMP spacing of 6.25 m, and were digitized using a 24-bit digitizer. The tuned, 139,946 cm^3 (8540 cu in) airgun array of the R/V *Maurice Ewing* provided the seismic source.

Line 2, the central of three primary transects, is the subject of this paper (Figure 1b-e). Line 2 reaches across the edge of the Grand Banks, the Flemish Pass, over Beothuk knoll, across flat "transitional" crust, and 60 km seaward of magnetic anomaly M0 (Srivastava et al., 2000), which is the first unambiguous seafloor-spreading anomaly (labeled in Figure 1c). Although the precise timing of these events is controversial because of the weak anomalies and probable ultraslow spreading rates, continental extension leading to breakup likely began in the Late Jurassic. At the location of line 2, anomaly M3 (Barremian, ~128 Ma) is generally undisputed and older anomalies might be indicated (Srivastava et al., 2000).

Modeling of wide-angle seismic refraction data acquired along line 2 during SCREECH indicates transitional crust thins from ~6 km near the continent to ~2 km at its seaward end and is characterized by low velocities (~5.5–6.5km/s; Van Avendonk et al. [2006]). A thick "7.x" km/s layer, which is commonly associated with serpentinized peridotite (Dean et al., 2000), is not observed. The base of the crust is marked by wide-angle reflections and an abrupt increase in velocity to 8 km/s, which is typical of unaltered mantle. Moho reflections are rare in areas of serpentinized peridotite because the gradual decrease in alteration with depth does not usually result in a sharp interface. For these reasons, Van Avendonk et al. (2006) interpret most of this zone as thinned continental crust. This is in strong contrast to the zone of exhumed mantle on Iberia, which is characterized by a thick 7.x km/s layer and the absence of Moho reflections, resulting from the gradational boundary between serpentinized and pristine mantle.

Prestack time and depth migrations of coincident seismic reflection data image a package of bright reflections at the base of the sedimentary section over transitional basement on Newfoundland; below this level, no intrabasement features or Moho reflections can be discerned (Shillington et al., 2004; Shillington et al., 2006; Figure 1d). Only where basement protrudes above this bright package of reflections can its seismic character be discerned. Farther seaward, Van Avendonk et al. (2006) interpret a narrow zone of exhumed mantle (near site 1277, Figure 1c), consistent with drilling results (Shipboard Scientific Party, 2004b; Müntener and Manatschal, 2006), followed by oceanic basement accreted in an embryonic, slow-spreading environment. Seismic reflection profiles show basement topography becomes significantly rougher in this crustal domain, and faults and other features are apparent within the basement, consistent with the interpretation of this basement as slow-spreading oceanic crust (Shillington et al., 2006; Figure 1e).

ODP leg 210 visited the Newfoundland margin in the summer of 2003. One of the primary purposes of this drilling leg was to test hypotheses for the origin of transitional basement (site 1276). Site 1276 was selected because it offered the opportunity to retrieve deep sediments overlying transitional basement, which record the timing and subsidence history of the margin. Although drilling did not reach basement at site 1276, it did reach the sequence of bright reflections that overlie acoustic basement. This sequence includes the "U" reflection, which is observed over a large portion of the Newfoundland Basin (e.g., Figure 1d). The U reflection has been put forward as a possible breakup unconformity because it appears to truncate basement within the transition zone in older seismic reflection data sets, and previous workers have linked the U reflection to the prominent Avalon unconformity on the shelf, whose age is close to that estimated for breakup (Tucholke and Ludwig, 1982; Tucholke et al., 1989). However, drilling of this interval recovered interlayered sediments and diabase sills at depths of 1611–1739 m below seafloor (mbsf) (Shipboard Scientific Party, 2004a; Figure 2a).

Radiometric dates indicate these sills have ages of ~105.3 and 97.8 Ma, respectively (Hart and Blusztajn, 2006), and thus postdate rifting by at least ~20 Ma. Some of the Albian mudstones between the two sills were undercompacted and had extremely low velocities and densities of ~1.6 km/s and ~2.1 g/cm^3 (Shipboard Scientific Party, 2004a; Karner and Shillington, 2005; Figure 2b and c). Conversely, velocities and densities within the diabase sills ranged from ~4.0–6.0 km/s and ~2.5–2.8 g/cm^3, respectively (Shipboard Scientific Party, 2004a). These large contrasts in material properties result in very large impedance contrasts and, consequently, high reflection coefficients and low transmission coefficients (Figure 2d). Synthetic seismograms created from shipboard laboratory measurements of velocity and density indicate the shallower of these two sills locally causes the bright U reflection (labeled in Figure 1d), and that the deeper sill causes a brighter underlying reflection (Shillington et al., 2007).

SIGNAL PENETRATION AND INSTANTANEOUS FREQUENCY AND AMPLITUDE

Complex trace analysis has long been used to extract amplitude and phase characteristics from seismic data (Taner et al., 1979). By considering the real and imaginary components of a seismic trace in the Fourier domain, attributes such as instantaneous amplitude, phase, and frequency can be separated and analyzed individually. Averaged amplitude and frequency have been employed in many seismic studies of continental crust to evaluate whether changes in lower crustal, Moho, and/or mantle reflectivity arise from variations in subsurface properties or variations in signal penetration (de Voogd et al., 1986; Mayer and Brown, 1986; Cannon et al., 1991; Barnes, 1994). Other settings in which signal penetration must be considered are sedimentary sections containing igneous sills and dikes, such as the northeast Atlantic (e.g., offshore Norway and U. K.; White et al., 2002; Ziolkowski et al., 2003; Maresh et al., 2006).

The dramatic changes in lithology within the deep sediments above transitional basement off Newfoundland discussed above could reflect or scatter a large portion of the seismic energy and thus inhibit signal penetration into the underlying section. One way to access signal penetration is to consider changes in the average instantaneous frequency and amplitude characteristics of seismic reflection data with increasing two-way traveltime. In principle, the average seismic frequency should decrease with increasing traveltime because of the preferential attenuation of higher frequencies in the earth (Yilmaz, 1987; Barnes, 1994). Similarly, average amplitude should also decrease gradually with increasing traveltime because of energy loss by scattering, absorption, and geometric spreading (de Voogd et al., 1986; Mayer et al., 1986; Barnes, 1994). As background noise becomes stronger than seismic energy returning from deeper levels of the subsurface, instantaneous amplitude will cease to change much with depth and average frequency will also return to the characteristics of background noise (de Voogd et al., 1986; Mayer et al., 1986; Barnes, 1994).

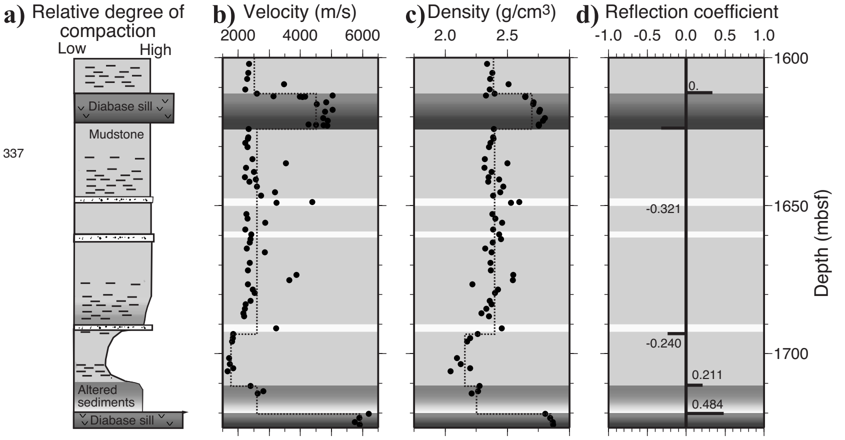

Figure 2. Variations in physical properties accompanying interlayered sills and sediments encountered at the base of site 1276 (1600–1740 mbsf). Modified after Tucholke et al. (2004). (a) Changes in lithology at the base of site 1276. White, stippled layers represent sandstone intervals. (b) and (c) Shipboard laboratory measurements of velocity and density taken on samples of core from each section (Shipboard Scientific Party, 2004a). Black dotted lines indicate averages of velocity and density, respectively, within lithologic layers in this interval. (d) Estimate of reflection coefficients based on contrasts in velocity and density between layers indicated.

In this contribution, we calculate the average instantaneous frequency and amplitude of seismic data along the seaward 225 km of SCREECH line 2 to examine possible variations in signal penetration (Figure 1c). Previous studies have shown that general trends in average frequency and amplitude can be obtained by calculating these attributes along numerous traces, filtering the results and averaging them (Brown, 1986; Mayer et al., 1986; Barnes, 1994). We have used the inner 20 traces of unfiltered shotgathers. No velocity corrections were applied because moveout does not strongly affect the traces at small (<250 m) source-receiver offsets (Figure 3). Instantaneous amplitude and frequency were calculated on each trace using a Seismic Unix module that follows the method of Taner et al. (1979). Traces were then averaged and smoothed using a 250-ms-boxcar operator to obtain a relatively smooth function of average frequency and amplitude with two-way traveltime for each shot.

An important assumption of this method is there is no nonstationary noise in the data set, such as long-period multiples. In the portion of this data set included in our analysis, average two-way traveltime to the seafloor is ~6 s, such that the first seafloor multiples arrive at ~12 s. These multiples do not compromise the analysis of average frequencies in this study because the zone of interest (6–11 s two-way traveltime) lies above the arrival of the first seafloor multiple.

Signal penetration studies of onshore data sets usually use a windstrip (Barnes, 1994) or the last second of the field records (Mayer and Brown, 1986) to estimate the spectral properties of ambient noise. Characterizing ambient noise in marine data sets is more difficult. Using a section of the trace above the seafloor arrival is not ideal because this portion of the data set contains arrivals from features within the water column (i.e., thermohaline structure; Holbrook et al., 2003). The amplitudes of these reflections are very low so that smoothed instantaneous amplitude might be representative of background noise. However, because water column reflections arise from gradients in salinity and temperature over 5–15 m (Nandi et al., 2004), the frequency content can be different from ambient background noise. Using the last second of the record is not a viable option because these data will be affected by long-period multiples. Consequently, we will consider relative changes in spectral characteristics in our discussion and compare the amplitudes with those of the water column.

RESULTS

Averaged, smoothed instantaneous frequency and amplitude were obtained along the seaward section of line 2 using the methods outlined above and several first-order variations in both parameters are apparent (Figure 4). Patterns in amplitude and frequency vary between crustal domains (Figure 4). In general, in the zone of exhumed mantle and oceanic crust (CMPs ~230,000–250,985, shots 28,700–31,250), both average frequency and amplitude decrease markedly with increasing two-way traveltime throughout the sediments and crust until at least 3 s beneath the top of basement (Figures 4 and 5). Below this, the changes in both attributes are more gradual; amplitude reaches levels similar to those observed in the water column and frequency begins to increase slightly. Figure 5 shows a section of seismic data in the seaward portion of line 2 where abundant intracrustal reflectivity is observed, and the change described above occurs between ~10–11 s two-way traveltime. However, beneath basement highs in this domain (CMPs 234000–239000, Figure 4) changes in average frequency and amplitude with two-way traveltime are more variable but both attributes typically decrease for at least 1.5 to 2 s beneath the basement surface.

Unlike the variability in amplitude and frequency characteristics observed in the exhumed mantle/oceanic crust domain, variations in these properties with two-way traveltime are more consistent within "flat" transitional crust (CMPs ~220,000–230,000, shots 27,400–28,600). Average frequency and amplitude decrease steadily throughout the sedimentary section. An increase in average frequency occurs immediately beneath bright reflections in the lowermost sedimentary section that overlie transitional basement, and frequencies continue to increase with depth within the basement for another ~1 s. Below this, frequencies continue to gradually increase with depth or stabilize at a relatively constant value (Figure 6). Likewise, amplitude ceases to change very much with depth at this level and reaches levels comparable to amplitudes observed in the water column (Figure 6). These changes in average frequency and amplitude do not occur at the same two-way traveltime everywhere within this domain, but instead always correspond to the bright reflections in the lowermost sedimentary section.

DISCUSSION

What causes observed variations in spectral properties?

Exhumed mantle and early oceanic crust

We show above that both amplitude and frequency typically decay steadily in the sedimentary section and upper 2 s below the top of basement in the domain of exhumed mantle and early oceanic crust. Below this, average frequency begins to increase slightly and instantaneous amplitude ceases to change as dramatically with depth and reaches levels comparable to those in the water column (e.g., Figure 5). However, significant variability in both attributes is observed within this domain (Figure 4). Variations in average frequency and amplitude with increasing two-way traveltime throughout oceanic crust might result from variations in the material present in the upper oceanic crust. Drilling at site 1277, located on a basement high ("Mauzy Ridge," location in Figures 1 and 4), recovered pillow basalts, breccias containing clasts of gabbro and peridotite, and serpentinized peridotite (Shipboard Scientific Party, 2004b). The composition of other basement highs observed along this line is unknown, but they exhibit diverse characteristics in seismic reflection data (Shillington et al., 2006).

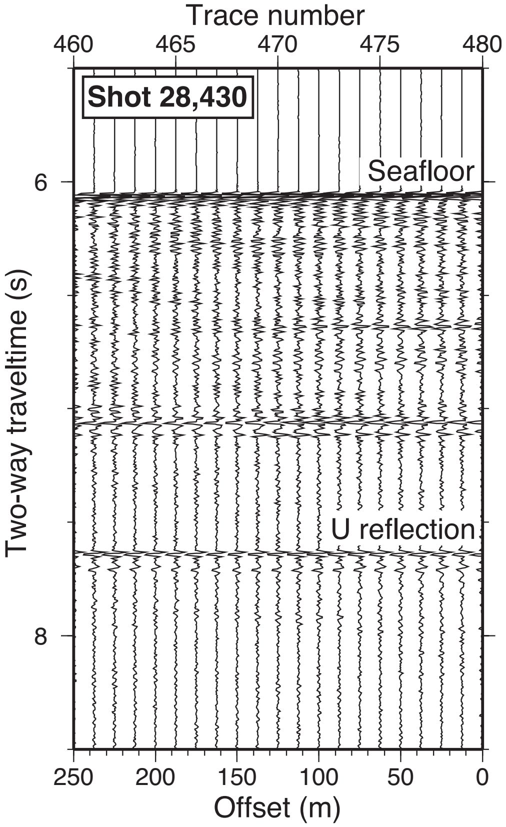

Figure 3. Inner 20 traces of shot 28,430, which is close to site 1276. Note that little moveout occurs within the inner 20 traces.

Variations in oceanic crustal structure have been shown to have markedly different attenuation properties (Goldberg and Sun, 1997). We interpret the observed variations in spectral characteristics to result from a combination of variable signal penetration and variable shallow velocity and density structure within the upper portions of this basement.

Toward the seaward end of line 2, a section of basement with clear intracrustal reflections is observed (Figures 1e and 5). As mentioned earlier, both average amplitude and frequency decrease markedly until two-way traveltimes that are greater than the deepest intracrustal reflections. Beneath this level, amplitude ceases to change as dramatically with depth and reaches levels comparable to those in the water column (e.g., 11 s, Figure 5), implying the strength of the signal can be overpowered by background noise at these two-way traveltimes. At equivalent two-way traveltimes, average frequency begins to increase somewhat, suggesting the frequency content of background noise has a higher average frequency than the deepest returning seismic arrivals. This is consistent with the preferential attenuation of higher frequencies as seismic energy travels farther through the subsurface. In this case, poor signal penetration appears to be marked by an increase in average frequency.

Flat transitional basement

In contrast to the exhumed mantle/oceanic crust domain described above, variations in frequency and amplitude with depth are less variable within flat transitional basement. Amplitude and frequency decrease throughout the sedimentary sequence until reaching bright reflections (including the U reflection) near the base of the section that are interpreted to overlie the top of basement. Below this, average frequency increases and then levels off, and amplitude decreases less dramatically with depth and reaches levels comparable to those in the water column (Figures 4 and 6). The decay of amplitude with increasing two-way traveltime in transitional basement (Figure 6) is much more subtle than variations observed farther seaward in oceanic crust (Figure 5). This pattern continues until reaching the first multiple. Unlike the most seaward domain, this change occurs consistently at the level of bright reflections in the lowermost sedimentary section. Results from deep continental seismic profiling have shown that as long as signal penetration continues, the amplitude and spectral properties of deep seismic reflection data continue to decay, even through "transparent zones" (Brown, 1986).

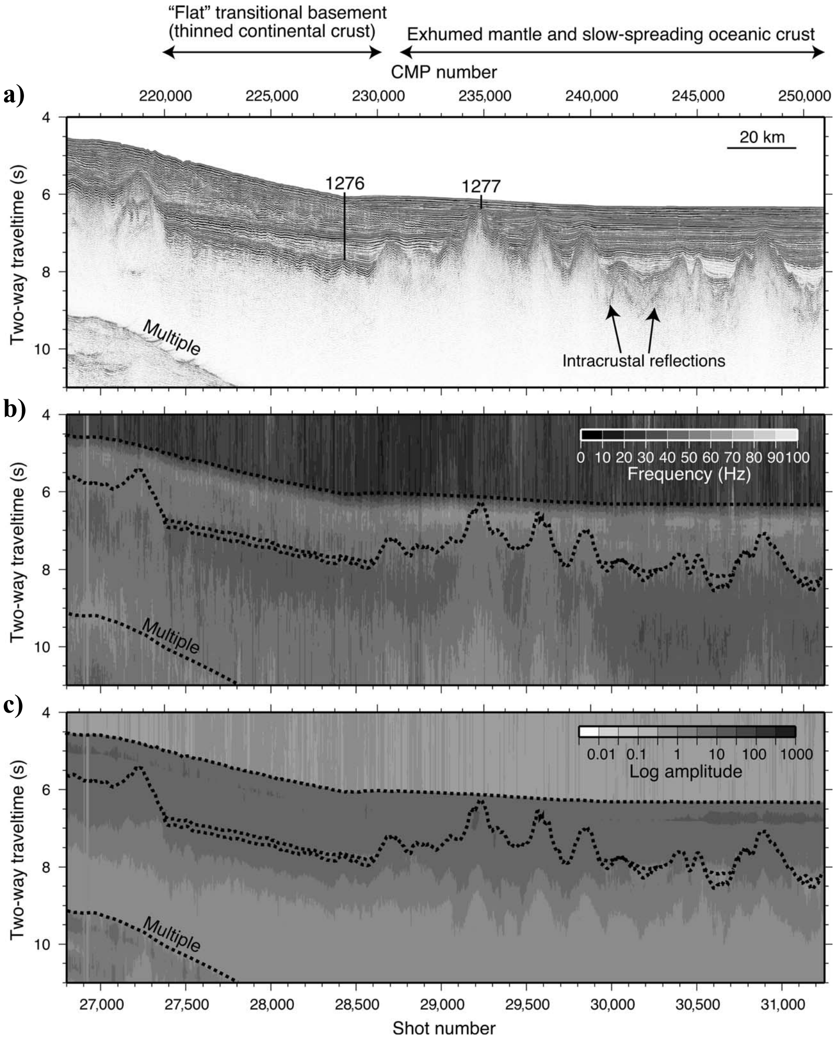

Figure 4. (a) Plot of prestack time-migrated section of SCREECH line 2. Arrows and text indicate the interpreted extent of each crustal domain. (b) Gridded average frequency. Black dotted lines give the location of the seafloor, U reflection, basement surface, and multiple for reference. Note the increase in frequency beneath bright reflections in the lowermost sedimentary section in the "transition zone." In contrast, average frequency continues to decrease beneath the surface of basement within oceanic crust. (c) Gridded average amplitude. Black dotted lines give the location of the seafloor, U reflection, basement surface, and multiple for reference.

Poor signal penetration can be characterized by very slight changes in amplitude with depth (Barnes, 1994). In the Newfoundland transition zone, spectral properties cease to change very much with depth below bright reflections in the deep sedimentary section, particularly compared with oceanic crust farther seaward. Consequently, poor signal penetration beneath these bright reflections is the best explanation for the apparent transparency of this crustal section.

This interpretation of observed frequency and amplitude patterns in transitional crust is consistent with findings from ODP site 1276, where interlayered sediments and diabase sills were recovered at the base of the sedimentary section (∼1612–1725 mbsf; Figure 2). Shipboard laboratory measurements generated during leg 210 indicate these materials have a large range of velocities (1.6–6.2 km/s) and densities (2.1–2.8 g /cm^2; Shipboard Scientific Party [2004a]), which will result in large impedance contrasts in this interval (Figure 2). To estimate predicted reflection coefficients, we have created simple velocity and density profiles based on shipboard laboratory measurements (Shipboard Scientific Party, 2004a) by averaging velocity and density values within various lithologic units, as illustrated in Figure 2. These profiles were then used to calculate impedances for each lithologic unit and reflection coefficients at the boundaries between lithologic units. Reflection coefficients as high as 0.484 are predicted to arise from these impedance contrasts. This is more than double the reflection coefficient calculated for the seafloor reflection in this area (~0.21). Our estimates of reflection coefficients based on laboratory measurements of velocity and density suggest that, taken together, these boundaries would reflect ~86% of downgoing seismic energy that reaches this depth. At these two-way traveltimes (~8.0 s), the remaining transmitted energy would likely be swamped by noise. These simple calculations predict signal penetration would be very limited below the level of these sills and sediments, consistent with our interpretations of variations in average frequency and amplitude.

Scattering of seismic energy off the tops of the sills can also contribute to poor signal penetration. Although the centers of both sills have relatively uniform physical properties (Figure 2), the tops and bottoms are more variable. Hydrothermal alteration increases toward the edges of the sills (Shipboard Scientific Party, 2004a) and the adjacent sediments also experienced significant thermal and mechanical alteration (Karner and Shillington, 2005; Pross et al., 2007). At a larger scale, the appearance of the U reflection, which is locally caused by sills at site 1276, is also variable along SCREECH line 2 and other seismic reflection profiles that cross transitional basement (Shillington et al., 2004; Lau et al., 2006a; Shillington et al., 2006). All of these heterogeneities could effectively result in a rough surface at the top of each sill that can scatter seismic energy and further limit signal penetration into the underlying sediments and basement (Martini and Bean, 2002). Such effects have been observed to arise from Paleogene basalts offshore Britain and Norway (Maresh et al., 2006).

The drilling results also reveal another secondary contribution to frequency characteristics associated with the deepest sediments over transitional crust. Because the deepest section contains a series of thin (~10–100-m thick) intervals with large variations in physical properties, thin bed tuning might affect both the amplitude and frequency attributes of this interval. Anomalously high instantaneous amplitudes are anticipated when a thin bed is approximately a half-wavelength thick and anomalously low instantaneous frequencies are anticipated when a thin bed is approximately a quarter-wavelength thick (Robertson and Nogami, 1984). These effects can contribute partially to the pronounced low-frequency zone observed at the base of the sediments around the U reflection, but they cannot account for the large-scale (1–2 s) patterns in frequency and amplitude throughout the sediments and the basement that are the focus of this contribution.

Implications for distribution of postrift sills on the Newfoundland margin

Poor signal penetration beneath deep sediments over much of the transition zone along line 2 implies large impedance contrasts similar to those found at site 1276 are widespread in this crustal domain. Other profiles from the SCREECH program (Lau et al., 2006a; Shillington et al., 2006) and seismic data acquired during previous studies (Tucholke et al., 1989) also show that basement in the Newfoundland Basin that is overlain by the U reflection and other bright reflections is often notably transparent. The most likely cause of large impedance contrasts is the sequence of interlayered sills and sediments encountered at site 1276 (Shipboard Scientific Party, 2004a). The amplitude and waveform characteristics of bright reflections in the lowermost sedimentary section overlying transitional basement remain consistent over this crustal domain. However, we cannot rule out the possibility that a sedimentary boundary might be capable of limiting signal penetration away from the drill site, although drilling at site 1276 did not re-

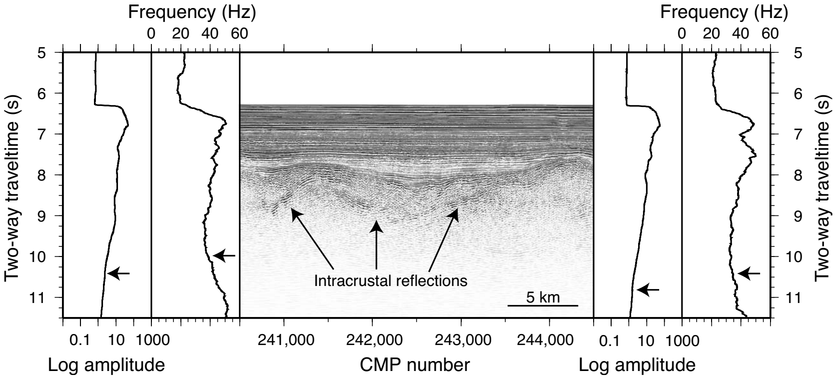

Figure 5. Section of a prestack time-migrated seismic reflection profile taken from the seaward portion of line 2 in a section of oceanic crust with abundant intracrustal reflectivity. Plots of average frequency versus two-way traveltime and average amplitude versus two-way traveltime for shot gathers taken from each end of the plotted section are shown to the left and right, respectively. Note the continued decrease in average frequency and amplitude throughout the crust until beneath the deepest occurrence of intracrustal reflectivity (~9.5 s), which is indicated with text and arrows. At 10–11 s, average frequencies begin to increase (indicated with black arrows in average frequency panels). At ~11 s, amplitudes are comparable to those in the water column above (indicated with black arrows in average amplitude panels).

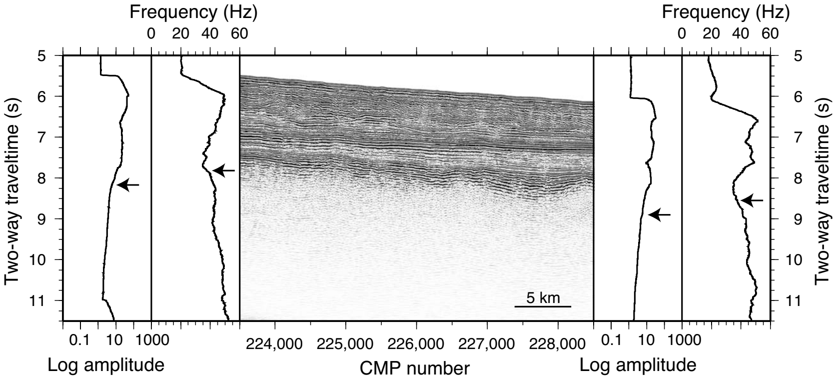

Figure 6. Section of a prestack time-migrated seismic reflection profile taken from "transitional" crust on line 2. Plots of average frequency versus two-way traveltime and average amplitude versus two-way traveltime for shot gathers taken from each end of this section are plotted to the left and right, respectively. Note the increase in average frequency and flattening of average amplitude beneath bright reflections in the lowermost section indicated with black arrows in the amplitude and frequency panels. This increase appears to correspond to bright reflections overlying basement throughout the transition zone.

cover sedimentary units with equivalent variations in physical properties to those observed between sills and sediments (Shipboard Scientific Party, 2004a).

Seaward of the transition zone, oceanic crust exhibiting high topography continues to the end of line 2. As a result, reflections that overlie transitional crust cannot be directly correlated farther seaward. However, at the seaward end of line 2, reflections at comparable two-way traveltimes to the bright reflections within the transition zone are observed (e.g., CMPs 241,000–243,000, 245,000–247,000, and 248,000–25,000; Figure 4). Here, no similar change in average frequency and amplitude occurs beneath these reflections and intracrustal features are evident in the underlying crust (Figure 4). This implies that there are not analogous material property contrasts (density and velocity) at this location that would inhibit seismic signal penetration in the same way. We infer that post-rift sills encountered at site 1276 are not present in deep sedimentary basins on the seaward end of line 2 where reflections at similar depths to the U reflection are observed.

Implications for usefulness of seismic characteristics of transitional basement

The results of amplitude and frequency analysis presented here suggest that seismic transparency cannot be used as a distinguishing characteristic of transitional basement on the Newfoundland margin. Seismic transparency observed in the upper basement in some parts of the transition zone on Iberia has been related to a lack of impedance contrast between deep sediments and highly serpentinized mantle (Pickup et al., 1996). Because of the poor signal penetration beneath bright reflections in the deep sedimentary section on the Newfoundland margin, it is not possible to assess variations in physical properties of this transitional basement from seismic reflection characteristics. Instead, the only places where the seismic reflection characteristics of this crust might be discerned confidently in the Newfoundland Basin are where the basement protrudes above bright reflections in the lowermost section.

CONCLUSIONS

The averaged, instantaneous amplitude and frequency characteristics of seismic reflection data collected on the Newfoundland magma-poor rifted margin demonstrate that the transparency of “transitional” crust between unambiguous oceanic and continental crust arises from poor signal penetration rather than from homogeneity within this crust or a lack of impedance contrast with the overlying sediments. Consequently, the featureless appearance of this crust in seismic-reflection profiles cannot be used to estimate its physical properties. Instead, only seismic characteristics observed in rare basement highs that rise above bright reflections of the lowermost sedimentary section provide meaningful information on transitional crust. The apparent lack of signal penetration in this crustal domain is consistent with findings at site 1276 during ODP leg 210, which recovered interlayered diabase sills and sediments above basement, including an undercompacted zone, which would likely result in high-reflection coefficients and possibly limited signal penetration. The poor seismic penetration inferred throughout the transition zone on Newfoundland implies interlayered sills and sediments might be widespread within this crustal domain.

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