Crustal structure across the Grand Banks–Newfoundland Basin Continental Margin – II. Results from a seismic reflection profile

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Summary

New multi-channel seismic (MCS) reflection data were collected over a 565km transect covering the non-volcanic rifted margin of the central eastern Grand Banks and the Newfoundland Basin in the northwestern Atlantic. Three major crustal zones are interpreted from west to east over the seaward 350-km of the profile: (1) continental crust; (2) transitional basement; (3) oceanic crust. Continental crust thins over a wide zone (~160 km) by forming a large rift basin (Carson Basin) and seaward fault block, together with a series of smaller fault blocks eastward beneath the Salar and Newfoundland basins. Analysis of selected previous reflection profiles (Lithoprobe 85-4, 85-2 and Conrad NB-1) indicates that prominent landward-dipping reflections observed under the continental slope are a regional phenomenon. They define the landward edge of a deep serpentinized mantle layer, which underlies both extended continental crust and transitional basement. The 80-km-wide transitional basement is defined landward by a basement high that may consist of serpentinized peridotite and seaward by a pair of basement highs of unknown crustal origin. Flat and unreflective transitional basement most likely is exhumed, serpentinized mantle, although our results do not exclude the possibility of anomalously thinned oceanic crust. A Moho reflection below interpreted oceanic crust is first observed landward of magnetic anomaly M4, 230 km from the shelf break. Extrapolation of ages from chron M0 to the edge of interpreted oceanic crust suggests that the onset of seafloor spreading was ~138Ma (Valanginian) in the south (southern Newfoundland Basin) to ~125Ma (Barremian-Aptian boundary) in the north (Flemish Cap), comparable to those proposed for the conjugate margins.

Keywords

Continental margins; crustal structures; reflection seismology; rifted margins; seismic structures

1. Introduction

Because extensional fabrics across non-volcanic margins are well preserved by the lack of excessive melt generation during rifting, their crustal structures, especially those of the North Atlantic margins, have been studied to define rifting and extensional processes (reviewed by Louden & Chian 1999). A common feature of these margins is an ocean-continent transition (OCT) zone, a region possibly consisting of exhumed and serpentinized upper mantle between rifted continental crust and normal, magmatically produced oceanic crust. The best-studied OCT is on the western Iberia margin. Its conjugate, the Grand Banks/Newfoundland basin margin (Fig. 1), however, has not been studied in the same detail, particularly within the deeper-water regions of the OCT where existing studies show ambiguities in interpretation of crustal structure. Thus, structural relations between the Newfoundland and the Iberia margins, and the associated rift processes remain poorly understood. For instance, Newfoundland and Iberia were proposed to have separated along an asymmetrical low-angle detachment, based on observations from only the Iberia margin (e.g. Boillot & Winterer 1988; Krawczyk *et al.* 1996). In contrast, Driscoll & Karner (1998) proposed that preferential thinning of the lower crust may have formed symmetrical conjugate margins, both of which resemble upper plates. Therefore, to further understand the processes involved, a detailed image of the crust beneath the Newfoundland basin is needed.

Fig. 2 shows different interpretations of crustal structure of the Newfoundland basin margin based on previous reflection profiles. On Lithoprobe profile 85-4 (Fig. 2a; Keen & de Voogd 1988), continental crust is interpreted to thin as indicated by tilted fault blocks beneath the Carson basin and the Salar basin. These fault blocks are not as well defined on Conrad profile NB-1 (Fig. 2b; Tucholke *et al.* 1989), where mobile evaporites are interpreted to cover the bottom of the Salar basin between two hinges. To the south on Lithoprobe profile

85-2 (Fig. 2c; Keen & de Voogd 1988), thinned continental crust is interpreted landward of a prominent landward dipping reflection, “L”. The “L”-reflection was proposed to define the continent-ocean boundary (COB) (Keen & de Voogd 1988) and was later suggested to mark the landward limit of serpentinized mantle beneath oceanic crust (Reid 1994). It is absent on profile 85-4 and NB-1 (Figs 2a and 2b).

Farther seaward, existing data suggested an ocean-continent transition within the Newfoundland basin where the basement may be:

(1) slow or ultra-slow spreading oceanic crust (Reid 1994; Keen & de Voogd 1988; Srivastava *et al.* 2000);

(2) extended continental crust (Tucholke *et al.* 1989; Enachescu 1992); or

(3) exhumed mantle as observed on the conjugate Iberia margin (e.g. Boillot *et al.* 1987; Dean *et al.* 2000).

The first hypothesis of slow or ultra-slow spreading oceanic crust within the Newfoundland basin is based on interpretations of profiles 85-4 and 85-2 (Figs 2a and 2c; Keen & de Voogd 1988). On profile 85-2, however, the low basement relief and the velocity structure (Reid 1994) are not typical of oceanic crust, and the basement on profile 85-4 is masked by a high-amplitude, reverberative reflection termed “U” (Fig. 2b; Tucholke *et al.* 1989). In contrast, the crust beneath the “U” reflection on profile NB-1 has been interpreted in the second hypothesis as a wide zone of highly thinned continental crust (Fig. 2b; Tucholke *et al.* 1989; Enachescu 1992). A third possibility of exhumed, serpentinized mantle within the OCT is explained in Lau *et al.* (2006).

The Grand Banks/Newfoundland basin margin (hereafter, Newfoundland margin) was rifted in two or three phases (e.g., Tankard & Welsink, 1987; Tucholke & Whitmarsh, in press): (1) late Triassic rifting between North America and Africa/Europe; (2) late Jurassic (Oxfordian-Kimmeridgian) rifting; and (3) latest Jurassic to early Cretaceous rifting between Newfoundland and Iberia leading to continental separation. However, ambiguities in the landward extent of oceanic crust have led to differences in a more detailed determination of onset ages of seafloor spreading. One proposal suggested onset between anomaly ~M1-M2 and M0 (Barremian-Aptian or ~121 Ma; Tucholke *et al.* 1989; timescale of Gradstein *et al.* 1994), while a much earlier onset at anomaly M17 (early Berriasian or 141 Ma) was based on interpretation of low-amplitude magnetic anomalies that might be caused by ultra-slow seafloor spreading (half rate = 6.7 mm/yr; Srivastava *et al.* 2000). However, Driscoll *et al.* (1995) observed that rifting continued in the Jeanne d'Arc basin until late Aptian time (~113 Ma), which would indicate either a later onset for seafloor spreading or simultaneous seafloor spreading and continental rifting. Interpretations of magnetic and seismic observations on the conjugate Iberia margin suggest an onset of seafloor spreading at ~M3 (~127 Ma; Whitmarsh & Miles 1995; Russell & Whitmarsh 2003).

To better understand the formation of the Newfoundland margin and the Newfoundland-Iberia rift, a large-scale international seismic survey was conducted in 2000 (SCREECH, Study of Continental Rifting and Extension on the Eastern Canadian sHelf; Fig. 1). Coincident multi-channel seismic (MCS) and wide-angle reflection/refraction data were collected along three major transects, and additional MCS data were collected around these transects (Shillington *et al.* 2004).

In this paper, we investigate basement structure, crustal origin, and the timing of seafloor spreading using MCS data collected along the seaward 350-km of Line 3, the southernmost transect. This profile passes southeastward across the south Jeanne d'Arc, Carson, and north Salar basins into the central Newfoundland basin (Fig. 1). It ends north of the Newfoundland Seamounts and intersects profiles 85-4 (Keen & de Voogd 1988), and NB-1, 6 and 4 (Tucholke *et al.* 1989). We first describe the data acquisition and processing procedures, and then present results and interpretations for the different crustal zones. A comparison with coincident wide-angle data on Line 3 and with previous results and the timing of seafloor spreading are discussed at the end of the paper.

2. Data acquisition and processing

Multi-channel seismic (MCS) data were collected along three primary transects (SCREECH-1, 2 and 3 in Fig. 1) aboard R/V Maurice Ewing. Locations of other secondary lines can be found in Fig. F5 of the Shipboard Scientific Party (2004) report. The seismic source was a 20-gun, 140 L (8540 in^3), tuned air gun array fired on distance every 50 m. Data were recorded by a 480-channel, 6-km streamer for 16.3 s at a sampling rate of 4 ms. This results in a common midpoint (CMP) fold of 60 and CMP spacing of 6.25 m.

We present only the seaward 350-km of Line 3 in this paper (shown as a thicker line in Fig. 1). Processing of this line has mainly followed conventional MCS processing procedures including muting of refracted arrivals, minimum phase bandpass filtering, spherical divergence correction, velocity analysis, normal moveout correction (NMO), stacking and post-stack time migration. Stacking velocities were picked every 200 CMP by at least two passes of velocity analysis - one before and one after the removal of water-bottom multiples. Additional velocity analysis was done for CMP 521000-539000 after further work on multiple removal. Additional processing procedures included an *f-k* filter applied on shot gathers for the continental shelf region (CMP <502000; Fig. 3) to remove pervasive, strong, linear coherent noise. Furthermore, because of low signal-to-noise ratio in crystalline basement and the irregular nature of noise amplitudes (incoherent and variable from trace to trace), automatic gain control was applied before stack for the shelf and slope areas. On the shelf the gain window was 500 ms but on the slope the window was time and space variant due to high amplitudes of reflections from the basement surface and associated problems with gain shadows.

a) Water-bottom multiple removal

Different methods were used for the removal of multiples on different parts of the profile because of changes in water depth. On the shelf (CMP <502000; Fig. 3), pervasive, high-amplitude reverberations were attenuated through near-trace predictive deconvolution before stack and predictive deconvolution designed in three separate time windows after stack. The upper-slope data were radon filtered (hyperbolic transform; Hampson 1986; Yilmaz 2001) for multiple removal in the CMP domain. Geometric distortion due to the strong seafloor dip prevented construction of events as super-gathers. Data from the lower slope where the seafloor was deeper and had less dip was radon filtered as CMP super-gathers. Further attenuation of multiple remnants after radon filtering was also achieved by near-trace muting before stack. An offset-dependent bandpass filter was applied to restrict relatively high frequencies that led to aliasing of steeply dipping water-borne arrivals on far traces. Careful mute design was necessary on far traces after the normal moveout correction to remove remaining water-borne waves.

For the deep-water part of the profile seaward of CMP 519000 (Fig. 3), the seafloor is relatively flat and the first multiple is greater than 9 s two-way travel time (TWTT). Because the crust was presumed to be thin (<10 km thick or <3 s TWTT) and the top of basement is ~7.5-8 s, the first two seconds of the first water-bottom multiple (starting at ~10 s) were predicted to overlap with primary reflections important to this study, and hence were the target of multiple removal. For this purpose, super-gathers (each constructed from eight consecutive CMP gathers) were produced and NMO-corrected at a constant velocity of 1700 m/s. The multiples were removed by applying an *f-k* filter manually designed to remove energy in the multiple quadrant of the spectrum (wavenumbers >0.009 m^{-1} and frequencies >4.7 Hz). Such a filter was applied only to time intervals overprinted by the multiples. After the NMO at 1700 km/s was removed, an inside-trace mute was applied to all CMP gathers for offsets ≤ 1500 m at TWTT equal to the first water-bottom multiple and below to remove multiple remnants.

b) U-related peg-leg removal

The “U” reflection is a strong event within the sedimentary section near basement, much as is observed on profiles NB-1 and 85-4 underneath the Newfoundland basin (Fig. 2). It created a series of peg-leg multiples that obscure interpretation of the top-basement reflection on Line 3 for CMP 521000-528600 and CMP 528801-539000 (Fig. 3). For CMP 521000-528600, minimum-phase predictive deconvolution was applied for "sub-U" times

(7100-9600 ms) before stacking. The operator was designed using the signal over the interval of the peg-leg events (72008200 ms). For CMP 528801-539000, a simpler approach was taken because of a lack of well defined basement reflections. An inside-trace mute was applied to remove the dominance of peg-leg events over the primaries at near offsets. The lower mute window was picked manually on the NMO-corrected CMP gathers (average of ~8300 ms) such that more than 2/3 of the total offsets could be kept for subsequent stacking.

c) Post-stack processing for sections shown

Post-stack processing prior to migration included deconvolution for the shelf area and time-variant bandpass filtering and amplitude balancing for the shelf and slope. The post-stack time-migration algorithms used are Kirchoff migration (CMP <500000), Stolt *f-k* migration (CMP 500000-527399) and finite-difference migration (CMP >527399). A 2-D velocity model modified from the stacking velocities by a trial-and-error approach was used to remove artifacts created by dipping structures. Data were then resampled every 8 ms with an anti-alias filter before subsequent processing performed to enhance the signal-to-noise ratio of the deeper structures in Fig. 3 and Figs 5-7. A post-stack *f-k* filter was applied to eliminate events dipping steeper than 0.4 ms/m to remove over-migrated multiple remnants and other noise. Further processing included bandpass filtering (9-35 Hz), automatic gain control (504 ms window), and coherency filtering. According to the dominant frequencies and the interval velocities, the vertical resolution (~1/4 of dominant wavelength) of the final section (Fig. 3) is ~17 m, ~50 m and ~100 m for TWTT intervals 0-2 s, 2-4 s and 4-6 s below seafloor, respectively. The lateral resolution is approximately 4 times the above values (Stolt

& Benson 1986).

3. Results

The processed reflection profile for Line 3 is shown in Fig. 3, along with the magnetic anomaly. The margin is divided into three major crustal zones: (1) rifted continental crust, (2) transitional basement, and (3) oceanic crust. Each zone is further sub-divided to reflect secondary changes in basement character. Details of interpretation are shown in Figs 5-7. Basement is covered by a sequence of well defined sedimentary layers (Fig. 4), but because the emphasis of this paper is on crustal structures, most profiles shown here (i.e., Fig. 3 and Figs 5-7) are optimized to illustrate deeper structures that have lower frequency content. Because of the long length of Line 3, seismic sections are plotted using every fourth trace and a vertical exaggeration at the seafloor of ~8 (assuming a mean velocity of 1.5 km/s).

a) Sedimentary layers

A thick section (~1-3.5 s) of post-rift sediment on Line 3 can be correlated along a tie line (Line 305; Shillington *et al.* 2004) to Line 2 (Fig. 1), where seismic sequences (labeled as A-F; Figs 4 and 5) were drilled during ODP Leg 210 at Site 1276 (Shipboard Scientific Party 2004). It was deposited after the rifting/extension of the basement underneath, starting at the top of syn-rift or pre-rift sediment (defined below) or the basement if these are absent. The deepest sequence, A, is defined at the top by the “U” reflection. At ODP Site 1276, this reflection appears to correlate with a diabase sill intruded into lower Albian turbiditic sediments. Sequence B is defined at the top by an unconformity and is a turbidite and black shale sequence (Lithologic Unit 5, upper Cenomanian-lowermost Turonian at the top). This sequence is weakly laminated and reflective below the more strongly laminated and reflective sequence C. The latter sequence is marked at the top by the “A^{u}” unconformity, attributed to erosion during the development of the Deep Western Boundary Current in the North Atlantic (Tucholke & Mountain 1979). It consists mainly of brown sandy mudstone and multicoloured hemipelagic claystones interbedded with turbidites (Lithologic Units 2-4) and its fabric suggests complexity in bottom current energy and depositional environment. Sequence D consists of gray-green hemipelagic claystones and mudstones of middle Eocene to lower Oligocene(?) age in the lower part, and shows predominately sub-horizontal and weak reflections, with several stronger and more continuous reflections at the base.

On Line 3, it does not contain a thick sequence of pinch-and-swell reflections close to the margin as it does on Line 2. We speculate the pinch-and-swell succession on Line 2 to be related to its proximity to Flemish Pass, which is a region of higher energy flow. However, the more laminated basal layer of this sequence observed on Line 3 becomes very condensed on Line 2. Sequences E and F are very similar to those observed on Line 2. Steep and small-throw normal faults are frequently observed seaward of ~CMP 513500 within these two sequences but not in the deeper sequences.

On Line 3, apparent pre-rift and syn-rift sediments just above basement and landward of CMP 526000 suggest that the underlying crust is upper continental crust (Figs 5 and 6). Sediments just above the basement that have reflections diverging from the shallower sediments are interpreted as either syn-rift or pre-rift sediment. These sequences usually show a dramatic change in reflection character from that of the overlying post-rift sediments.

Tilted sediments that parallel the underlying basement (e.g., CMP 505000-508000, Fig. 5) are interpreted as pre-rift sediments, while tilted sediments with fanning reflections (e.g., CMP 505000-506500) are interpreted as syn-rift sediments. These sequences are best developed within Carson basin but are also present seaward as very thin packages in the Salar basin (Fig. 5).

b) Rifted continental crust (C1, C2)

The zone of rifted continental crust (C1 and C2; Figs 3, 5 and 6) contains tilted basement fault blocks, with overlying syn-rift and pre-rift sediments. Interpreted seaward-dipping faults (dashed lines in Figs 5 and 6) are poorly imaged and are mostly inferred from the basement geometry and configuration of pre- and syn-rift sediments. Most observed intracrustal reflections are landward dipping, although interpreted faults are seaward dipping. The top-of-basement reflection is relatively weak and discontinuous.

In the landward section of rifted continental crust (section C1), basement can be distinguished from the overlying sediment relatively easily compared to section C2 (Fig. 3). No rift structures are observed at the western end of the profile seaward of the Jeanne d'Arc basin (CMP 500000-501500) and a deep crustal reflection (possibly Moho) is observed at ~11.3-12 s. Thick continental crust with little or no thinning is thus indicated. The crust thins seaward where one or a series of normal faults (CMP 502000-505000) forms a major, large-throw border-fault system bounding the western margin of Carson basin (CMP 502000-507000; Figs 1 and 8). The large, rotated fault block at CMP 50600-50900 (Fig. 5) is a prominent basement high that separates Carson basin from the Salar basin to the east. The sharp increase in basement depth seaward of this large basement high suggests significant crustal thinning. The western flank of the basement high is capped by a sequence of parallel, landward-dipping reflections that are interpreted as pre-rift sediments. A group of deep reflections (R; Fig. 5) is observed beneath the basement high but they could be a remnant of seafloor multiple reflections.

Although it is located at the seaward edge of the Grand Banks, Carson basin probably formed as early as the first phase of the Mesozoic rifting (see Introduction), much like the Jeanne d'Arc basin, when the continental crust was still thick. Two major sequences of syn-rift sediment are observed within the basin (Fig. 5). The lower sequence exhibits weak, divergent reflectors. The upper sequence has strong, parallel reflections that lap onto the lower sequence at its seaward end. The upper sequence may have in-filled the basin during a quiet period after an initial period of extension, followed by some sag or later extension. These reflection characteristics are comparable to those of the two major sequences observed within the Jeanne d'Arc basin (Driscoll *et al.* 1995). The lower sequence is likely to have been deposited during the first phase of Mesozoic rifting, which in Jeanne d'Arc basin produced a divergent sequence that includes reflective bedded salt (Keen *et al.* 1987; Sinclair 1995). The upper sequence may be related to the second phase of rifting during which Jurassic sequences were deposited in Jeanne d'Arc basin (Driscoll *et al.* 1995). Furthermore, a structural high, similar to the Hibernia structural high (south of the Nautilus transfer zone), at the landward end of this sequence (Fig. 3) suggests some deformation caused by basin inversion.

Seaward of the large basement high is a series of smaller tilted fault blocks with smaller throw (Fig. 5). The bottom of the Salar basin deepens seaward and reaches its deepest point (~CMP 516000) where the top of basement is observed at 8 s (Fig. 5). At least one apparent fault block at ~CMP 516000 shows dipping events that are likely caused by out-of-plane structures. Out-of-plane energy is a problem throughout the section and complicates interpretation of the data. A tilted fault block forms another major basement high at CMP 520000, which interrupts the "U" reflection and forms the seaward hinge of the Salar basin (Fig. 3). The basement surface can be traced easily across this high.

A prominent set of intra-crustal reflections at CMP 509000-513500 and 9.5 7.5 s is interpreted to be comparable to the "L" reflection of Keen & de Voogd (1988) on profile 85-2. The "L" reflections are low frequency, high amplitude and are very coherent (Fig. 5). At CMP 509000-510500, the "L" reflections consist of two major landward dipping reflections that merge seaward. Amplitude of the single reflection decreases at ~CMP 511000 but increases as it shallows seaward and branches into two other major reflections.

In the seaward section of continental crust (C2), beyond CMP 523000, the top-basement reflection becomes very weak and difficult to define (Fig. 6). This is either because "U" is so strong that little energy penetrates below it or there is only a small acoustic impedance contrast between the lowermost sediments and basement, or both. Observed structures within basement, together with possible evidence of pre- or syn-rift sediments, suggest that this crust consists of small tilted fault blocks (Fig. 6). A strong landward-dipping reflection (labelled Moho, CMP 525500526500) marks the location of the seaward-most rifted continental crust and may be related to a fault that led to continental breakup.

c) Transitional basement (T1, T2, T3)

Seaward of section C2 is a zone characterized by a general lack of crustal and Moho reflections (Figs 3 and 6). Picking of the basement surface is very difficult and it is inferred from the downward disappearance of flat reflections that suggest sedimentary layers. This basement has a reflection character that is significantly different from interpreted continental crust landward and interpreted oceanic crust seaward, and it is thus termed transitional basement.

T1 is the landward-most section of the transitional basement and consists of a round-topped basement high (~CMP 529000). The basement high resembles a diapiric, uplifted or intrusive structure, based on the disturbance of sub-“U” sediments above the basement high. The displacement was likely to have occurred before the emplacement of "U", since the layer of pre-“U” displaced sediment is thinner above the high than its surrounding. The sub-“U” sediment was displaced above the depths of the surrounding seafloor. Therefore, “U” and several subsequent layers lap onto the flanks of the high and do not cross the high (Fig. 6). Complex internal structures of unknown origin are observed within the deeper region of the basement high (Fig. 6) with both landward- and seaward-dipping reflections present.

T2 is the middle part of the transitional zone (Fig. 3) and lies seaward of the basement high mentioned above. The top-basement reflection is mostly absent and, internally, this basement is unreflective, especially in its upper part. The latter feature may be due to the application of an inside-trace mute for the upper basement, which could have caused an apparent decrease in both amplitude and coherent reflectivity. The basement surface is interpreted to be very near "U" (or ~0.3 s below "U"). The lack of top-basement reflections may be caused by the presence of a strong “U” reflection and weak impedance contrast between sediment and basement, as suggested earlier for section C2. A band of higher reflectivity is observed ~0.6 s below "U". Tests using different AGC lengths show that this event is not an artifact of the application of AGC (i.e., AGC shadow) and, therefore, is likely to be a primary event. There is no evidence of a reflection Moho in this section, suggesting that there is no sharp break in velocities within the basement. Based on changes in reflection character of section T2 compared to landward sections, we can probably exclude the possibility that T2 basement is rifted continental crust, assuming that the pre-rift crust was uniform. The flat and unreflective basement and the lack of Moho reflection are very similar to the upper part of the interpreted exhumed, serpentinized mantle on profile IAM-9 across the Iberia Abyssal Plain (Pickup *et al.* 1996), suggesting that the transitional basement may consist of exhumed, serpentinized mantle. However, the strong “U” could have masked deeper structures representative of ultra-slow spreading oceanic crust such as those described near Flemish Cap (Hopper *et al.* 2004).

Within section T3, two basement highs are observed (Figs 3 and 7). Their steep dips, however, may not be properly imaged by conventional MCS processing, so further work with pre-stack migration will be needed to improve the image quality. Similar basement highs to the southwest on Line 306 (Fig. 1) show that these features extend along strike at least 15 km (Hawken 2003). Sub-parallel reflections within the landward of the two highs appear to be conformable with the basement topography. These reflections are predominately landward dipping. High-amplitude reflections between the two highs at ~8.5-9.5 s may be Moho reflections (Fig. 7). Unfortunately, none of these features are diagnostic of basement origins.

d) Oceanic crust (O1, O2)

The zone of interpreted oceanic crust is characterized most uniquely by its rough basement surface, which tends to create diffractions in the stacked section. After migration, the top-basement reflection becomes relatively clear (Fig. 3 and 7). The exact start of oceanic crust is not obvious, but the presence of a sub-horizontal reflection starting at ~CMP 539500 and 8.7 s (Fig. 7) may be the most landward evidence for the presence of oceanic crustal Moho. In section O1 (Fig. 3), interpretation of possible Moho reflections (Figs 7 and 8) indicates that the crust thickens seaward to a thickness that is approximately normal for oceanic crustal (1.5 s TWTT or ~5 km) starting at ~CMP 541500, where the basement becomes shallower. Tilted fault blocks are observed in this region (CMP 546000-550000) suggesting that tectonic extension characterized the early stage of seafloor spreading and may be evidence for a slow spreading rate. Section O2 is the most seaward part of our interpreted oceanic crust. Reflections near the top of the basement are chaotic and may be caused by interbedded volcanic rocks and sediments. Therefore, the top of unequivocal basement would occur at the base of this chaotic layer.

4. Discussion

Results presented in the previous section are discussed here and integrated with other related observations. These include a coincident velocity model of Line 3 (Lau *et al.*, this issue) and selected seismic profiles (Fig. 1) previously collected in the region, i.e., SCREECH Line 1 (Hopper *et al.* 2004; Funck *et al.* 2003), Lithoprobe profiles 85-2 and 85-4

(Keen & de Voogd 1988; Reid 1994), and Conrad profile NB-1 (Tucholke *et al.* 1989). These provide additional support for our interpretations and allow us to generalize them into a more regional context for the Newfoundland basin.

a) Comparison with velocity model

A velocity model has been derived along Line 3 from coincident wide-angle data (Lau *et al.*, this issue) and in Fig. 8 the MCS data are converted into depth using this velocity model to better approximate true structural geometry, with selected model boundaries from the velocity model superimposed. Variations in the velocity model agree remarkably well with the sedimentary and crustal reflectivity zones identified in the MCS data.

Major sedimentary units observed in the MCS data can also be identified in the velocity model. High-amplitude MCS reflections of post-rift sediments coincide with model boundaries derived from wide-angle refraction data (removed for clarity in Fig. 8), except in thick sediments beneath the continental slope where compaction rather than lithology dominates the influence on velocity. For example, the “U” reflection coincides with a model boundary across which velocity changes from 3.4 km/s to 4.4 km/s. The pre- and syn-rift sequence on the landward flank of the large basement high (CMP 504000-508000) also correlates with a high-velocity sediment layer (~5.2 km/s; Fig. 8). Both velocity and reflectivity observations suggest that this sequence is equivalent to the highly reflective, high-velocity (~5.4 km/s; Lau *et al.*, this issue) syn-rift sequence at the base of Jeanne d’Arc basin (including bedded salt of the Upper Triassic-Lower Jurassic Argo Formation; Keen *et al.* 1987; Sinclair 1995).

Changes in crustal velocities and boundary depths of the velocity model also agree well with our interpretation of three crustal zones based on the MCS data (Figs 3 and 8). Over the zone of continental crust at the landward end of the profile, the crustal velocities are typical of Newfoundland Appalachian crust (Marillier *et al.* 1994) consisting of upper (5.8-6.2 km/s), middle (6.3-6.5 km/s) and lower (6.8-6.9 km/s) layers. The Moho reflection observed under the thick crust is within 0.5 second of the velocity-model Moho (CMP 500000-502000; Fig. 8). At ~CMP 510000, the model Moho matches the lower part of the "L" reflection (compare Figs 5 and 8). This reflection also coincides with the landward limit of a wide (~200 km) layer of low-velocity (7.6-7.9 km/s) mantle that is interpreted to be partially serpentinized (Lau *et al.*, this issue).

Above this mantle layer, the velocity-model boundaries show that the middle and the lower continental crust thin slowly to near zero thickness at CMP 518500, although a thin layer (<5 km) of upper continental crust (~5.9 km/s) appears to extend much farther seaward to the start of the transition zone at CMP 528000. Our interpreted, rifted continental crust (section C2) has basement topography similar to that off Galicia Bank, but it lacks a sub-horizontal "S"-type reflection indicative of brittle decoupling between upper and lower plates (Reston *et al.* 1996). This implies that the mechanism of crustal thinning was different in these two regions of the rift. Furthermore, no "S" reflections are observed in profile IAM-9 across the Iberia margin (Pickup *et al.* 1996) in a position roughly conjugate to Line 3. Therefore, we do not observe an asymmetrical detachment system across the Newfoundland basin-Iberia Abyssal Plain conjugates similar to that of the Flemish Cap-Galicia Bank conjugates (for further discussion on conjugate reconstructions, see Lau *et al.*, 2006). The lack of near-incidence Moho reflections despite a strong velocity contrast (5.9 and 7.6 km/s; Lau *et al.*, this issue) may suggest that a layer of high velocity gradient exists at the base of the crust but is too thin to be resolvable by the seismic methods used.

Within the transition zone, the velocity model suggests a high-gradient basement layer (4.5-7.7 km/s and ~5 km thick) with weak or no velocity discontinuity separating it from the mantle. This explains the lack of internal reflectivity and Moho reflection in section T2 (Fig. 3). According to its velocity structure, the transitional crust could consist either of exhumed and highly serpentinized mantle or ultra-thin oceanic crust, in agreement with the change in reflection character from that of the rifted continental crust landward. The round-topped basement high, observed at the landward end of the transitional crust (section T1), is more likely to consist of serpentinite; since otherwise as oceanic crust, it is unlikely to have been uplifted later to disturb the overlying sediment.

Finally, at the seaward end of the profile, the MCS observations of interpreted oceanic crust are also consistent with the velocity model. At the landward limit of this crust, the possible Moho reflections match the refraction Moho (~CMP 540000; Fig. 8). As the crust becomes thicker seaward, velocities characteristic of oceanic layer 2 (4.5-6.3 km/s) and layer 3 (6.3-7.2 km/s) are observed.

b) Comparison with other data sets

Based on Line 3, a re-interpretation of nearby profiles (Fig. 9) shows variations in the width of rifted continental crust and the onset age of seafloor spreading. On profile 85-2, continental crust is interpreted seaward of the reflection “L”, which marks the landward limit of a deep serpentinized mantle layer (Reid 1994), until the proposed transitional basement, where the top-of-basement is relatively flat, similar to section T2 on Line 3. Oceanic crust starts where variations in the basement topography become greater seaward (Fig. 2c).

On profiles NB-1 and 85-4, a large continental fault block is interpreted between the Carson and the Salar basins, as is observed on Line 3. This feature coincides with a gravity high that extends northeastward along strike from ~45°N to ~47.5°N (Fig. 9). Our interpretation of the structure as a ~N-S elongated fault block conflicts with a previous interpretation of this feature as a salt structure (Enachescu 1992). Diapiric structures associated with evaporites have previously been interpreted in the Salar basin further south (Fig. 2b; Tucholke *et al.* 1989), but these deposits may be limited or non-existent around Line 3; we observe no deformation in the sediment that might be associated with evaporite diapirism or flow (CDP 505000-516000; Fig. 3). On profiles NB-1 and 85-4, a zone similar to section C2 on Line 3, is also proposed where the basement surface of rifted continental crust is only weakly reflective. Its seaward limit is extrapolated from that of Line 3, assuming that its strike is parallel to those of other boundaries (Fig. 9). Farther seaward, a transitional zone of exhumed mantle, where clear basement reflections are absent, is also proposed landward of oceanic crust and a basement high that marks a significant seaward change in top-of-basement topography (Fig. 2).

On SCREECH Line 1, which crosses the southeastern Flemish Cap margin farther north (Fig. 1), no large basement high is observed as continental crust thins rapidly across the slope (Hopper *et al.* 2004; Funck *et al.* 2003). A prominent landward dipping reflection, "M", interpreted as Moho, is observed at the slope (See further discussion below). Seaward of the rifted continental crust, ultra-slow spreading oceanic crust is proposed consistent with highly reflective basement and wide-angle arrivals from oceanic layer 3 (Hopper *et al.* 2004; Funck *et al.* 2003). This is unlike the transitional basement observed on Line 3.

The “M” reflection on Line 1 and the “L” reflections on Line 3 and profile 85-2 may be related to the landward boundary of the serpentinized mantle (Reid 1994) as opposed to oceanic crust (Keen and de Voogd, 1988). They also may represent shear zones, as the crust becomes completely brittle when it thins to <6 km. At this point, seawater may penetrate along faults into the mantle, causing serpentinization (Pérez-Gussinyé & Reston 2001). Although “M” is restricted to the base of the crust on Line 1, it may also have extended to the “S” reflection observed on the conjugate Galicia Bank margin (Hopper *et al.*, 2006). Note that the absence of “L” on profile 85-4 and NB-1 may be caused by the processing mute, used to remove the strong water-bottom multiple across the continental slope.

c) Onset of seafloor spreading

Finally, we calculate the onset of seafloor spreading by extrapolating the crustal ages of the landward limits of the zone of interpreted oceanic crust from the locations of M0 (Fig. 9 and Table 1). The spreading rate is 8mm/yr on the Newfoundland side, according to Srivastava *et al.* (2000), and is 10mm/yr on the Iberia side, according to Whitmarsh & Miles (1995), for M0 time. Both rates are used for comparison (Table 1). The age of M0 is 121Ma (Barremian-Aptian boundary; Gradstein *et al.* 1994) and the spreading rate is assumed to be constant. Results show that the onset ages of spreading for the Newfoundland margin are very close to those for the Iberia margin (Table 1). For the crustal origin of the transitional basement to be oceanic crust, the onset ages would have to be much earlier and would require oceanic crust to exist farther landward on the Iberia margin. We suggest that the transitional basement is more likely to be formed by exhumed mantle, as proposed for the Iberia margin. This interpretation indicates that seafloor spreading started earlier in the south (~135 Ma) and propagated to the north (~124 Ma).

An alternate interpretation is given by Srivastava *et al.* (2000), who identified magnetic reversals farther landward and proposed that seafloor spreading to have started as early as M20 (southeastern Grand Banks) to M4 (eastern Flemish Cap). However, these earlier magnetic reversals would exist where extended continental crust or exhumed mantle is interpreted based on seismic observations. On the other hand, Tucholke *et al.* (in review), who interpreted the "U" reflection as a breakup unconformity, proposed an onset age of seafloor spreading at late Aptian (~112 Ma). This agrees with the pinchout of sub-"U" sediment landward of our interpreted oceanic crust and supports our interpretation of exhumed mantle for the transitional basement. However, it conflicts with the identification of older magnetic anomalies (M0-M4; Srivastava *et al.*, 2000) on our interpreted oceanic crust.

5. Conclusions

New seismic reflection data from the Grand Banks and Newfoundland basin is interpreted together with coincident refraction data.

Three major crustal zones are observed:

(i) A zone of rifted continental crust is ~160-km wide (or ~170-km, according to the velocity model; Lau *et al.*, this issue) with steep thinning (~12 to ~4 s TWTT) beneath the Carson basin and a large tilted fault block (sub-zone C1). Continental crust extends 120 km into the Newfoundland basin where top basement reflectivity becomes very weak at its seaward end (sub-zone C2).

(ii) A 70-km wide transitional zone is observed with a flat and unreflective basement in its central parts (sub-zone T2), most likely consisting of highly serpentinized exhumed mantle. Its landward edge exhibits a possible serpentinite diapir (sub-zone T1) and its seaward edge contains a pair of basement highs of unknown origin (sub-zone T3).

(iii) A zone of oceanic crust is interpreted seaward of the transitional basement beginning near anomaly M4. This zone contains a series of basement highs with rough surface (sub-zone O1), followed seaward by relatively flat basement at the end of the profile (sub-zone O2).

Observations on Line 3 show better-imaged details of similar features observed on previous seismic profiles (i.e., profile 85-4, 85-2 & NB-1). By building upon present observations, crustal structure on a more regional scale is interpreted:

(i) Prominent landward dipping reflections across the slope (e.g., "L") are regionally associated with the landward limit of serpentinized mantle.

(ii) Calculated onsets of seafloor spreading of the Newfoundland margin are 125 Ma (Flemish Cap) to 138 Ma (southern Newfoundland basin), similar to those of the Iberia margin.

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Figure legends

Figure 1. Bathymetric map with locations of SCREECH MCS profiles (thick solid lines), ODP Leg 210 sites (filled circles), and selected previous MCS profiles within the survey area (thin solid lines). Magnetic anomaly M0, modified from Srivastava *et al.* (2000), and the J-anomaly, interpreted by tracing the magnetic high lineation near Line 3, are shown in gray solid and dashed lines, respectively. Bathymetry is contoured every 1000 m (dashed lines). Shaded regions indicate sediment thicknesses ≥ 3500 m (Louden *et al.* 2004). The thicker part of Line 3, labelled with CMP numbers, is presented in this paper. Lithoprobe profiles 85-2 and 85-4 (labelled with the same shot point numbers as in Fig. 2) and Conrad line NB-1 are shown in Fig. 2. The inset shows the positions of the survey area and the three primary SCREECH transects relative to Newfoundland.

Figure 2. Line drawings of previous MCS profiles (a) 85-4, (b) NB-1 and (c) 85-2.

Location of these profiles is shown in Fig. 1. Profiles 85-4 and 85-2 are modified from Keen & de Voogd (1988) with addition of transition zones proposed here. See text for definition of transition zone. Shot point numbering is as in Fig. 1. Fig. 2b is modified from Shipboard Scientific Party (2004) with new crustal zone interpretations proposed. These sections are plotted using the same vertical and horizontal scale (vertical exaggeration of seafloor ~ 4). COB: continent-ocean boundary suggested previously by Keen & de Voogd (1988); U: a deep, high-amplitude sedimentary reflection; L: a strong crustal landward-dipping reflection within basement.

Figure 3. (Bottom) Time-migrated section of SCREECH Line 3 located in Fig. 1 across the rifted margin of Grand Banks/Newfoundland basin and (top) the magnetic anomaly along profile from gridded data (Verhoef *et al.* 1996). Based on interpretations of the profile, the section is divided into three crustal zones: (1) continental (light grey), (2) transitional (medium grey), and (3) oceanic (dark grey), as indicated at the bottom. Each of these zones is subdivided into sub-zones (e.g. C1, C2, etc.) to reflect secondary differences in basement character. Detailed interpretation of important parts of the section is shown in Figs 4-6, with locations as indicated. Vertical exaggeration of the seafloor is ~8, and CMP numbering is as in Fig. 1. Identifications of magnetic anomalies M4, J and M0 are modified from Srivastava *et al.* (2000).

Figure 4. Comparison between sedimentary sequences on (a) SCREECH Line 2 and (b) Line 3. Migrated section shown for Line 2 is near ODP Site 1276 (see Fig. 1 for location) and is modified from Shipboard Scientific Party (2004). The bold black line shows penetration in the borehole (un-cored where dashed). See text for descriptions of sedimentary

sequences A-F. The migrated section of Line 3 is the same data as in Fig. 3 but was not processed to optimize deeper reflections as described in text. Thus it shows more details in the sedimentary column but weaker basement reflections than in Fig. 3.

Figure 5. Detailed plot of the migrated section in Fig. 3 (top) and its interpretation (bottom), showing the zone of rifted continental crust. Vertical exaggeration of the seafloor is ~8. Sedimentary sequences are shaded in different colours with boundaries in thin purple lines. Blue lines within sequences are interpreted sedimentary reflections. See text for definitions of post-rift, syn-rift and pre-rift sequences. Red lines are crustal reflections interpreted with confidence (solid) or with uncertainty (dashed). U: “U” reflection. L: landward-dipping reflection (see text). R (shaded in blue): crustal reflection group (see text). Sequences A-E: post-rift sedimentary sequences (see text) following Shipboard Scientific Party (2004). The B-C sequence boundary is shown across the entire section.

Figure 6. Detailed plot of the migrated section shown in Fig. 3 (top) and its interpretation (bottom), showing the seaward end of interpreted continental crust and landward end of transitional basement. See caption of Fig. 5 for explanations of line colours and labels. Vertical exaggeration of seafloor is ~8. The top-of-basement and near-basement reflections are very weak and diffuse in this part of the margin (subzones C2, T1, T2), resulting in uncertain interpretations of syn- and pre-rift sediments and the top of basement. White region, rifted continental crust (T2); yellow-brown region, section T1 interpreted as a serpentinite diapir (see text); dark brown region, transitional basement (section T2) with low reflectivity. A peg-leg multiple (resulting from reflection between "U" and the seafloor) is identified.

Figure 7. Detailed plot of the migrated section in Fig. 3 (top) and its interpretation (bottom), showing the seaward end of transitional basement (T3; brown region) and the landward end of interpreted oceanic crust (O1; blue region) which shows the first appearance of flat reflections interpreted as Moho. Vertical exaggeration of the seafloor is ~8. T3 is composed of two basement highs and its crustal origin is uncertain (see text). The seaward limit of the "U" reflection is uncertain (dashed purple line). See caption of Fig. 5 for explanations of line colours and labels.

Figure 8. Comparison between reflectivity on Line 3 and coincident velocity model derived from wide-angle data (Lau *et al.*, this issue). Upper panel (a) shows the migrated MCS section, converted to depth using the velocity model, for CMP 500000-532500 and the lower panel (b) shows CMP 525000-555828, both overlain by interpretation and velocity model boundaries (red lines). See legend for explanations of shading and line colours; colour shading in the mantle is our interpretation based on seismic velocity. The lowermost velocity-model boundary defines the top of serpentinized (7.6-8.0 km/s) or unaltered mantle (>8.0 km/s). Velocities are 5.8-6.9 km/s in rifted continental crust, 5.5-7.6 km/s in transitional crust (TC), and 5.4-7.2 km/s in interpreted oceanic crust. PS, the package of pre/syn-rift sediment within Carson basin; M, Moho reflections that coincide with the velocity model Moho; L: landward-dipping reflections.

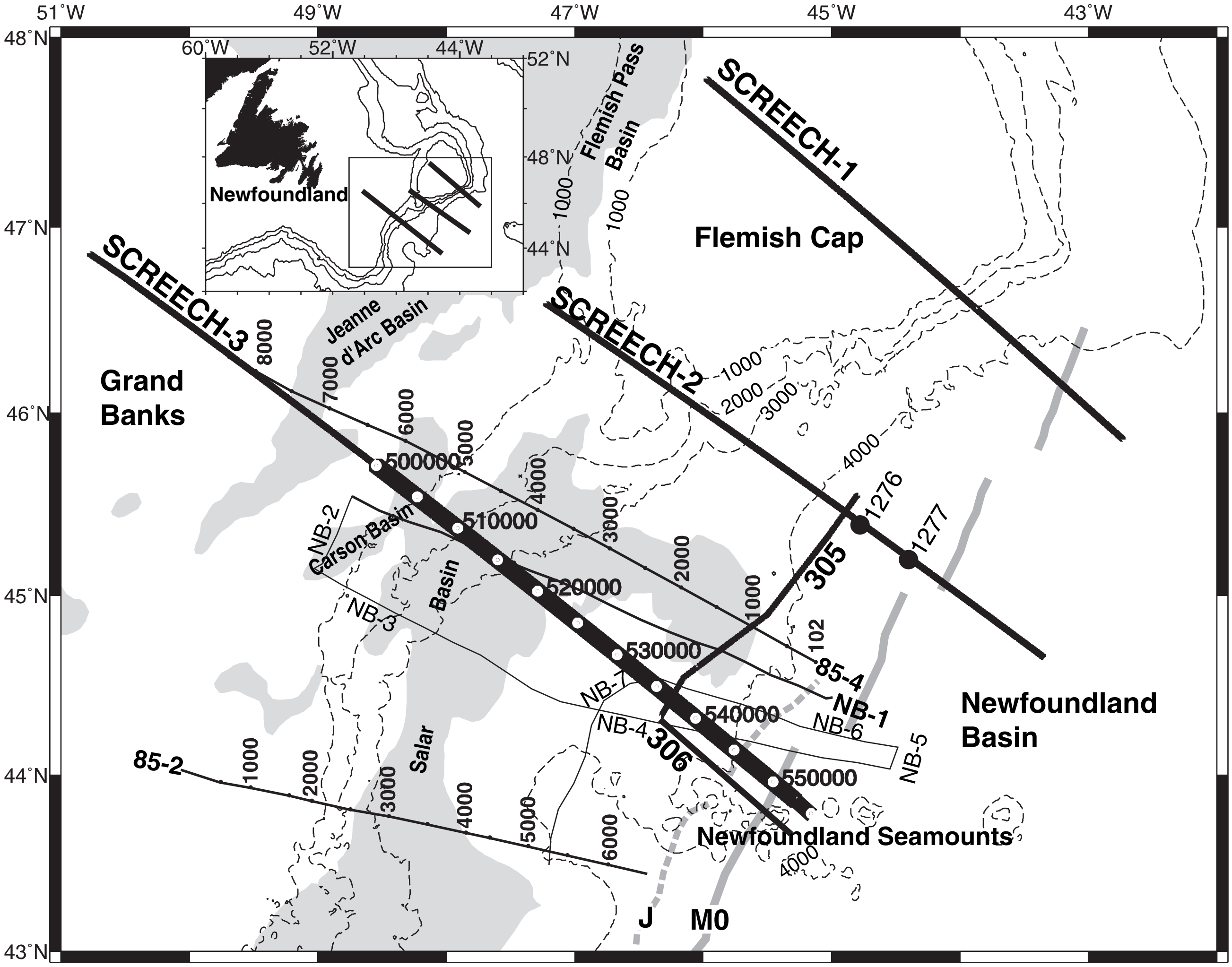
Figure 9. Summary of proposed crustal interpretations over selected profiles within the study area, with free-air gravity anomaly (Sandwell & Smith 1997) in the background. Dashed lines are bathymetric contours (every 1000 m). Crustal types are specified using gray shades (see legend). Re-interpretation of selected previous profiles is based on comparison

with Line 3. Crustal boundaries with a question mark are extrapolations (see text). M0 and J are magnetic anomalies (see Fig. 1 caption). See text for explanations of crustal zones T1 to O2 and large basement high. L: prominent landward dipping reflections where the length of line shows the seaward and landward limit of the reflection on the profile.

Table 1. Onsets of seafloor spreading for the Grand Banks/Flemish Cap Margin and the Tagus/Iberia/Galicia Bank Margin at different spreading rates.

	Onset ages (Ma):		
	8 mm/yr	10 mm/yr	other
Flemish Cap			
Line 1	125	124	-
Galicia Bank			
Leg 103, Site 641	-	-	118 (a)
N. Newfoundland Basin			
85-4 and NB-1	133	130	-
Line 3	130	128	-
Iberia A. P.			
magnetic profiles	-	130 (c)	126(b)
S. Newfoundland Basin			
85-2	138	135	-
Tagus A. P.			
magnetic profiles	-	134(c)	-

(a) Ogg (1988); Boillot and Winterer (1988); Boillot et al. (1988).
(b) Whitmarsh et al. (1990).
(c) Whitmarsh and Miles (1995).



51°W
49°W
47°W
45°W
43°W
48°N
47°N
46°N
45°N
44°N
43°N
60°W
52°W
44°W
52°N
48°N
44°N
Newfoundland
Flemish Pass Basin
Flemish Cap
SCREECH-1
SCREECH-2
SCREECH-3
Grand Banks
Jeanne d'Arc Basin
Carson Basin
Salar Basin
Newfoundland Basin
Newfoundland Seamounts
500000
510000
520000
530000
540000
550000
1276
1277
305
306
85-4
85-2
NB-1
NB-2
NB-3
NB-4
NB-5
NB-6
NB-7
102
J
M0
1000
2000
3000
4000
5000
6000
7000
8000

Figure 1

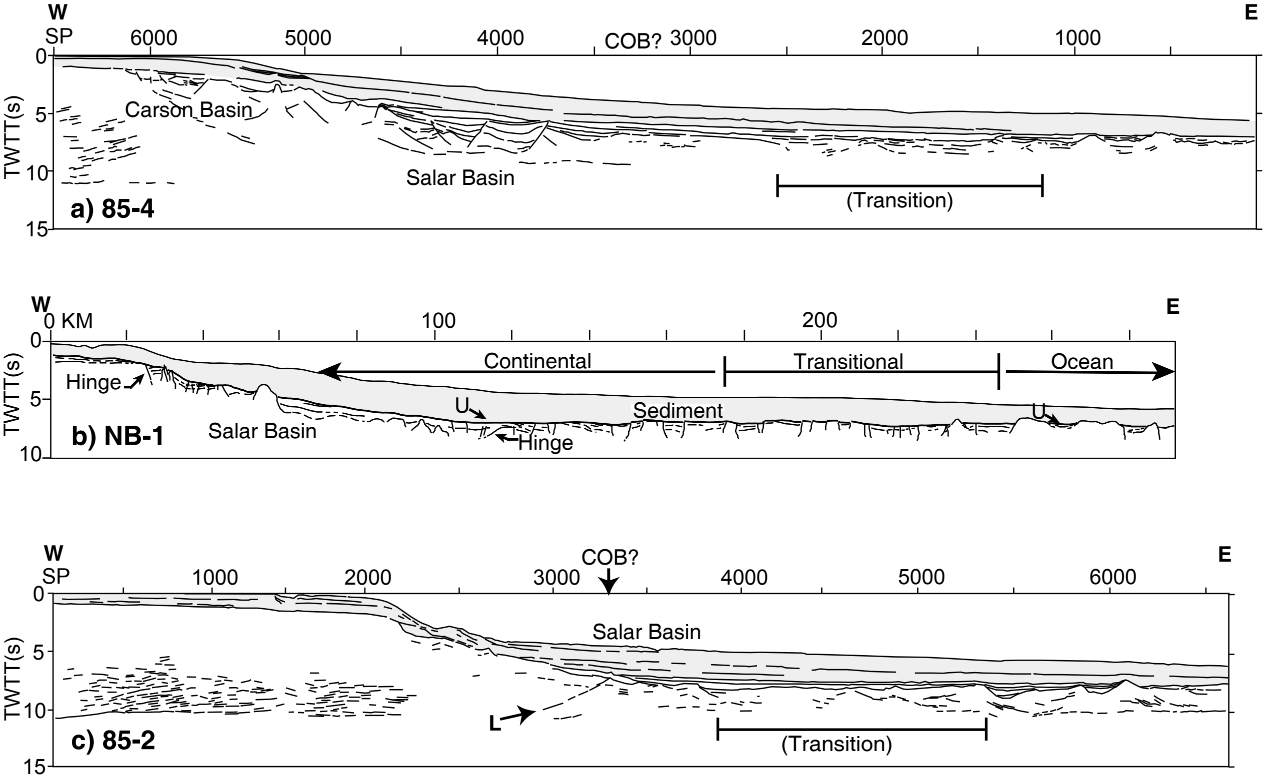

W
SP
6000
5000
4000
COB?
3000
2000
1000
E
0
5
10
15
TWTT(s)
Carson Basin
Salar Basin
(Transition)
a) 85-4
W
0 KM
100
200
E
0
5
10
TWTT(s)
Continental
Transitional
Ocean
Hinge
U
Sediment
U
Salar Basin
Hinge
b) NB-1
W
SP
1000
2000
3000
COB?
4000
5000
6000
E
0
5
10
15
TWTT(s)
Salar Basin
L
(Transition)
c) 85-2

Figure 2.


J
M4?
M0?
300
0
-300
Magnetic anomaly (nT)
500000
505000
510000
515000
520000
525000
530000
535000
540000
545000
550000
555000
CMP number
Basin inversion structure?
Carson Basin
Figure 5
Salar Basin
Figure 4
Figure 6
Figure 7
0
1
2
3
4
5
6
7
8
9
10
11
12
Two-way travel time (s)
20 km
vertical exaggeration of seafloor~ 8
CONTINENTAL
TRANSITIONAL
OCEANIC
C1
C2
T1
T2
T3
O1
O2
220
240
260
280
300
320
340
360
380
400
420
440
460
480
500
520
540
560
Distance (km)

Figure 3.

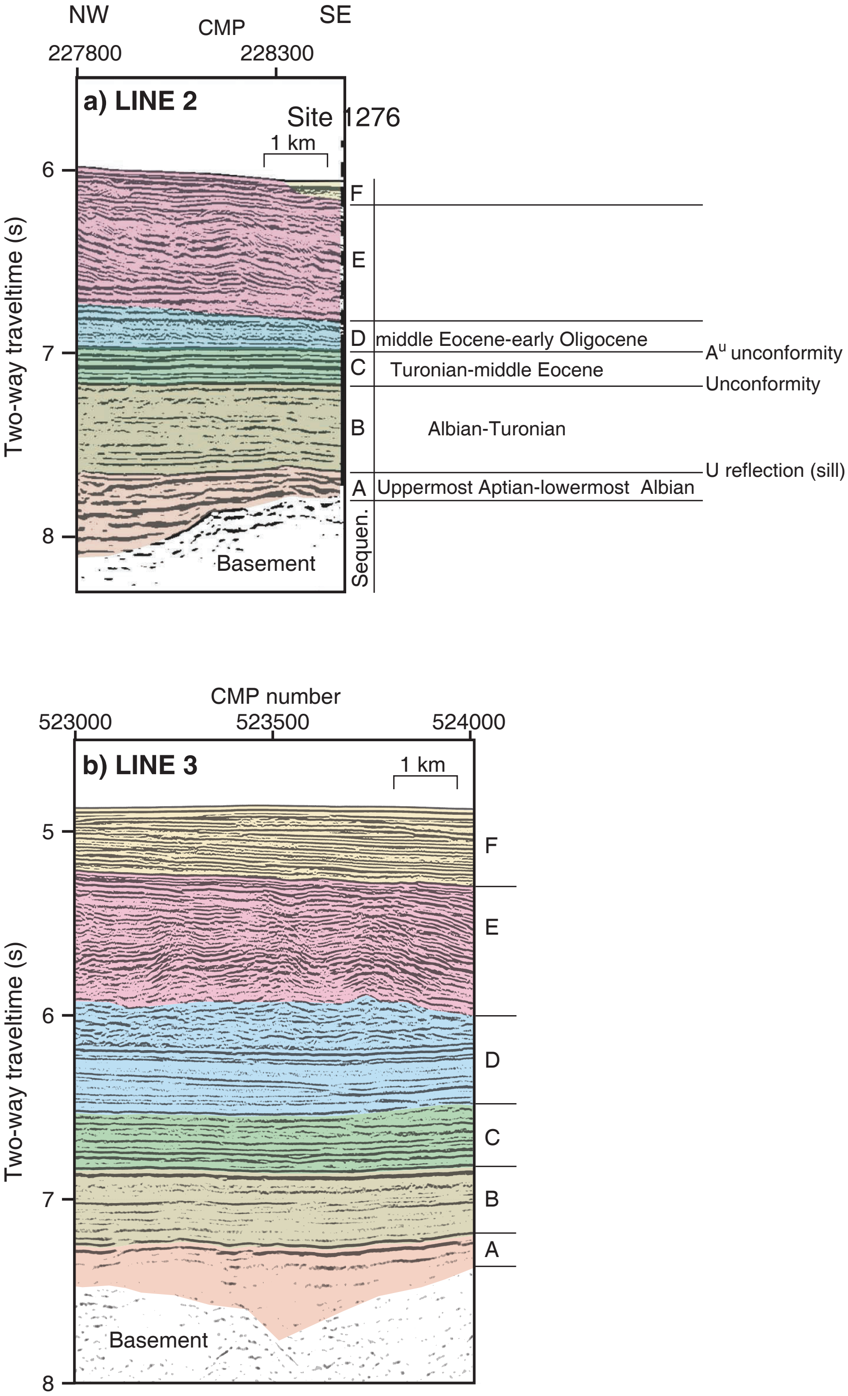

NW
CMP
SE
227800
228300
a) LINE 2
Site 1276
1 km
6
7
8
Two-way traveltime (s)
F
E
D
middle Eocene-early Oligocene
A^u unconformity
C
Turonian-middle Eocene
Unconformity
B
Albian-Turonian
U reflection (sill)
A
Uppermost Aptian-lowermost Albian
Sequen.
Basement
CMP number
523000
523500
524000
b) LINE 3
1 km
5
6
7
8
Two-way traveltime (s)
F
E
D
C
B
A
Basement

Figure 4

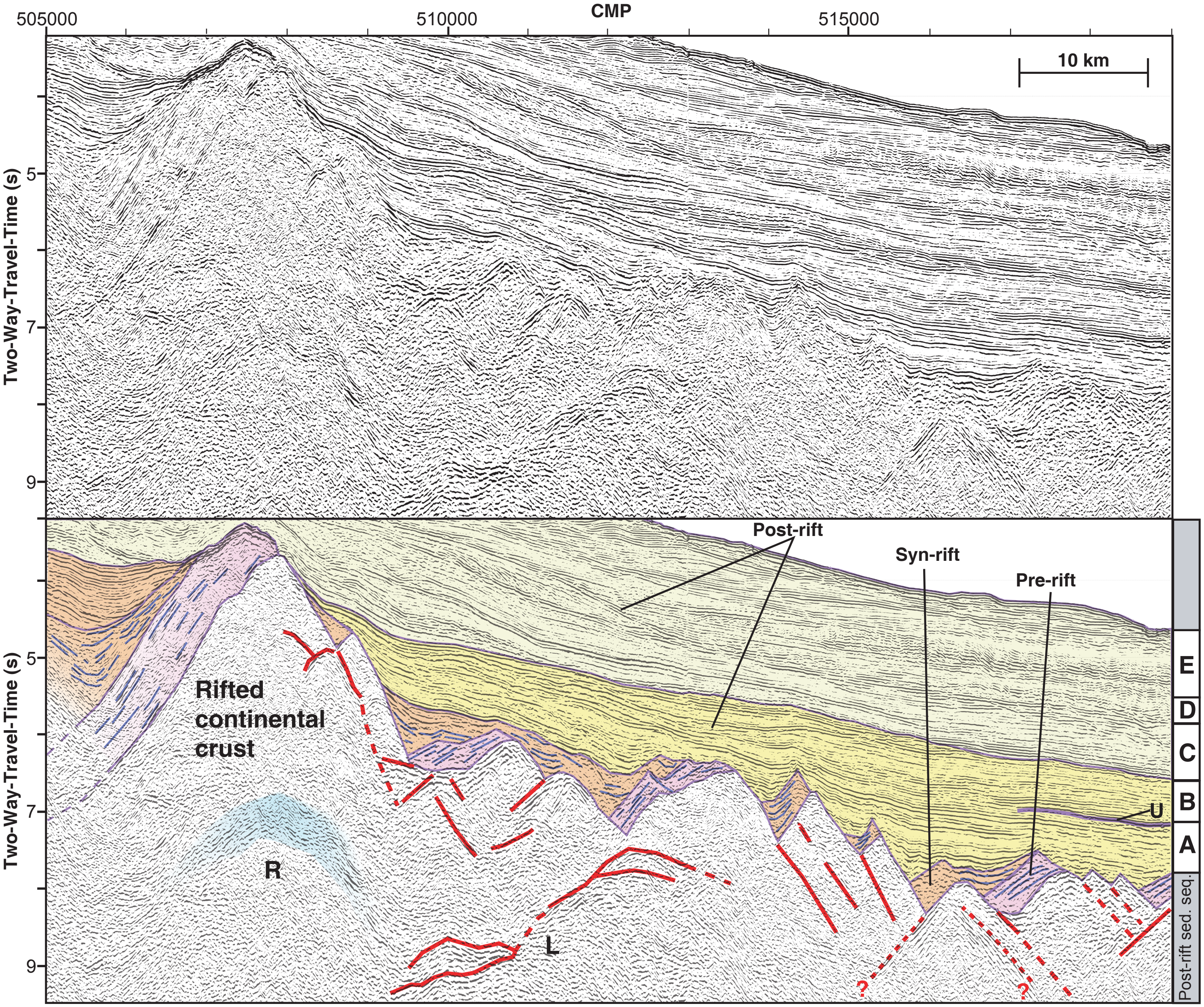
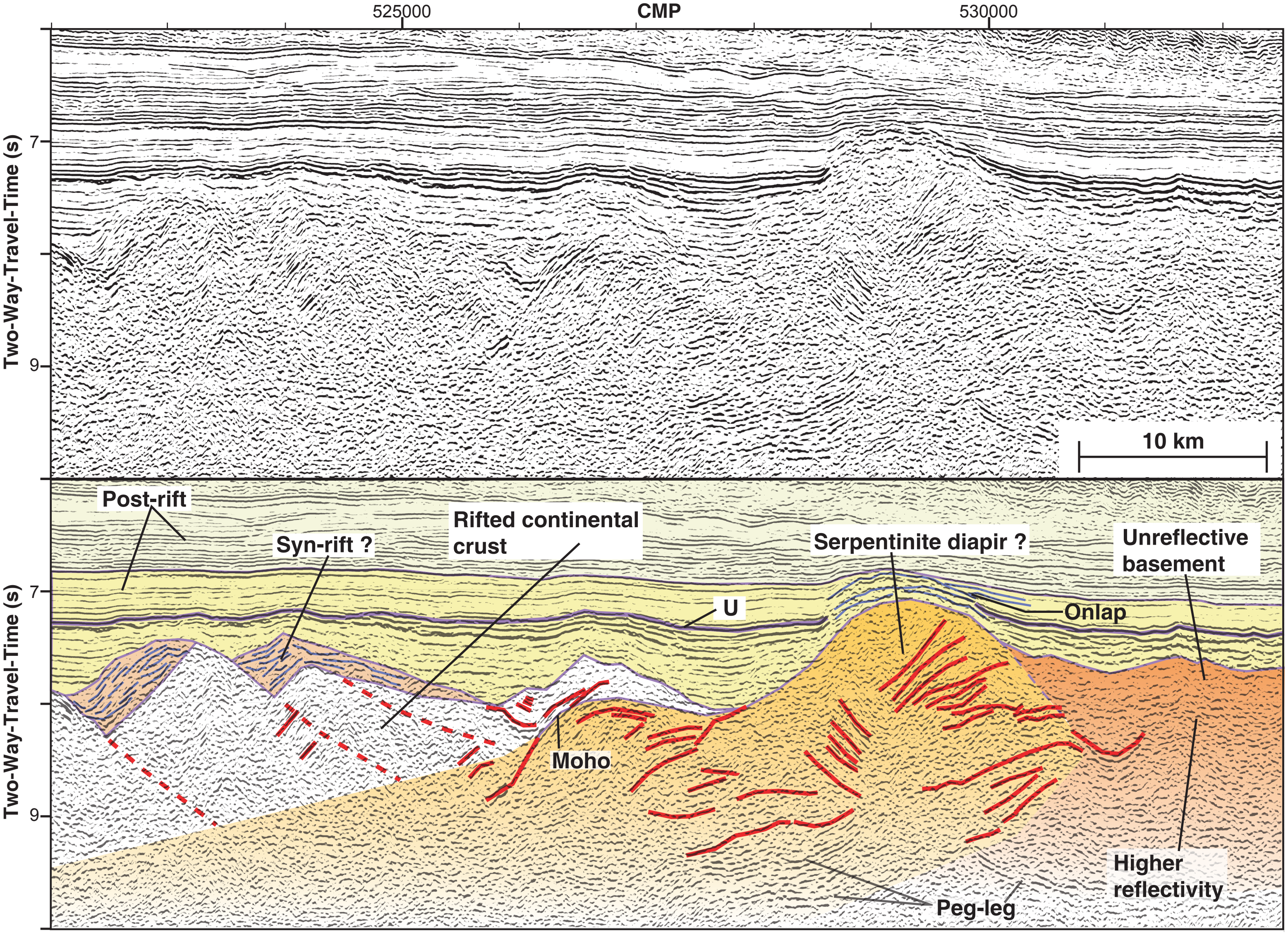

CMP
505000
510000
515000
10 km
Two-Way-Travel-Time (s)
5
7
9
Post-rift
Syn-rift
Pre-rift
Rifted continental crust
R
L
U
?
?
E
D
C
B
A
Post-rift sed. seq.

Figure 5.



525000
CMP
530000
Two-Way-Travel-Time (s)
7
9
10 km
Post-rift
Syn-rift ?
Rifted continental crust
Serpentinite diapir ?
Unreflective basement
U
Onlap
Moho
Higher reflectivity
Peg-leg

Figure 6.

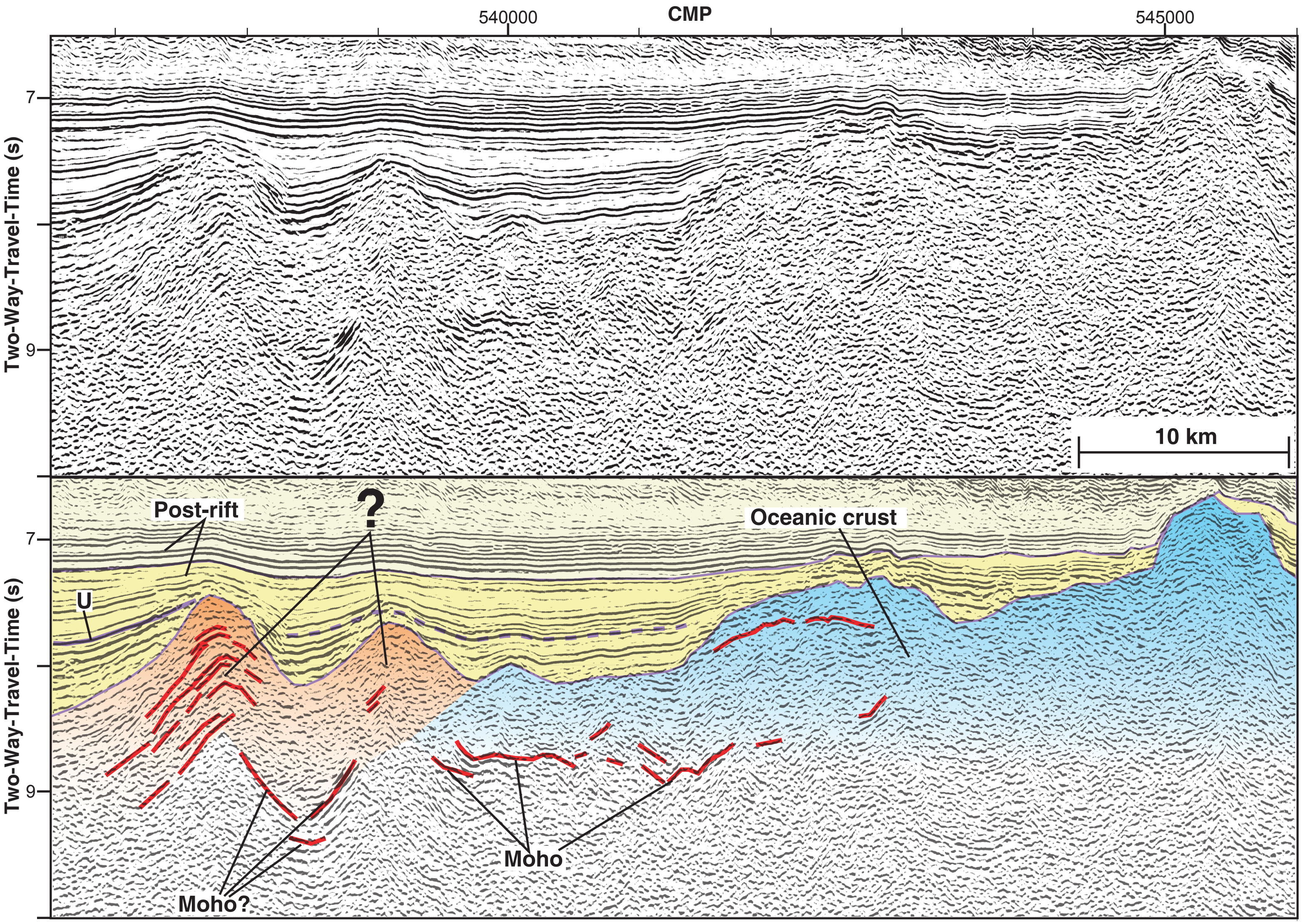

CMP
540000
545000
Two-Way-Travel-Time (s)
7
9
10 km
Post-rift
?
Oceanic crust
U
Moho?
Moho

Figure 7

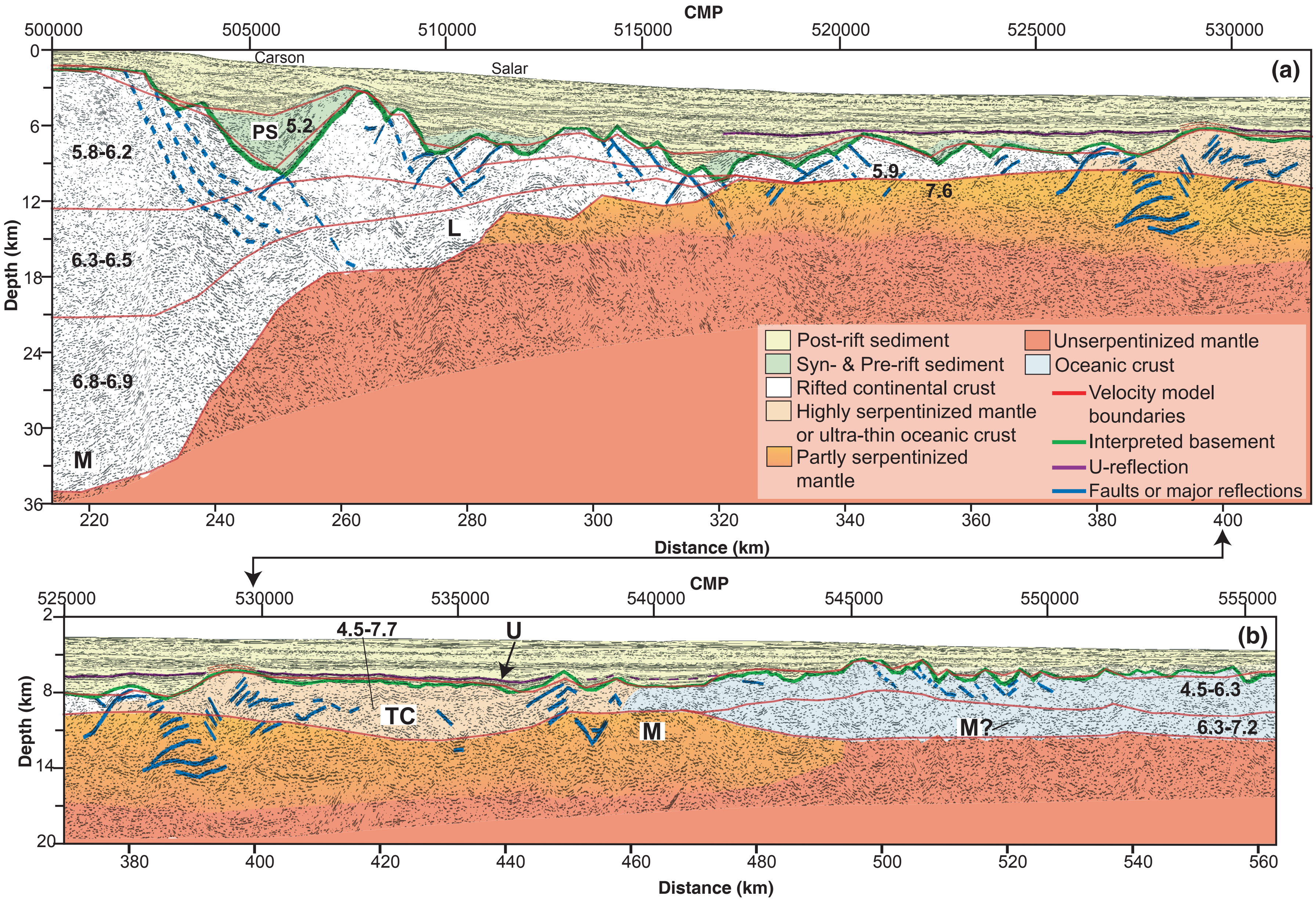

CMP
500000
505000
510000
515000
520000
525000
530000
Carson
Salar
(a)
PS
5.2
5.8-6.2
6.3-6.5
6.8-6.9
M
L
5.9
7.6
Depth (km)
0
6
12
18
24
30
36
220
240
260
280
300
320
340
360
380
400
Distance (km)
Post-rift sediment
Syn- & Pre-rift sediment
Rifted continental crust
Highly serpentinized mantle or ultra-thin oceanic crust
Partly serpentinized mantle
Unserpentinized mantle
Oceanic crust
Velocity model boundaries
Interpreted basement
U-reflection
Faults or major reflections
CMP
525000
530000
535000
540000
545000
550000
555000
(b)
4.5-7.7
U
TC
M
M?
4.5-6.3
6.3-7.2
Depth (km)
2
8
14
20
380
400
420
440
460
480
500
520
540
560
Distance (km)

Figure 8

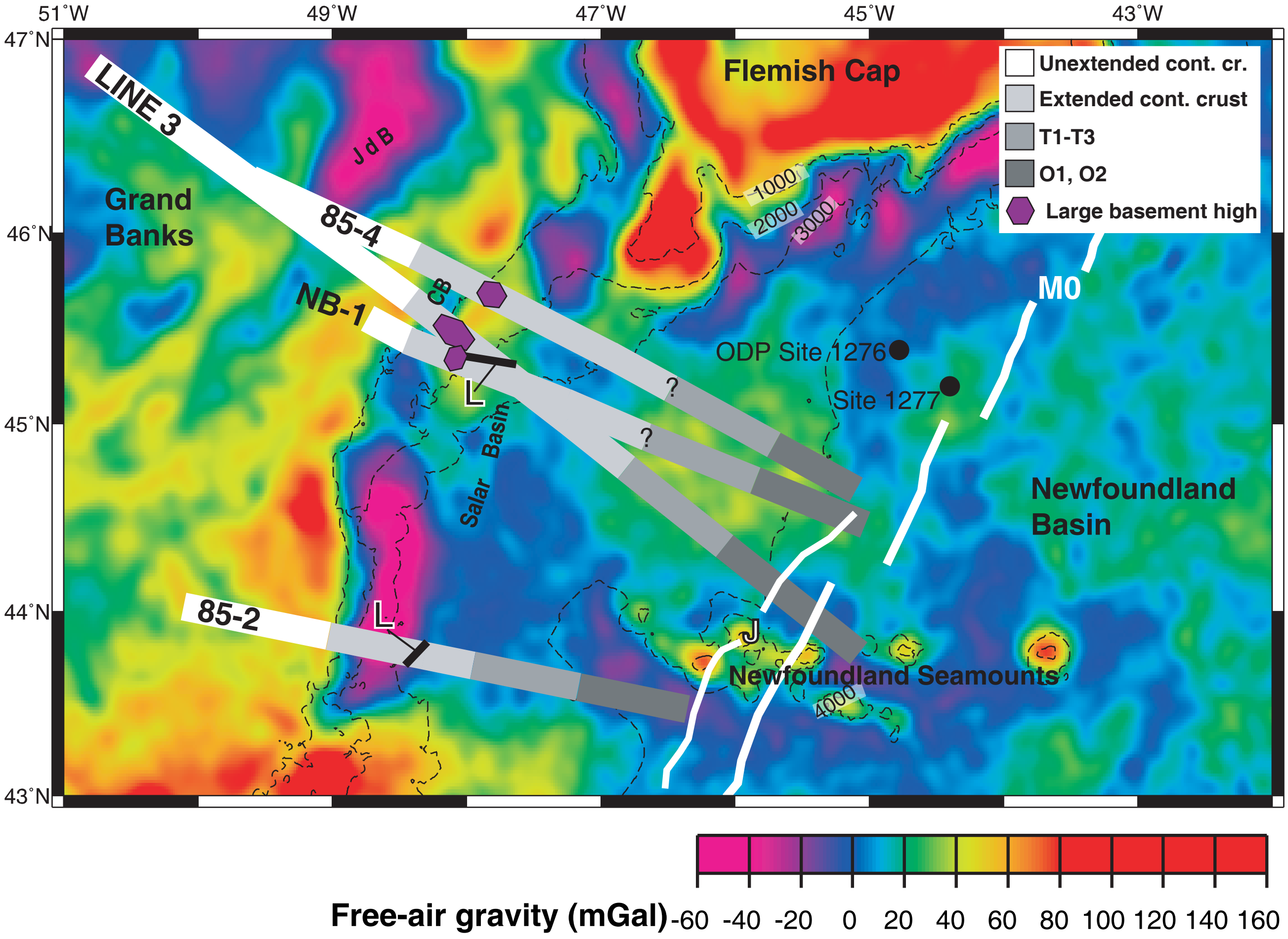

51˚W
49˚W
47˚W
45˚W
43˚W
47˚N
46˚N
45˚N
44˚N
43˚N
LINE 3
85-4
NB-1
85-2
J d B
CB
L
L
J
Salar Basin
Grand Banks
Flemish Cap
1000
2000
3000
4000
?
?
ODP Site 1276
Site 1277
M0
Newfoundland Basin
Newfoundland Seamounts
Unextended cont. cr.
Extended cont. crust
T1-T3
O1, O2
Large basement high
Free-air gravity (mGal)
-60
-40
-20
0
20
40
60
80
100
120
140
160

Figure 9.