Continental breakup and the onset of ultraslow seafloor spreading off Flemish Cap on the Newfoundland rifted margin

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ABSTRACT

Prestack depth-migrated seismic reflection data collected off Flemish Cap on the Newfoundland margin show a structure of abruptly thinning continental crust that leads into an oceanic accretion system. Within continental crust, there is no clear evidence for detachment surfaces analogous to the S reflection off the conjugate Galicia Bank margin, demonstrating a first-order asymmetry in final rift development. Anomalously thin (3–4 km), magmatically produced oceanic crust abuts very thin continental crust and is highly tectonized. This indicates that initial accretion of the oceanic crust was in a magma-limited setting similar to present-day ultraslow spreading environments. Seaward, oceanic crust thins to <1.3 km and exhibits an unusual, highly reflective layering. We propose that a period of magma starvation led to exhumation of mantle in an oceanic core complex that was subsequently buried by deep-marine sheet flows to form this layering. Subsequent seafloor spreading formed normal, ~6-km-thick oceanic crust. This interpretation implies large fluctuations in the available melt supply during the early stages of seafloor spreading before a more typical slow-spreading system was established.

Keywords: continental margin, seafloor spreading, extension tectonics, continental breakup.

INTRODUCTION AND TECTONIC SETTING

The breakup of continents and the opening of ocean basins are fundamental parts of the plate tectonic cycle. Investigations of rifting and breakup in magma-starved settings have led to new paradigms regarding the mechanical response of crust to extensional stresses. Surveys and sampling on the Galicia Bank and Iberian margins revealed complicated structural patterns that suggest the presence of detachment surfaces near the base of the continental crust. The presence of such surfaces has been used to infer large-scale asymmetry of the entire rift system (Reston et al., 1996; Whitmarsh et al., 2001). These surveys further showed that extreme thinning of the crust is not necessarily accompanied by large-scale decompression melting and volcanism. Instead, upper mantle is mechanically exhumed and serpentinized to form a layer with crust-like seismic velocities (Pickup et al., 1996; Dean et al., 2000; Whitmarsh et al., 2001).

A lack of seismic data at conjugate locations off the Newfoundland margin has left many open questions, especially with regard to hypothesized margin asymmetry. A seismic survey was conducted in 2000 to acquire data at key locations relative to the main geophysical and drilling transects off Iberia (Fig. 1). Data were collected along three main transects aboard R/V *Maurice Ewing* and R/V *Oceanus* using *Ewing*'s 140 L, 20 airgun, tuned source array. Wide-angle data were recorded on ocean-bottom seismometers (OBSs) deployed from *Oceanus*. Multichannel seismic (MCS) data were recorded on *Ewing*'s 480 channel, 6-km-long streamer. Here we show the results of prestack depth migration of MCS data from the seaward portion of line 1, which crosses Flemish Cap (Fig. 1) and is conjugate to lines IAM-11 (Whitmarsh et al., 1996) and GP-101 (Reston et al., 1996).

Flemish Cap is a roughly circular block of 30-km-thick continental crust with a velocity structure similar to Appalachian crust measured elsewhere (Fig. 1; Funck et al., 2003). Rifting between Newfoundland and Iberia included an early phase of extension in Late Triassic to Early Jurassic time (Tankard and Welsink, 1987; Wilson, 1988; Rasmussen et al., 1998), followed by Late Jurassic to Early Cretaceous extension that culminated in seafloor spreading by Barremian to Aptian time (anomaly M3 to M0, or 127–112 Ma according to the time scale of Gradstein et al., 1994). Between Flemish Cap and Galicia Bank, seafloor spreading began around anomaly M0 (Boillot et al., 1987). Srivastava et al. (2000) estimated the full spreading rate to be 14 mm/yr during initial seafloor spreading. Off the southern Iberian Abyssal Plain, the transition from continental crust to oceanic crust is marked by a broad, >130-km-wide, zone of mechanically unroofed continental mantle (Dean et al., 2000). This zone narrows to the north and at Galicia Bank is replaced by a single, <10-km-wide peridotite ridge (Whitmarsh et al., 1996).

NEW SEISMIC DATA

Continental Crust

Figure 2[1] shows the final depth image. From km 203 to km 231 is unequivocal continental crust, and the velocity structure is consistent with that measured on Flemish Cap, which can be divided into three distinct layers with P-wave velocities of 6.0–6.2 km/s, 6.3–6.4 km, and 6.6–6.7 km/s (Funck et al., 2003). Several sets of deep reflections are found, including four very coherent reflections (labeled B, V, W, and M) as well as a band of pronounced reflectivity deeper in the section.

Reflection B is the top of crystalline basement. Above B is a package of sedimentary rocks most likely comprising prerift to synrift sequences. Although the sedimentary units are broken up by high-angle, east-dipping normal faults, they appear to have relatively small offset and could not have accommodated significant horizontal extension. The basement surface is also faulted. With the exception of the graben at km 224–231, the maximum throw is <200 m, and there is only minor block rotation. Where imaged, rotated units dip 10°–20° landward. Nonetheless, significant crustal thinning has occurred. At km 203, crust is 12.5 km thick and by km 220, it is only 5 km thick (Funck et al., 2003). Assuming that prerift crust was 30 km thick, thinning factors of $2.5 < \beta < 6.5$ are indicated.

[1]Loose insert: Figure 2, Kirchoff prestack depth migration of line 1 and interpretation of depth-migrated image.

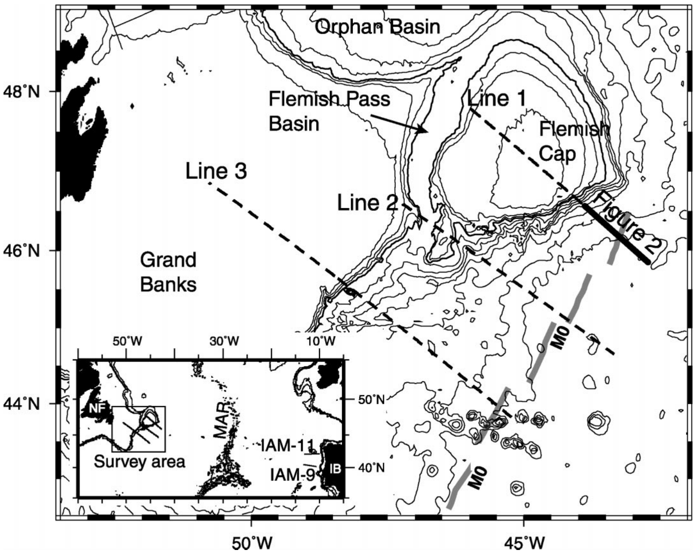

Figure 1. Location of seismic survey offshore Newfoundland. Multichannel seismic reflection and wide-angle refraction data were collected along lines 1, 2, and 3. Solid portion of line 1 is shown in Figure 2. Magnetic anomaly M0 is from Srivastava et al. (2000). Inset shows regional overview. Line 1 is conjugate to lines IAM-11 (Whitmarsh et al., 1996) and GP-101 (not shown; Reston et al., 1996) on Galicia Bank margin. MAR—Mid-Atlantic Ridge; NF—Newfoundland; IB—Iberia.

In the middle to lower crust is a band of strong reflectivity similar to that seen in reflection sections in many continental regions (Mooney and Meissner, 1992). The reflections here dip 10°–20° seaward and are laterally discontinuous over short lengths, although several stronger reflections are coherent for several kilometers. At km 216–220 they may cut across the Moho, the position of which is well defined. However, this section of data requires further processing to interpret fully and to draw firm conclusions.

Reflections V and W are intracrustal reflections, and M is interpreted as the Moho, which is a well-imaged, landward-dipping (30°) event. Reflection V correlates with a wide-angle reflection seen on OBS 16 and marks the top of the middle crust (Funck et al., 2003). It truncates against W, a strong, but discontinuous reflection that dips 45° landward and may be a fault. Both reflections W and M terminate seaward at a large, sediment-filled graben bounded by two large, high-angle normal faults. The fault surfaces are not imaged in the data, but their locations are clearly indicated by changes in reflectivity patterns.

East of this graben is an enigmatic block (km 231–240) that has neither a velocity structure nor a reflectivity pattern consistent with oceanic crust. The upper part has strong but discontinuous reflectivity and a velocity of 3.8–5 km/s, although the details are not well resolved. The lower part is transparent, and the velocity is too low (<6.8 km/s) to indicate mafic intrusive rocks associated with crustal accretion or magmatic underplating. Reflection Moho is not observed, but the refraction data show that mantle velocities beneath the block are anomalously low (~7.6 km/s) and grade up to 8 km/s by 13 km depth (Funck et al., 2003). Two origins are considered: (1) a peridotite ridge and (2) a block of continental crust. Peridotite ridges off Iberia are well studied and often show velocities as low as 4 km/s, depending on the degree of serpentinization (Dean et al., 2000). The top of such basement, however, is distinctly different from the block observed here. Peridotite ridges show little evidence for stratigraphic layering and are angular and blocky (Beslier, 1996; Pickup et al., 1996), presumably due to brittle deformation associated with their emplacement. The Newfoundland block is more plateau like, with a smooth cap. Although the reflectivity is somewhat chaotic, some stratigraphic layering is seen, suggesting a possible sedimentary origin. From the layering and the observed velocities, the block is interpreted to be sediment-capped, thin continental crust.

Oceanic Crust

The continent-ocean boundary is observed at km 241, and it appears to be a distinct boundary, rather than a transition zone as found off the southern Iberian Abyssal Plain and hypothesized to exist off Flemish Cap (e.g., Dean et al., 2000). Crust immediately seaward of continental crust is a series of domino-style rotated blocks bounded by normal faults dipping 45° seaward and spaced every ~1.5 km. Although the crust is only 3–4 km thick, the wide-angle data are best fit by assuming a typical oceanic layer 2–layer 3 structure (Funck et al., 2003). Such thin oceanic crust is formed at ultraslow spreading ridges. At Gakkel Ridge, the full spreading rate is 6–13 mm/yr and crust is <4 km (Coakley and Cochran, 1998). At Southwest Indian Ridge, the full spreading rate is 11.3–16.5 mm/yr and crust averages 3.8 km thick (Muller et al., 2000). The reflectivity observed in the upper crust is most likely volcanic stratigraphy similar to the tilted fault blocks imaged along the abandoned spreading center in the Labrador Sea (Srivastava and Keen, 1995).

Wide-angle data show that seismic layer 3 disappears between km 265 and km 270. Just to the east at km 273 is the weak, but coherent, reflection Z. At km 275–279, a few normal faults in the upper crust may be west dipping, rather than east dipping as in the rest of the section. Reflection Z increases in coherence and amplitude to the east and clearly marks the base of the crust. The wide-angle data show Pn arrivals from just below this level, although the velocity is anomalously low (7.6 km/s; Funck et al., 2003). Crust east of km 281 is highly tectonized; variable, intersecting dips of intracrustal reflections suggest multiple generations of faulting. Some faults can be traced as nearly linear, 45° dipping surfaces that penetrate the entire crust and terminate at the Z reflection. Between km 288 and km 290, an intact block of layered crust is rotated 20° landward. The Z reflection becomes indistinct at this point and may be faulted and rotated. From km 290 to km 301, moderately layered, probably faulted crust is present, and a second rotated, layered block appears at km 302. Basement depth shallows by ~500 m from the first rotated block to the second; this change is likely an isostatic effect of thickening crust to the east. Ray coverage in the crust from wide-angle data extends approximately to km 305–310. Although not strongly constrained, thickening of oceanic crust to ~6 km toward the end of the profile is indicated (Funck et al., 2003).

DISCUSSION

Rifted Continental Crust

The sharp necking profile and steeply rising Moho reflection off Flemish Cap are quite different from what is seen at Galicia. Near Galicia Bank, crust thins from 16 km to 3 km over a distance of 100 km for a maximum Moho dip of 8° (on the basis of profiles from Reston et al., 1996; Pérez-Gussinyé et al., 2003). Models of a wide-rift mode of extension show that breakup is likely to occur preferentially along one edge of a wide rift, leaving a narrow and wide conjugate-margin pair (Dunbar and Sawyer, 1989; Hopper and Buck, 1996). This wide-rift mode appears to be the case here, with Flemish Cap marking the breakup location.

What is particularly striking, however, is the final breakup asymmetry that can now be documented. Seismic images from the Galicia Bank margin show the strong, well-imaged, regional S reflection, often interpreted as a detachment surface between lower crust and mantle (Reston et al., 1996). It is within what is unequivocally continental lithosphere, and may mark the crust-mantle boundary (e.g., Reston et al., 1996). Reston et al. (1996) showed from depth images that it dips primarily to the west and thus would have accommodated top-to-the-west motion. They hypothesized large-scale margin asymmetry in

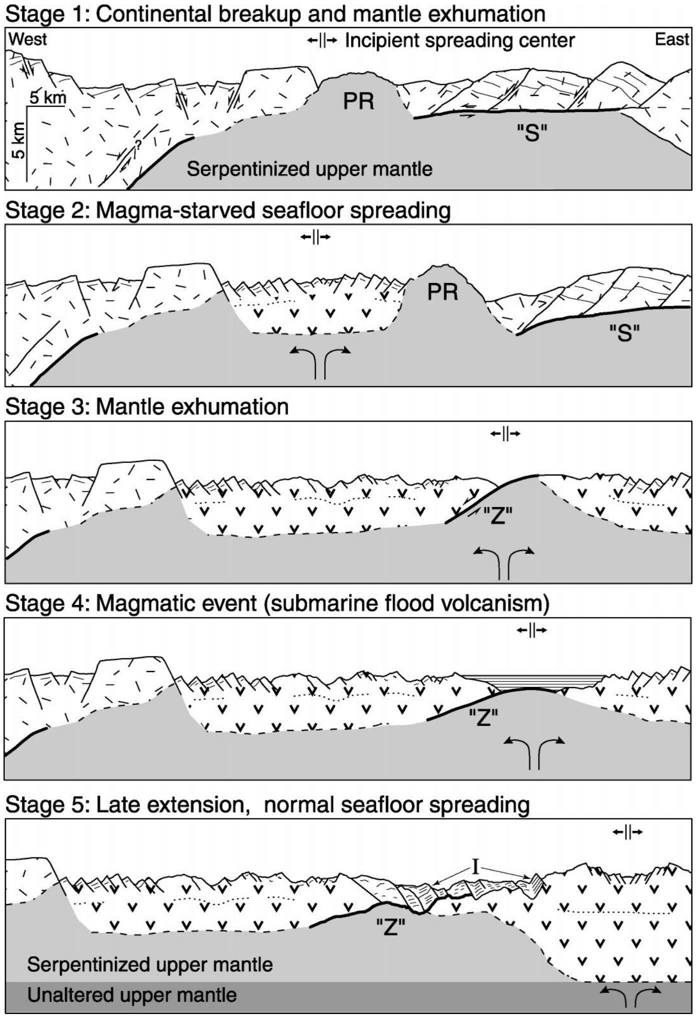

Figure 3. Schematic model showing suggested evolution of Newfoundland rifted margin, drawn with 2:1 vertical exaggeration. Random-dash pattern—continental crust; v pattern—oceanic crust; light gray shading—serpentinized upper mantle; dark gray shading—unaltered upper mantle; thick lines—strong reflections on seismic sections; dashed lines—inferred crust-mantle boundary; dotted lines—inferred layer 2–layer 3 boundary; PR—peridotite ridge. Features labeled I in panel 5 are intact, rotated blocks of oceanic crust. Z and S are reflections. See text for discussion.

which the west-dipping detachment surface either terminates or steepens beneath Flemish Cap. The top panel of Figure 3 shows a schematic reconstruction between our profile and GP-101 from Reston et al. (1996). The S reflection lines up well with the location where the steeply dipping Moho reflection from SCREECH line 1 flattens out, although in the reconstruction they are separated by a peridotite ridge. Our results are consistent with the asymmetry predictions of models that argue for S as a detachment surface at the crust-mantle boundary off Galicia Bank. Following Pérez-Gussinyé and Reston (2001), we speculate that when crust was thinned to the point at which it became entirely brittle, fluids penetrated into the mantle along faults, initiating serpentinization. Along this profile, Funck et al. (2003) have documented that anomalously low mantle velocities, interpreted as evidence for serpentinization, appear where the continental crust is 8–10 km thick. This is the same thickness at which simple thermal models predict the embrittlement of the entire crust (Pérez-Gussinyé and Reston, 2001). Thus, major rheological changes during the final stages of breakup are likely associated with the formation of reflection S.

Origin of Extremely Thin Crust

A key result of depth imaging is evidence for an abrupt continent-ocean boundary and the establishment of a magmatic seafloor-spreading system that produced anomalously thin oceanic crust, on average only 3 km thick over a distance of nearly 60 km. At its thinnest, crust is only ~1 km thick, and oceanic layer 3 is absent. For completeness, alternative hypotheses for the origin of thin crust from km 241 to km 300 are considered. A model for initial seafloor spreading that can explain the observed structure, crustal thickness, and composition is proposed.

One hypothesis for thin oceanic ‘‘crust’’ is that it actually is exhumed upper mantle that has been heavily serpentinized to create a thin layer with crust-like seismic velocities, as documented off Iberia along the IAM-9 profile (Pickup et al., 1996; Dean et al., 2000). Such ‘‘crust’’ is nonreflective in the upper 1–2 km on seismic images, is underlain by a highly reflective zone grading downward into relatively unaltered mantle, and lacks domino-style fault blocks. In contrast, the Newfoundland data show clear reflectivity in the uppermost basement that decreases with depth, and there are well-developed, rotated fault blocks. Thus, a transition zone composed of exhumed upper mantle is ruled out.

The possibility that the thin crust is continental is excluded on the basis of results of the wide-angle data (Funck et al., 2003). A clear difference between seismic phases observed west of OBS 19 and those observed to the east (Fig. 2) is best explained by assuming an oceanic layer 2–layer 3 velocity structure to the east. Combined with results of the reflection data, there is little doubt that oceanic crust accreted to thin continental crust beginning at km 241. It is possible, however, that the layered, rotated blocks at km 288 and km 303 could be continental. This requires an eastward ridge jump to capture a slice of Galicia Bank and isolate it off Flemish Cap. In this scenario, the strong Z reflection is the seaward continuation of S, transferred to the Newfoundland margin. Without direct sampling, this possibility cannot be eliminated, but it is not favored for several reasons. First, Reston et al. (1996) showed that S is west dipping with crustal-scale synthetic faults. In contrast, Z appears domal, and overlying high-angle faults dip to the east. What is more important is that evidence for a major ridge jump is equivocal. Nearly all faults in oceanic crust between km 241 and km 280 dip to the east. The lack of a comparable zone of west-dipping faults in the seaward section indicates either that there is no abandoned spreading center, or that spreading was totally one-sided. In this case, a few west-dipping faults near km 275 could indicate an abandoned median valley. To our knowledge, such one-sided accretion has never been observed, so we find this idea difficult to support. Last, if the layering at km 280–304 is sedimentary, it must be prerift to explain the lack of fanning reflections, and well lithified to explain the high velocity. However, the reflectivity is distinctly different from that observed in the prerift sequences both here (km 210–220) and on the conjugate margin (Reston et al., 1996). We conclude that the layering is volcanic and is related to seafloor spreading.

Figure 3 shows a proposed model for the early evolution of seafloor spreading between Flemish Cap and Galicia Bank. Stage 1 was final breakup, in which continental crust was thinned to only a few kilometers. The entire crust was brittle, enabling fluids to penetrate into and serpentinize the upper mantle. Detachment tectonics above this weak material formed the S reflection and unroofed a peridotite ridge. Breakup just west of the peridotite ridge isolated it on the Galicia Bank margin and led to stage 2, where mantle melts reached the surface and seafloor spreading was established. Limited magmatism produced highly tectonized crust only 3–4 km thick. Although asymmetric accretion was possible at this stage, it is unlikely that it was entirely one-sided. During stage 3, a dramatic reduction in the melt supply occurred, leading to dominantly tectonic extension along a major detachment fault. An oceanic core complex was exhumed, similar to those observed in slow-spreading environments near segment ends, where melt supply is considerably less than at segment centers (Tucholke et al., 1998). As much as 20 km of extension at this stage led to removal of oceanic layer 3 from beneath previously accreted crust east of km 260. Upper mantle was also exposed at the seafloor from km 280 to km 295. This stage was followed by voluminous but localized magmatism (stage 4) that emplaced to 1.5 km of layered, deep-marine flood basalts over the detachment surface (reflection Z) and probably disrupted the surface in places. An intrusive (layer 3) counterpart to the basalts may be in the wedge at km 289–296 (marked by question marks; Fig. 2) or is incorporated in presumed thickening of the crust to the east. The flood event appears to have been a single pulse of high volcanic productivity that heralded seafloor spreading that formed normal-thickness oceanic crust (stage 5). Late stage 4 and stage 5 extension broke up the narrow zone of flood basalts, but left two relatively intact rotated blocks. Extension of the basalts may have been facilitated by detachment on the underlying serpentinized fault surface, Z.

CONCLUSIONS

Until now, understanding final breakup between Iberia and Newfoundland has suffered because of a lack of data off Newfoundland. New prestack depth-migrated seismic reflection data off Flemish Cap show clear images of abrupt continental thinning leading into magmatic oceanic crust. The sharp necking profile shown here and the lack of evidence for detachment surfaces in continental crust contrast strongly with structure of the conjugate Galicia Bank margin and confirm first-order asymmetries in final rift development. In addition, magmatically produced, 3–4-km-thick oceanic crust accreted directly to thin continental crust at a distinct continent-ocean boundary. Thin crust shows that initial accretion was in a magma-limited setting. Farther seaward, extremely thin (~1.3 km thick) layered oceanic crust directly overlies serpentinized mantle. Such crust has never been imaged before and relates directly to understanding ultraslow-spreading-ridge processes. The section is best explained by a period of magma starvation leading to mantle exhumation and the formation of an oceanic core complex that was subsequently buried by deep-marine flood basalts. The observations indicate large fluctuations in the melt supply during early stages of seafloor spreading before a more typical slow-spreading system was established.

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Figure 2. A and B: Kirchoff prestack depth migration of line 1 plotted with no vertical exaggeration. To facilitate comparison to Funck et al. (2003), horizontal distances are referenced to same origin, so that beginning of profile here is at km 203. Data processing included amplitude and spherical divergence correction, Butterworth bandpass filter from 4 to 80 Hz, minimum phase-predictive deconvolution to attenuate bubble pulse, and trace muting to reduce coherent noise. Postmigration *f-k* filter was applied to reduce steeply dipping migration noise. There is no automatic gain correction. Circles on seafloor are ocean-bottom seismometer (OBS) locations. Red fill in circles indicates stations with good data; gray fill is station with unusable data. C: Interpretation of depth-migrated image, based in part on velocity boundaries picked for depth migration as well as velocities derived from wide-angle data. Numbers plotted within section are P-wave velocity from both wide-angle (white, italicized lettering) and migration analyses (black lettering). Migration velocities are derived from ray tracing of reflection traveltime curves and thus represent estimates of true medium velocities. They are not hyperbolic semblance picks, which have no relationship to true velocity. Reflections labeled B, V, W, M, and Z are discussed in text. Dipping reflections marked CN are coherent noise and not geologic structure. Yellow colors are interpreted continental crust and green colors are interpreted oceanic crust. Red colors are mantle. CDPó common depth point.