Flemish Cap–Goban Spur conjugate margins: New evidence of asymmetry

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ABSTRACT

We present the combined results of deep multichannel reflection and refraction seismic surveys across the Flemish Cap–Goban Spur conjugate margin pair (North Atlantic), which we use to infer rifting style and breakup. Profiles on both margins cross magnetic anomaly 34 and extend into oceanic crust, making it possible to observe the complete history from continental rifting through to the formation of initial oceanic crust. The deep multichannel seismic (MCS) reflection data have previously been used to support a model of symmetric pure shear extension followed by asymmetric breakup and a sharp continent-ocean boundary. Using both types of seismic data, our results indicate instead that asymmetric structures are formed during all stages of rifting, breakup, and complex transition to oceanic spreading. The differing nature of the two ocean-continent transition zones is particularly striking. For Flemish Cap, our reprocessed image of the MCS profile clearly shows tilted fault blocks beneath back-tilted sediment packages, consistent with a wide region of highly thinned continental crust inferred from wide-angle seismic data. In contrast, normal incidence and wide-angle seismic data for the Goban Spur transition zone indicate the presence of exhumed serpentinized mantle.

INTRODUCTION

Deep seismic reflection data were used for the first time in the 1980s to derive the rifting style of a passive conjugate margin pair (Keen et al., 1989). Seismic reflection profiles from the Flemish Cap–Goban Spur margins (Fig. 1) were used to support a symmetric pure shear model of extension followed by an asymmetric breakup and a sharp continent-ocean boundary (COB; Fig. 2). A more recent wide-angle seismic study across Goban Spur (Bullock and Minshull, 2005) coincident with the Western Approaches Margin multichannel seismic (MCS) profile (Peddy et al., 1989) indicates that extension is more complex on the Flemish Cap–Goban Spur conjugate margins than initially proposed. The Bullock and Minshull (2005) velocity model of the Goban Spur margin includes a wide ocean-continent transition zone with a serpentinized mantle composition. In order to determine a complete conjugate section, the Flemish Cap margin has been reexamined, including results from a 460-km-long refraction seismic profile (Gerlings et al., 2011) situated along the original deep MCS reflection profile (Lithoprobe Line 85–3; Keen and de Voogd, 1988). The MCS profile has been reprocessed and Kirchhoff time migrated (see the GSA Data Repository[1] for details).

The dating of synrift sedimentary sequences from boreholes [Deep Sea Drilling Project (DSDP) Sites 549, 550, and 551] on the Goban Spur margin indicates that extension of the Flemish Cap–Goban Spur conjugate margin pairs started in the early Barremian (126–128 Ma; de Graciansky et al., 1985). Early and latest Albian postrift sediments indicate final breakup ca. 100 Ma (using the time scales of Ogg and Smith, 2004) leading to formation of oceanic crust. Magnetic chron 34 (ca. 84 Ma; Srivastava et al., 1988) is the oldest, undisputed magnetic anomaly identified on the Flemish Cap–Goban Spur margins, and is located close to the continental margin (Fig. 1). Unlike many other margins without clear seafloor spreading anomalies, both of the conjugate MCS and wide-angle profiles cross magnetic anomaly 34 and extend onto unambiguous oceanic crust.

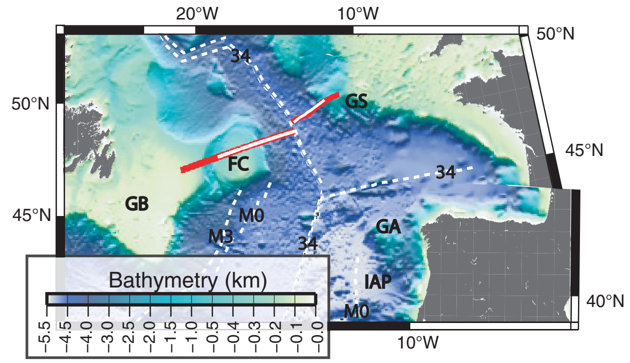

Figure 1. Plate reconstruction of North Atlantic Ocean at magnetic chron 34. Red lines indicate multichannel seismic profiles 85–3 and 87–3 (Flemish Cap) and Western Approaches Margin line (Goban Spur); solid white lines indicate refraction profiles. White dashed lines indicate magnetic anomalies M3, M0, and 34 from Srivastava et al. (1988). Abbreviations: FC—Flemish Cap; GB—Grand Banks; GS—Goban Spur; GA—Galicia Bank; IAP—Iberia Abyssal Plain.

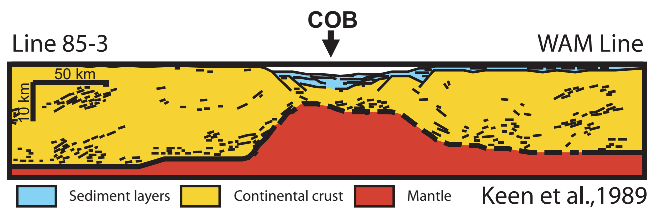

Figure 2. Previous line drawing of reconstruction of Flemish Cap–Goban Spur (FC-GS) conjugate margin pairs using Lithoprobe 85–3 and Western Approaches Margin (WAM) multichannel seismic profiles. COB—continent-ocean boundary. Modified from Keen et al. (1989).

FLEMISH CAP–GOBAN SPUR CONJUGATE PROFILES

The crustal structure across Goban Spur was determined along a 640-km-long MCS profile, the Western Approaches Margin (WAM; Peddy et al., 1989; Figs. 1 and 3). Previous studies of the Goban Spur margin (Peddy et al., 1989; Horsefield et al., 1994) identified three large fault blocks beneath which Moho depths decrease from 28 km to 12 km over a distance of 80 km. Tholeiitic basalt was recovered from DSDP Sites 551 and 550 (de Graciansky et al., 1985) and was interpreted as

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[1]GSA Data Repository item 2012320, seismic reflection profiles, is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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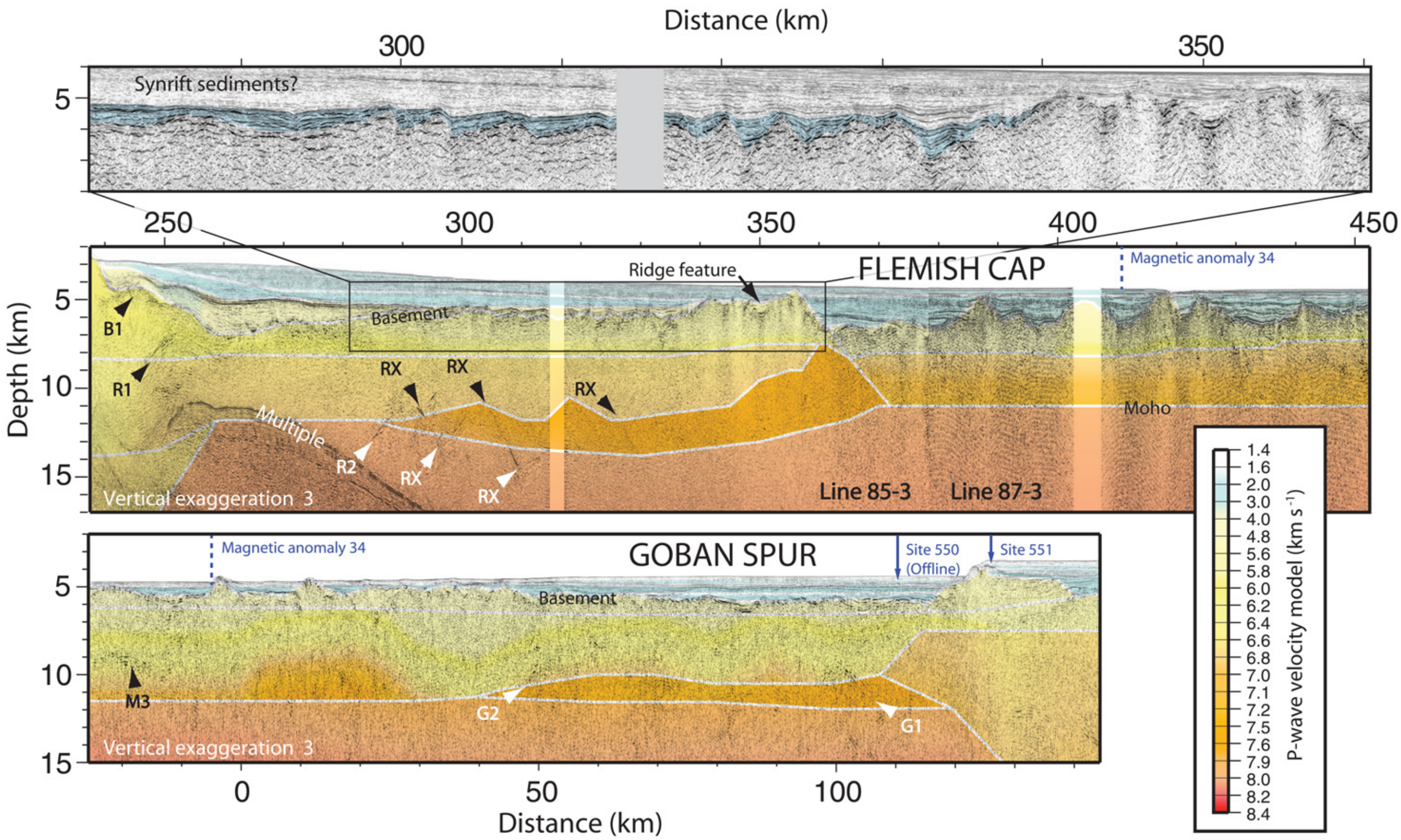

Figure 3. Deep-water sections of poststack time migrated and time-to-depth converted multichannel seismic (MCS) profiles across Flemish Cap (top, lines 85–3 and 87–3) and MCS profile across Goban Spur (bottom, Western Approaches Margin line, WAM) superimposed on P-wave velocity models (Bullock and Minshull, 2005; Gerlings et al., 2011). Layer boundaries of velocity model are indicated by white lines. Velocity model of Bullock and Minshull (2005), which deviates by as much as 8 km from WAM profile (Fig. 1), has been modified to better fit seabed, basement, and sedimentary layer boundaries. Top section is close-up of basement morphology in ocean-continent transition zone of Flemish Cap. Light blue indicates (synrift?) sediment package above tilted fault blocks. B1—prominent fault block; G1—landward-dipping reflection; G2—seaward-dipping reflection; M3—Moho reflection; R1, R2—landward-dipping reflections; RX—landward- and seaward-dipping reflections.

evidence for a sharp continent-ocean boundary located at the foot of the continental slope (Figs. 2 and 3). Major element compositions of these basalts are consistent with synrift melting of normal-temperature mantle (Dean et al., 2009). Although dating of the basalt was not possible, the earliest overlying sediments are late Cenomanian postrift chalks (de Graciansky et al., 1985). Seaward of the inferred continent-ocean boundary (120 km distance in Fig. 3), the basement is initially smooth (60–120 km), but increases in relief further seaward (0–60 km). There is no clear Moho reflection in the region of subdued basement relief, but several weak dipping reflections (G1 and G2) are observed at 10–12 km depth. The Moho reflection (M3) appears just seaward of magnetic anomaly 34. Poisson's ratio in this zone is constrained by traveltime delays for S-wave converted at the top of the basement, resulting in values of 0.34–0.36 in the upper 1 km of the crust (Bullock and Minshull, 2005). These values are too high for typical continental crustal lithologies and are more representative of exhumed serpentinized mantle. The composition of the zone of higher relief is less well constrained, consisting of a basaltic layer on top of either partially serpentinized mantle or gabbro (Figs. 3 and 4).

The Lithoprobe MCS Lines 85–3 and 87–3 (Keen and deVoogd, 1988; Fig. 3) cross Flemish Cap and extend well into oceanic crust beyond anomaly 34. Only one prominent fault block is observed at the foot of the continental slope (B1), underlain by a landward-dipping reflection (R1). Seaward of this fault block the basement relief is subdued over a distance of 40 km (245–285 km distance in Fig. 3), similar to Goban Spur. Our reprocessed image (Fig. 3) clearly shows several minor faults over a distance of 50 km overlain by back-tilted (synrift?) sediment packages. Here also, Poisson's ratio is constrained in the subdued basement region, but values of 0.27 in the upper and 0.28 in the lower crust are obtained (Gerlings et al., 2011), indicating a crust of a continental composition. The thin continental crust is underlain by partially serpentinized mantle. Some landward- and seaward-dipping reflections (RX in Fig. 3; distance 290–320 km) are observed within and just beneath this layer. The basement abruptly changes character at a distance of ~290 km. Between distances 340 and 360 km a basement high is observed with velocities consistent with the presence of either continental crust or a combination of serpentinized mantle and incipient melt. Further seaward, over distances of 365–460 km, is a region of rugged basement with crustal velocities of slow-spreading oceanic crust.

DISCUSSION

A combined interpretation using both the MCS and wide-angle seismic data is presented in Figure 4. The crust at the Flemish Cap margin thins rapidly from 32 km to 6 km over a distance of only 40 km (Gerlings et al., 2011). In comparison, the Goban Spur margin thins from 28 km to 6 km over a distance of ~80 km (Horsefield et al., 1994; Peddy et al., 1989). Thus the Flemish Cap margin displays a sharper necking profile than that of the Goban Spur margin, indicating asymmetry during rifting.

A prominent asymmetric feature of the two conjugate margins is the different nature of the ocean-continent transition zone. The similarity in basement features (low relief) was previously inferred to indicate a similar composition of the crust. Keen and deVoogd (1988), Horsefield et al. (1994), and Peddy et al. (1989) initially interpreted the thin

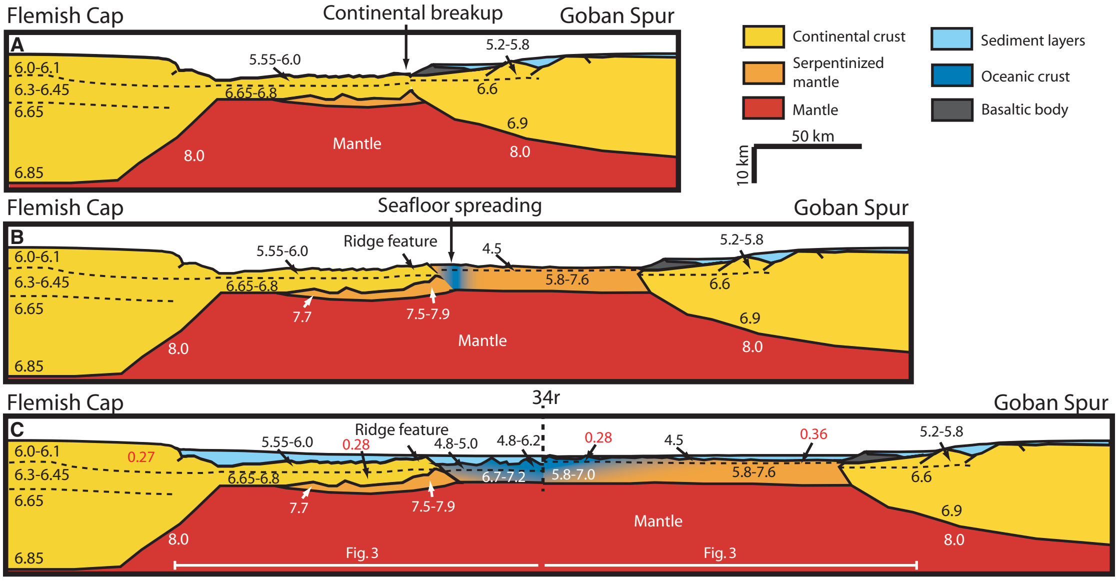

Figure 4. Reconstruction of Flemish Cap–Goban Spur (FC-GS) conjugate margin pairs. A: Under extension. B: Mantle exhumation. C: At magnetic chron 34, with seafloor spreading. Dashed horizontal black lines indicate layer boundaries. Numbers are P-wave velocities (black and white, in km s^{-1}) and Poisson's ratio (red). Poisson's ratio of 0.28 and P-wave velocity of 6.7 km s^{-1} indicate continental composition (Christensen, 1996), whereas Poisson's ratio of 0.28 and P-wave velocity of 4.5 km s^{-1} indicate basaltic composition. Poisson's ratio of 0.36 and P-wave velocities of 5.8–7.6 km s^{-1} indicate serpentinized mantle.

layer at the foot of the slope on both margins as oceanic with a sharp continent-ocean boundary. However, this interpretation is incompatible with S-wave velocities for the Goban Spur margin (Bullock and Minshull, 2005) that indicate the presence of serpentinized mantle. Across Flemish Cap, a landward-dipping reflection (R2 in Fig. 3) on line 85–3 has previously been suggested to represent a sharp continent-ocean boundary (Fig. 3; Keen et al., 1989). In light of the inferred presence of wide zones of exhumed serpentinized mantle with low relief on the west Iberia margin, Louden and Chian (1999) suggested that this layer consisted of exhumed serpentinized mantle. However, S-wave velocities now favor a zone with the composition of continental crust on the Flemish Cap margin (Gerlings et al., 2011). Tilted (synrift?) sediment packages on the Flemish Cap margin (distances 285–340 km; Fig. 3) also support the presence of thin continental crust. The presence of a tongue of thin continental crust on the Flemish Cap margin and the absence of thin continental crust on the Goban Spur margin suggest that continental breakup is asymmetric toward the side of Goban Spur (Figs. 4A and 4B). This interpretation contrasts with the suggestion by Keen et al. (1989) of an asymmetric breakup toward the Flemish Cap margin.

In general, observations elsewhere (e.g., Reston, 2009) would predict the breakup to occur either within the thin continental crust or toward the Flemish Cap margin, which has the sharper necking profile. However, the basaltic body observed at the Goban Spur margin (Fig. 4) may represent a local weakness in the thin continental crust and explain why continental breakup occurred at this location. The basalt was emplaced in the late stage of rifting by decompression melting prior to mantle exhumation (Bullock and Minshull, 2005). Melting at this time apparently was not extensive enough to initiate seafloor spreading; instead, mantle exhumation followed the thinning stage (Fig. 4B). Prior to mantle exhumation, the thin crust became brittle and part of the mantle beneath was serpentinized, in agreement with the model of Pérez-Gussinyé and Reston (2001; Fig. 4A). This interpretation is also consistent with observations further south on the Newfoundland margin, where there is direct evidence of partially serpentinized mantle (e.g., Shipboard Scientific Party, 2004). The zone of exhumed mantle spans a width of ~100 km, similar to the maximum observed width on the west Iberia margin (e.g., Dean et al., 2000).

The few profiles that exist of conjugate margin pairs with wide zones of exhumed mantle show zones of mantle exhumation on both sides (e.g., Reston, 2009), indicating that often seafloor spreading begins somewhere within this zone. However, our observations suggest that at Flemish Cap–Goban Spur initial seafloor spreading began at the same location as continental breakup, i.e., the eastward end of the tongue of thin continental crust (Fig. 4B), leaving all the exhumed mantle on the Goban Spur margin. Similar asymmetry has been suggested elsewhere. A wide zone of exhumed mantle is observed on the Nova Scotia margin but is inferred to be absent on the conjugate Morocco margin (Maillard et al., 2006). A wide zone of exhumed mantle is also observed on the northern margins of the Gulf of Aden, but this zone is narrow or absent on the southern margins (Leroy et al., 2010).

Such significant asymmetry between these transition zones remains a feature that has not yet been explained by numerical models. A broad region of highly thinned continental crust is observed at some South Atlantic margins and may be explained in models by the presence of a weak layer in the lower continental crust (Huismans and Beaumont, 2011). However, such models do not predict mantle exhumation, which instead in the Huismans and Beaumont (2011) model requires a strong lower crust.

The formation of the first 50 km of oceanic crust just landward of chron 34 also appears different on the two margins (Figs. 4B and 4C). On the Flemish Cap margin, both the MCS and wide-angle seismic results indicate a sharp boundary immediately seaward of a ridge feature, where the basement morphology becomes typical of slow seafloor spreading crust. The velocity (6.7–7.2 km s^{-1}) of the lower crust is typical for gabbro (e.g., Miller and Christensen, 1997). Further seaward toward chron 34, there are no significant changes in either reflectivity or velocity. The velocity model of the Goban Spur margin indicates a change from the zone of exhumed serpentinized mantle ~50 km landward of chron 34. In this region of initial oceanic crust, the basement morphology is shallower and has a more subdued relief than that of Flemish Cap (Fig. 3). The velocity (5.8–7 km s^{-1}) of the lower crust is more ambiguous and could support either a gabbroic or serpentinized composition (e.g., Miller and Christensen, 1997). Therefore, neither MCS nor wide-angle data clearly support the presence of normal oceanic crust, although S-wave velocities are consistent with a basaltic composition for the upper crust (Bullock and Minshull, 2005). Evidence from plutonic rocks sampled by drilling on the Newfoundland and west Iberia margins suggests that melt supply is subdued during earliest seafloor spreading there; instead, mantle exhumation is interspersed by short periods of igneous accretion and off-axis volcanism (Jagoutz et al., 2007). The initial oceanic crust of the Flemish Cap margin has the characteristics of slow-spreading crust (velocity, density, and basement morphology) formed primarily by igneous accretion. The initial oceanic crust of the Goban Spur margin has lower velocity and basement relief characteristic of both igneous crust and exhumed mantle. Thus we infer that the initial igneous accretion was more dominant on Flemish Cap than on its conjugate. Such asymmetry is also observed on the ultraslow-spreading Southwest Indian Ridge (Cannat et al., 2006), where subdued seafloor relief on one flank is interpreted as mantle exhumation, while at the conjugate location, a volcanic ridge topography is typical of slow seafloor spreading.

CONCLUSIONS

We have shown the following. (1) The rifting style of the Flemish Cap–Goban Spur conjugate margin pair is asymmetric during all stages of formation, i.e., crustal thinning, continental breakup, mantle exhumation, and initial seafloor spreading. (2) Evidence from P- and S-wave velocities and a clearer MCS image of basement morphology documents the presence of transition zones of contrasting compositions for the Flemish Cap–Goban Spur margins. On Flemish Cap, both observations indicate the presence of thin continental crust throughout the transition zone. (3) Based on our results, when determining the nature of the ocean-continent transition zone, careful imaging of the basement morphology is necessary with additional constraint from P- and S-wave velocities. Other margins, where subdued basement relief has been attributed to mantle exhumation, may need to be reevaluated. (4) The transition to initial seafloor spreading appears complex and varies between margins. To better understand these breakup processes, combined MCS and wide-angle seismic surveys need to be acquired on both margin conjugates and extend into oceanic crust unambiguously identified by seafloor spreading magnetic anomalies.

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