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Erik R. Lundin and Anthony G. Doré

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Hyperextension, serpentinization, and weakening: A new paradigm for rifted margin compressional deformation

Erik R. Lundin[1], and Anthony G. Doré[2]
[1]Statoil ASA, Trondheim 7005, Norway
[2]Statoil, 2103 City West Boulevard, Houston, Texas 77042, USA

ABSTRACT

The Early Eocene magma-rich northeast Atlantic rifted margins contain a large number of pre-breakup and post-breakup compressional structures, located in abandoned Early Cretaceous hyperextended basins with crustal stretching factors of 3–4 or more. The deformation both predates and postdates the magma-rich breakup. The hyperextended basins are often underlain by high-velocity lower crustal bodies, which we argue represent partially serpentinized upper mantle. Long-lived lithospheric weakening and proneness to deformation is proposed to relate to crustal hyperextension, probably enhanced by mantle hydration.

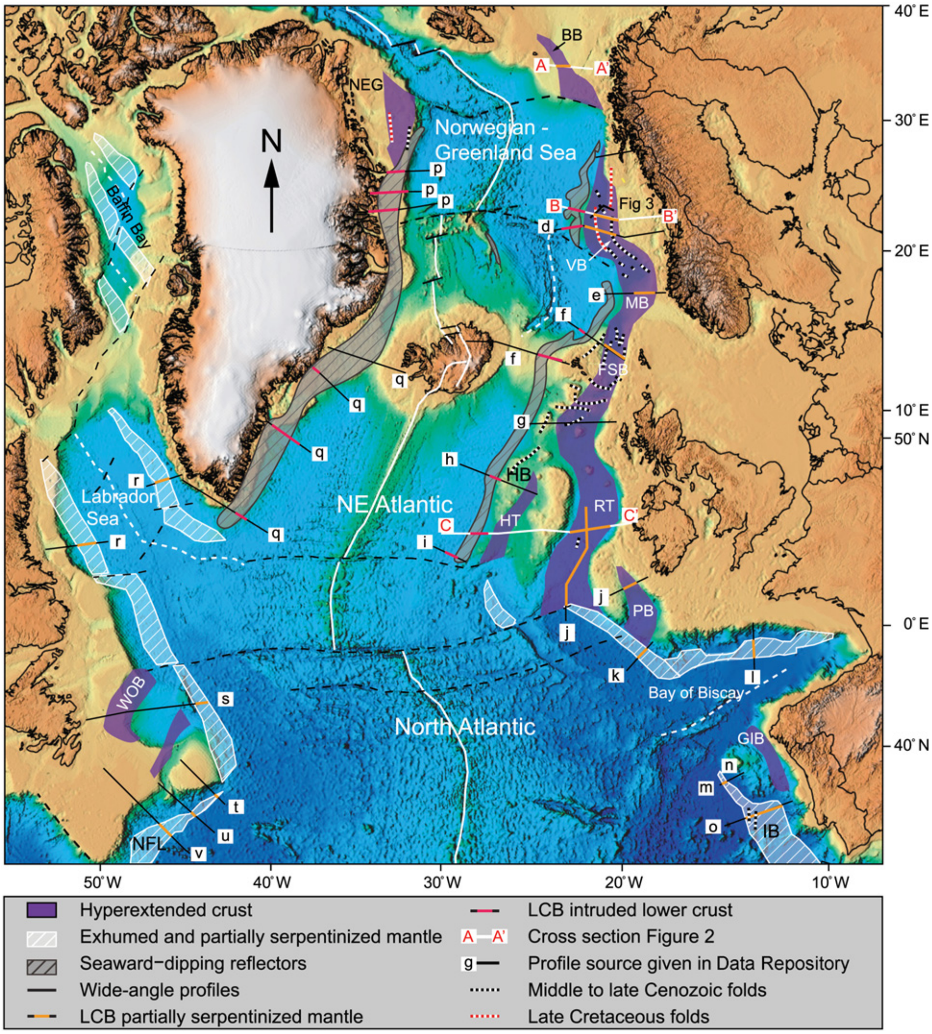

Figure 1. Map of north and northeast Atlantic and Labrador Sea, showing locations of cross sections, wide-angle profiles, distribution of Cretaceous magma-poor margins, Early Cretaceous hyperextended basins, Early Eocene magma-rich margins, and compressional features. Abbreviations: LCB—lower crustal body; BB—Bjørnøya Basin, FSB—Faroe-Shetland Basin, GIB—Galicia Interior Basin, HB—Hatton Bank, HT—Hatton Trough; IB—Iberia margin, MB—Møre Basin, NEG—northeast Greenland, NFL—Newfoundland margin, PB—Porcupine Basin, RT—Rockall Trough, VB—Vøring Basin, WOB—West Orphan Basin. (For table with labeled deep crustal profiles and associated references, see the Data Repository [see footnote 1]). Three examples are shown in Figure 2. Polar stereographic north projection.

INTRODUCTION

The north and northeast Atlantic margins contain type examples of magma-poor (e.g., Whitmarsh et al., 2001) and magma-rich margins, respectively (e.g., Eldholm et al., 2000) (Fig. 1). The Cretaceous magma-poor North Atlantic and Labrador Sea rifted margins are characterized by ~50–100-km-wide zones of exhumed and partially serpentinized mantle, located between oceanic crust and the feather edge of continental crust. These margins evolved during slow plate separation from intercontinental rifts characterized by high-angle faults with small amounts of extension, via hyperextended rifts marked by large displacement on low-angle detachments, to magma-poor margins with exhumed mantle (e.g., Péron-Pindivic and Manatschal, 2009, and references therein).

Northeast Atlantic rifting took place episodically from the Carboniferous until early Cenozoic breakup. During this unusually long episodic rift history, the stress orientation rotated significantly, leading to oblique overprinting of older by younger rifts (Doré et al., 1999). Prior to northeast Atlantic breakup, an Early Cretaceous basin chain (e.g., Faleide et al., 1993; Naylor et al., 1999; Doré et al., 1999; Sibuet et al., 2007) spanned from the West Orphan Basin to the Bjørnøya Basin in the southwest Barents Sea, a distance of ~3000 km (Figs. 1 and 2). Breakup occurred obliquely across the Cretaceous basin axis, such that basins originally joined along strike are now asymmetrically preserved off mid-Norway and northeast Greenland (Figs. 1 and 2). Wide-angle seismic data (Fig. 1) and gravity modeling (e.g., Ebbing et al., 2006; Reynisson et al., 2010) reveal that these basins overlie severely thinned crust (Fig. 2; GSA Data Repository[1]). Deep seismic imaging of the inner to central part of the mid-Norwegian margin reveals that the Cretaceous basins are floored by highly rotated crustal-scale fault blocks bounded by low-angle faults, some of which appear to have detached on the mantle (Osmundsen and Ebbing, 2008), typical for magma-poor margins (Péron-Pindivic and Manatschal, 2009) and basins (Pérez-Gussinyé

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[1] GSA Data Repository item 2011116, table with sources to wide-angle profiles shown in Figure 1, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Geology, April 2011; v. 39; no. 4; p. 347–350; doi: 10.1130/G31499.1; 3 figures; Data Repository item 2011116.

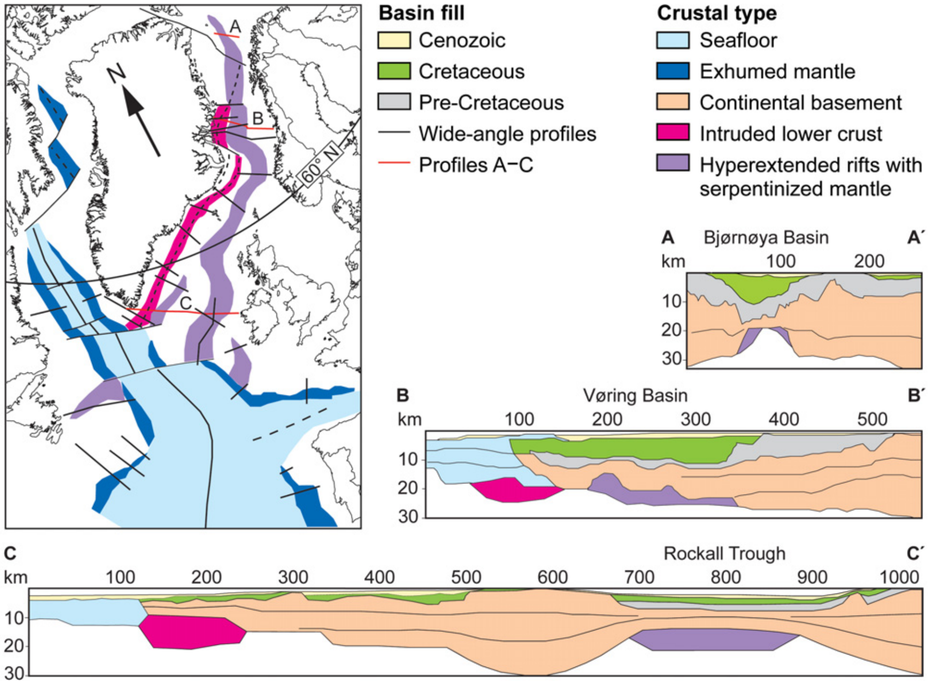

Figure 2. Plate reconstruction to Early Eocene (ca. 53 Ma) revealing chain of hyperextended Early Cretaceous rift basins, oblique line of northeast Atlantic breakup and associated underplated areas, and examples of crustal profiles (see Fig. 1).

et al., 2003). The Labrador Sea and Baffin Bay evolution was much simpler. There rifting started in Early to middle Cretaceous time (e.g., Balkwill, 1987), evolved to a magma-poor margin with exhumed mantle, and gave way to seafloor spreading in the Paleocene (Chalmers and Pulvertaft, 2001). These margins appear to have evolved more or less continuously without oblique rift overprinting.

Figure 1 demonstrates a strong spatial relationship between the northeast Atlantic Cretaceous basin chain and pre-breakup and post-breakup compressional structures. Middle to late Cenozoic post-breakup compressional features are well documented (e.g., Doré et al., 2008), and there is mounting evidence of pre-breakup compression. The thick mid-Norwegian Cretaceous succession does not show simple postrift subsidence; it is overprinted by a series of Late Cretaceous broad-wavelength regional folds (e.g., Blystad et al., 1995), implying compression. Anticlines, such as the Nyk and Utgard Highs, are faulted at their crests and, while they have been viewed in terms of extensional footwall uplift, they have also been interpreted as compressional (Brekke, 2000). Onset of the broad-scale folding has been constrained to latest Turonian time. The compression appears to have been interrupted by a phase of Campanian extension (e.g., Ren et al., 2003) followed by renewed compression in Maastrichtian–Late Paleocene time (Fig. 3), after which further extension led to Early Eocene breakup. Both body force and far-field plate tectonic drivers have been suggested as initiators for these compressional episodes (Doré et al., 2008).

HYPEREXTENSION AND HIGH-VELOCITY LOWER CRUSTAL BODIES

Wide-angle seismic surveys have revealed lower crustal bodies (LCBs) immediately inboard of the northeast Atlantic continent-ocean transition, but also at the base of the Cretaceous basin chain (Fig. 1). Many have interpreted these LCBs as intruded lower crust (underplate), and have related them to the northeast Atlantic magma-rich breakup. However, there are alternative interpretations of partially serpentinized mantle for the LCBs beneath the Rockall Trough (e.g., O'Reilly et al., 1996), Porcupine Basin (Reston et al., 2001), and Møre Basin (Reynisson et al., 2010).

At magma-poor margins, partial serpentinization of the upper mantle has been related to severe extension (Pérez-Gussinyé and Reston, 2001); when sufficiently thinned the remaining upper and lower crust is embrittled, allowing faults to cut the crust, and in turn enabling water to reach the mantle. The above observations and models, together with outcrop evidence from obducted magma-poor margins (Manatschal 2004), have led to a growing acceptance that mantle can become partially serpentinized beneath hyperextended rifts. For an assumed starting crustal thickness of ~30–35 km, and for a slowly extending rift, embrittlement occurs at a crustal stretching factor of ~3–4 (Pérez-Gussinye and Reston, 2001); our usage of the term hyperextension implies that such extension has been achieved.

The edge of the northeast Atlantic margin is underlain by LCBs interpreted as intruded lower crust, generated by decompression of the mantle (e.g., White et al., 1987). Wide-angle data have been interpreted in terms of a lower crustal intrusion LCB along the northeast Atlantic margin edge, and a partially serpentinized mantle LCB beneath the hyperextended Cretaceous Rockall Trough, ~500 km further east (O'Reilly et al., 1996; Morewood et al., 2005) (Fig. 2). Off mid-Norway, an unusually wide LCB has to date mainly been interpreted as underplate (e.g., Mjelde et al., 2009). Some have alternatively suggested that the LCB may relate to inherited high-grade metamorphic rocks, possibly mixed with intrusions (Ebbing et al., 2006), or to partially serpentinized mantle (Osmundsen and Ebbing, 2008; Reynisson et al., 2010). We propose that the anomalously wide LCB has two origins, an inner part made up of partially serpentinized mantle related to Early Cretaceous hyperextension, and an outer narrower part of intruded lower crust that overprinted the margin edge during breakup, as reportedly occurred on the Hatton margin to the southwest (White and Smith, 2009).

The mid-Norwegian LCBs have P-wave velocities ranging between 7.1 and 7.7 km/s, and even higher (e.g., Mjelde et al., 2009). While the outer body may well relate to Early Eocene lower crustal intrusion, such an explanation is less satisfactory for the inner body. Notably, it appears difficult to generate gabbroic melts with P-wave velocities (Vp) much in excess

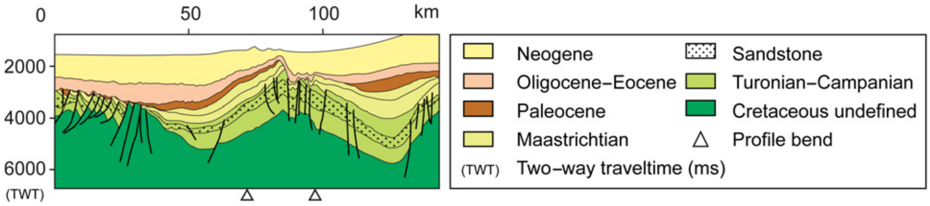

Figure 3. Cross-section (see Fig. 1) across northern Vøring Basin revealing Maastrichtian–Late Paleocene inversion of the broad-wavelength Turonian Vigrid Syncline.

of 7.3 km/s (White and McKenzie, 1989). Vp/Vs ratios (~1.8–1.9) have been used to support an underplate interpretation (e.g., Mjelde et al., 2009), but we argue that it is not possible to distinguish gabbroic rocks from partially serpentinized mantle for the P-wave velocity range in question (cf. Carlson and Miller, 1997).

Clearly, Early Cretaceous extension cannot have induced decompressional melting and underplating beneath the central Møre and Vøring Basins in the early Cenozoic, ~70 m.y. later. The lack of Cretaceous magmatism in the region also rules out Cretaceous underplating. As far as we are aware, underplate proponents have exclusively related the mid-Norwegian LCB to the early Cenozoic magma-rich breakup. Emplacement of melts far from the margin has been explained in terms of lateral spreading of melts (from a plume head) beyond the area of early Cenozoic lithospheric thinning, infilling thin spots in the crust (e.g., Sleep, 1997). However, White and Smith's (2009) work on the Hatton and Faroes margins, more proximal to the proposed plume center (e.g., White and McKenzie, 1989), does not support this idea. The identification of narrow LCBs representing breakup-related intruded lower crust places significant lateral constraints on the Early Eocene LCB and calls into question Sleep's (1997) concept. We thus consider it more persuasive that the mid-Norwegian LCBs beneath the Early Cretaceous basins simply represent a one-to-one relationship between the axis of maximum (hyper) extension and partially serpentinized mantle.

Although complete serpentinization beneath hyperextended continental crust is unlikely, partial serpentinization (10%–30%) can readily account for the P-wave velocities of the LCBs beneath the Cretaceous basin chain (Miller and Christensen, 1997; Escartin et al., 2001). Partial serpentinization probably takes place during or soon after hyperextension (Skelton et al., 2005), and an LCB formed in this manner will have a temporal and spatial relationship to the crustal thinning and overlying basin fill.

PRONENESS OF HYPEREXTENDED AREAS TO COMPRESSIONAL DEFORMATION

Two principal schools of thought exist for the strength of continental lithosphere: (1) the "jelly sandwich" model that implies strong upper crust and upper mantle (Burov and Watts, 2006), and (2) the "crème brûlee" model with most strength associated with the upper crust (e.g., Maggi et al., 2000). In either of these models hyperextension of the crust would significantly weaken the lithosphere. Pérez-Gussinyé and Reston's (2001) models suggest that the upper and lower crust become embrittled upon hyperextension. Furthermore, if polyphase faulting dissected the crust during hyperextension (Reston, 2005), the crustal strength may be even lower than its thickness suggests. The embrittlement in turn enables serpentinization of the mantle. Partial serpentinization of 10%–15% reduces the strength of peridotite by 50% or more (Escartin et al., 2001). Small amounts of water in the mantle dramatically reduce its strength (Maggi et al., 2000, and references therein). Thus, even if one prefers a model with the upper mantle as a load-bearing element, hydration is considered to cause significant strength reduction. Subsequent dehydration is conceivable, but complete dehydration requires temperatures of ~600 ºC at 1–2 GPa (e.g., Hacker et al., 2003). Within the stability range of serpentine, further weakening is proposed at increased temperatures (e.g., Escartin et al., 2001). Even if serpentine minerals are dehydrated, talc is stable to ~800 °C at 1–2 GPa and has a very low coefficient of friction (Wang et al., 2009).

Estimates of elastic thickness are often used as a measure of crustal strength (e.g., Watts, 2001). Methods used for such estimations are based on the calculation of the flexural rigidity (*D*), whereby a standard parameter of 10^{11} Pa commonly is used for the Young's modulus (*E*).

Wienecke (2006) demonstrated the importance of including the *E* variation in elastic thickness estimates. At the same temperature, *E* for serpentinite (~10 GPa) is considerably lower than that of gabbro (~100 GPa) or metagabbro (~1000 GPa) (Christensen, 1978), so the flexural rigidity of a serpentinite body will be smaller than that of a gabbroic one. Therefore, in the postrift phase the lithosphere of the final breakup magmatic margin, interpreted to consist of thin crust underplated by gabbro, is probably stronger than that of the inboard hyperextended basins, where the thin crust is interpreted to be underlain by weaker serpentinized mantle. Given this circumstance, hyperextended basins underlain by serpentinized mantle will tend to act as a stress guide for deformation during the postrift phase. Support for this idea comes from the observation that compressional deformation in the Iberia margin (Masson et al., 1994; Péron-Pinvidic et al., 2008) focused on exhumed and serpentinized mantle ~60–80 m.y. into the postrift phase (i.e., cooled lithospheric mantle), indicating that this part of the margin was the weakest element.

CONCLUSIONS

Because the northeast Atlantic breakup was magma rich, the importance of the abandoned Early Cretaceous hyperextended rifts in this region appears to have been overlooked. The strong spatial coincidence of these rifts, the axial LCBs, and the pre-breakup and post-breakup compressional structures support the idea of a lithosphere made more deformable by hyperextension.

We conclude that hyperextension and associated partial serpentinization of the mantle leads to long-term weakening and that hyperextended basins are prone to compressive deformation. We further speculate that proneness to compressive deformation by comparatively small body forces may be an *a priori* indicator of a buried hyperextended basin or margin.

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