

Hyperextended continental margins—Knowns and unknowns

Tony Doré¹ and Erik Lundin²¹Statoil (UK) Ltd., One Kingdom Street, London W2 6BD, UK²Statoil Research Centre, Arkitekt Ebbells veg 10, 7053 Trondheim, Norway

In this issue of *Geology*, Tugend et al. (2015, p. 15) discuss rift geometries and hyperextension in the Bay of Biscay–Parentis (BBP) area. This is a well-defined propagating rift/ocean (e.g., Sibuet et al., 2012), with crustal architecture revealing a succession of zones typical of magma-poor margins: (1) limited crustal stretching, (2) hyperextension, (3) exhumed mantle, and (4) ultraslow or normal oceanic crust (cf. Péron-Pinvidic and Manatschal, 2009). The zones probably formed as the rift propagated, a common mode of continental break-up (e.g., the South Atlantic, Heine et al., 2013; Central Atlantic, Kneller and Johnson, 2011, and North Atlantic oceans; Sibuet et al., 2012). Tugend et al. show how this margin evolved as partitioned transtensional domains along the nascent plate boundary and, perhaps most significantly, describe how hyperextension along the boundary localized deformation during later plate convergence.

Hyperextension is defined as stretching of the crust such that the lower and upper crust become coupled and embrittled, allowing major faults to penetrate to the mantle, leading to partial hydration (serpentinization) of the uppermost mantle, as observed in obducted margins in the Swiss Alps (e.g., Manatschal, 2004). Hyperextension is documented worldwide, e.g., in the South Atlantic (Contrucci et al., 2004), off southern Australia (Direen et al., 2007) and in the Red Sea (Cochran and Karner, 2007), and requires stretching by a factor of 3–4, with crustal thinning to ~8 km or less (e.g., Pérez-Gussinyé and Reston, 2001). Off Iberia-Newfoundland and in the Labrador Sea, fully exhumed serpentinized mantle forms 50–100 km belts between the hyperextended basins and (“Penrose”) oceanic crust with linear magnetic anomalies (Fig. 1).

The Iberian and Newfoundland conjugate margins are testing grounds for the concept of hyperextension, with exhumed mantle rocks, serpentinized peridotites of continental affinity, sampled at Ocean Drilling Program (ODP) sites (e.g., Whitmarsh and Miles, 1995; Tucholke et al., 2004). Fault blocks have been drilled and correlated with seismic data on the Galicia Bank and seaward (e.g., Tucholke et al., 2007; Ranero and Pérez-Gussinyé, 2010). ‘Necking’, the process whereby the lithosphere thins through time and across a basin, is controversial in these margins. Conjugate margins are commonly asymmetric, one margin characterized by gradual thinning with a wide transition between continent and ocean, the other by more abrupt thinning and a narrower transition (e.g., Hopper et al., 2004). Both types, however, show a discrepancy between overall crustal thinning and stretching as derived from seismically observable brittle faults. Models to explain this discrepancy include large-scale crustal detachments (Lister et al., 1991), depth-dependent (coaxial) stretching (i.e., differential extension of upper brittle and lower ductile crust), and masking of extensional events by polyphase faulting (Reston, 2007). Recent models explain broad hyperextended margins such as offshore Galicia or Angola in terms of sequential upper crustal faulting, with the extension focus migrating oceanward, and with upper crustal brittle faulting balanced by lower crustal flow (e.g. Ranero and Pérez-Gussinyé, 2010). Higher resolution seismic grids are needed to decide which model, or hybrid of models, is valid.

Early Cretaceous break-up along the Galicia margin and in the Bay of Biscay may represent the southern end-member of a chain of hyperextended basins along the north Atlantic (e.g., Lundin and Doré, 2011), all characterized by highly thinned crust. All failed to achieve full oceanic status, subsided rapidly and accumulated sedimentary infill (10 km or more in the Møre Basin). Sub-crustal bodies in some basins have been

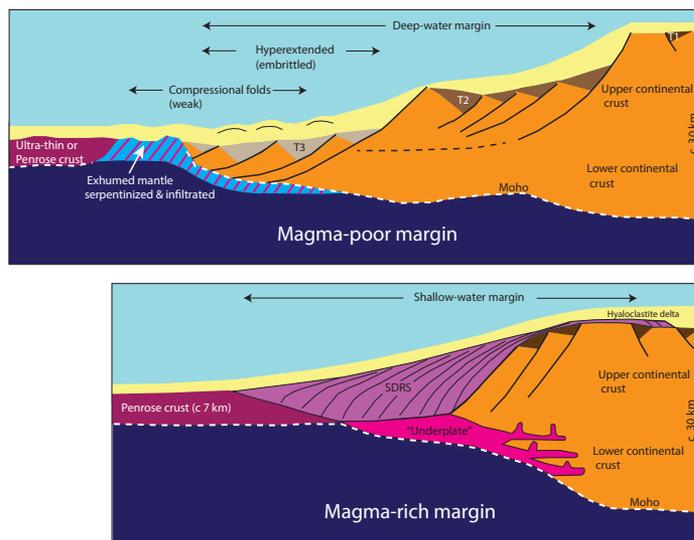


Figure 1. Schematic structure of hyperextended (magma-poor) and magma-rich passive margins.

identified as serpentinized mantle (e.g., O’Reilly et al., 1996, Reynisson et al., 2010), but this can be difficult to identify from velocity structure alone: P-wave to S-wave velocity ratios (V_p/V_s) can be used as a lithology indicator, but at a V_p range of 7.0–7.5 km/s there is significant overlap with gabbroic rocks (“underplate”), and other potential sub-crustal bodies (e.g., Mjelde et al., 2009).

The most intriguing aspect of hyperextended margins may be what differentiates them from volcanic passive margins (Fig. 1 and Table 1; see also Franke, 2013). Hyperextended margins result from slow extension rates and are magma-poor, but it is not clear why. The assumption of slow extension rates is based on initial sea-floor spreading half-rates in the order of 10 mm/yr (e.g., Sibuet et al., 2004). Magma-rich margins, in contrast, are more sharply necked and associated with initial spreading half-rates of ~25–30 mm/yr (e.g., Schreckenberger et al., 2002; Hopper et al., 2003). Extension rates immediately prior to break-up are difficult to quantify in hyperextended margins, which provide few clues as to the duration of their evolution. Even the well-studied Iberia margin provides limited constraints, since boreholes are short and on structural highs rather than in syn-rift wedges, and rift successions tend to be too deeply buried to interest the

TABLE 1. FACTORS DIFFERENTIATING HYPEREXTENDED (MAGMA-POOR) AND VOLCANIC PASSIVE MARGINS

Hyperextended Margin	Volcanic Margin
Magma-poor (mantle melt ~10%)	Magma-rich
Wide necking zone	Narrow necking zone
Slow extension rate	Rapid extension rate
Serpentinized mantle	Seaward-dipping reflectors (SDRs)
No Moho in outer (exhumed) zone	Clear Moho
Deep-water breakup	Subaerial breakup

petroleum industry. Exhumed mantle is particularly challenging, because it cannot be isotopically dated and does not show linear magnetic anomalies.

Differences in magmatism between the two margin types are also a rich topic for debate. Hyperextended margins are not amagmatic: exhumed mantle contains up to ~12% infiltrated melt in the Swiss Alps and Iberian margin (Müntener et al., 2010). The degree of melting varies from ~10% to 100% between magma-poor and magma-rich margins. The latter (e.g., the northeast Atlantic) are attributed by most workers to elevated mantle temperatures associated with a plume (e.g., Smallwood and White, 2002). It is commonly assumed that the rapid continental break-up and the initial spreading are caused by this additional heat source, absent in hyperextended margins. Alternatively, reversing cause and effect, the amount of magmatism may be a function of the spreading rate, correlated with distance from the plate tectonic pole of rotation, so that slower separation rates and magma-poor margins occur closer to the pole (Lundin et al., 2014).

Hyperextended magma-poor margins will probably react differently to ocean closure than stronger, thicker magma-rich margins. Hyperextended lithosphere is deformation-prone due to extreme crustal thinning and partial replacement of peridotite by rheologically weak serpentinite, and exhumed mantle will be even weaker. Such zones may have focused compressional deformation on the North Atlantic margin (Lundin and Doré, 2011) and such weak elements may become important in localizing subduction when oceans close (Tugend et al.). Thus, hyperextended margins may have significant roles to play at critical stages of the Wilson Cycle, the process whereby oceans open and close along broadly similar lines during supercontinent break up (Wilson, 1966).

REFERENCES CITED

- Cochran, J.R., and Karner, G.D., 2007, Constraints on the deformation and rifting of from rifting to drifting continental lithosphere of the Red Sea: The transition, *in* Karner, G.D., et al., eds., *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup*: Geological Society of London Special Publications, v. 282, p. 265–289, doi:10.1144/SP282.13.
- Contrucci, I., Matias, L., Moulin, M., Geli, L., Klingelhofer, F., Nouze, H., Aslanian, D., Olivet, J.L., Rehault, J.P., and Sibuet, J.C., 2004, Deep structure of the West African continental margin (Congo, Zaire, Angola), between 5°S and 8°S, from reflection/refraction seismics and gravity data: *Geophysical Journal International*, v. 158, p. 529–553, doi:10.1111/j.1365-246X.2004.02303.x.
- Direen, N.G., Borissova, I., Stagg, H.M.J., Colwell, J.B., and Symonds, P.A., 2007, Nature of the continent–ocean transition zone along the southern Australian continental margin: A comparison of the Naturaliste Plateau, SW Australia, and the central Great Australian Bight sectors, *in* Karner, G.D., et al., eds., *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup*: Geological Society of London Special Publications, v. 282, p. 239–264.
- Franke, D., 2013, Rifting, lithosphere breakup and volcanism: Comparison of magma-poor and volcanic rifted margins: *Marine and Petroleum Geology*, v. 43, p. 63–87, doi:10.1016/j.marpetgeo.2012.11.003.
- Heine, C., Zoethout, J., and Müller, D., 2013, Kinematics of the South Atlantic rift: *Solid Earth*: arXiv:1301.2096, doi:10.5194/sed-5-41-2013.
- Hopper, J.R., Dahl-Jensen, T., Holbrook, W.S., Larsen, H.C., Lizarralde, D., Korenaga, J., Kent, G.M., and Kelemen, P.B., 2003, Structure of the SE Greenland margin from seismic reflection and refraction data: Implications for nascent spreading center subsidence and asymmetric crustal accretion during North Atlantic opening: *Journal of Geophysical Research*, v. 108, p. 2269, doi:10.1029/2002JB001996.
- Hopper, J.R., Funck, T., Tucholke, B.E., Larsen, H.C., Holbrook, W.S., Loudon, K.E., Shillington, D., and Lau, H., 2004, Continental breakup and the onset of ultra-slow seafloor spreading off Flemish Cap on the Newfoundland rifted margin: *Geology*, v. 32, p. 93–96, doi:10.1130/G19694.1.
- Kneller, E.A., and Johnson, C.A., 2011, Plate kinematics of the Gulf of Mexico based on integrated observations from the Central and South Atlantic: *Gulf Coast Association of Geological Societies (GCAGS): Transactions*, v. 61, p. 283–299.
- Lister, G.S., Etheridge, M.A., and Symonds, P.A., 1991, Detachment models for the formation of passive continental margins: *Tectonics*, v. 10, p. 1038–1064, doi:10.1029/90TC01007.
- Lundin, E.R., and Doré, A.G., 2011, Hyperextension, serpentinization and weakening: A new paradigm for rifted margin compressional deformation: *Geology*, v. 39, p. 347–350, doi:10.1130/G31499.1.
- Lundin, E.R., Redfield, T.F., and Peron-Pindivic, G., 2014, Rifted continental margins: Geometric influence on crustal architecture and melting, *in* Pindell, J., et al., eds., *Sedimentary Basins: Origin, Depositional Histories, and Petroleum Systems: 33rd Annual Gulf Coast Section of the Society for Sedimentary Geology (SEPM) Foundation, Bob F. Perkins Conference*, 26–28 January, Houston, Texas, p. 18–53.
- Manatschal, G., 2004, New models for evolution of magma-poor rifted margins based on a review of data and concepts from West Iberia and the Alps: *International Journal of Earth Sciences*, v. 93, p. 432–466, doi:10.1007/s00531-004-0394-7.
- Mjølde, R., Faleide, J.I., Breivik, A., and Raum, T., 2009, Lower crustal composition and crustal lineaments on the Vøring margin, NE Atlantic: A review: *Tectonophysics*, v. 472, p. 183–193, doi:10.1016/j.tecto.2008.04.018.
- O'Reilly, B.M., Hauser, F., Jacob, A.W.B., and Shannon, P.M., 1996, The lithosphere below the Rockall Trough: Wide-angle seismic evidence for extensive serpentinization: *Tectonophysics*, v. 255, p. 1–23, doi:10.1016/0040-1951(95)00149-2.
- Pérez-Gussinyé, M., and Reston, T.J., 2001, Rheological evolution during extension at non-volcanic rifted margins: Onset of serpentinization and development of detachments leading to continental break-up: *Journal of Geophysical Research*, v. 106, p. 3961–3975, doi:10.1029/2000JB900325.
- Péron-Pindivic, G., and Manatschal, G., 2009, The final rifting evolution at deep magma-poor passive margins from Iberia-Newfoundland: A new point of view: *International Journal of Earth Sciences*, v. 98, p. 1581–1597, doi:10.1007/s00531-008-0337-9.
- Ranero, C., and Pérez-Gussinyé, M., 2010, Sequential faulting explains the asymmetry and extension discrepancy of conjugate margins: *Nature*, doi:10.1038/nature09520.
- Reston, T.J., 2007, The extension discrepancy at North Atlantic non-volcanic rifted margins: depth-dependent stretching or unrecognised faulting?: *Geology*, v. 35, p. 367–370, doi:10.1130/G23213A.1.
- Reynisson, R.F., Ebbing, J., Lundin, E., and Osmundsen, P.T., 2010, Properties and distribution of lower crustal bodies on the mid-Norwegian margin, *in* Vining, B.A., and Pickering, S.C., eds., *Petroleum Geology: From Mature Basins to New Frontiers: Proceedings of the 7th Petroleum Geology Conference*: Geological Society of London Petroleum Geology Conference series 7, p. 843–854, doi:10.1144/0070843.
- Schreckenberger, B., Hinz, K., Franke, D., Neben, S., and Roeser, H.A., 2002, Marine magnetic anomalies and the symmetry of the conjugated rifted margins of the South Atlantic: *American Geophysical Union, Fall Meeting, Supplement*, T52C–1217, 83 p.
- Sibuet, J.-C., Rouzo, S., and Srivastava, S., 2012, Plate tectonic reconstructions and palaeogeographic maps of the central and North Atlantic oceans: *Canadian Journal of Earth Sciences*, v. 49, p. 1395–1415, doi:10.1139/e2012-071.
- Sibuet, J.-C., Srivastava, S.P., and Spakman, W., 2004, Pyrenean orogeny and plate tectonics: *Journal of Geophysical Research*, v. 109, p. B08104, doi:10.1029/2003JB002514.
- Smallwood, J.R., and White, R.S., 2002, Ridge-plume interaction in the North Atlantic and its influence on continental breakup and seafloor spreading, *in* Jolley, D. W. and Bell, B.R., eds., *The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes*: Geological Society of London Special Publications, v. 197, p. 15–37.
- Tucholke, B.E., et al., 2004, *Proceedings of the Ocean Drilling Program, Initial reports*, v. 210: College Station, Texas, Ocean Drilling Program. (CD-ROM)
- Tucholke, B.E., Sawyer, D.S., and Sibuet, J.-C., 2007, Breakup of the Newfoundland–Iberia rift, *in* Karner, G.D., et al., eds., *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup*: Geological Society of London Special Publications, v. 282, p. 9–46, doi:10.1144/SP282.2.
- Tugend, J., Manatschal, G., and Kuszniir, N.J., 2015, Spatial and temporal evolution of hyperextended rift systems: Implication for the nature, kinematics, and timing of the Iberian-European plate boundary: *Geology*, v. 43, p. 15–19, doi:10.1130/G36072.1.
- Whitmarsh, R.B., and Miles, P.R., 1995, Models of the development of the West Iberia rifted continental-margin at 40°30'N deduced from surface and deep-tow magnetic-anomalies: *Journal of Geophysical Research. Solid Earth*, v. 100, p. 3789–3806, doi:10.1029/94JB02877.
- Wilson, J.T., 1966, Did the Atlantic close and then re-open?: *Nature*, v. 211, p. 676–681, doi:10.1038/211676a0.

Printed in USA