Testing the Lithospheric Counterflow Hypothesis

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In the past three decades since the publication of McKenzie (1978), which presented what is now termed the Uniform Lithospheric Extension model, significant quantitative advances have been made in understanding the structure of rifted continental margins using multiple geophysical, geochronological, petrological and geochemical techniques. Despite these advances, we have only a rudimentary understanding of the processes involved in the development of rifted continental margins, particularly the roles of depth-dependant lithospheric extension, inherited crustal weaknesses, flow of lower continental mantle lithosphere, and syn-rift sedimentation.

Huismans and Beaumont (2011) have advanced the new hypothesis that partly metasomatized (refertilized) lower cratonic lithosphere may be sufficiently weak (low viscosity) and chemically depleted (low density, $\Delta\rho$ = 10-80 kg/m^3, (Lee, 2003)) that it will flow toward the rift axis under gravity during rifting. If correct, this implies that the mid and outer regions of some continental margins will be underplated by thick lower cratonic lithosphere….'lost continent under the oceans'. Huismans and Beaumont proposed this model in the context of the flow of thick cratonic lithosphere and suggested that it applies to the west African margin outboard of the Congo craton and the Exmouth plateau margin outboard of the Pilbara craton.

More recently, Ings and Beaumont (2011) have generalized this hypothesis and propose that thick depleted continental mantle lithosphere in general, not just cratonic lithosphere, may flow in the manner proposed by Huismans and Beaumont (2011). They have termed this the Lithospheric Counterflow hypothesis because the lower lithosphere flows in the opposite direction from the motion of the overlying rifting margins (Figs 1 and 2).

The lithospheric counterflow hypothesis has several significant implications. It may explain: i) exhumed continental mantle lithosphere at rifted margins as noted above; ii) anomalous geochemical signatures in magmas contaminated when passing through this continental lithosphere and properties of xenoliths derived from this mantle (O'Reilly et al., 2009); iii) the paradox that both sides of many conjugate margins appear to be 'upper plate' margins; iv) a two-stage breakup in which crustal rupture occurs before that of the mantle lithosphere; v) a significantly longer syn-rift interval than previously indicated and a significant delay of up to 20 Ma between crustal rupture and final breakup of the continental mantle underplate and onset of ocean-floor spreading;
vi) anomalously shallow water syn-rift conditions at margins of this type owing to the reduced subsidence caused by low density underplate (Huismans and Beaumont, 2011).

Rifted continental margins are commonly divided into volcanic (magma-rich) and non-volcanic (magma-poor) types. There is general agreement that the east coast United States margin is volcanic, whereas the Newfoundland-Iberia conjugate margins and margins of Labrador and West Greenland are largely non-volcanic. The transition from volcanic to non-volcanic type occurs offshore Nova Scotia and represents a primary target for study in regard to the reasons for transitions between these two types (see Nedimovic et al., 2011, white paper, this volume)

Counterflow may also contribute to the difference between volcanic (e.g. US east coast) and non-volcanic (e.g. Newfoundland-Iberia) margins. We propose that margins subject to counterflow will be magma poor because the already depleted lower continental lithosphere will not yield decompression melts, and upwelling of asthenosphere, which normally produces magma, is inhibited by the counterflow. Melt infiltration will be therefore be delayed, consistent with observations (Jagoutz et al., 2007; Muntener et al., 2010) and potentially contribute to initially thin oceanic crust. Moreover, 3D lithospheric counterflow with a component of strike parallel flow may dam or absorb magma from a remote source that is flowing axially along the base of the lithosphere beneath the rift, e.g. CAMP magmatism.

In this 'white paper' we propose that GeoPRISMS–Earthscope evaluate and test the lithospheric counterflow concept. This is a proposal for a study in which the seismic and associated experiments can be tuned to test this hypothesis based on existing numerical results. From the arguments presented above, we suggest that non-volcanic margins are most likely to be underplated in this manner. An obvious choice is a detailed study of the Newfoundland conjugate of the Newfoundland -Iberia margins system, particularly focussed on the mantle lithosphere of the ocean-continent transition and the evidence for flow of the exhumed mantle lithosphere normal to the margin during rifting. A similarly good target is the volcanic to non-volcanic transition within Nova Scotian margin and the prolongation of the margin to the northeast.

We base this proposal on results from 2D thermomechanical upper-mantle scale finite element The models shown here contrast rifting of standard 125 km thick lithosphere (Fig. 1) with that of 200 km thick chemically depleted mantle lithosphere. Depending on the properties of the crust and mantle, two types of two-layer two-stage rift systems develop: Type I margins where the crust remains coupled to the mantle lithosphere during rifting producing narrow margins in which the crust necks before the mantle lithosphere; Type II margins where the crust is weaker allowing it to decouple from the mantle during extension producing wide margins in which the mantle necks before the crust finally rifts (Huismans and Beaumont, 2008, 2011).

When the mantle lithosphere is thick and chemically depleted, the hotter buoyant lower mantle lithosphere flows toward to rift axis during rifting and is exhumed toward the surface. Depending on the stretching width of the overlying crust (Type I vs Type II) and the run-out length-scale of the buoyant lower mantle lithosphere, the continental mantle will either underplate the crust or be exhumed in the ocean-continent transition. The combination of a Type I-rifting style with a long run-out results in the exhumation of wide tracts of continental mantle lithosphere, subsequently serpentinized owing to hydration (Fig.2).

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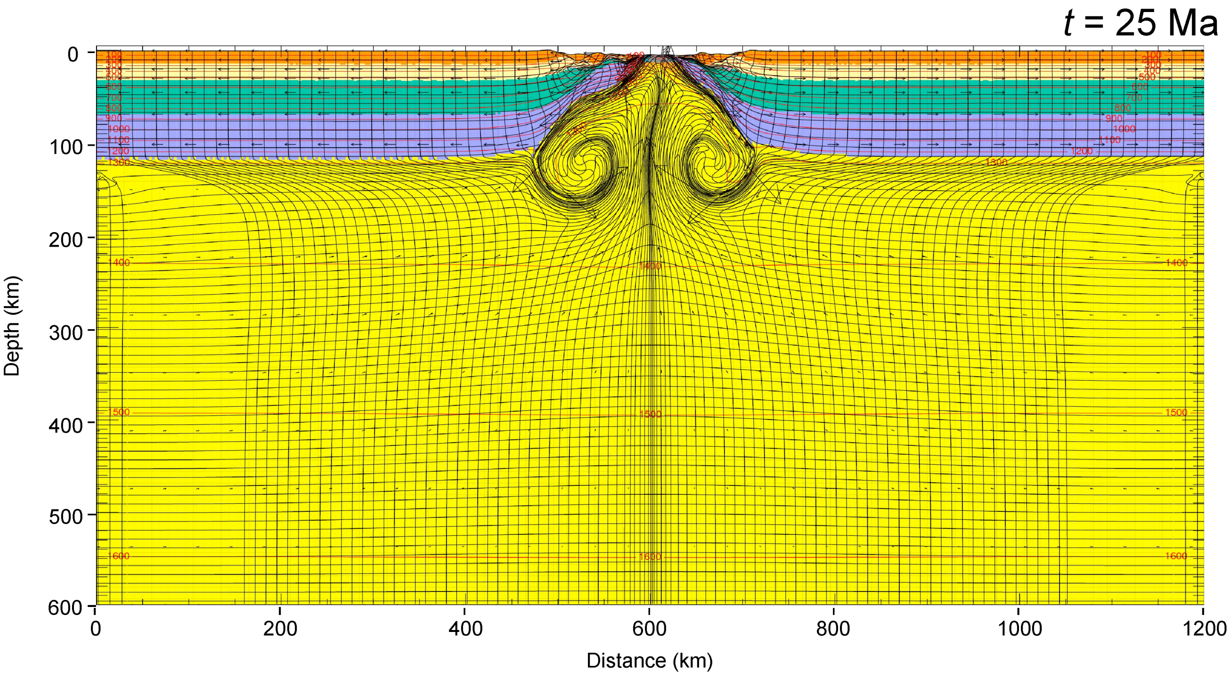

Figure 1. Post-rift configuration of a numerical model with 125 km thick lithosphere with no chemical depletion. The crust (orange and sand-color) and continental lithospheric mantle (green and light blue) have rifted at approximately the same time. Asthenosphere shown in yellow.

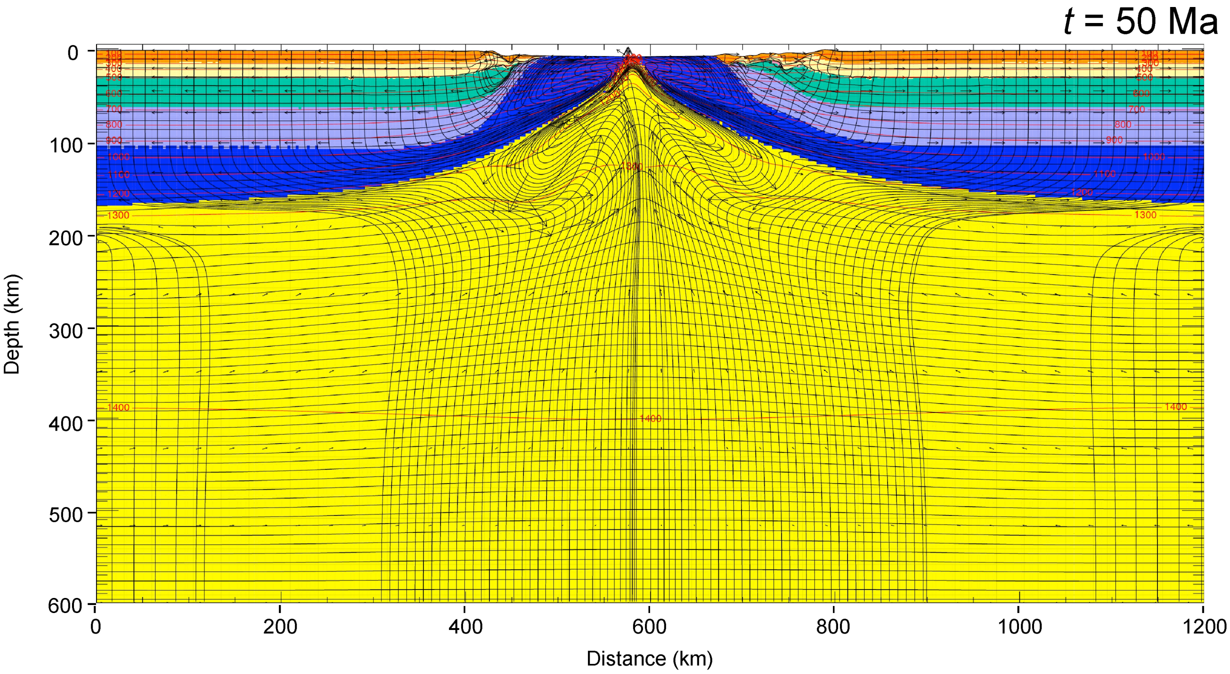

Figure 2. Post-rift configuration of a numerical model with 200 km thick lithosphere with 80 kg/m^3 chemical depletion. Other properties are as in Fig. 1. Rifting of the crust (orange and sand-color) occurred before the rifting of the buoyant continental lithospheric mantle (green, light, and dark blue). Hot, buoyant, low viscosity lower continental lithosphere (dark blue) flows toward to evolving mid-ocean ridge during rifting; counter to the tectonically driven movement of the crust and brittle upper mantle.