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Evolution of the Newfoundland–Iberia conjugate rifted margins

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ABSTRACT

It is accepted that mildly extended sedimentary basins form by largely uniform thinning of continental lithosphere. No such consensus exists for the formation of highly extended conjugate rifted continental margins. Instead, a wide range of models which invoke differing degrees of depth-dependent thinning have been proposed. Much of this debate has focussed on the well-studied Newfoundland–Iberia conjugate margins. We have tackled the problem of depth dependency at this pair of margins in three steps. First, we have reconstructed water-loaded subsidence histories by making simple assumptions about changes in water depth through time. Secondly, we have used these reconstructed subsidence histories to determine the spatial and temporal variation of lithospheric strain rate. An inversion algorithm minimizes the misfit between observed and predicted subsidence histories and crustal thicknesses by varying strain rate as a smooth function of distance across the margin, depth through the lithosphere, and geologic time. Depth-dependent thinning is permitted but, crucially, our algorithm does not prescribe its existence or form. Given the absence of significant volumes of syn-rift magmatism, we have also applied a minimal melting constraint. Inverse modeling has yielded excellent fits to both reconstructed subsidence and crustal observations, which suggest that rifting occurred from ~150–135 Ma and at rates of up to 0.3 Ma^{-1}. Strain rate distributions are depth-dependent, suggesting that lithospheric mantle thins over a wider region than the crust. Beneath highly extended parts of the margin, crustal strain rates greatly exceed lithospheric mantle strain rates. Thirdly, we have tested our strain rate histories by comparing the total horizontal extension with the amount of extension inferred from normal faulting patterns. Both values agree within error. We freely acknowledge that there are important uncertainties in reconstructing the subsidence histories of deep-water margins. Nevertheless, stratigraphic records remain the only, albeit imperfect means of determining how crust and lithospheric mantle thin through time and space.

1. Introduction

Over the past 40 years, there has been much interest in the development of passive continental margins, which are a primary manifestation of plate tectonics. It is generally accepted that passive margins form by extension and cooling of continental lithosphere. Simple kinematic models have been developed which describe the growth of margins in terms of either uniform or depth-dependent stretching (e.g. McKenzie, 1978; Le Pichon and Sibuet, 1981; Hellinger and Sclater, 1983; Keen and Dehler, 1993). The temporal and spatial variation of crustal and lithospheric thinning across a margin control variations in temperature, heatflow, subsidence, extensional faulting and decompression melting (White et al., 2003).

Despite acceptance of the basic model, there is much disagreement about the spatial distribution of lithospheric extension. This controversy has particularly focussed on the Newfoundland–Iberia conjugate margins which have been studied in detail using deep-seismic reflection and wide-angle surveys, calibrated by deep-water boreholes. There are two substantive and unresolved issues. First, a significant discrepancy between the amount of extension measured from upper crustal faulting and the amount of extension measured from crustal thickness is often reported (e.g. Davis and Kusznir, 2004). Secondly, broad tracts of exhumed and mostly unmelted lithospheric mantle occur at deep-water margins (e.g. Whitmarsh et al., 2001; Minshull et al., 2001). These two observations are mutually incompatible but if either or both are correct, they imply that various forms of depth dependency occur, perhaps at different stages of margin evolution.

A closely related puzzle concerns the existence and importance of lithospheric detachment faults (e.g. Wernicke, 1985). These gently dipping detachment faults may offset stretching of the crust and lithospheric mantle, generating asymmetric patterns of syn- and post-rift subsidence. It is generally accepted that detachment faults do not control lithospheric extension in mildly extended basins (White, 1989). However, spectacular detachment faults are sometimes imaged on rifted margins and mapped in collisional mountain belts where the original rift architecture can sometimes be inferred (e.g. Hoffmann and Reston, 1992; Pérez-Gussinyé and Reston, 2001; Hölker et al., 2003). Symmetric

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shear zones have also been invoked as a mechanism for extending, but not significantly melting, lithospheric mantle (Froitzheim et al., 2006).

The existence and form of depth dependency have been explored in two different ways. The first approach is observation-based and relies upon making detailed measurements of upper crustal faults and comparing them with crustal thickness measurements. The extension discrepancy is reported for highly extended margins and there is much debate about its cause. One school of thought argues that it is real, which implies that the brittle upper crust barely extends at deep-water margins compared with the rest of the crust and lithospheric mantle (Davis and Kusznir, 2004). The unlikely inference is that there is a major change in the depth distribution of extension at the brittle–plastic transition. A second school of thought argues that the extension discrepancy is not real but arises from the limitations of seismic imaging of highly deformed rocks. Once stretching factors exceed about 1.7, a second generation of faulting forms which dissects the older generation. Reston (2007) has shown convincing examples similar to those observed in the field but, in general, multiple generations of faulting are exceedingly difficult to image. Moreover, 40–70% of brittle deformation occurs on scales which cannot be resolved by seismic imaging (Walsh et al., 1991; Marrett and Allmendinger, 1992).

A second approach uses numerical experiments to investigate the dynamic evolution of conjugate margins. The starting point of these thermo-mechanical models is an assumed rheological structure of the continental lithosphere. Typically, the upper crust is assumed to deform by frictional failure according to Byerlee's Law while the lower crust and lithospheric mantle deform by power-law creep (e.g. Braun and Beaumont, 1987; Chéry et al., 1992; Bassi et al., 1993; Tett and Sawyer, 1996; Huismans et al., 2001; Huismans and Beaumont, 2003; Rosenbaum et al., 2005; Lavier and Manatschal 2006; Burov, 2007; Harry and Grandell, 2007). These models are intricate and it is important to bear in mind that rheological descriptions of the lithosphere are at best educated guesses. The inevitable uncertainties have led to a major debate about lithospheric strength (e.g. Jackson, 2002).

Fig. 1 summarizes two end members from a recent set of numerical simulations which were designed to investigate the effects of frictional-plastic and viscous strain softening (Huismans and Beaumont, 2003). Strain softening promotes asymmetric extension of that portion of the lithosphere controlled by the dominant rheology. By increasing or decreasing strain rate, Huismans and Beaumont (2003) showed that the locus of the dominant rheology moves, promoting varying degrees of asymmetry. The first simulation was generated using an unrealistically slow extensional velocity of 0.06 cm/yr over 400 km (i.e. $\dot{\varepsilon}_{xx}\sim 0.002$ Ma^{-1}). Extension is highly asymmetric and non-uniform with depth, closely resembling the lithospheric simple shear model of Wernicke (1985). In contrast, the second simulation was generated using a much faster velocity of 10 cm/yr over 400 km (i.e. $\dot{\varepsilon}_{xx}\sim 0.3$ Ma^{-1}) and deformation is dominated by pure shear (McKenzie, 1978). These simulations may, or may not, be directly applicable to the Newfoundland–Iberia rift but it is clear that radically different lithospheric geometries can be obtained simply by varying the rate of deformation.

Asymmetric extension is evidently an attractive way of producing tracts of exposed and largely unextended lithospheric mantle. Fig. 1a also makes a crucial point: if lithospheric mantle is largely unextended on one margin, then the opposite must be true on the conjugate margin. Thus, if the lithospheric mantle under the Iberian margin is relatively unextended, the Newfoundland margin should show evidence consistent with a highly extended lithospheric mantle (e.g. a large ratio of post-rift to syn-rift subsidence and evidence for significant volumes of decompression melting). We all seek a dynamic understanding of conjugate margin formation but existing models share three important drawbacks. First, the rheological descriptions upon which they are based rely upon extrapolation of laboratory experiments by up to ten orders of magnitude. Secondly, they are very slow to run and so the more interesting inverse problem is not yet tractable. Thirdly, dynamic models are seldom concerned with fitting geologic observations in a formal sense. Instead, they are essentially 'thought experiments' which permit the consequences of particular rheological frameworks to be explored.

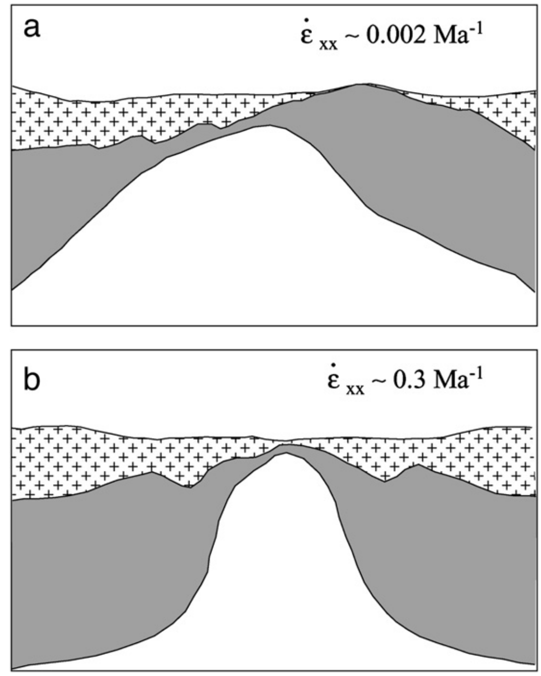

Fig. 1. Sketches of two dynamical models redrawn from numerical experiments 8 and 9 of Huismans and Beaumont (2003). In both cases, a complicated rheological stratification of the lithosphere was used which includes frictional-plastic strain softening. Model (a) was generated using a very slow strain rate and closely resembles highly depth-dependent stretching of the lithosphere (Wernicke, 1985). Note that the form of depth dependency at each margin must be of opposite sense in order to conserve mass. Model (b) was generated using a moderate strain rate and closely resembles uniform stretching of the lithosphere (McKenzie, 1978). Stippled shading indicates crust, and grey shading lithospheric mantle.

In order to determine the spatial and temporal evolution of deep-water margins, we argue that a kinematic approach is more fruitful. Our strategy is threefold. An obvious starting point is that conjugate margins must be modeled simultaneously since their structural evolution should be compatible. We then suggest that the best way to identify the existence and form of depth dependency is to model subsidence histories. Although present-day crustal structure is an important constraint, it cannot reveal how strain has been partitioned between the crust and lithospheric mantle. Subsidence histories, on the other hand, contain valuable, albeit indirect, information about the distribution of thermal anomalies and thus deformation throughout the lithosphere in both space and time. Finally, we seek smooth models which minimize the misfit between observed and predicted subsidence and crustal histories. An important corollary is that no prior assumptions should be made about either the existence or the form of depth dependency. These aims are best achieved using an inverse model. We focus on the well-studied Newfoundland–Iberian conjugate margin pair, but our inverse strategy is generally applicable.

2. A general strategy

Heterogeneous sedimentary records are used to calculate the water-loaded (i.e. tectonic) subsidence histories of basins and margins. For many years, these tectonic subsidence histories have been investigated using forward models which assume either instantaneous or finite-duration stretching.