Tectonophysics 680 (2016) 28–49

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Constraining lithosphere deformation modes during continental breakup for the Iberia–Newfoundland conjugate rifted margins

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ARTICLE INFO

Article history:
Received 20 February 2015
Received in revised form 26 April 2016
Accepted 3 May 2016
Available online 10 May 2016

Keywords:
Continental rifted margins
Kinematic modelling
Lithosphere deformation mode
Continental lithosphere breakup
Decompression melting
Mantle exhumation

ABSTRACT

A kinematic model of lithosphere and asthenosphere deformation has been used to investigate lithosphere stretching and thinning modes during continental rifting leading to breakup and seafloor spreading. The model has been applied to two conjugate profiles across the Iberia–Newfoundland rifted margins and quantitatively calibrated using observed present-day water loaded subsidence and crustal thickness, together with observed mantle exhumation, subsidence and melting generation histories. The kinematic model uses an evolving prescribed flow-field to deform the lithosphere and asthenosphere leading to lithospheric breakup from which continental crustal thinning, lithosphere thermal evolution, decompression melt initiation and subsidence are predicted. We explore the sensitivity of model predictions to extension rate history, deformation migration and buoyancy induced upwelling. The best fit calibrated models of lithosphere deformation evolution for the Iberia–Newfoundland conjugate margins require; (1) an initial broad region of lithosphere deformation with passive upwelling, (2) lateral migration of deformation, (3) an increase in extension rate with time, (4) focussing of the deformation and (5) buoyancy induced upwelling. The model prediction of exhumed mantle at the Iberia–Newfoundland margins, as observed, requires a critical threshold of melting to be exceeded before melt extraction. The preferred calibrated models predict faster extension rates and earlier continental crustal separation and mantle exhumation for the Iberia Abyssal Plain–Flemish Pass conjugate margin profile than for the Galicia Bank–Flemish Cap profile to the north. The predicted N–S differences in the deformation evolution give insights into the 3D evolution of Iberia–Newfoundland margin crustal separation.

1. Introduction

How the lithosphere and asthenosphere deforms during continental rifting leading to breakup is poorly understood. Observations and interpretations at present-day and fossil analogue magma-poor rifted margins show hyper-extended continental crust and lithosphere (e.g. West-African Margin, Contrucci et al., 2004), detachments faults (e.g. Alpine Tethys, Iberia–Newfoundland, Reston et al., 1996; Manatschal, 2004; Reston and McDermott, 2011), exhumed mantle and scattered embryonic oceanic crust (e.g. Iberia and Newfoundland margins, Reid, 1994; Jagoutz et al., 2007; Bronner et al., 2011), which cannot be explained by a single lithosphere deformation mode during continental rifting. Fletcher et al. (2009) explored two deformation mode end-members, pure-shear and upwelling divergent flow, in order to examine the process of continental rifting and breakup. They showed that these deformation modes exert a strong control on the resulting architecture of rifted margins and the relative timing of melt generation and crustal separation. Nevertheless these two lithosphere deformation mode end-members, taken individually, cannot predict the observed rifted margin architecture.

This study aims to give insights into the main lithosphere deformation processes occurring during continental rifting and to determine the lithosphere deformation history of the Iberia–Newfoundland rifted margins that led to their present-day configuration. Dynamic numerical models have previously been applied to the formation of the Iberia–Newfoundland conjugate rift system (e.g. Huismans and Beaumont, 2011). The mode of deformation in this dynamic modelling approach is defined by constitutive equations where the rheology is fully thermo-mechanically coupled, permitting the model to be self-consistent with rock-rheology parameterisation (Fernàndez and Ranalli, 1997). As a consequence, strength anomalies must be implanted within the lithosphere in order to initiate the deformation; for example, Harry and Grandell (2007) used initial anomalies in the continental crustal thickness and initial weakness of the rheology of the continental crust to reproduce an architecture consistent with that observed at Galicia Bank and Flemish Cap. Lavier and Manatschal (2006) also constrained their numerical model using geological and geophysical observations on the Iberia–Newfound-land and the Alpine Tethys rifted margins from which they proposed a polyphase continental rifting evolution. Dynamic models show a self-

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http://dx.doi.org/10.1016/j.tecto.2016.05.006

consistent thermo-rheological evolution determined by the rheological properties of continental crust and mantle, however they evolve in their own way, not necessarily corresponding to specific rifted margins architecture, which makes them difficult to calibrate against real observations.

In this paper we use a kinematic rather than a dynamic modelling approach, to investigate the formation of the Iberia–Newfoundland rifted margins which we calibrate using quantitative geological and geophysical data. Lithosphere and asthenosphere deformation in the kinematic models is described by prescribed flow velocity fields which, while omitting rheological properties, allow the model predictions to be quantitatively calibrated against observations. Kinematic models have been previously applied to specific case histories in order to predict crustal structure, subsidence and heat flow of sedimentary basins and rifted margins (e.g. McKenzie, 1978; Le Pichon and Sibuet, 1981; Beaumont et al., 1982; Kusznir and Karner, 2007; Crosby et al., 2008; Mohn et al., 2015). In particular, Crosby et al. (2008) successfully constrained the extensional strain rate history during the development of Iberia–Newfoundland conjugate margin profiles using observed subsidence and crustal structure; however no existing study has determined the full lithosphere extensional deformation history constrained and calibrated using quantitative observed data.

The approach used in this study is closely related to the work of Fletcher et al. (2009). Two principal lithosphere deformation modes are defined in our kinematic model: (1) upper lithosphere pure-shear inducing passive upwelling below and (2) buoyancy induced upwelling. The pure-shear lithosphere deformation is the dominant mode and is parameterised by its width, depth and half spreading rate. The contribution of buoyancy gives additional upwelling and accelerates lithosphere thinning. Because a single lithosphere deformation mode cannot explain complex rifted margins architecture, we prescribe a sequence of lithosphere deformation events of finite duration represented by a succession of flow-fields. The evolving flow-fields are used to advect temperature and material during continental lithosphere stretching and thinning leading to rifting, breakup and seafloor spreading initiation. The kinematic flow-field evolution allows migration and lateral jumps of lithosphere and asthenosphere deformation. We use the kinematic model to show how lithosphere deformation history controls the timing of crustal separation and melt initiation. We apply the kinematic models to specific conjugate margin profiles across the Iberia–Newfoundland rifted margins.

The conjugate Iberia–Newfoundland rifted margins are an ideal natural laboratory because these are magma-poor rifted margins and are among the best studied rifted margin systems of the world. The Iberia–Newfoundland sections, located in the North Atlantic, recorded a polyphase evolution characterised by an initial rift event during the Late Triassic to Early Jurassic followed by a second rift event during Middle-Late Jurassic, before the localisation of the deformation during the early Cretaceous (145–130 Ma), which led to lithospheric breakup at the Aptian–Albian boundary (112 Ma) (Tucholke and Sibuet, 2007; Tucholke et al., 2007; Bronner et al., 2011; Sutra et al., 2013). Two pairs of conjugate margins are modelled in this work; one across the Galicia Bank-Flemish Cap and the other one across the southern Iberia Abyssal Plain–Flemish Pass (Fig. 1).

Our modelling of the Iberia–Newfoundland conjugate rifted margins uses 2 forms of calibration:

(1). ***Present day rifted margin crustal thickness and water-loaded subsidence:*** The model predictions of the conjugate rifted margin crustal architecture must fit the observed present-day water-loaded subsidence and crustal thickness, which are obtained from flexural backstripping and gravity inversion respectively.

(2). ***The evolution of crustal separation, melt initiation and subsidence:*** The timing of mantle exhumation, melt initiation and the subsidence history, deduced from existing datasets, are used to constrain the lithosphere deformation modes during rifting.

We examine and discuss the development of rifting for both conjugate margin pairs of Iberia–Newfoundland and explore whether they are synchronous or diachronous. The study also investigates how mantle exhumation may persist in time without decompression melting forming an oceanic crust.

2. Model formulation

This section presents the formulation of the kinematic model that has been developed to deform lithosphere and asthenosphere during continental rifting leading to lithospheric breakup and seafloor spreading. Kinematic modelling using a single deformation flow-field is not able to describe the complex evolution of deformation processes and the resulting architecture observed at magma-poor rifted margins. While Fletcher et al. (2009) explored two lithosphere deformation mode end-members, pure-shear and upwelling divergent flow, we use a sequence of deformation modes so that lithosphere and asthenosphere deformation can evolve kinematically. The evolution of rifted margins derived from observations and interpretations at magma-poor rifted margins (Péron-Pinvidic and Manatschal, 2009) or based on numerical modelling (Lavier and Manatschal, 2006; Huismans and Beaumont, 2011) favour the idea of an evolving lithospheric deformation process from intra-continental rifting leading to mantle exhumation, lithospheric breakup and seafloor spreading.

2.1. How does the lithosphere deform?

Our lithosphere deformation model assumes that the dominant deformation mechanism of the cooler brittle upper lithosphere is extensional faulting. Similar extensional faulting processes in the cool brittle 15–20 km upper lithosphere, with ductile distributed deformation in the lithosphere below, have been proposed for continental rifting (Jackson, 1987) and at slow-spreading ocean ridges (Cannat et al., 2009). However, the width within which extension faults occur are different for these tectonic settings; extensional faulting may be distributed over a wide region (≤ 100 km) during continental rifting (Brun and Choukroune, 1983) but is focused within a narrow region of about 10–20 km at slow and ultraslow spreading ocean ridges (Wilson, 1989; Cannat et al., 2009). As a consequence, we envisage a similar mode of upper lithosphere deformation for continental rifting, breakup and magma-poor sea-floor spreading but with an evolving extensional deformation width.

2.2. Generation of flow-fields

The flow-fields that are used to advect lithosphere and asthenosphere temperature and material are generated by a finite-element viscous flow model which uses a 6 noded triangular element grid. We calculate two distinct component types of flow-field; (1) a pure-shear mode inducing passive upwelling below and (2) an additional active upwelling due to buoyancy. The finite-element viscous flow solution generates flow-fields using a layered Newtonian viscosity structure which is shown in Fig. 2. The brittle upper lithosphere is set to 20 km thick with a high viscosity of 10^{23} Pa s outside the region of prescribed pure-shear extension. Within the pure-shear region of a width W, which approximates the brittle upper lithosphere deforming by normal faulting, a low viscosity of 10^{20} Pa s is set for the upper 20 km lithosphere. The width W can be varied from broad to narrow. Beneath the top-most brittle upper lithosphere, between 20 and 100 km depth, the viscosity is set to 10^{21} Pa s. Below this level, between 100 and 660 km, the viscosity is set at 10^{20} Pa s, and below 660 km for the remaining mantle it is set to 10^{22} Pa s.

2.2.1. Pure-shear + passive upwelling

Pure-shear is often used to describe the deformation mode occurring during intra-continental rifting (McKenzie, 1978). In our model pure-