Earth and Planetary Science Letters 407 (2014) 148–162

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Rifted continental margins: The case for depth-dependent extension

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ARTICLE INFO

Article history:
Received 25 June 2014
Received in revised form 17 September 2014
Accepted 19 September 2014
Available online 13 October 2014
Editor: P. Shearer

Keywords:
rifted passive margins
geodynamics
basin evolution
forward modelling

ABSTRACT

Even though many basic properties of non-volcanic rifted margins are predicted by uniform extension of the lithosphere, uniform extension fails to explain other important characteristics. Particularly significant discrepancies are observed at: 1) the Iberia–Newfoundland conjugate margins (Type I), where large tracts of continental mantle lithosphere are exposed at the seafloor, and at 2) ultra-wide central South Atlantic margins (Type II) where continental crust spans wide regions below which it appears that lower crust and mantle lithosphere were removed. Neither corresponds to uniform extension in which crust and mantle thin by the same factor. Instead, either the crust or mantle lithosphere has been preferentially removed during extension. We show that the Type I and II styles are respectively reproduced by dynamical numerical lithospheric stretching models (Models I-A/C and II-A/C) that undergo depth-dependent extension. In this notation A and C imply underplating of the rift zone during rifting by asthenosphere and lower cratonic lithosphere, respectively. We also present results for models with a weak upper crust and strong lower crust, Models III-A/C, to show that lower crust can also be removed from beneath the rift zone by horizontal advection with the mantle lithosphere. From the model results we infer that these Type I, II, and III margin styles are controlled by the strength of the mid/lower crust, which determines the amount of decoupling between upper and lower lithosphere during extension and the excision of crust or mantle. We also predict the styles of sedimentary basins that form on these margins as a test of the concepts presented.

1. Introduction

Thirty-five years ago Dan McKenzie (1978) introduced the now widely accepted lithospheric stretching model for the formation and evolution of extensional basins and rifted continental margins. His uniform extension (UE) (pure shear) kinematic model explains many of their basic properties. However, as observations have improved in recent years it now appears that uniform extension fails to explain other important characteristics, leading to the present situation where we strongly suspect UE is too simple (Fraser et al., 2007). McKenzie's model assumes that the lithosphere undergoes UE, i.e. extension that is uniform with depth but varies laterally. It, like the corresponding derivative models, including depth-dependent extension (Royden and Keen, 1980; Kusznir and Karner, 2007), simple shear (Wernicke, 1981, 1985), detachment (Lister et al., 1986, 1991) and other compound models (Wernicke, 2009; Huismans and Beaumont, 2002, 2003) do not provide insight into the mechanics because they are kinematic descriptions. We don't even know when UE is favored. From a mechanical viewpoint this leaves us with the knowledge that UE is a quite good first approximation, and that other modes can be expected, e.g. Buck's (1991) analysis and general classification of narrow, wide and core complex rift modes. However, we have no overarching quantitative general model for styles of lithospheric extension, as is evidenced by the recent review by Cloetingh et al. (2013), particularly when the lithosphere acts as a laminate with horizontal decoupling and shear among the layers. Analytical and numerical models that address this decoupled system do, however, suggest it leads to depth-dependent extension (e.g. Zuber et al., 1986; Huismans and Beaumont, 2003, 2008; Nagel and Buck, 2007; Weinberg et al., 2007; Kusznir and Karner, 2007).

Despite the lack of an overarching general understanding we can identify end-member situations that deviate from UE the most. Particularly significant discrepancies are observed at: 1) the Iberia–Newfoundland conjugate margins (which we call Type I), where the continental crust thins across a narrow region and large tracts of continental mantle lithosphere are exposed at the seafloor (Dean et al., 2000; Whitmarsh et al., 2001; Funck et al., 2003; Péron-Pinvidic et al., 2013; Sibuet and Tucholke, 2013), and at 2) ultra-wide central South Atlantic margins (which we call Type II) where thin, 'hyperextended', continental crust spans

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http://dx.doi.org/10.1016/j.epsl.2014.09.032

wide regions below which it appears that continental mantle lithosphere was removed (Meyers et al., 1996; Rosendahl et al., 2005; Contrucci et al., 2004; Moulin et al., 2005; Huismans and Beaumont, 2008; Aslanian et al., 2009; Sibuet and Tucholke, 2013). Neither of these styles corresponds to uniform extension in which crust and mantle thin equally. Instead, either the crust or mantle lithosphere has been preferentially removed.

In this paper we amplify our previous research that uses numerical models of continental lithospheric stretching to investigate the properties that lead to Type I and Type II styles of extension, and by inference, their natural equivalents. This approach was used by Huismans and Beaumont (2008) and the Type I and Type II styles were explicitly introduced in Huismans and Beaumont (2011). We also demonstrate an additional depth-dependent mechanism, lower lithosphere counterflow, to explain exposure of large regions of continental mantle lithosphere in the outer region of a margin, as noted above. In this concept buoyant lower continental lithosphere flows laterally and underplates the rift axis ahead of the upwelling asthenosphere as was demonstrated by Huismans and Beaumont (2011) and Beaumont and Ings (2012).

We present the case that the contrasting characteristics described above are a consequence of depth-dependent lithospheric extension (Kusznir and Karner, 2007), and that the Type I and Type II margin styles represent end members (Contrucci et al., 2004; Moulin et al., 2005; Huismans and Beaumont, 2008; Aslanian et al., 2009; Sibuet and Tucholke, 2013; Péron-Pinvidic and Manatschal, 2009; Péron-Pinvidic et al., 2013). We build on the brief, partial set of results (Huismans and Beaumont, 2011) and use a complete set of consistent models to illustrate our hypothesis that these styles are a direct consequence of the properties of the mid/lower crust, which determines the amount and level of decoupling, and style of excision between upper and lower lithosphere during extension. We first list the characteristics of Type I and Type II margins. Models I demonstrate that strong coupling between rheological layers reproduces the Type I style of the Iberia–Newfoundland system. Models II, which have weak crustal layers that allow decoupling during extension, reproduce characteristics of Type II margins. Models III, which we introduce here, have a weak mid-crust but strong lower crust. They also decouple, but within the mid-crust, and demonstrate a contrasting mechanism for removing lower crust from beneath the rift. We lack a clear example of the corresponding natural Type III margin.

For each of the Model I–III types we also consider the role of asthenospheric upwelling beneath the rift axis (A models) versus cratonic underplating by lower lithosphere counterflow (C models). Lastly, we describe the characteristics of sedimentary basins that form on Model I–III margins and propose these as templates to be used as direct tests of the concepts presented.

2. Characteristics of the Type I and Type II rifted margins

The defining characteristics of Type I non-volcanic margins (e.g., Iberia–Newfoundland, Péron-Pinvidic and Manatschal, 2009; Van Avendonk et al., 2009; Sibuet and Tucholke, 2013; Sutra et al., 2013) and Labrador–Southern Greenland (Keen et al., 1994, 2012; Chian et al., 1995; Louden and Chian, 1999) conjugate margins (Fig. 1a) are listed below in order of their development. Following distributed deformation (Huismans and Beaumont, 2007), which may lead to the formation of offset rift basins (Beaumont and Ings, 2012; Chenin and Beaumont, 2013), extension becomes focused in one region and is characterized as follows (Fig. 1a, 1–7): 1) development of major basin forming faults/shears that penetrate into the crust possibly rooting in the lower crust; 2) formation of narrow transitional regions (<100 km wide) where the continental crust thins abruptly; 3) a clearly asymmetric geometry in some cases and uplift of rift flanks; 4) breakup of the crust before breakup of the mantle lithosphere; 5) exhumation and exposure, or near exposure, of serpentinized continental mantle lithosphere in the transition between continental and oceanic crust (OCT); 6) relatively little surface magmatism during rifting; 7) oceanic crust that is initially thin, and late stage establishment of a magmatic ocean spreading centre. Examples from the Newfoundland–Iberia conjugate margins (Figs. 1b–d) illustrate these Type I characteristics. The focus is on the central rift and not the offset rift basins. Some of these characteristics are still debated (see Sibuet and Tucholke, 2013 for a recent review). For example, Jagoutz et al. (2007) present the case for magma-starved embryonic oceanic crust which would be thin, and Van Avendonk et al. (2006) and Hopper et al. (2007) interpret seismic data to support this thin oceanic crust. However, in a recent reanalysis Minshull et al. (2014) interpret it to be normal thickness.

In contrast, Type II margins (e.g. some wide margins in the central South Atlantic (Contrucci et al., 2004; Moulin et al., 2005; Huismans and Beaumont, 2008; Aslanian et al., 2009; Sibuet and Tucholke, 2013; Péron-Pinvidic et al., 2013; Kumar et al., 2013), and the Exmouth plateau (Kusznir and Karner, 2007) (Fig. 1e, A–I), are characterized by: A) ultra-wide (>350 km) regions of very thin continental crust, with little evidence for a lower crustal layer; B) faulted early syn-rift sedimentary basins; C) undeformed late syn-rift sediments (but also including salt deformed by gravitational flow in some instances); D) sediments deposited under demonstrated shallow marine or lacustrine-fluvial conditions in syn-rift 'sag' basins, leading to the inference; E) that continental mantle lithosphere has been replaced by hot asthenosphere beneath large regions of the margin; F) lack of mechanical flexural flank uplifts of the crust; G) no clear evidence of exposed exhumed mantle lithosphere; H) limited magmatism during rifting, with lower crustal seismic layers with velocities consistent with magmatic underplating, and seaward dipping reflectors in some cases, and; I) a mature magmatic mid-oceanic ridge established system soon after crustal breakup and normal thickness oceanic crust. These properties are illustrated (Fig. 1f) for two South Atlantic margins. Some of the characteristics are also observed in the Basin and Range (Fig. 1g) (Jones et al., 1992, Fig. 6; Wernicke, 2009), which we consider as an early stage underdeveloped analogue of rifted margins where lower crust has yet to be removed. To be clear, some Type II African and South American margins are elevated but this is interpreted to result from regional mantle induced dynamical uplift, magmatic underplating, or other mechanisms, for example compression (e.g. Japsen et al., 2012), that do not have the short wavelength lithospheric flexural characteristics observed at Type I margins.

A particular characteristic of Type II margins is the absence of seismically identified lower crust beneath much of the margin (Figs. 1e, f) (Karner et al., 2003; Sibuet and Tucholke, 2013), or that it is highly attenuated. An example is the Angola margin where the Moulin et al. (2005) crustal velocity model shows only extremely thin (∼1 km thick) regions where the seismic velocity exceeds 6.7 km/s, which would commonly be interpreted as characteristic of lower crust. Assuming lower crust was present before rifting started, there is a need to understand what has happened to this layer. Aslanian and Moulin (2013) have followed Karner et al. (1997, 2003) in drawing attention to this problem, specifically in the context of 'balancing' the crustal cross sectional area of the margins. It appears that the final upper crust contains added 'allochthonous crust', which was not part of the original mid/upper crust. One mechanism that removes lower crust and creates 'allochthonous crust' is formation of metamorphic core complexes, as in the Basin and Range (Fig. 1g). We suggest below that structures analogous to those in the Basin and Range may be present in Type II margins. In addition, ductile lower continental crust may flow to the distal regions of the margin during rifting