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Structural style of formation of passive margins, insights from dynamical modelling

R. S. HUISMANS[1*] AND C. BEAUMONT[2]

[1]*Dep. Earth Science, Bergen University, Bergen, Norway.*

[2]*Dep. Oceanography, Dalhousie University, Halifax, Canada.*

[*]*e-mail: Ritske.Huismans@geo.uib.no*

Abstract: We use thermo-mechanical finite element model experiments to investigate factors that are potentially important controls during volcanic and non-volcanic passive margin formation which may explain these characteristic differences. Our focus is on processes that create shear zones, on the rheological stratification of the lithosphere, and on processes that lead to differential thinning of upper and lower lithosphere during rifting. Dynamic modelling cases are compared where the crust is strong, weak, or very weak, and the mantle lithosphere is either strong or weak. Strain softening takes the form of a reduction in the internal angle of friction with increasing strain. Predicted rift modes belong to three fundamental types: 1) narrow, asymmetric rifting in which the geometry of both the upper and lower lithosphere is approximately asymmetric; 2) narrow, asymmetric, upper lithosphere rifting concomitant with narrow, symmetric, lower lithosphere extension; and 3) wide, symmetric, crustal rifting concomitant with narrow, mantle lithosphere extension.

Keywords: modelling, lithosphere extension, rifting, strain localization.

A large number of studies of continental rifts and rifted continental margins have produced high quality data (Keen *et al.*, 1987a, b; Keen and de Voogd, 1989; Mutter *et al.*, 1989; Boillot *et al.*, 1992; Sibuet, 1992; Brun and Beslier, 1996; Louden and Chian, 1999; Dean *et al.*, 2000; Funck *et al.*, 2003; Hopper *et al.*, 2004; Funck *et al.*, 2004) that reveal a wide range of styles which both include wide and narrow rifts, and non-volcanic and volcanic passive margins. A unified understanding of the mechanical and thermal processes that control their extensional geometry is, however, still lacking.

Kinematic and dynamic models have been developed to provide kinematic end-member templates and insight into the dynamic processes associated with these range of styles. The kinematic templates, pure shear (McKenzie, 1978), simple shear (Wernicke and Burchfield, 1982; Wernicke, 1985) and combinations of these styles (Lister *et al.*, 1986), referred to here as compound models, were primarily used in interpretations that ascribed symmetry or asymmetry to the large scale rift geometry. Dynamical modelling studies (Buck, 1991; Bassi *et al.*, 1993; Buck *et al.*, 1999), on the other hand, proposed a number of alternative explanations for the occurrence of narrow, wide, and core-complex modes of extension.

The modes can be defined based on the general geometry of the crust and mantle lithosphere during extension. 1) core complex mode, where upper crustal extension is concentrated in a local area concomitant with lower crustal thinning over a wide area; 2) wide rift mode, with uniform crustal and mantle lithosphere thinning over a width greater than the lithospheric thickness; and 3) narrow rift mode, with crust and mantle lithosphere thinning over a narrow area. Narrow rifting is attributed to local weakening factors such as thermal thinning of the lithosphere, local strain weakening of the strong layers in the system, or local magmatism (Buck, 1991; Buck *et al.*, 1999) to be important, where extension is always localized in the weakest and thinnest area. Three explanations have been provided for wide rifts: 1) a local increase of the integrated strength resulting from replacement of crustal material by stronger mantle lithospheric material and concomitant cooling during lithosphere extension causing extension to migrate to un-thinned weaker areas of lithosphere resulting in a wide rift mode (England, 1983; Houseman and England, 1986); 2) flow of weak lower crust to areas of thinned crust in response to pressure gradients related to surface topography that result in delocalization of deformation (Buck, 1991; Buck *et al.*, 1999); and 3) the degree of brittle-ductile coupling in systems containing a frictional layer bonded to a viscous layer, where the occurrence of localized or distributed, pure shear modes depends on the coupling between the layers and the lower layer viscosity (Huismans *et al.*, 2005). Core complex modes of extension are understood to result when rapid lower crustal flow removes the crustal thickness variations required for mechanisms that would results in a wide rift zone (Buck, 1991).

Upper mantle scale, plane strain viscous-plastic finite element models are used to explore the consequences of a range of initial mechanical conditions on the predicted style of deformation. First-order variation of the thermo-mechanical structure of the lithosphere is accomplished by simple scaling of the viscous properties of the crust and mantle lithosphere. This allows us to represent a range of conditions that occur in natural systems, ranging from cold cratonic, through intermediate Phanerozoic, to very weak continental crusts. Rift styles are found to depend on the integrated strength of the model lithosphere, and on the propensity of sub-horizontal shear zones to form in the crust, thereby decoupling different levels of the models. The extensional deformation of the multilayer system results in distinct crustal and lithospheric thinning patterns and the associated basin architecture and heat flow characteristics.

Thermo-mechanical numerical model

We use an Arbitrary Lagrangian-Eulerian (ALE) finite element method for the solution of thermo-mechanically coupled, plane-strain, incompressible viscous-plastic creeping flows (Fullsack, 1995; Willett, 1999; Huismans and Beaumont, 2003) to investigate extension of a layered lithosphere with frictional-plastic and thermally activated power-law viscous rheologies (Fig. 1).

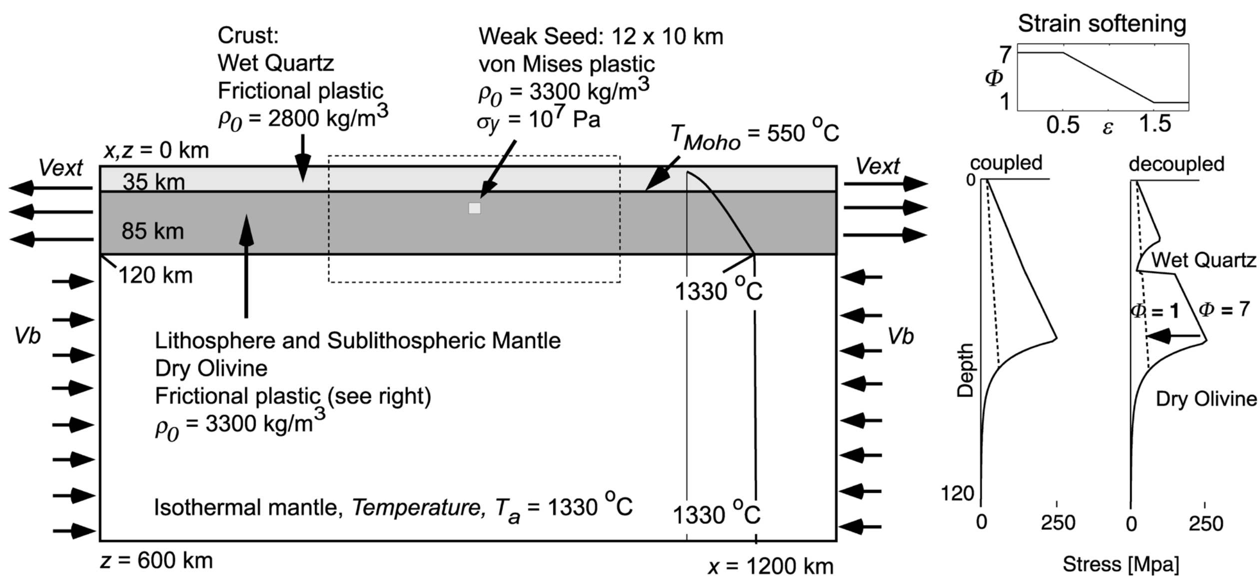

Figure 1. Model geometry showing crust and mantle lithosphere layer thicknesses, their corresponding properties, and the velocity boundary conditions, V, with Vb chosen to achieve a mass balance. Extension is driven by velocity boundary conditions and seeded by a small plastic weak region ("weak seed"). The model has a free top surface and the other boundaries have zero tangential stress (free slip). Whether materials deform plastically or viscously depends on the ambient conditions. At yield, flow is plastic. Below yield, deformation is viscous.

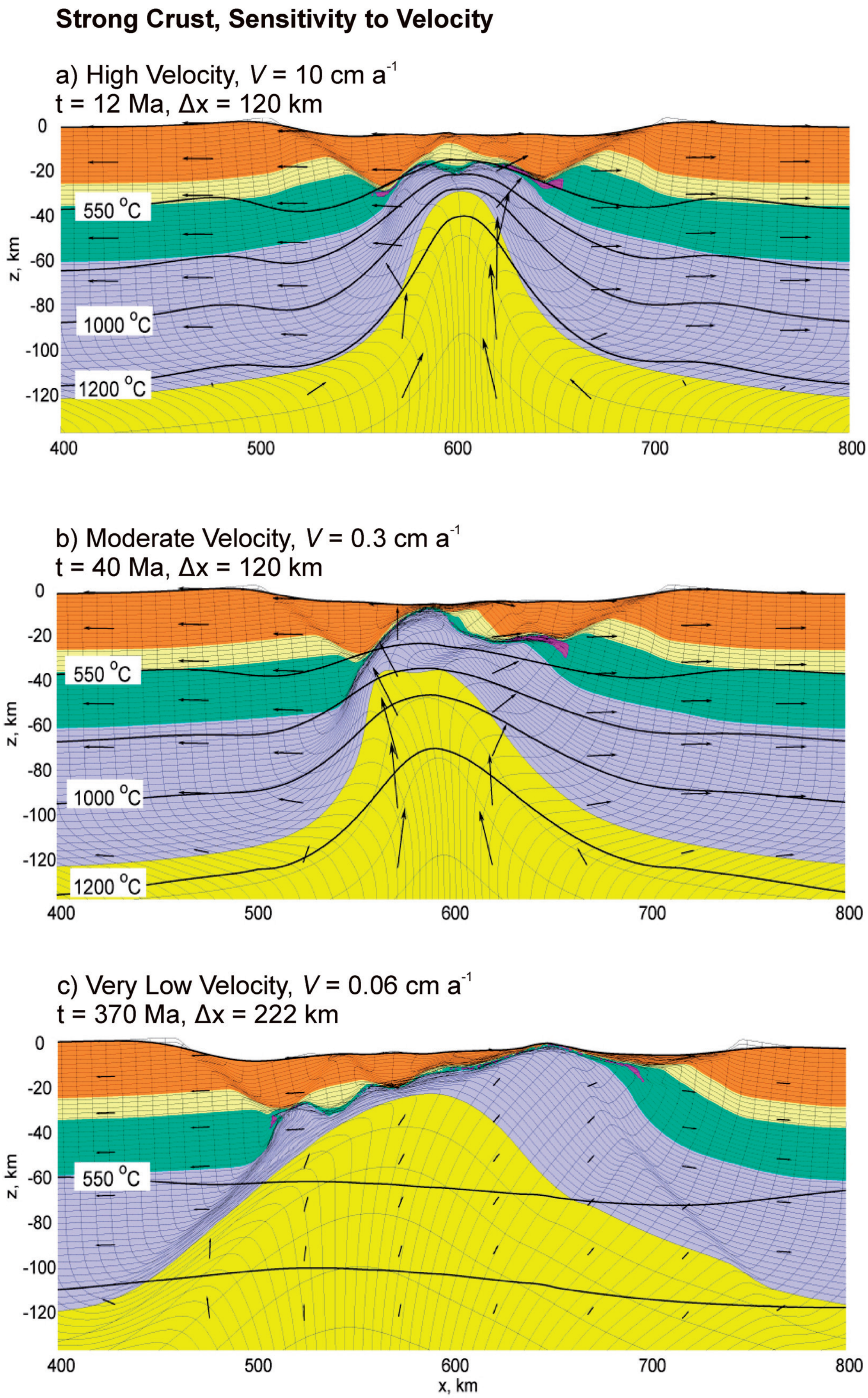

Figure 2. Rift mode sensitivity to extension velocity. Strong lower crust models with frictional plastic strain softening, showing deformed Lagrangian mesh, velocity vectors and sample isotherms, for dashed area in figure 1. Model layers from top down denote upper and lower crust, strong frictional upper mantle lithosphere, ductile lower lithosphere and ductile sub-lithospheric mantle.

When the state of stress is below the frictional-plastic yield the flow is viscous and is specified by temperature-dependent non-linear power law rheologies based on laboratory measurements on 'wet' quartzite (Gleason and Tullis, 1995) and 'dry' olivine (Karato and Wu, 1993). The frictional-plastic deformation is modelled with a pressure-dependent Drucker-Prager yield criterion which is equivalent to the Coulomb yield criterion for incompressible deformation in plane-strain. In addition to solving the equilibrium equations for viscous plastic flows, we also solve for the thermal evolution of the model in two dimensions. The mechanical and thermal systems are coupled though the temperature dependence of viscosity and density are solved alternately during each time step. Initial conditions and other thermal properties are given in figure 1. The initial thermal state represents reference continental lithosphere conditions with a surface heat flow of 45 mW m^{-2}, a temperature of 550 °C at the Moho at 35 km, and a temperature of 1330 °C at the base of the lithosphere which is of reference thickness of 120 km (Fig. 1). In the models presented here the thermal conditions are not varied. However, the variation of crust and mantle strength could equivalently have been obtained by varying the thermal structure of crust and mantle lithosphere, and may be taken to represent a range of thermal conditions.

Thermo-mechanical models of lithosphere extension

We present an overview of a more comprehensive set of models from Huismans and Beaumont (2002, 2003, 2007, 2008) and Huismans *et al.* (2005). The models selected here have frictional-plastic strain softening and deformation is nucleated by deterministic noise in the form of a single weak seed (Fig. 1). Most of the results can be classified as narrow rifts as defined by Buck (1991). We review the sensitivity of deformation style to the extension velocity and the strength of the middle and lower crust.

Sensitivity of model results to rifting velocity

In order to demonstrate that rifting velocity is an important control on the extension mode we show results for a reference velocity of 0.3 cm a^{-1} and for end member variations of velocity of 0.06 cm a^{-1} and 10 cm a^{-1} (Fig. 2). The models have strong middle and lower crusts and include strain softening of the frictional plastic rheology.

At the reference velocity (Fig. 2b), strain softening in the frictional plastic parts of the lithosphere results in strong localization in a single system of 'faults', resulting in an asymmetric mode of extension. Middle and lower crust has been cut out and mantle lithosphere has been exhumed by large scale frictional detachment. The proto-margins show distinct differences resembling an upper and lower plate conjugate margin pair. The main cause of asymmetry in the model is the frictional plastic strain softening. After an initial phase of symmetric extension, feedback of strain softening results in preferential weakening of one of the two conjugate shears. The single weak shear zone remains the weakest part in the system and results in lithosphere scale asymmetry. During later stages, thermal advection results in a viscous necking style and final break up phase is symmetric. However, asymmetry remains from the initial stages of the model evolution.

At high rifting velocities (Fig. 2a) the style of extension is markedly different. The proto-margins are essentially symmetric. We have interpreted (Huismans and Beaumont, 2002, 2003) this model behavior in terms of the increased role of viscous rheologies in the system and a stronger viscous coupling, where higher strain rates equate to higher viscous stresses at the base of the frictional layer. The viscous layer promotes a distributed, symmetric style of extension and the tendency for localization and asymmetry given by the frictional plastic strain softening is suppressed.

The effect of an end-member low value for the extension velocity, V = 0.06 cm a^{-1}, is illustrated in figure 2c. The model is strongly asymmetric throughout its evolution. At this velocity thermal conduction is more efficient than thermal advection. Consequently frictional strain softening results in the localization of deformation along one major weak shear zone. As the thermal evolution in the model lithosphere is at the conductive limit (e.g. $Pe<<1$), the frictional weak shear zone remains the single major weakness in the lithospheric system which allows for ongoing asymmetric extension.

Sensitivity of model results to strength of the lower crust

We examine the sensitivity of the model behavior to the strength of the lower crust. The viscous creep strength of the middle and the lower crust is varied as wet quartz viscous flow viscosities ×100 (Fig. 3c), through nominal wet quartz viscosities (Fig. 3b), to wet quartz viscosities /10 (Fig. 3a). In these models the mantle has a dry olivine power law rheology. The strong crust case is the same as shown in figure 2b.

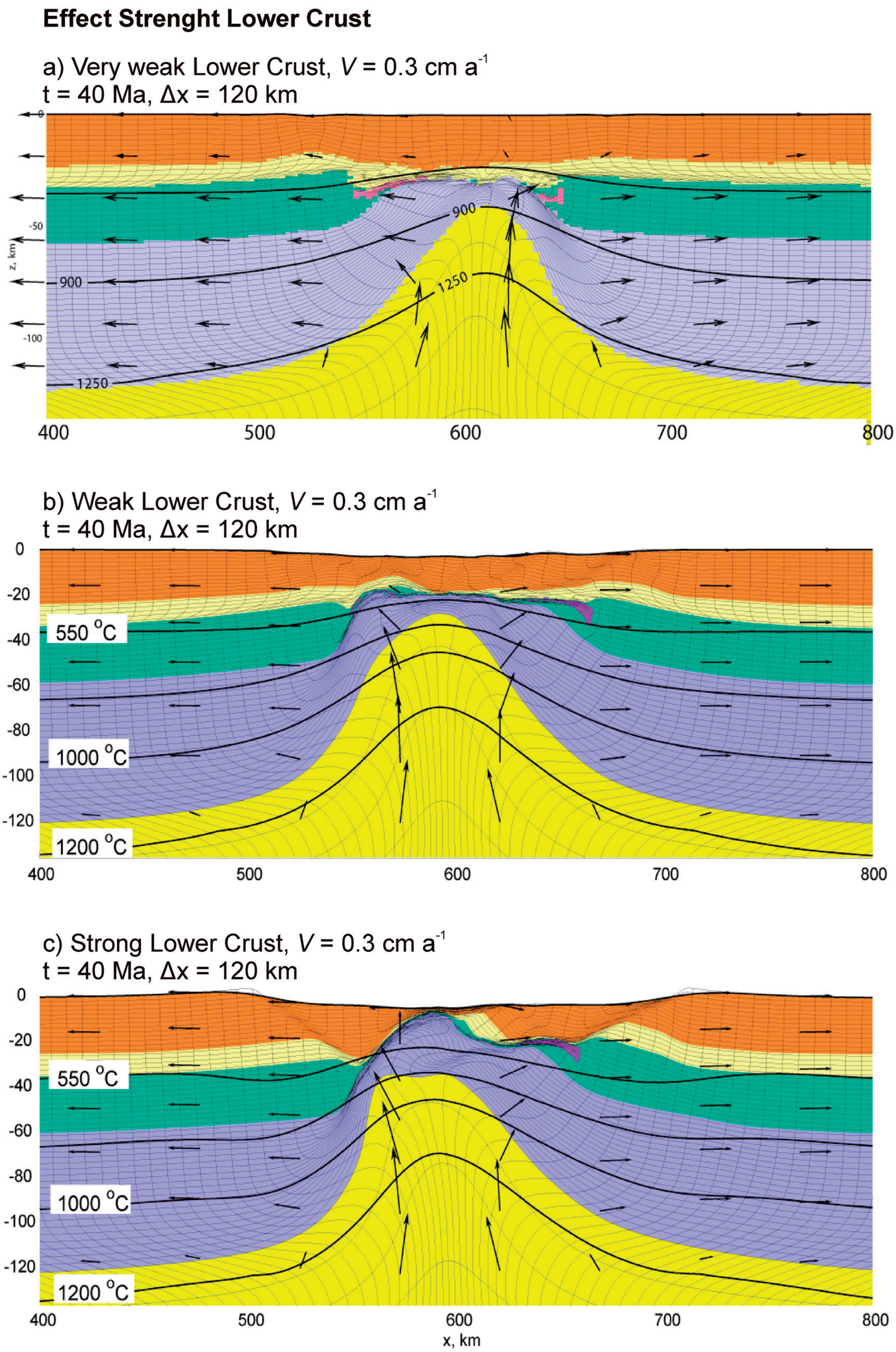

Figure 3. Rift mode sensitivity to strength of the middle and lower crust. a) Very weak lower crust model, with η (wet quartz/10) at t = 40 Ma and 120 km of extension. Note very wide crustal rifting concomitant with narrow mantle lithosphere necking, b) weak lower crust model at t = 40 Ma and 120 km of extension with (wet quartz). Note asymmetric crustal necking and symmetric lithospheric mantle necking, c) asymmetric strong middle to lower crust model at reference velocity at t = 40 Ma and 120 km of extension is given for reference (same as in figure 2b).

For moderate weak lower crust (Fig. 3b, nominal wet quartz viscosity) the crustal asymmetry is diminished by comparison with the strong crust model because the conjugate frictional shears sole out in the weak ductile lower crust. Extension of the lower lithosphere remains asymmetric with deformation focused on one shear zone. Later, sets of synthetic crustal shear zones form on either side of the central rift zone, thereby creating blocks bounded by frictional shear zones that sole out in the viscous lower crust and that propagate outward beneath the rift flanks. During the later stages of deformation, the lower mantle lithosphere undergoes nearly symmetric ductile necking. The weak lower crust results in much reduced rift flank topography and slightly wider basin geometry compared to the strong crust model.

When the strength of the crust is further reduced by scaling the wet quartz flow law to $\eta = \eta_{\text{wet quartz}}/10$ deformation in upper crust is essentially decoupled from that of the mantle lithosphere over a broad region. During the initial stages (Fig. 3a), deformation in the mantle lithosphere remains asymmetric. This asymmetry is no longer transferred to the upper crust but is absorbed and lost in the deformation of the very weak lower crust and the upper crust extends in a distributed wide rift mode. At later stages, the major differences between the thinning distributions of the upper crust and the mantle lithosphere results in complete removal of the mantle lithosphere from beneath the center of the system in contrast to moderate distributed thinning of the middle and upper crust. The base of the crust is exposed to the sub-lithospheric mantle in the center of the rift zone. Crustal extension is accommodated by large 50-70 km wide blocks of moderately thinned crust bounded by nascent sets of frictional shears that appear in the viscous lower crust. During the final stages of breakup (not shown here) continued attenuation and removal of low viscosity, lower crust results in progressively stronger coupling between the crust and the mantle lithosphere which facilitates ultimate localized thinning and breakup of the crust.

Conclusions

Here we have focused on models of extensional processes with application to lithospheric extension during rifting and the formation of rifted continental margins. Even though rifts and rifted margins have been studied intensively for more than thirty years, a fundamental understanding of the factors that control the extensional process, the distribution of extension and the associated rift and rift margin geometry is still lacking. The purpose of the model studies reported here and in associated articles (Huismans and Beaumont, 2002, 2003; Huismans *et al.*, 2005; Buiter *et al.*, 2008) is to test a limited range of conceptual models that combine distributed viscous-plastic flows with feedback mechanisms, specifically plastic strain-softening, that lead to localized deformation. This localization allows the models to represent faults and shear zones approximately.

Here we have demonstrated a strong sensitivity of rift mode to both extension velocity and rheological stratification of the lithosphere. Predicted rift modes belong to three fundamental types: i) narrow, asymmetric rifting in which the geometry of both upper and lower lithosphere is approximately asymmetric, ii) narrow asymmetric upper lithosphere rifting concomitant with narrow symmetric lower lithosphere extension, and iii) wide symmetric crustal rifting concomitant with narrow mantle lithosphere extension. If natural lithosphere behaves in the same manner as the model lithosphere some general predictions can be made concerning non-volcanic rifts and rifted margins. Rifting of strong, cold cratonic lithosphere with a frictional-plastic upper lithosphere will adopt the narrow rift mode, with deep syn-rift basins and high amplitude flank uplifts. These systems will likely have an asymmetric crust and uppermost mantle architecture. At the opposite extreme, rifting of lithosphere in which the viscous mid/lower crust is very weak and the uppermost mantle is frictional-plastic will adopt the wide rift mode. Crustal extension occurs over a wide region and produces symmetric wide shallow syn-rift basins without significant flank uplifts. Intermediate modes, including the narrow rift mode that couples asymmetric crustal extension with symmetric mantle lithosphere extension, occur for intermediate viscosities of the mid/lower crust.

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