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Modes of continental extension in a crustal wedge

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ABSTRACT

We ran numerical experiments of the extension of a crustal wedge as an approximation to extension in an orogenic belt or a continental margin. We study the effects of the strength of the lower crust and of a weak mid-crustal shear zone on the resulting extension styles. A weak mid-crustal shear zone effectively decouples upper crustal extension from lower crustal flow. Without the mid-crustal shear zone, the degree of coupling between the upper and the lower crust increases and extension of the whole crust tends to focus on the thickest part of the wedge. We identify three distinct modes of extension determined by the strength of the lower crust, which are characterized by 1) localized, asymmetric crustal exhumation in a single massif when the lower crust is weak, 2) the formation of rolling-hinge normal faults and the exhumation of lower crust in multiple core complexes with an intermediate strength lower crust, and 3) distributed domino faulting over the weak mid-crustal shear zone when the lower crust is strong. A frictionally stronger mid-crustal shear zone does not change the overall model behaviors but extension occurred over multiple rolling-hinges. The 3 modes of extension share characteristics similar to geological models proposed to explain the formation of metamorphic core complexes: 1) the crustal flow model for the weak lower crust, 2) the rolling-hinge and crustal flow models when the lower crust is intermediate and 3) the flexural uplift model when the lower crust is strong. Finally we show that the intensity of decoupling between the far field extension and lower crustal flow driven by the regional pressure gradient in the wedge control the overall style of extension in the models.

1. Introduction

The yield strength of the continental lithosphere is primarily constrained by the thermal structure and rheological composition of the lithosphere and is often represented as a yield stress envelope (YSE) (e.g., Burov and Diament, 1995). In extension, its yield strength is such that only when weakened by heating or magmatic processes, a continental lithosphere can breakup (e.g., Buck, 1991; Buck et al., 2005, 2009). For example, Buck (1991) showed that a hot, and therefore weak, orogenic lithosphere with a thick crust is weak enough to stretch in the "wide rift" or "core complex" mode. Some of the best examples of such extensional environments are the Basin and Range province in the western US, Papua New Guinea, and the Aegean.

Several intriguing observations have further driven the search for a more detailed mechanical model for the formation of a rift basin in similarly hot lithosphere including: 1) the lack of variations in crustal thickness over large wavelength, 2) the exhumation of lower crust in metamorphic core complexes (MCCs) and 3) the formation of large-offset low-angle normal fault. The first observation is a key characteristic of the extension of hot lithosphere. Hot ductile lower crust flows to smooth out variations in crustal thickness caused by differential extension (Block and Royden, 1990; McKenzie et al., 2000). Likewise, the topographic gradient in a differentially thickened crust can also drive the flow of ductile lower crust (Braun and Beaumont, 1989; Kruse et al., 1991; Bird, 1991). Several mechanisms were proposed to explain the remaining characteristic observations, i.e., the exhumation of middle crust along shallow-dipping mylonitic shear zone and brittle normal faults (e.g., Gans, 1987; Wernicke, 1981; Buck, 1988; Block and Royden, 1990; Melosh, 1990; McKenzie et al., 2000). The rolling-hinge model proposed that the middle crust is exhumed from large depths by an offset greater than 15 km along a high- or low-angle normal fault rooted in the middle crust (Axen, 1988; Buck, 1988). Other models (Gans, 1987; Block and Royden, 1990; McKenzie et al., 2000) proposed that lower crustal flow caused by local or regional pressure gradients drives exhumation and causes the rotation of an initially high-angle normal fault to a low

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angle. Explaining the formation of large-offset normal faults in the rolling-hinge model remains the main issue. Hypotheses include fault strength decreasing with fault offset in a thin brittle upper crust (Buck, 1988; Axen, 1988; Lavier et al., 2000) and stress rotation caused by basal shear or along a weak frictional fault interface (e.g., Yin, 1989; Melosh, 1990). Accordingly, the low dip of a large-offset normal fault can be achieved either through the rotation of a high-angle normal fault (e.g., Buck, 1988) or as a primary fault (e.g., Yin, 1989; Melosh, 1990).

However, in spite of a few exceptions (e.g., Rey et al., 2010), most numerical and theoretical studies of lithospheric extension assumed an initially uniform crustal thickness and ignore regional pressure gradients that would be caused by preexisting variations in crustal thickness. For instance, Buck (1991) showed that a localized mode of crustal extension similar to core complex extension would occur in a uniformly thick lithosphere with weak lower crust. The rolling-hinge model (Buck, 1988; Lavier et al., 1999; Choi et al., 2013) also assumed a lithosphere that initially has a uniform thickness. Following the same mechanical principles with those of the rolling-hinge model proposed by Buck (1988) (i.e., that an active high-angle normal fault is rotated into a low-angle normal fault when exhumed at the surface), sometimes with the addition of melt, numerical models of core complexes forming in a hot and uniformly thick lithosphere with a thick crust have shown that the high-angle rolling-hinge is successful at explaining some of the observations at core-complexes (e.g., Lavier and Buck, 2002; Tirel et al., 2008; Rey et al., 2009; Huet et al., 2011; Gessner et al., 2007). Although successful in explaining the low dip and geometry of normal faults observed at many MCCs, rolling-hinge models failed to explore the combined effects of regional flow due to gradients in crustal thickness (Bird, 1991) and differential stretching (Block and Royden, 1990) on the mechanics of core complex formation. Bialas et al. (2007), Rey et al. (2010), and Whitney et al. (2013) considered the effects of non-uniform crustal and lithospheric thickness but did not analyze the details of the mechanical consequences like the interaction between lower crustal flow and faulting. Huet et al. (2011) used a wedge-shaped layering of the crust without initial topography, Moho relief, or mid-crustal shear zone. In addition, they did not systematically vary the strength of the lower crust.

Another important but often-ignored possibility in lithospheric extension is that a weak mid-crustal shear zone can decouple upper crust from lower crust and mantle. The presence of such a decoupling zone is supported by the inference of the dip of subhorizontal mylonitic shear zone near the base of brittle crust using GPS measurements (Velasco et al., 2010) and by subhorizontal detachment surface detected in seismic reflection profiles such as the S reflector in the Iberia margin (Reston et al., 1996). Even in studies that considered the mechanical effect of a decoupling mid-crustal surface on rifting (e.g., Nagel and Buck, 2006; Lavier and Manatschal, 2006; Huismans and Beaumont, 2011), the crust–mantle boundary and the topography were assumed to be initially flat.

These overlooked components might have substantial influence on the dynamics of lithospheric extension. For instance, it is very likely that the interaction between regional lower crustal flow and normal faulting in a hot lithosphere can result in different extensional styles with single or multiple zones of active basins and ranges. Previous studies of extension (Buck, 1988, 1991; Lavier et al., 2000) have demonstrated that several weakening and hardening phenomena control whether extension in wide rifts stays localized on a single zone (one MCC or graben) or multiple zones (multiple MCCs or grabens) of extension. The loss of cohesion or frictional strength on a fault competes with the resistance of the brittle upper plate to bending (Lavier et al., 2000) to accommodate extension on multiple normal faults rather than on a single normal fault. Viscous strengthening in response to normal faulting at the base of the brittle upper crust can also occur if the lower crust is strong (Lavier and Buck, 2002). In that case, strengthening lead to the formation of multiple normal faults in the upper crust (Lavier and Buck, 2002). At the scale of the lithosphere, thinning of the crust and the associated mantle upwelling strengthen the lithosphere and force deformation to delocalize over multiple extensional centers (Buck, 1991). If the pressure gradient and the strength of the lower crust are such that the lower crust can flow efficiently and smooth out variations in crustal thickness (Buck, 1991) then strengthening due to mantle upwelling is suppressed and extension should continue on one given extensional center or normal fault. When the shear resistance in a high viscosity lower crust opposes flow, it cannot suppress crustal thinning efficiently and as a result mantle upwelling may occur. This mechanism increases the lithosphere's resistance to extension and causes the formation of multiple rift basins (Buck, 1991; Buck et al., 2009).

In this paper, we explore the effects of lower crustal flow driven by a regional pressure gradient on the decoupling of deformation in the lithosphere and the style of rifting that the presence or absence of decoupling generates. Specifically, we conducted numerical experiments on the extension of a two- or three-layer crust in wedge-shaped crust (Fig. 1). We also studied the effects of the composition of the lower crust and included the effect of a preexisting decoupling shear zone at the brittle ductile transition (BDT). While a two-layer division of the crust (upper and lower crust) may be sufficient for most tectonic settings, the presence of a strong gabbroic lowermost lower crust (termed mafic lower crust throughout the paper) has been inferred in some regions, such as the US Cordillera and some parts of the Variscan orogeny in Europe (McGuire, 1994; Müntener et al., 2000). That motivates us to assume a three-layer crust and analyze the effect of a strong gabbroic lower crust on extension mechanisms and styles.

2. Simple analysis of decoupling

We seek to describe the capacity of lower crustal flow driven by a pressure gradient imposed by topographic loading and mantle buoyancy, compared with that driven by far field extension applied at the side of the lithosphere. While the simple analysis presented here ignores the complex non-linear interactions between the brittle and ductile deformation, it is a useful guide to the mechanics of the lithosphere and the interpretation of our numerical models.

2.1. Definition of coupled versus decoupled deformation

Local isostasy occurs when loading or unloading on the lithosphere is counterbalanced at the same location. In contrast, regional isostasy involves the non-local effects such as elastic strength (flexure) and lateral ductile flow over a large distance. Compensation becomes local when the flexural strength of the lithosphere is small so that flexural wavelength is much smaller than the scale of loading and ductile flow is not fast enough (Watts, 2001). In the case of local compensation, brittle deformation in the upper crust is typically compensated by local mantle stretching and upwelling and the deformation appears to be coupled. When the lithosphere has a large flexural rigidity and/or ductile flow is intense, deformation in the brittle upper crust is regionally compensated. Since the regional compensation would involve vigorous lateral flow of the ductile lower crust even for a highly localized deformation of the brittle upper crust (Watts, 2001), the deformation of the upper crust and the mantle lithosphere would appear decoupled.

Here we assume that decoupling and regional compensation occur when the flow rate in the ductile lower crust is greater than