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Asymmetric vs. symmetric deep lithospheric architecture of intra-plate continental orogens

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ABSTRACT

The initiation and subsequent evolution of intra-plate orogens, resulting from continental plate interior deformation due to transmission of stresses over large distances from the active plate boundaries, is controlled by lateral and vertical strength contrasts in the lithosphere. We present lithospheric-scale analogue models combining 1) lateral strength variations in the continental lithosphere, and 2) different vertical rheological stratifications. The experimental continental lithosphere has a four-layer brittle–ductile rheological stratification. Lateral heterogeneity is implemented in all models by increased crustal strength in a central narrow block. The main investigated parameters are strain rate and strength of the lithospheric mantle, both playing an important role in crust–mantle coupling. The experiments show that the presence of a strong crustal domain is effective in localizing deformation along its boundaries. After deformation is localized, the evolution of the orogenic system is governed by the mechanical properties of the lithosphere such that the final geometry of the intra-plate mountain depends on the interplay between crust–mantle coupling and folding versus fracturing of the lithospheric mantle. Underthrusting is the main deformation mode in case of high convergence velocity and/or thick brittle mantle with a final asymmetric architecture of the deep lithosphere. In contrast, lithospheric folding is dominant in case of low convergence velocity and low strength brittle mantle, leading to the development of a symmetric lithospheric root. The presented analogue modelling results provide novel insights for 1) strain localization and 2) the development of the asymmetric architecture of the Pyrenees.

1. Introduction

Intra-plate orogens are the result of continental plate interior deformation due to transmission of stresses at large distances from active plate boundaries (Raimondo et al., 2014; Vauchez et al., 1998).

The initiation and subsequent evolution of such mountain belts strongly depend on 1) lateral strength contrasts in the lithosphere allowing for localization of deformation (Vauchez et al., 1998; Ziegler et al., 1998), and 2) the rheological structure of the lithosphere, which governs its overall geometry (Burov, 2011).

The response of the lithosphere to applied stresses is controlled by its strength and thus by composition of crust and mantle, thermal gradient, strain rate and fluids related processes (Burov, 2011). In general, low strength leads to distributed deformation and symmetry, while high strength results in localization and asymmetry (Davy and Cobbold, 1991; Gueydan et al., 2008).

Previous numerical and analogue modelling studies allowed classifying the behaviour of continental lithosphere, when subject to compressional horizontal stresses, into three main modes of deformation: 1) lithospheric folding, 2) volumetric shortening with distributed or localized thickening, 3) underthrusting, and continental subduction (Cloetingh et al., 1999; Sokoutis et al., 2005; Toussaint et al., 2004).

Lithospheric folding is considered to be a primary response to shortening (Cloetingh et al., 1999). The wavelength of folding, as well as its persistence in time, is a strong function of thermo-mechanical age of the lithosphere (Cloetingh et al., 1999; Martinod and Davy, 1992; Toussaint et al., 2004).

The occurrence of continental subduction or pure shear thickening is largely controlled by lithospheric strength. While the former mechanism dominates for stable old continents, the latter

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Table 1
Geometrical and kinematical parameters.

Experiment	Width (cm)	Length (cm)	h_{UC} (cm)	h_{LC} (cm)	h_{BUM} (cm)	h_{DUM} (cm)	Width CB (cm)	Velocity (cm/h)	Bulk shortening (cm)
1	36.0	42.0	1.0–1.3	0.5–0.2	0.5	1.3	4.0	5.0	≈8.5
2	36.0	42.0	1.0–1.3	0.5–0.2	0.5	1.3	4.0	1.0	≈8.5
3	36.0	42.0	1.0–1.3	0.5–0.2	1.0	1.3	4.0	1.0	≈8.5
4	36.0	42.0	1.0–1.3	0.5–0.2	1.0	1.3	4.0	5.0	≈8.5
5	36.0	42.0	1.0–1.3	0.5–0.2	0.5	1.3	4.0	2.0	≈8.5
6	36.0	42.0	1.0–1.3	0.5–0.2	0.8	1.3	4.0	1.0	≈8.5

The values for the thickness of Upper Crust (h_{UC}) and Lower Crust (h_{LC}) refer to the proximal/distal block (left) and central block (right); CB: central block.

is the rule for hot and young lithosphere (Cagnard et al., 2006; Davy and Cobbold, 1991; Toussaint et al., 2004).

Lithospheric folding and pure shear thickening result in symmetric structures, while continental subduction geometries are strongly asymmetric (Davy and Cobbold, 1991; Toussaint et al., 2004). The Pyrenees are a good example of the latter case, being characterized by a pronounced asymmetric architecture both at crustal and lithospheric scale (Roure et al., 1989). Our study aims to provide insights into the parameters that controlled the development of such asymmetric mountain belts.

The presence of lateral heterogeneities in the lithosphere can affect and interfere with the manner shortening is accommodated. The mechanical properties of continental lithosphere are strongly heterogeneous in space, as documented by observations and suggested by mechanical models (Burov, 2011; Cloetingh et al., 2005; Gueydan et al., 2014; Ranalli, 1997). The reactivation of lithospheric heterogeneities controlled the evolution of intra-plate orogens in Iberia (Pyrenees, Spanish Central System, Iberian Range), Australia (Petermann and Alice Spring orogens), Central America (Laramide orogen), and Central Asia (Tian Shan) (Beaumont et al., 2000; Cerca et al., 2004; Cloetingh et al., 2005; Delvaux et al., 2013; Fernández-Lozano et al., 2011; Gorczyk et al., 2013; Kennett and Iaffaldano, 2013; Raimondo et al., 2014; Sainz and Faccenna, 2001). At lithospheric scale the nature of the reactivated heterogeneities is diverse and debated. Rift basins are convenient structures for localization of intra-plate deformation due to their lower strength with respect to the surrounding lithospheric domains (Brun and Nalpas, 1996; Buiter et al., 2009; Cloetingh et al., 2008; Jammes and Huismans, 2012). On the other hand, strong microplates can also localize deformation at their margins and thus promote intra-plate orogeny (Keep, 2000).

Previous modelling studies investigated the reactivation of lithospheric scale weak zones in compression in order to study rifts inversion (Brun and Nalpas, 1996; Buiter et al., 2009; Cerca et al., 2004) or deformation of weak orogenic wedges (Gerbault and Willingshofer, 2004; Jammes and Huismans, 2012; Willingshofer et al., 2005). A more limited number of studies focused on the role of strong domains in the origin of intra-plate mountain belts (Calignano et al., 2015; Keep, 2000). Among these, Calignano et al. (2015) considered the role of a strong domain embedded within a weak lithosphere.

The aim of this study is to contribute to the understanding of deformation mechanisms of continental lithosphere in compressional intra-plate settings under various rheological conditions. To this purpose, we used lithospheric-scale analogue models where we combined 1) lateral strength variation in the continental lithosphere, and 2) diverse vertical rheological stratification. As a novelty, we focused on the role of a strong domain embedded in an overall strong lithosphere. Other main investigated parameters are strain rate and strength of the lithospheric mantle, both playing an important role in crust–mantle coupling and thus in the final asymmetry/symmetry of the orogenic system.

We discuss the results of the experiments with emphasis on the final geometry of the deep lithospheric structure and the possibility of development of intra-plate continental subduction-type geometries. In particular, the experimental results provide valuable insights on the parameters that controlled strain localization and asymmetry of the Pyrenees.

2. Experimental set-up

The initial geometric and rheological conditions adopted in this study are representative for reactivation of strength heterogeneities within the lithosphere under compression. In particular, the behaviour of a four-layer continental lithosphere under variable strain rates and with different vertical rheological stratification is investigated.

2.1. Initial geometry

Fig. 1 illustrates the set-up and geometrical configuration for the experiments described in the results section. Geometric and kinematic parameters for the experimental series are specified in Table 1.

All experiments consist of three domains with different mechanical properties: a central block where the thickness of the brittle upper crust is increased in order to simulate the presence of a stronger domain is located in between two blocks that share the same lithospheric stratification (Fig. 1). The boundaries between rheologically different domains strike perpendicular to the convergence direction. The experiments represent an area of 840 km × 720 km. The central block, with increased crustal thickness, has a width of 4 cm (80 km in nature).

As discussed above, lateral strength contrasts in the lithosphere can result from rheological and mechanical heterogeneities located at different depth. Variation in composition or thermal structure can affect the crust or the mantle or both layers. Increased crustal strength can result from the presence of 1) a dehydrated residue after melt extraction processes, 2) high-viscosity mafic lower crust or 3) low concentration of radiogenic heat-producing elements (Bürgmann and Dresen, 2008). In the present study we focus on lateral variation of bulk lithospheric strength resulting from rifting and subsequent cooling of the rift basin. If the integrated strength of a lithospheric column is considered, a strong domain can be representative for an old, cooled rift. In fact, rifting induces thinning of the lithosphere, with upward displacement of the Moho and mantle material to shallower levels with the respect to the surrounding regions (McKenzie, 1978). During the post-rift phase, the rift cools and will eventually become stronger than the unstretched continental lithosphere (Buiter et al., 2009; Cloetingh et al., 2008; Leroy et al., 2008). Thus, the creation and thermal relaxation of a continental rift is an important process leading to lateral strength contrasts in the continental lithosphere (Vauchez et al., 1998). We simulate a strong cold/old rift by lateral variation of brittle crustal thickness. In particular, a narrow block characterized by increased crustal strength (deeper brittle/ductile transition), serves as analogue for the presence of a strong rift. This geometry serves to create a localized increase in bulk lithospheric strength, even if it