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Lithospheric-scale centrifuge models of pull-apart basins

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ABSTRACT

We present here the results of the first lithospheric-scale centrifuge models of pull-apart basins. The experiments simulate relative displacement of two lithospheric blocks along two offset master faults, with the presence of a weak zone in the offset area localising deformation during strike–slip displacement. Reproducing the entire lithosphere–asthenosphere system provides boundary conditions that are more realistic than the horizontal detachment in traditional 1 *g* experiments and thus provide a better approximation of the dynamic evolution of natural pull-apart basins. Model results show that local extension in the pull-apart basins is accommodated through development of oblique–slip faulting at the basin margins and cross-basin faults obliquely cutting the rift depression. As observed in previous modelling studies, our centrifuge experiments suggest that the angle of offset between the master fault segments is one of the most important parameters controlling the architecture of pull-apart basins: the basins are lozenge shaped in the case of underlapping master faults, lazy-Z shaped in case of neutral offset and rhomboidal shaped for overlapping master faults. Model cross sections show significant along-strike variations in basin morphology, with transition from narrow V- and U-shaped grabens to a more symmetric, boxlike geometry passing from the basin terminations to the basin centre; a flip in the dominance of the sidewall faults from one end of the basin to the other is observed in all models. These geometries are also typical of 1 *g* models and characterise several pull-apart basins worldwide. Our models show that the complex faulting in the upper brittle layer corresponds at depth to strong thinning of the ductile layer in the weak zone; a rise of the base of the lithosphere occurs beneath the basin, and maximum lithospheric thinning roughly corresponds to the areas of maximum surface subsidence (i.e., the basin depocentre).

1. Introduction

Strike–slip tectonics is a fundamental process affecting many parts of the Earth's lithosphere and resulting in prominent surface expressions (Mann, 2007; Sylvester, 1988; Woodcock and Schubert, 1994). Although strike–slip faults form linear and relatively continuous fault systems, they are typically segmented, resulting in localised extension/transtension or contraction/transpression as displacement along the boundary fault system is transferred through a variety of discontinuities or steps (Cunningham and Mann, 2007; Mann, 2007; Mann et al., 1983; Sylvester, 1988). Pull-apart basins form where bends or sidesteps (jogs) in the main strike–slip fault system (principal displacement zone or PDZ) produce zones of localised extension where the sense of step or bend in the fault system is the same as the sense of slip on the PDZ. More than 160 basins around the globe have been attributed to strike–slip motion across segmented systems (Mann, 2007).

Physical models have greatly advanced our understanding of pull-apart-basin genesis and evolution using models in clay (e.g., Atmaoui et al., 2006; Hempton and Neher, 1986; Mitra and Paul, 2011; Raynaud, 1987; Soula, 1984), in sand (e.g., Dooley and McClay, 1997; Dooley and Schreurs, 2012; Dooley et al., 1999; Faugère et al., 1986; McClay and Dooley, 1995; Rahe et al., 1998; Richard et al., 1995) and in mechanically layered systems (brittle–ductile; e.g., Basile and Brun, 1999; Dooley and Schreurs, 2012; Mitra and Paul, 2011; Sims et al., 1999; Smit et al., 2008a,b; Wu et al., 2009) using deformation rigs with the same basic design. In most of these models the basal detachment to the pull-apart basin was a horizontal shear zone underlain by a stretching rubber sheet between the rigid baseplates. In this paper we present a new series of centrifuge models designed to investigate the development, evolution and architecture of pull-apart basins on a lithospheric scale. Our new models adopt a set-up that is analogous to that used in the majority of 1 *g* models; however, by reproducing the entire lithosphere–asthenosphere system, our new set-up provides boundary conditions that are more realistic than the horizontal detachment typically used in traditional models. Moreover, our new models complement previous results from classical 1 *g* models by providing insights into the patterns of lithospheric thinning, in addition to the brittle deformation in the upper crust. To our knowledge, this is the first application of lithospheric-scale centrifuge modelling and structural analysis to pull-apart basins and one of the few experimental works in which strike–slip displacement is investigated at a lithospheric scale.

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2. Model set-up and experimental series

The three models presented in this paper were performed in an artificial gravity field of ~18 *g* using a large-capacity centrifuge and simulated strike–slip deformation of a brittle–ductile continental lithosphere floating above a low-viscosity material representing the asthenosphere. The models were built inside a transparent rectangular Plexiglas® box (with internal dimensions of 25 × 16 × 7 cm) and confined by two moveable side walls. Models consisted of two lithospheric blocks that moved past each other to simulate symmetric, pure strike–slip deformation; the main strike–slip fault system (principal displacement zone) was characterised by an offset in the central part of the model in order to produce a zone of localised extension and give rise to a pull-apart basin, similar to other strike–slip modelling studies (Dooley and Schreurs, 2012; Figs. 1 and 2). A weak zone was introduced between the two lithospheric blocks within the offset area, reproducing conditions analogous to the use of a basal rubber sheet between rigid plates or a localised ductile layer in 1 *g* models (Dooley and Schreurs, 2012). Removal of rectangular blocks (spacers) at the sides of the moving walls allowed lateral motion of the two lithospheric blocks in response to the centrifugal forces to fill the empty space (Fig. 1). Sequential removal of spacers during successive runs in the centrifuge allowed control of the amount and rate of deformation. Top-view photos of the models were taken after the end of each stage in order to monitor the evolution of surface deformation. Model surface topography was monitored by a laser scanner. Once the experiment was completed, models were frozen before being thinly slabbed to study their 3-D internal geometry.

2.1. Rheological layering and experimental materials

A vertical sequence of brittle and ductile materials was used to reproduce the rheological multilayering that is characteristic of the continental lithosphere (Fig. 1e). As in several previous centrifuge experiments (e.g., Agostini et al., 2009; Corti, 2012), the upper crust was simulated by using a K-feldspar powder characterised by a linear increase in strength with depth to reproduce natural brittle behaviour. The lower crust was modelled by a ductile mixture of silicone (Dow Corning® 3179 Dilatant Compound, hereafter referred to as *DC3179*) and corundum sand (100:10% in weight). The strong uppermost lithospheric mantle was simulated with a mixture (100:20% in weight) of plasticine (Pongo Fantasia® modelling dough, distributed by FILA) and PDMS — Polydimethylsiloxane (Dow Corning® SGM36). A mixture of DC3179, corundum sand and oleic acid (100:50:1% in weight) modelled the lower lithospheric mantle. The weak zone in the offset area was reproduced by introducing a weak mixture of DC3179, corundum sand and oleic acid (100:20:5% in weight) beneath a 1 mm-thick layer of the standard lower crust model material (Fig. 1g). The crustal–mantle layers rested

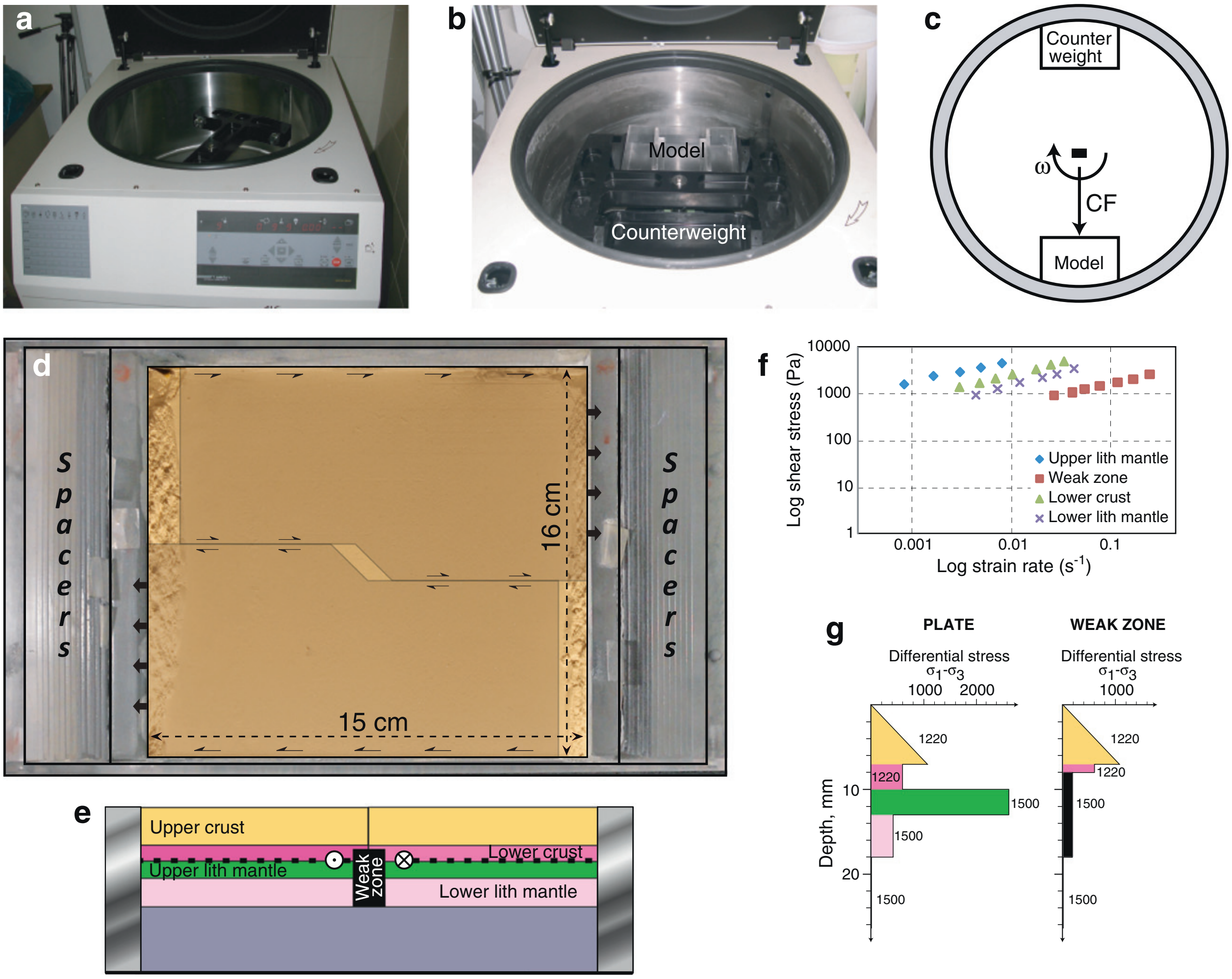

Fig. 1. Experimental setup. (a) Frontal view of the large-capacity centrifuge at the Tectonic Modelling Laboratory of the Institute of Geosciences and Earth Resources (National Research Council of Italy). (b) Close-up of the internal rotor. (c) Loading conditions in the centrifuge (CFF, centrifuge force field). (d) Top-view photo of a model, illustrating the geometry of deformation. (e) Model cross section illustrating the vertical rheological layering. (f) Stress–strain-rate relationships for the different viscous materials used to simulate the continental lithosphere (lith) plotted in a log–log graph. (g) Strength profiles of the model lithosphere in the different domains; numbers indicate the density of the different materials (in kg m^{-3}).