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4D analogue modelling of transtensional pull-apart basins

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ABSTRACT

Scaled sandbox models were used to investigate the 4D evolution of pull-apart basins formed above underlapping releasing stepovers in both pure strike-slip and transtensional basement fault systems. Serial sectioning and 3D volume reconstruction permitted analysis of the full 3D fault geometries. Results show that very different pull-apart basins are developed in transtension compared to pure strike-slip. Both types of models produced elongate, sigmoidal to rhomboidal pull-apart systems, but the transtensional pull-apart basins were significantly wider and uniquely developed a basin margin of en-echelon oblique-extensional faults. Dual, opposing depocentres formed in the transtensional model whereas a single, central depocentre formed in pure strike-slip. In transtension, a distinct narrow graben system formed above the principal displacement zones (PDZs). Cross-basin fault systems that linked the offset PDZs formed earlier in the transtensional models.

Sequential model runs to higher PDZ displacements allowed the progressive evolution of the fault systems to be evaluated. In cross-section, transtensional pull-aparts initiated as asymmetric grabens bounded by planar oblique-extensional faults. With increasing displacement on the PDZs, basin subsidence caused these faults to become concave-upwards and lower in dip angle due to fault block collapse towards the interior of the basin. In addition, strain partitioning caused fault slip to become either predominantly extensional or strike-slip. The models compare closely with the geometries of natural pull-apart basins including the southern Dead Sea fault system and the Vienna Basin, Austria.

1. Introduction

Pull-apart basins are topographic depressions that form at releasing bends or steps in basement strike-slip fault systems. Traditional models of pull-apart basins usually show a rhombic to spindle-shaped depression developed between two parallel master vertical strike-slip fault segments, also known as principal displacement zones (PDZs). The basin is bounded longitudinally by a transverse system of oblique-extensional faults, termed "basin sidewall faults", that link with the bounding PDZs (e.g. Burchfiel and Stewart, 1966; Crowell, 1974; Mann et al., 1983; Christie-Blick and Biddle, 1985; Woodcock and Fischer, 1986; Sylvester, 1988; Mann, 2007).

The relative motion of the crustal blocks involved in a pull-apart system can either be parallel to the bounding PDZs (pure strike-slip) or oblique and divergent to the PDZs (transtensional). However, traditional models of pull-apart basins usually only consider the case of pure strike-slip motion (Fig. 1a) (e.g. Crowell, 1974; Mann et al., 1983; Christie-Blick and Biddle, 1985). Garfunkel (1981) proposes that significant changes occur when continental boundary strike-slip fault systems open with transtensional motion. Transtension introduces new surface area through the stretching of the plate edges, and fault slip partitions into pure strike-slip and transverse extensional components causing complex pull-apart basins to develop within a wide boundary zone. Three-dimensional elastic modelling by ten Brink et al. (1996) showed that a small component (5°) of transtension produces an area of subsidence 2–3 times wider at the surface compared to pure strike-slip. Accordingly, it is unclear whether pre-existing pull-apart basin models would also apply to transtensional pull-apart basins (Fig. 1b) and if not, how a transtensional pull-apart basin would evolve temporally and spatially.

Pull-apart basins that have developed with transtensional displacement on the PDZs are of significant economic importance and can contain giant hydrocarbon fields (e.g. Matzen Field, Vienna Basin; Fuchs and Hamilton, 2006), significant mineralisation (e.g. Escondida, Chile; Richards et al., 2001), and geothermal fields (e.g. Coso Geothermal Field, California; Monastero et al., 2005). They are usually zones of intense fracturing (e.g. Vienna Basin; Connolly and Cosgrove, 1999), elevated heat flow (Bohai Basin; Hu et al., 2001) and elevated seismicity (Marmara Sea; Armijo et al., 2002).

Scaled analogue modelling has proved to be a useful tool for simulating pull-apart basin geometries and evolution, with successful application to both pull-apart basins developed with

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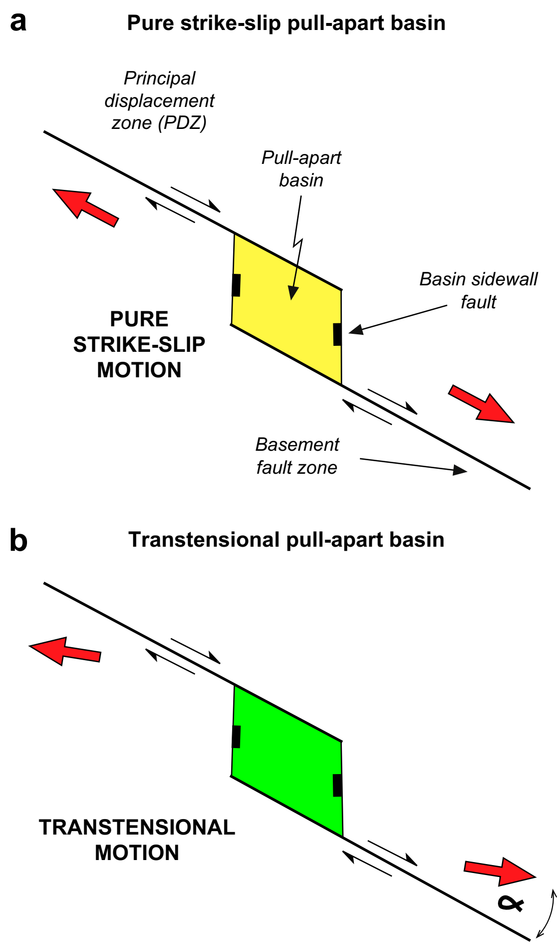

Fig. 1. General characteristics of a pull-apart basin in a dextral side-stepping fault system. The pull-apart basin is defined to develop in pure strike-slip when $\alpha = 0°$ and in transtension when $0° < \alpha \leq 45°$.

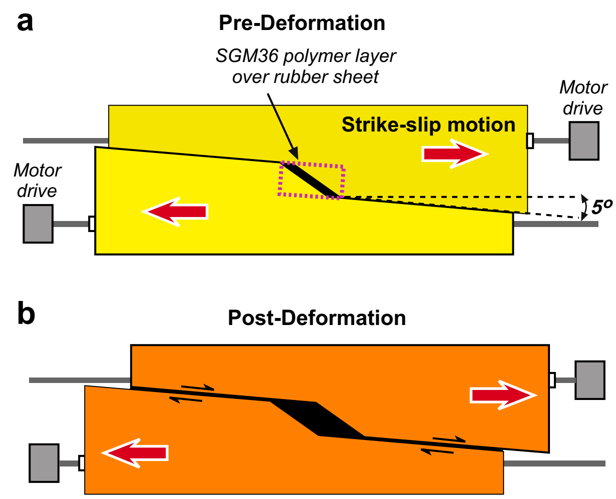

Fig. 2. Plan view of baseplate geometry used in transtensional pull-apart experiment.

displacement on the PDZs that is pure strike-slip (e.g. Hempton and Neher, 1986; Richard et al., 1995; Dooley and McClay, 1997; Rahe et al., 1998; Sims et al., 1999) and transtensional (Dooley et al., 2004).

This study compares scaled physical models of pull-apart basins developed with pure strike-slip and with transtensional motion along the PDZs. Subsequently, the 4D evolution of an analogue transtensional pull-apart basin is described using a suite of transtensional pull-apart models that have been serially sectioned at progressively greater levels of strike-slip displacement. Model results are compared to ancient and modern examples of transtensional pull-apart basins and a synoptic model for transtensional pull-apart basins is proposed.

2. Experimental procedure

To simulate a right-stepping dextral strike-slip fault system in rigid basement, aluminium plates were cut with a 30° underlapping releasing bend stepover geometry with a stepover width of 10 cm (Fig. 2). For pure strike-slip motion, the plates were displaced parallel to the trace of the PDZs and for transtensional motion, the plates were displaced at an angle of 5° oblique and divergent to the PDZs. During the experiments, the plates were displaced in opposing directions by stepper motors at an average rate of 2 cm/h.

In each experiment, a thin rubber membrane glued beneath the plates maintained extension across the PDZ and stepover and distributed strain across the plate boundaries. A spatially limited 1.5 cm-thick layer of 'SGM 36' polymer measuring 21 cm × 11 cm was placed over the stepover to simulate a local rise in the brittle–ductile transition at depth, or the presence of a local viscous decollement. SGM 36, a Newtonian viscous material manufactured by Dow Corning Ltd., has a density of 965 kg m^{-3} with an effective viscosity of 5×10^4 Pa s at room temperature (20 °C). The use of SGM 36 in analogue modelling is well documented (Weijermars, 1986) and is analogous to a raised brittle–ductile transition in continental crust under a pull-apart basin (e.g. Petrunin and Sobolev, 2006; Monastero et al., 2005) or to a pre-kinematic sequence of brittle sedimentary rocks over a viscous decollement such as a salt layer (e.g. Al-Zoubi and ten Brink, 2001; Smit et al., 2008).

The dimensions of the sandpack in the rig were approximately 150 × 50 × 7.5 cm. Sand at the longitudinal margins of the model (parallel to strike-slip displacement direction) rested against fixed walls while sand at the transverse edge of the model was allowed to spill over freely at the angle of repose to minimize boundary effects. Dry quartz sand has an average angle of internal friction of 31°, a negligible cohesive strength (1.05 kPa) and deforms according to Navier–Coulomb failure, making it a favourable material for simulating the brittle deformation of sediments in the upper crust (e.g. Horsefield, 1977; McClay, 1990). The scaling of the model was set to a ratio of approximately 10^{-5}, such that 1 cm in the model represented approximately 1 km in nature.

The top surfaces of the models were photographed every 1 mm of strike-slip displacement and scanned with a laser every 2 mm of displacement according to methodologies described by Whitehouse (2005). Subsidence of the top surface was calculated from the incremental difference between successive gridded laser scans of the top surface.

In this paper, the results of six pull-apart experiments with identical starting conditions are described. The first experiment tested the development of a pull-apart basin with 6 cm of pure strike-slip displacement along the PDZs. Five experiments were then run with 5° transtensional displacement on the PDZs. These experiments were run to progressively greater transtensional displacements (2, 3, 4, 5 and 6 cm on the PDZs). In all models, syn-kinematic sedimentation was simulated by completely infilling the basin with a layer of red sand after 3 cm of strike-slip displacement and a layer of white sand after 5 cm of displacement. Completed models were impregnated with a gelling agent and serial vertical sections were sliced at 4 mm intervals and photographed. The photographs of the sections were reconstructed in 3D using Paradigm Geophysical's VoxelGeo software. Repeat experiments reproduced the results described in this study.