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The role of syntectonic sedimentation in the evolution of doubly vergent thrust wedges and foreland folds

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ABSTRACT

This paper shows the evolution of time-constrained two-dimensional scaled analogue models of doubly vergent thrust systems in the presence of syntectonic sedimentation. Two sets of experiments were considered: (1) the addition of a syntectonic layer composed of a polymer and overlying sand in the prowedge; and (2) the addition to the previous condition of a progradational sedimentary load. Results from the first set of experiments indicate that the foreland fold-and-thrust belt has a strong relationship with the competence of the syntectonic layers. When the competence is low, the deformation produces tight asymmetric detachment-folds. As the competence increases, the fold-and-thrust belt shows break-trough folds with longer and better defined foreland-vergence. Results from the second set of experiments indicate that structural vergence is determined by the sense of progradation of the syntectonic layers, and in the case of strong aggradation at the prowedge, extension and reactive diapirism form contemporaneously with the contraction. Three end-members are proposed for mountain front thrust systems formed in the presence of syntectonic polymer and sand sedimentation: (1) outcropping fold-and-thrust belt sequence, in the case of no syntectonic sedimentation; (2) long displacement blind-thrust sheets, in the case of under-filled basins and (3) short displacement blind-thrust sheets, in the case of over-filled basins. All results indicate that ductile units at the base of syntectonic layers increase the displacement of the underlying frontal thrusts at the prowedge, and reduce the critical taper. Results also indicate that at very high sedimentary rates and hyper-critical taper conditions the prowedge collapses. Conclusions drawn from this research may be applied as an analogue to foreland evolution and to evaluate hydrocarbon generation, migration, and entrapment in thrust belts in areas where seismic imaging is generally poor.

1. Introduction

Physical analogue modelling is commonly used to simulate the development, sequence and geometries of thrust structures (Davis et al., 1983; Dahlen, 1990; Liu et al., 1992; Storti and McClay, 1995; Koyi, 1995; Lewis, 1997; Storti et al., 2000; Cotton and Koyi, 2000; Koyi and Mancktelow, 2001; Persson, 2001; Costa and Vendeville, 2002; Turrini et al., 2001; Koyi and Vendeville, 2003; Couzens-Schultz et al., 2003; Lujan et al., 2003; Koyi and Cotton, 2004; McClay and Whitehouse, 2004). Using a deformable backstop, similar to those made by Storti and McClay (1995) and McClay and Whitehouse (2004), an analogue modelling programme has been designed in order to simulate the deformation of thrust structures, and the formation of fault-related folds in shale dominated foredeep basins. In particular, models with different patterns of syn-kinematic sedimentation were run in order to study the effects of variable sedimentation on foredeep deformation.

Doubly vergent thrust wedges have been shown to form in two stages, a closely spaced thrust system (Stage I) and a widely spaced thrust sequence (Stage II) similar to that described for the deformation of foreland basins (cf. McClay and Whitehouse, 2004). In order to simulate the tectono-sedimentary evolution of this kind of basin, a syntectonic layer was added at the initiation of Stage II. In this manner, deformation in Stage I formed the central thrust wedge, which corresponds to the uplift of a mountain range, while Stage II coincides with the deepening of the foreland basin and with the deposition of thick shale sequences simultaneously with the continuous shortening at the prowedge.

Sand and polymer are the two basic materials that have long been used to simulate deformation in the upper crust (e.g. Lewis, 1997; Couzens-Schultz et al., 2003; Cotton and Koyi, 2000; Costa and Vendeville, 2002; Turrini et al., 2001; Lujan et al., 2003). In the

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experiments shown here, polymer and sand are used to represent foredeep shales overlaid by coarser infilling units formed at the latest stage of foreland basins (Fig. 1).

2. Analogue modelling materials

Dry quartz sand deforms independently of strain rate and fails according to the Navier–Coulomb criterion with an angle of sliding friction of $\sim 31°$ (McClay, 1990). Sand used in these experiments was 190 μm in diameter and had a density of 1300 kg/m. The sand was artificially coloured and separated into layers of different colours in order to permit the monitoring of the deformation. The geometric similarity factor (Hubbert 1937 in McClay, 1990) normally used in sandboxes is $\sim 10^{-5}$ thus, 1 cm in an analogue model is representative of 1 km in nature. The low cohesive strength of dry sand (approximately 0), compared with the upper crust cohesive strength (250 kPa), is an ideal material to simulate the deformation in the upper brittle crust (e.g. Vendeville et al., 1987; McClay and Ellis, 1987; McClay, 1990; Weijermars et al., 1993; Costa and Vendeville, 2002).

Silicone, polymethylsiloxane polymer PDMS (SGM-36), has been commonly used to model ductile sequences in the upper crust (Weijermars, 1986). The polymer has a Newtonian linear viscous behaviour at low strain rates, a density of 965 kg m^{-3}, a strength of 4 Pa and a viscosity of 5×10^4 Pa s^{-1}. Although polymer is commonly used to model salt, it is also considered an analogue material for overpressured shales from surface to ~ 6 km depth (Cohen and McClay, 1996).

3. Shortening rates in the analogue models

An important issue for analogue models involving Newtonian fluids (polymers) is the shortening rate compared with the prototype. Strain rate is a time dependant parameter proportional to stress (Childs et al., 1993), therefore a slow shortening rate with polymers may reproduce better natural prototypes (Cotton and Koyi, 2000; Costa and Vendeville, 2002). In the experiments described in this paper, a shortening rate of 0.66 cm/h gives 1 cm of deformation after 1.5 h. Each of the experiments from Stage II expands 18 h each approximately, so considering that 1 h is equivalent to 10^6 years (cf. Duerto, 2007), each model represents approximately 18 m.y. for a natural prototype.

4. Deformation apparatus

The deformation apparatus consisted of a glass-sided, rectangular deformation box, 30 cm wide and 200 cm long (Fig. 1a). A slow motion motor (deformation rate of 0.01 cm s^{-1}) connected to a roller, pulled a thin polyester film (Mylar sheet with coefficient of friction 0.47) along the base of the model and then down through a subduction slot located 30 cm from the right-hand end wall (Fig. 1a). This apparatus can be compared with published conceptual models of doubly vergent thrust wedges (e.g. McClay and Whitehouse, 2004; Fig. 1b).

5. Experimental procedure

5.1. Stage I of deformation

A manually sieved sand pack, 200 cm long × 30 cm wide and 2.5 cm thick, was placed over the polyester Mylar film (Fig. 2a). Dry quartz sand, 190 μm average grain size with a 1300 kg/m density, was used. The sand pack consisted of alternating white and blue pre-kinematic layers 2 mm thick with a black layer at the fourth and tenth layer (from the bottom to the top).

5.2. Stage II of deformation

Upon the formation of the first widely spaced thrust sheet ($\sim$23 cm shortening), a syntectonic sand and polymer layer were placed in front of the prowedge (Fig. 2b and c). A polymer layer was carefully placed over the undeformed layers ahead of the

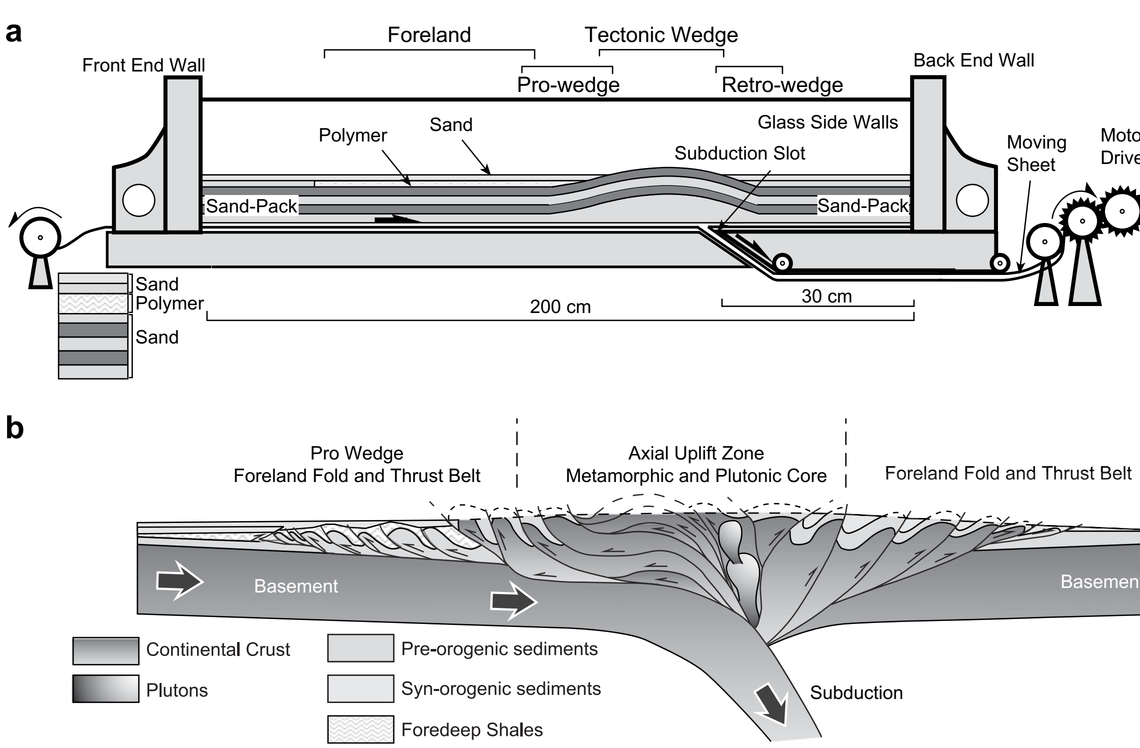

Fig. 1. (a) Apparatus design used in these Experiments, and (b) comparison with model for a doubly vergent wedge (modified from McClay and Whitehouse, 2004).