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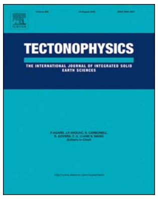

Impact of an interbedded viscous *décollement* on the structural and kinematic coupling in fold-and-thrust belts: Insights from analogue modeling

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ABSTRACT

Fold-and-thrust belts (FTBs) can be segmented both across and along strike because of various factors including tectonic and stratigraphic inheritance. In this study, we investigated along/across-strike structural interactions in a FTB propagating toward a foreland which displays contrasted lithological sequences. A set of analogue models was performed in a compressional box where a single viscous level of varying width was interbedded within a frictional series. The tectonic interaction between the viscous and the frictional provinces was tested both along and across strike. Results indicate that a frictional province influences the along-strike tectonic evolution of an adjacent viscous province. This influence decreases when the width of the viscous province increases. The frictional provinces control the taper, structural style, obliquity of the structures' trend and kinematics of the shallow deformation front of the viscous province. Results evidence how far a frictional province can impact the deformation of an adjacent viscous province. For frictional-viscous wedges, it appears that the critical taper theory, which is generally applied in 2-D, should be likely considered in terms of 3-D. Moreover, the kinematics of the deep deformation front shows mutual influences between the adjacent viscous and frictional provinces.

Experimental results are compared to natural examples in the Kuqa Basin (Southern Tian Shan, China) and the Salt Range (Pakistan), and give an insight to a better understanding of the dynamics of fold-and-thrust belts bearing a viscous *décollement*, such as salt.

1. Introduction

The influence of *décollement* strength on the dynamics of accretionary systems has been largely investigated through experimental and numerical modeling (Buiter, 2012; Graveleau et al., 2012). Several studies investigated the influence of low or high strength basal *décollement* (*e.g.* Contardo et al., 2011; Costa and Vendeville, 2002; Nilfouroushan et al., 2012; Ruh et al., 2012) and the effect of an interbedded low-strength *décollement* (Ahmad et al., 2014; Ballard et al., 1987; Corrado et al., 1998; Couzens-Schultz et al., 2003; Guillier et al., 1995; Kukowski et al., 2002; Letouzey et al., 1995; Massoli et al., 2006; Santolaria et al., 2015; Verschuren et al., 1996; Wang et al., 2013). In the commonly accepted critical taper theory setting (Dahlen, 1990; Davis et al., 1983), general results indicate that the surface slope of the wedge is steeper for a strong basal mechanical coupling than for a weaker one. Deformation propagates also typically toward the foreland for purely frictional *décollement* (with the so-called "in sequence" mode), whereas deformation alternates back and forth between the hinterland and the foreland if the basal *décollement* is viscous ("out-of-sequence mode"). The wedges grow also rather by frontal accretion of successive box folds at a low basal strength whereas it grows by imbrication of long thrust slices at high basal strength. The question of structure vergence across accretionary systems remains still not fully understood. Many works in the field and with modeling approaches have addressed the topic (*e.g.* Greenhalgh et al., 2015; Gutscher et al., 2001; Zhou et al., 2015), but the control exerted by décollement strength, 3-D local stresses and rotation of structures, among others, is still a subject of recurrent investigations in fold-and-thrust belts (FTB). The dynamics of triangular zones, that are wedge-shaped bodies bounded by opposite verging thrusts (Banks and Warburton, 1986; Jones, 1996) remains also to be elucidated.

In nature, the strength of the detachment layer may vary along and across strike because of changes in depositional environments in the foreland (Morley, 1987). This implies variations in the mechanical stratigraphy of the foreland, and therefore variations in the structural style when the deformation front reaches this area. Several studies have analyzed the dynamics of a wedge advancing toward provinces displaying across-strike variations in the basal detachment strength. For

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instance, when a high friction detachment passes outward to a low friction (or viscous) detachment, it leads to a segmentation of deformation between a steeply tapered rear foreland to a shallow tapered front (Agarwal and Agrawal, 2002; Contardo et al., 2011). Conversely, a low strength detachment evolving outward to a higher strength detachment leads to an increase in taper slope (Agarwal and Agrawal, 2002; Lallemand et al., 1992; Larroque et al., 1995). For brittle-viscous systems, a sudden jump of the deformation front toward the foreland pinch-out is often observed when the deformation reaches the ductile level (Costa and Vendeville, 2002; Cotton and Koyi, 2000).

Additionally, along-strike differences in the rheological properties of the basal *décollement* have been investigated for numerous natural FTB (Bahroudi and Koyi, 2003; Calassou et al., 1993; Colletta et al., 1991; Cotton and Koyi, 2000; Koyi and Sans, 2006; Letouzey et al., 1995; Li and Mitra, 2017; Luján et al., 2003, 2006; Macedo and Marshak, 1999; Nilforoushan and Koyi, 2007; Ruh et al., 2014; Schreurs et al., 2002, 2003; Sherkati et al., 2006; Turrini et al., 2001; Vidal-Royo et al., 2009; Wu et al., 2014). Typically, the deformation front is arcuate, creating “salients” and “recesses” (Marshak, 2004), and propagates at different rates in the two provinces. A transfer zone with wrench tectonic features, rotating structures, interplays and relays generally forms at the limit between the two provinces. The dynamics of “drag” interaction between adjacent provinces has been a matter of debate (Costa and Vendeville, 2004; Koyi and Cotton, 2004) and the purpose of several investigations in purely brittle (Souloumiac et al., 2012) and brittle-viscous models (Zhou et al., 2015). However, these works did not investigate how adjacent provinces having different *décollement* strength may influence one another. This question has been preliminary explored both in the case of a basal *décollement* (Li and Mitra, 2017) or an interbedded *décollement* (Borderie, 2016; Tang et al., 2010). Results suggest a coupling of deformation between the foreland and hinterland, and also point out some structural influence between the viscous and the purely frictional domain. To go further, we explore in this paper along-strike and across-strike couplings in FTBs in the case of an interbedded *décollement*. We present a set of analogue models of FTBs that propagated toward a heterogeneous foreland basin made of adjacent purely frictional and brittle-viscous provinces. We analyzed 1) the reciprocal interactions occurring between the adjacent provinces (along-strike interactions), 2) the interaction between the inner hinterland and the outer foreland domains (across-strike interactions), and 3) the relationships between deep and shallow structures. Surface processes (*i.e.*, erosion and sedimentation) were not modeled although their primordial influence on tectonics both at the scale of single structures (*e.g.* Barrier et al., 2002; Darnault et al., 2016; Pichot and Nalpas, 2009) and FTBs (*e.g.* Bonnet et al., 2007; Storti and McClay, 1995) is known and demonstrated.

2. Methodology

2.1. Material and scaling

Our experimental approach focuses on modeling the segmentation of deformation in fold-and-thrust belts displaying contrasted sedimentary provinces in the foreland. The sedimentary sequence in the foreland is characterized by a basal frictional *décollement* overlain by a brittle overburden within which, in some models, a viscous *décollement* is interbedded. The basal frictional detachment is made of glass microbeads, whose bulk volumetric mass is 1.66 g/cm^{-3}, D_{50} grain size is about 100 µm and angle of internal friction is about 20°. The brittle overburden is made of fine dry quartz sand (GA39, produced by Sibelco, France) whose volumetric mass is 1.42 g/cm^{-3}, D_{50} grain size is about 115 µm and angle of internal friction is 30° (Klinkmüller et al., 2016). Some sand layers were colored and layer interfaces were highlighted with a thin black marker to provide a marker of deformation. The upper viscous *décollement* was modeled using silicone SGM36 (Costa and Vendeville, 2004; Ferrer et al., 2014; Sellier et al., 2013; Weijermars and Schmeling, 1986), which is a transparent high-viscosity polydimethylsiloxane (PDMS) polymer. Volumetric mass is 0.965 g/cm^3 and viscosity is 2.2×10^4 Pa.s at room temperature (Rudolf et al., 2016). Within the range of strain rates used in the experiments ($2 \times 10^{-6}\, s^{-1}$), PDMS behaved as a Newtonian fluid having a very low yield strength (Rudolf et al., 2016; ten Grotenhuis et al., 2002; Weijermars and Schmeling, 1986). Under these conditions, PDMS is a good analogue to the behavior of salt rock.

Following the rules of scaling for tectonic experimental models (Hubbert, 1937; Ramberg, 1981), granular materials are good analogues for brittle rocks in the upper continental crust because they obey a Mohr-Coulomb criterion of failure (Hubbert, 1951; Krantz, 1991; Lohrmann et al., 2003; Schellart, 2000). Scaling rules imply that the model-to-nature ratio for stress, σ*, is:

$$\sigma^* = \rho^* \times g^* \times L^*, \qquad (1)$$

where ρ* is the model-to-nature ratio for volumetric mass, g* is the ratio for gravity acceleration and L* is the ratio for length. L* is set to 0.66×10^{-5}, which means that 10 mm in the model corresponds to 1.5 km in nature. g* is 1 because the models were deformed under the natural gravity field. The average scaling ratio for volumetric mass (ρ*) is 0.5 because the volumetric mass is 2.6 g/cm^3 for natural sedimentary rocks and 2.2 g/cm^3 for halite (Santolaria et al., 2015; Weijermars et al., 1993). Considering these values, stress ratio σ* is 3.33×10^{-6}. The cohesion in the range of a few tens of Pascal for our granular materials (70–110 Pa, reported in Klinkmüller et al., 2016) would correspond to a value for natural sedimentary rocks in the range of 10–30 MPa (*e.g.* Byerlee, 1978), which in agreement with most classical measurements or estimations of natural rock strength (Ritter et al., 2016; Schellart, 2000).

As for scaling of viscosity and time, we used an average dynamic viscosity for rocksalt of 5×10^{18} Pa.s (*e.g.* van Keken et al., 1993) and 2.2×10^4 Pa.s for the silicone polymer (Rudolf et al., 2016). This yields a model-to-prototype ratio for viscosity η* of $4.4 {*} 10^{-15}$. Note that natural viscosities measured for natural rock-salt range from a wide range of value; *i.e.* from 10^{16} Pa.s to 10^{19} Pa.s (Carter, 1976; van Keken et al., 1993, 1993). Strain rate ratio, Ɛ*, is linearly related to stress and viscosity ratios:

$$\sigma^* = \eta^* \times \varepsilon^* \qquad (2)$$

Calculation of the strain rate yields to $Ɛ^* = 7.5 \times 10^8$, from which a model-to-nature time ratio can be quantified. As $t^* = 1/Ɛ^* = 1.33 \times 10^{-9}$, it means that one hour in the experiments is equivalent to about 85,000 years in nature. As our experiments lasted around 65 h, this represents around 5.6 My of deformation time in nature. Finally, we applied a convergence velocity of 5 mm/h in our model to ensure that PDMS behaves as a very low strength material. This velocity, scaled to nature is:

$$v^* = \varepsilon^* \times L^* \qquad (3)$$

which corresponds to a velocity of about 9 mm/y in nature.

2.2. Experimental setup and protocol

We conducted 17 experiments at the Tectonic Modeling Laboratory of Lille University (France), mostly in a 950 mm long and 1250 mm wide box. The base of the deformation box was flat and made of plastic. The coefficient of basal friction was estimated to about $\mu_b = 0.40$ (angle of internal friction equivalent to ~ 22°). The box comprised three fixed glass walls, and one mobile wall (backstop) (Fig.1.A). The lateral friction along the glass sidewalls was decreased by lubricating them with a thin film of silicone polymer (see protocol in Costa and Vendeville, 2004; Santolaria et al., 2015). Deformation was imposed by a screw-jack controlled by a stepping motor that pushed the backstop at a constant velocity of 5 mm/h.

All models comprised 5–6 layers and displayed an initial total