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Impact of synkinematic sedimentation on the geometry and dynamics of compressive growth structures: Insights from analogue modelling

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ABSTRACT

Analogue sandbox models have been set up to study the impact of synkinematic deposits on the geometry and evolution of single thrusts and folds according to different sedimentation modes (a slow or rapid sedimentation rate that is constant or changing in space and time) and rheological profiles (thin or thick sedimentary series, with or without a basal décollement level). A first series of experiments documents the influence of synkinematic deposits according to their sedimentation rate and the rheology of the prekinematic materials. A second series investigates the influence of changes in the sedimentation rate through time. A third one considers the influence of changes in the sedimentation rate in space. All these experiments suggest that the geometry and evolution of single compressive growth structures vary according to the sedimentation rate. The number and dip of their frontal thrust segments change with the ratio R between the sedimentation rate at the footwall of the faults and the uplift rate of their hanging wall. The latter is then more or less uplifted depending on the dip of the thrusts. As a result, the overall structure has either a fault-bend fold or a fault-propagation fold geometry. These rules are verified when the ratio R changes in space or through time. In addition, the rheological profile of the models also affects the geometry and evolution of compressive growth structures. Their structural style, as well as the synsedimentary splitting and steepening of the associated thrusts, varies according to the occurrence and strength of the brittle and ductile layers. According to this modelling study, the ratio R and its changes in space and time, along with the rheology of the deformed materials, are key parameters to better understand the geometrical and kinematical complexities of natural growth thrusts and folds and to improve their interpretation.

1. Introduction

Based on fieldwork, experimental or numerical models, and theoretical studies, it has been demonstrated that erosion and sedimentation impact the geometry and kinematics of compressive systems (e.g., Avouac and Burov, 1996; Barrier et al., 2002; Beaumont et al., 1994; DeCelles and Mitra, 1995; Duerto and McClay, 2009; Graveleau et al., 2012; Hilley et al., 2004; Konstantinovskaia and Malavieille, 2005; Konstantinovskaya and Malavieille, 2011; Koons, 1990; Malavieille, 2010; McClay and Whitehouse, 2004; Meigs and Burbank, 1997; Mugnier et al., 1997; Stockmal et al., 2007; Storti et al., 2000; Whipple, 2009; Whipple and Meade, 2006; Willett, 1999; Willett et al., 1993). In particular, many studies have shown that deformation of thrust wedges and compressive basins changes according to the magnitude of these surface processes (e.g., Bonnet et al., 2007, 2008; Braun and Pauselli, 2004; Fillon et al., 2013; Hardy et al., 1998; King et al., 1988; Simpson, 2006; Storti and McClay, 1995; Wu and McClay, 2011). When submitted to low erosion or sedimentation rates, fold-and-thrust belts exhibit widely spaced thrusts that develop in sequence toward the foreland. In contrast, when submitted to high erosion or sedimentation rates, these belts show tightly spaced thrusts, which activate out of sequence toward the foreland or the hinterland alternately. High sedimentation rates also promote the subsidence of compressive basins and prolong the activity of their bordering faults. Hence, it appears that synkinematic erosion and sedimentation influence the location, activity and sequences of thrusts within compressive belts. However, previous works on thrust wedges have not clearly investigated the effect of surface processes at the scale of the elementary structures that composed these systems.

Only a few studies have addressed the impact of erosion and sedimentation on single growth thrusts and folds. They demonstrate that erosion facilitates and prolongs the activity of thrusts without changing their geometry (Elliott, 1976; Johnson, 1981; Merle and Abidi, 1995; Price and Johnson, 1982; Raleigh and Griggs, 1963; Willemin, 1984). They also highlight that sedimentation affects the geometry and dynamics of thrusts and folds (Barrier et al., 2002; Casas et al., 2001; Gestain et al., 2004; Nalpas et al., 1999, 2003; Pichot and Nalpas, 2009; Strayer et al., 2004; Tondji Biyo, 1995; Vidal-Royo et al., 2011). However, the influence of synkinematic deposits on compressive

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growth structures has not yet been systematically explored according to the different sedimentation modes (a slow or rapid sedimentation rate that is constant or changing in space and time) that can occur in natural systems. Moreover, this influence is usually studied by considering only one rheological layering of the prekinematic terrains, whereas these structures can develop within various stratigraphic stacks (thin or thick, with or without a basal décollement level).

In this article, we present three series of brittle and brittle–ductile analogue models designed to further document the effect of synkinematic sedimentation on the geometry and evolution of single thrusts and the associated folds. The first series of experiments investigates the influence of synkinematic deposits according to their sedimentation rate and the rheology of the prekinematic materials. The second series focuses on the influence of changes in the sedimentation rate through time. The third one considers the influence of changes in the sedimentation rate in space. Herein, we describe the experimental technique, present the results of the models and discuss these results. Our experiments show how synkinematic deposits, along with the rheology of the deformed layers, can impact the structure and kinematics of the growth thrust and folds depending on the sedimentation rate and its changes in space and time. Consequently, many geometrical and kinematical complexities of natural compressive growth structures can be explained.

2. Experimental methodology

The physical models presented below are replicas of natural examples scaled-down in terms of dimensions, rheology, and boundary conditions. The experimental procedure is similar to the one frequently used to model compressive systems with brittle and brittle–ductile rheologies (e.g., Ballard et al., 1987; Cotton and Koyi, 2000; Graveleau et al., 2012; Liu et al., 1992; Malavieille, 1984; Nalpas et al., 2003; Smit et al., 2003; Storti and McClay, 1995 and references therein). A geometric and dynamic similarity between the experiments and nature is obtained by keeping the average strength of the ductile layers correctly scaled with respect to the strength of the brittle layers and the gravity forces (e.g., Davy and Cobbold, 1991; Hubbert, 1937; Ramberg, 1981; Weijermars et al., 1993).

In this study, the models were designed to represent sedimentary covers a few kilometres thick that deform with a shortening rate of a few millimetres per year to reach a total shortening of a few kilometres. In practice, given the physical properties of the materials used, these experiments must fulfil two main conditions to be properly scaled (e.g., Bonini, 2001; Brun, 2002; Costa and Vendeville, 2002). First, the ratios of the lengths and stresses between the models and their natural prototypes must be nearly equal. Second, the models must deform a few billion times faster than nature, which is archived for a shortening velocity of a few centimetres per hour. The corresponding geometric and dynamic scaling of the experiments is presented in Table 1. In this table, (1) the length ratio between the models and nature is fixed by the experimenter, (2) the density and viscosity ratios are fixed by the rheology of the analogue materials, and (3) the shortening rate, time and stress ratios are imposed by the ones in (1) and (2). The models to nature ratios, chosen or fixed from scaling laws (see Davy and Cobbold, 1991; Hubbert, 1937; Ramberg, 1981; Weijermars et al., 1993), are thus 10^{-5} for length (1 cm in the models represents 1 km in nature), 10^{-10} for time (2 h represents approximately 1.5 My) and 10^{-5} for stresses (the models are nearly 10^5 times weaker than their natural prototypes).

In these experiments, dry Fontainebleau quartz sand is used to model the brittle (i.e. frictional) behaviour of sedimentary rocks with Mohr–Coulomb properties. This sand has a mean grain size of approximately 250 μm, an internal friction angle close to 30–35°, a negligible cohesion, and a mean density of approximately 1400 kg/m^3. Silicone putty (Rhodorsil Gomme GS1 RG 70,009 manufactured by Rhône-Poulenc, France) is used to model the ductile (i.e. viscous) behaviour of weak sedimentary rocks such as shales, clays, marls, or evaporites. When submitted to deformation velocities of a few centimetres per hour, this silicone putty is a quasi-newtonian fluid with a mean viscosity close to 10^4 Pa s at 20 °C and a mean density of approximately 1300 kg/m^3. Piling up sand and silicone layers provides analogue models with strength profiles homothetic to those of natural sedimentary series (e.g., Davy and Cobbold, 1991; Faugère and Brun, 1984; Weijermars et al., 1993). Before compression, the models were a few centimetres thick and were made up of a white and black sand pile either lying or not on a silicone layer (Fig. 1). In these stacks, the silicone layer represents a potential décollement level at the applied strain rate, whereas the overlying sand represents a brittle prekinematic cover. In this brittle cover, the sand layers of different colours have the same rheological behaviour.

The experimental models were set in an apparatus that comprises a box wide enough (55 × 60 cm) to permit large deformations without boundary effects. This box had two opposing walls: one attached on a fixed bottom and one stuck on a rigid mobile basal plate that could slide over the fixed bottom (Fig. 1). The two other sides were free in order to avoid sideways frictions and ensure uniform compressive stresses. To transmit horizontal displacements within the box, the mobile wall and the basal plate were pushed inward at a constant velocity by a screwjack. At the base of the models, the free moving edge of the mobile basal plate induces a linear velocity discontinuity (VD) that forces deformation localization (e.g., Allemand et al., 1989; Ballard et al., 1987; Malavieille, 1984). According to the scaling requirements, a constant deformation velocity of 2.5 cm/h was used to reach a total shortening of 5 cm for all experiments. During shortening, fresh white and blue sand was sprinkled manually onto the models to mimic synkinematic sedimentation. Using this technique, synkinematic deposits can be evenly distributed or localized along strike with a constant or changing rate through time (e.g., Barrier et al., 2002; Gestain et al., 2004; Nalpas et al., 1999, 2003; Pichot and Nalpas, 2009; Tondji Biyo, 1995), in order to reproduce a spectrum of sedimentation modes that can occur in compressive systems.

In the three series of experiments presented below, the sedimentation rate was chosen relative to the uplift rate of the growth structures that developed during shortening. The different models can thus be compared using a non-dimensional parameter R that corresponds to a ratio between two velocities: the sedimentation rate at the footwall of the main fault zone of each model (V_{sed}) and the uplift rate of its hanging wall (V_{upl}) (see also Barrier et al., 2002; Pichot and Nalpas, 2009; Storti and Salvini, 1996). In the first series of experiments, models were uniformly covered by synkinematic sand deposited with a constant sedimentation rate during the entire shortening period. In these models, the ratio R (V_{sed} / V_{upl}) was set to 0 ($V_{sed} = 0$), 1/2 ($V_{sed} < V_{upl}$), 1 ($V_{sed} = V_{upl}$), 2 or higher ($V_{sed} > V_{upl}$), in order to simulate the development of a growth structure above or below a sedimentation base level.

Table 1

Scaling parameters of the models. L, ρ, μ, V_{short}, t, and σ are respectively the length, density, viscosity, shortening rate, time and stress in nature and in the experiments. Note that the ratio between the strength and gravitational forces (σ / ρgL) is the same in the models and their natural prototypes, while the ratio between the inertial and gravitational forces (V_{short} / gt) is negligible in both systems.

	L (m)	g (m/s^2)	ρ (kg/m^3)	μ (Pa s)	V_{short} (m/s)	t (s)	σ (Pa)	σ/ρgL	V_{short}/gt
Nature	1000 (1 km)	9.81	2300	10^{19}	~10^{-10} (~3 mm/y)	~5×10^{13} (~1.5 My)	2.25×10^7	1	10^{-23}
Model	0.01 (1 cm)	9.81	1400	10^4	7×10^{-6} (2.5 cm/h)	7.2×10^3 (2 h)	1.4×10^2	1	10^{-11}
Model/nature ratio	10^{-5}	1	0.6	10^{-15}	6×10^4	1.7×10^{-10}	0.6×10^{-5}	Identical	Equally negligible