



Influence of synkinematic sedimentation in a thrust system with two decollement levels; analogue modelling

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ABSTRACT

Compressive systems in foreland domains are characterised by fold and thrust belts linked to the presence of one or several ductile layers in depth acting as a decollement level. The main parameters controlling the structural evolution are: the presence of a decollement level, the amount and rate of shortening, and the amount of synkinematic sedimentation. The effect of these parameters has only been studied on a thrust belt scale. Furthermore, only the effect of synkinematic sedimentation on a simple system with one decollement level has been studied at the scale of a single structure. The aim of this study was to use analogue modelling to test the effect of shortening rate, velocity and the localization of sedimentation on a single system characterised by the presence of two prekinematic decollement levels. The main results showed variations in the structural vergence, folding geometry (symmetric or asymmetric), the evolution of the deformation (horizontal propagation versus vertical uplift), and the decoupling of the lower and upper brittle structures in relation with the main parameters (shortening rate and mass transfer). The results of the experiments were then compared to natural examples from the sub-Andean thrust belt.

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1. Introduction

In a compressive system, and especially in a thin-skinned thrust belt, a deformation induced by one or several decollement levels is commonly observed (e.g. flat, ramp, fault-related folding). Decollement levels present a low basal friction directly related to the lithology (marls, shales, coals and evaporites) and/or to overpressure conditions. The Sub-Andean fold and thrust belt shows a major west-to-east propagation of the deformation (Fig. 1). This deformation is characterised by north–south folds–faults (Fig. 1b) and is related, in depth, to two decollement levels (Fig. 1c). These structures, which developed during sedimentation, present mostly a west-to-east vergence with a huge horizontal and vertical displacement. Previous analogue studies have investigated the entire scale of the thrust belt (Leturmy et al., 2000; Couzens-Schultz et al., 2003; Smit et al., 2003). The main characteristics of this system are the basal angle of the wedge and the shortening rate, which control the propagation of the thrust sequences (Smit et al., 2003). The presence of two decollement levels favours either coupling or decoupling, related to the shortening rate (Couzens-Schultz et al., 2003; Massoli et al., 2006). The presence of synkinematic sedimentation modifies the thrust wavelength and the major propagation of the deformation (Leturmy et al., 2000). On a structural scale, only a few studies have addressed the relationship between deformation and sedimentation using analogue modelling

(Nalpas et al., 1999; Casas et al., 2001; Barrier et al., 2002; Nalpas et al., 2003; Gestain et al., 2004). All of these studies were carried out with only one prekinematic ductile layer and showed an increase in the uplift associated with the sedimentation rate. At the scale of a single structure with two prekinematic ductile layers, the vergence of thrust, the localization of deformation, the relation between structuration in depth and at the surface, and the effect of mass transfer are still in debate.

The aim of this paper is to study the deformation of a structure in a domain presenting two prekinematic decollement levels in relation to the (i) shortening rate variation, (ii) synkinematic velocity of the sedimentation and (iii) localization of the synkinematic sedimentation. Our approach was based on analogue modelling and field examples (e.g. Sub-Andean thrust belt).

2. Experimental procedure

The modelling techniques used here are similar to those usually used for experiments dealing with brittle–ductile systems in the Laboratory of Experimental Tectonics of Géosciences Rennes (Rennes University, France) and which have been described in numerous studies (e.g. Faugère and Brun 1984; Vendeville et al., 1987; Davy and Cobbold 1991). Brittle layers (pre and synkinematic) were represented by sand, with an angle of internal friction close to 30° (Krantz, 1991) and a density (ρ) around 1400 kg/m³. Weak ductile layers such as shales, clay, marl or salt were represented by two silicone putties (Rhône Poulenc, France) with a viscosity (μ) around 10⁵ Pa s at 20 °C

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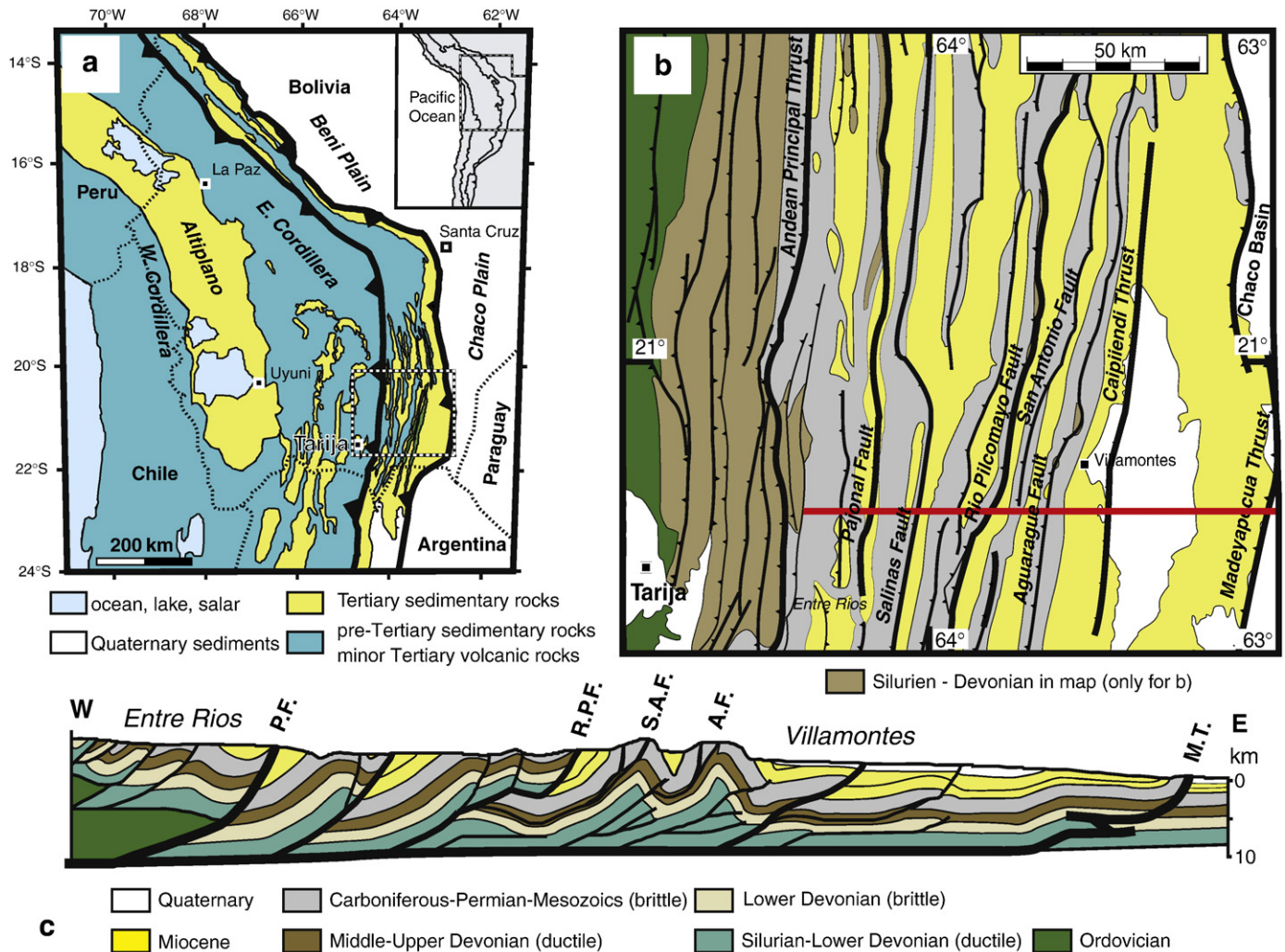


Fig. 1. (a) Geological map of the central Andean compressive system (after Horton, 1999), and (b) focus geological map of the Bolivian Sub-Andean thrust belt (modified from Dunn et al., 1995). (c) Cross-section of this system (see red line in panel b for location) showing the main structural organisation (modified from Labaume and Moretti, 2001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and a density (ρ) close to 1400 kg/m^3 for the silicone putty 70009, and a viscosity (μ) around 10^4 Pa s at 20°C and a density (ρ) close to 1000 kg/m^3 for the transparent silicone putty SGM 36.

The experimental apparatus consisted of a fixed rigid basal plate over which a thin mobile plate fixed on a mobile wall was pushed at a constant rate (Fig. 2a). The shape of the mobile plate induces a velocity discontinuity (VD) at the base of the model, which localises the deformation (cf. Malavielle 1984; Balé, 1986; Allemand et al., 1989; Ballard, 1989). The model was set in a $70 \times 60 \text{ cm}$ sandbox, wide enough to achieve a relatively large amount of shortening without border effects.

In order to make comparisons with natural examples, where the thickness of the ductile and brittle layers are different from the base to the top of the sedimentary pile of the basin, we chose a four-layer brittle–ductile model with ductile and brittle material that is thicker in the lowermost layers than in the uppermost layers. The prekinematic pile of the models was made of a four-layer brittle–ductile system, composed of, from bottom to top: 1 cm of either pink or purple silicone; 1.5 cm of black and white sand; 0.5 cm of transparent silicone; and 1 cm of black and white sand (see Fig. 2a). The basal and the medium silicone layers represent potential decollement levels, while the sand layers represent brittle prekinematic formations. Several shortening rates, ranging from 0.25 to 10 cm/h, were tested, and a rate of 0.5 cm/h was kept for the experiment. The geometric and

dynamic scaling of these models was presented in Table 1. The scale ratio and stress ratio between model and nature has the same order (10^{-5}), and the velocity in the model corresponds to observed velocity in nature (see Table 1).

In order to simulate synkinematic sedimentation, fresh sand was continuously sprinkled manually onto the model during the shortening (Barrier et al., 2002). The sedimentation modes (Fig. 2b) were chosen to constrain the possible sedimentation modes within natural basins (see Section 3.2). Photographs of the model surface were taken at regular time intervals in order to observe structure development. After deformation, the internal structure was observed on a series of cross-sections cut parallel to the compression direction (perpendicular to the VD). Brittle sand layers were made of various colours of sand in order to reveal the structures and to observe them on photographs. The colour of the sand does not modify its behaviour.

3. Analogue results

3.1. Shortening rate variation

The first aim of our experiments was to test several shortening rates in order to define the best rate to match thin-skinned tectonic features (e.g. flat, ramp, fault-related folding) unaffected by the influence of the experimental apparatus. Six different shortening rates

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