Journal of Structural Geology 76 (2015) 35–51

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Double evaporitic *décollements*: Influence of pinch-out overlapping in experimental thrust wedges

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ARTICLE INFO

Article history:
Received 13 October 2014
Received in revised form
3 April 2015
Accepted 20 April 2015
Available online 28 April 2015

Keywords:
Analogue modeling
Multiple *décollements*
Salt tectonics
Evaporites
Southern Pyrenees

ABSTRACT

This article focuses on how deformation and displacements are transferred between two *décollements* located at different stratigraphic levels by means of analogue modeling using brittle/viscous, sand/silicone systems. We present results from ten analogue models, in which we varied key parameters, such as the amount of horizontal offset or overlap between the pinch-outs of the upper and lower *décollements*, the total amount of shortening, and the planform geometry of the upper *décollement*. Results indicate that (i) structures root onto the basal and upper *décollement*, defining an inner and an outer domain and (ii) the offset/overlap of the *décollements* controls the geometry of the transition zone located between the two *décollements*, the propagation of deformation into the foreland both in space and time, and the deformation style and kinematics in the different domains of the model. When the pinch-out of the upper *décollement* is at an angle with the backstop, oblique structures form, and the geometry and propagation-mode of the structures change progressively along-strike. We compare our experimental results with other silicone/sand analogue models and with the natural examples of the Southern Pyrenees, where Upper Triassic and Eocene–Oligocene syn-tectonic evaporites acted as basal and upper *décollements*, respectively.

1. Introduction

The presence of pre-tectonic evaporitic horizons is a common feature in numerous tectonically driven fold-and-thrust belts (Davis and Engelder, 1987). Evaporites often act as preferred detachment levels and greatly affect the forward evolution of fold-and-thrust belts (Cotton and Koyi, 2000; Costa and Vendeville, 2002; Hudec and Jackson, 2007), as has been documented in numerous natural examples such as the Atlas Mountains (Beauchamp et al., 1996, 1999), the Betic Cordillera (Blankenship, 1992), the Jura (Laubscher, 1962; Philippe et al., 1996), the Pyrenees (Teixell, 1996; Teixell and Muñoz, 2000), the central Appalachians (Davis and Engelder, 1985, 1987), the Sierra Madre Oriental in northeast Mexico (Carmelo, 1998; Fischer and Jackson, 1999; Marret, 1999), the Salt Ranges in Pakistan (Butler et al., 1987; Davis and Lillie, 1994), the Tian Shan (Li et al., 2012), the Polish Carpathian (Krzywiec and Vergés, 2007), the Zagros in Iran (Ala, 1974; Colman-Sadd, 1978) and the Reforma fold-and-thrust belt in Mexico (Peterson, 1983; González-García and Holguin-Quinones, 1991; Santiago and Baro, 1992). How basal ductile *décollements* control deformation in compressional settings has been studied extensively during the last decades by seismic analysis of on- and offshore natural examples (Letouzey et al., 1995; Brun and Fort, 2004; McQuarrie, 2004; Canérot et al., 2005; Graham et al., 2012; Callot et al., 2012) and by analogue modeling (Letouzey et al., 1995; Cotton and Koyi, 2000; Costa and Vendeville, 2002; Bahroudi and Koyi, 2003; Luján et al., 2006; Bonini, 2007; Storti et al., 2007; Konstantinovskaya and Malavielle, 2011; Bonini et al., 2012; Graveleau et al., 2012) and numerical modeling (Ellis et al., 2004; Buiter et al., 2006; Nilforoushan and Koyi, 2007; Nilforoushan et al., 2012; Wenk and Huhn, 2013). However, less attention has been paid to the interaction between two *décollements* in fold-and-thrust belts and the modes of deformation transfer between them.

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http://dx.doi.org/10.1016/j.jsg.2015.04.002

Our article focuses on the deformation style of a system that comprises two *décollements* that are vertically and laterally offset. Such geometric configuration can result either from deformation of a single, initially continuous *décollement* that has been subsequently offset by slip along a large basement fault (Fig. 1A) (Withjack and Callaway, 2000; Boston et al., 2014) or from deposition of two *décollements* of different age (Fig. 1B). In the first case, the basement fault propagates and normal movement would generate a lateral gap (Fig. 1A). Despite *décollement* location is supposed to channelize deformation coming from basement, rapid deformation could strengthen enough the evaporitic horizon which becomes nearly a brittle layer. In the second case, younger *décollement* results from deposition of evaporitic levels, where superposition between the two *décollements* depends on the sedimentary and deformation features within the basin. In several natural examples (*e.g.,* Southern Pyrenees, Carpathians, Ionian Sea, Zagros), syn-tectonic evaporites were deposited in the foreland basin (Fig. 1B) and were progressively involved in the orogenic growth. These levels, which act as upper *décollements*, contribute to widen the deformed area during the late tectonic pulses, and control its subsequent forward propagation (Martínez-Peña and Pocoví, 1988; Soto et al., 2002; Sans, 2003; Koyi and Sans, 2006). A variety of parameters, such as the relative strength of the *décollements*, the cover-*décollement* thickness ratio and the relative dimensions, stratigraphic position, geometry of the upper *décollement* with respect to that of the basal *décollement* and synkinematic sedimentation of ductile levels have been tested previously using analogue models (Verschuren et al., 1996; Leturmy et al., 2000; Bonini, 2001, 2003, 2007; Couzens-Schultz et al., 2003; Nalpas et al., 2003; Cotton and Koyi, 2000; Gestain et al., 2004; Koyi and Sans, 2006; Sherkati et al., 2006; Pichot and Nalpas, 2009). These works have pointed out that the cross sectional and/or planform geometry of the *décollements* largely influence the geometry and evolution of structures, the deformation style of the overburden (*i.e.,* from outward fold propagation to formation of passive-roof duplexes) and the coupling/decoupling of deformation.

Our study aims at better understanding how deformation is transmitted from a basal *décollement* to an upper *décollement* while varying three simple parameters: i) the amount of offset or overlap between the pinch-outs of both *décollements*, ii) the planform geometry of the upper *décollement* (pinch-out trending parallel or obliquely with respect to the basal *décollement*), and iii) the total amount of shortening. We carried out ten experiments considering systematically the geometry and timing of formation of each structure, and how and where shortening was accommodated. All experiments were analyzed by detailed monitoring, DEM (Digital Elevation Models) measurements, PIV (Particle Image Velocimetry) post-treatment and serial cross sections cut at the end of the experiment. Our experimental results show the importance of the amount of the original horizontal offset between the pinch-outs of the two *décollements*, conditioning not only the geometry and deformation between the two *décollements*, but also the geometry and kinematics of the entire thrust wedge. These results provide a better understanding of some natural examples from the South-Pyrenean foreland fold-and-thrust belt, where deformation was transferred upward from the basal Upper-Triassic evaporites and shale (the regional *décollement*) to the Eocene–Oligocene evaporitic horizons deposited in front of the advancing Pyrenean thrust sheets.

2. Methodology

2.1. Materials and scaling

Our experimental approach focuses on compressional thin-skinned deformation processes occurring in foreland basins characterized by a basal *décollement* overlain by a brittle overburden within which there is another viscous *décollement* (Upper *décollement*). We used SGM36 silicone (Weijermars and Schmeling, 1986; Weijermars et al., 1993; Mugnier et al., 1997; Leturmy et al., 2000; Bonini, 2001, 2003; Costa and Vendeville, 2002; Ellis et al., 2004; Mukherjee et al., 2012) to simulate the two viscous *décollement* layers. SGM36 is a transparent high-viscosity polydimethylsiloxane (PDMS) polymer. Within the range of strain rates (2×10^{-6} s^{-1}) used in all experiments, the silicone polymer behaved as a Newtonian fluid having a very low yield strength (Weijermars and Schmeling, 1986), as it is the case in nature with halite at geological time and space scales. We chose dry aeolian quartz sand from Nemours, France (NE34, manufactured by Sibelco,

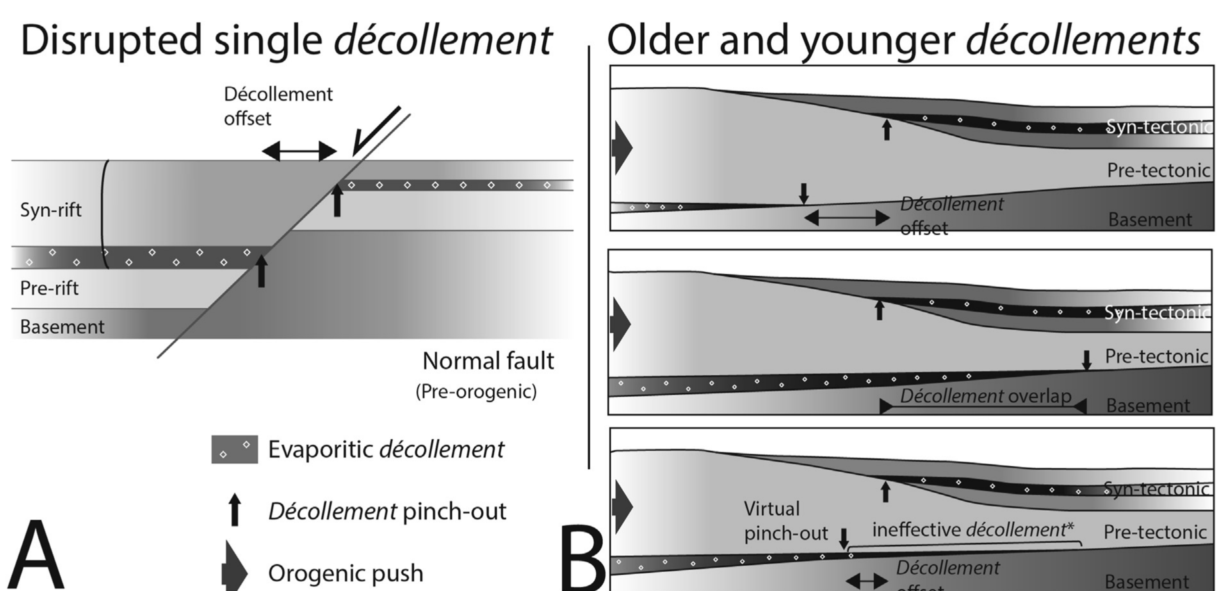

Fig. 1. Idealized natural examples illustrating several situations where a basal and an upper *décollements* are vertically separated or overlapped. A: A single evaporitic *décollement* is disrupted by a normal fault. B: Two evaporitic layers are deposited at different orogenic periods. The second might be syntectonic.