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Role of sedimentation during basin inversion in analogue modelling

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ABSTRACT

Sand-box experiments were designed to reproduce the effect of sedimentation during extensional basin development and tectonic inversion. These experiments were motivated by growing evidence for tectonic inversion in early Miocene times of an extensional basin (Abanico Basin) in the central Chilean Andes with contemporaneous intense volcanic activity. The experiments perform an extension followed by compression. The first series of experiments were performed without sedimentation in the developing basin; the second series were performed with partial filling of the basin, and the third series with total filling of the extensional basin. The effect of sedimentation on the sides of the basin was also controlled. Compression experiments reproducing tectonic inversion of the previously developed extensional basin were also performed with and without coeval sedimentation (series with null, partial or total fill, and also external sedimentation). The analogue experiments show that high amounts of sediments accumulated during the evolution of an extensional basin enhance subsidence and lead to the development of shortcuts in the footwall of the basin bounding faults during tectonic inversion. During extension the earliest appearance of normal faults occurs in the compartment with the greater sedimentary fill, and this causes asymmetric basin development. The post-extension compressional models show that the greater burden caused by a thicker accumulation of sediments within the basin inhibits tectonic inversion, causing the development of thrust structures rooted in the basin bounding faults. The accumulated sedimentary load affects both the extension and compression phases of the experiments, but has greater influence in the case of sedimentation during extension. A higher burden on the outer edges of the basin compared to the interior enhances the reactivation of normal faults and hampers the development of new thrust structures. The thrust fault(s) originating from the most loaded basin compartment develops as a footwall shortcut from the reactivated fault. With increasing sedimentation the shortcut is developed more superficially. The shortcut absorbs less deformation than the associated main fault.

1. Introduction

The concept of tectonic or structural inversion was generated from the study of petroleum basins (Lamplugh, 1920; Stille, 1924; Pruvost, 1930; Voigt, 1963). Positive tectonic inversion describes those basins that have been initially controlled by extensional faults and later reactivated with a reverse movement during a tectonic compression. Conversely, negative inversion occurs when inverse faults are reactivated with normal movement; however this case is rare (Cooper and Williams, 1989). In this paper, we will refer to positive inversion.

Analogue modelling has been frequently used to understand the mechanisms involved in the tectonic inversion of basins and the origin of associated structures (e.g. Del Ventisette et al., 2005, 2006). This experimental method is a representation of the natural system with materials similar to those existing on the Earth but with a simplified scale. There are several studies that have used analogue modelling to study tectonic inversion. Bally (1984) modeled the inversion process using a hemigraben on a listric fault. He differentiated between partial and total inversion depending on whether there is partial or complete recovery of the pre-graben situation. In the case of total inversion, the reactivation of movement along normal fault(s) results in the recovery of the stratigraphic situation as it was before extension and the extrusion of the basin-fill deposited during extension. The first studies of tectonic inversion used models where a rigid and a mobile block induced the initial geometry of the normal faults (e.g. Bally, 1984; Koopman et al., 1987; McClay, 1989; Buchanan and McClay, 1991, 1992; Mitra, 1993; McClay and White, 1995; Yamada and McClay, 2003a, b). In later models, the experiments were made with free blocks in order to study the geometry and kinematic evolution during extension and compression. Several authors have also analyzed the experimental behavior of several analogue materials

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including sand, clay and silicone (Richard and Cobbold, 1990; Nalpas and Brun, 1993; Nalpas et al., 1995; Brun and Nalpas, 1996; Keep and McClay, 1997; Dubois et al., 2002; Panien et al., 2005). Furthermore, it has been also shown that to produce inversion along high-angle normal structures in a brittle system modeled by analogue experiments, a non-coaxial angle between the compressive and extensive stresses is required (Brun and Nalpas, 1996; Gartrell et al., 2005), with an optimum angle for inversion close to 15° (Brun and Nalpas, 1996). Other studies have shown that inversion can be generated with higher angles even with orthogonal compression (Del Ventisette et al., 2006). However, these systems have been modeled generally with large ductile silicone basal layers, which creates an experimental device more easily deformable that even produces rotation of blocks on the dip direction of the faults (Brun et al., 1994; Corti et al., 2003; Del Ventisette et al., 2006). An interesting geometry generated in inverted systems results from the development of new thrust faults in the footwall block, named “footwall shortcuts”, that absorb further deformation in the inverted systems (Buchanan and McClay, 1991, 1992); but there is little analysis of their evolution and the specific factors that influence it.

There are abundant worldwide examples of regions where extension has been followed by tectonic inversion. There are classic cases of inversion in marine environments in North America, and other mountain chains (e.g. Hansen, 1986; Stone, 1989; Walker and Cooper, 1986; Buchanan and Buchanan, 1995; Knott et al., 1995; Lowell, 1995). In the Andean subduction margin, there are good examples of extensional basins, i.e., the Jurassic and Early Cretaceous back arc basins, and the Late Cretaceous and Paleogene intra-arc basins, which underwent tectonic inversion (e.g. Jordan et al., 2001; Charrier et al., 2002, 2007). Inversion, in these cases, occurred during major changes of plate dynamics that resulted in modification of the stress regime affecting the continental margin (e.g. Pardo-Casas and Molnar, 1987). A well studied case is the Abanico Basin (e.g. Vergara and Drake, 1979; Nyström et al., 1993, 2003; Kay and Kurtz, 1995; Charrier et al., 2002; Muñoz et al., 2006), developed between Middle Eocene and Late Oligocene times in the Principal Cordillera of central Chile (e.g. Charrier et al., 1994, 2002, 2005; Godoy and Lara, 1994; Burns and Jordan, 1999; Godoy et al., 1999; Jordan et al., 2001; Fock 2005; Fock et al., 2006a, b). In this basin, thick deposits of lava, volcaniclastics and minor sediments were accumulated during extension. Deposition was uninterrupted by the start of the inversion, and continued to form a new and thick volcanic succession (e.g. Charrier et al., 2002, 2005, 2007; Fock 2005; Fock et al., 2006a, b). Therefore, it is particularly interesting to understand how a partial inversion of the basin was possible along with the coeval accumulation of thick volcanic successions. Moreover, the volcanic rocks accumulated during tectonic inversion host giant Late Miocene porphyry Cu–Mo deposits such as Los Pelambres, Río Blanco-Los Bronces and El Teniente, which were emplaced along fault systems associated with the extension and tectonic inversion of the Abanico Basin (Garrido et al., 1994, 2002; Rivera and Cembrano, 2000; Rivera and Falcón, 2000; Charrier et al., 2002, 2005; Godoy, 2005). Deposition coeval to tectonic inversion (i.e. volcanic activity during compression) has not yet been considered by analogue models. In terms of mass transfer, this situation does not correspond to the classic definition of inversion (Voigt, 1963). Some analogue modelling experiments have attempted to assess the influence of sedimentation on basin development, depositing material in the basin at later stages in the extension and pre-compression phases (Nalpas and Brun, 1993; Nalpas et al., 1995; Brun and Nalpas, 1996; Dubois et al., 2002; Panien et al., 2005). These studies show that if there is no sedimentation all normal faults are reactivated to some extent, whereas with sedimentation the reactivation of the structures is limited, generating thrusts and backthrusts that cut and accommodate shortening (Dubois et al., 2002; Panien et al., 2005). However, so far no systematic attempt has been made to evaluate the influence of sedimentation on extensional basin development or the evolution of basin inversion considering all possible cases of syntectonic sedimentation. The inversion associated with deposition of volcanic deposits, and the fact that there are no detailed studies on the subject, has motivated the development of analogue models experiments described here. The application of the results to the Abanico Basin will be the focus of a future publication.

The aim of this study is to understand the effect of syntectonic sedimentation on basin development during inversion, by the way of analogue modelling. The key parameter is the location and amount of sedimentation during both extension and compression. The experiments are designed in order to simulate not only the geological example presented (from the Andean system), but also to simulate the general situation of inverted basins.

2. Analogue modelling

Modelling techniques used in these experiments are similar to those used in the experiments of brittle–ductile systems at the Laboratory of Experimental Tectonics of the Department of Geosciences, Université de Rennes I, described in detail in the literature (e.g. Faugère and Brun, 1984; Vendeville et al., 1987; Davy and Cobbold, 1991). Brittle behavior is represented by sand, with a mean friction coefficient (φ) of 0.58, a density (ρ) of 1400 kg/m^3 and a medium sand average grain size between 297 and 425 μm. Ductile behavior is represented by a mass of transparent silicone with a viscosity (μ) of 4×10^4 Pa/s at 20 °C and a density (ρ) of 960 kg/m^3 (Davy and Cobbold, 1991). The scaling parameters for extension and compression are included in Table 1.

The experimental device is similar to the one often used to model grabens and graben inversion in analogue experiments (Allemand et al., 1989; Allemand and Brun, 1991; Tron and Brun, 1991; Brun and Nalpas, 1996). It consists of a fixed and rigid base, on which a thin plate moving at a constant rate is pulled (extension) or pressed (compression) (Fig. 1). The limit of the mobile plate induces an asymmetric velocity discontinuity (VD) in the base of the model (Malavielle, 1984; Balé, 1986; Allemand et al., 1989; Ballard, 1989). The angle of obliquity used in the compressive experiments is 30° with respect to the VD (Fig. 1a) and is the best angle to produce inversion in analogue experiments according to previous studies (Letouzey, 1990; Brun and Nalpas, 1996; Panien et al., 2005; Del Ventisette et al., 2006). However, it should be noted that there are other parameters in nature that facilitate inversion, which in the aim of simplicity have not been considered here, such as the presence of internal fluids and/or ductile minerals along the fault-plane. For this reason, inversion in the presence of such factors might be produced with greater angles. Therefore, the results obtained from our experiments are not only applicable to oblique tectonic regimes, but also to more orthogonal compressive systems.

The models were built primarily with sand to represent the basement and brittle cover. In addition, a fine layer of silicone was added (1 cm thick) on top of the VD to distribute the strain on it and create a wider zone of deformation. In these experiments the silicone does not simulate any character of the crust and has exclusively a geometrical use (Brun and Nalpas, 1996). The dimensions of the experimental device are shown in Fig. 1. The basal plate used to generate the VD is glued to the mobile wall and is 0.5 mm thick and 22 cm long. The dimensions of the silicone layer are 5 cm wide, 1 cm thick and 60 cm long. Over the silicone a 5 cm thick layer of sand was placed (Fig. 1a).

Two groups of experiments were performed during this study. The first group consisted of models with extension orthogonal to the