Journal of Structural Geology 89 (2016) 30–43

Contents lists available at ScienceDirect

Journal of Structural Geology

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

Control of syntectonic erosion and sedimentation on kinematic evolution of a multidecollement fold and thrust zone: Analogue modeling of folding in the southern subandean of Bolivia

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ARTICLE INFO

Article history:
Received 30 October 2015
Received in revised form
18 May 2016
Accepted 29 May 2016
Available online 30 May 2016

Keywords:
Southern subandean of Bolivia
Multidecollement thrust zone
Analogue modeling
Syntectonic erosion and sedimentation
Decrease of exploration uncertainties

ABSTRACT

Several analogue modeling studies have been conducted during the past fifteen years with the aim to discuss the effects of sedimentation and erosion on Foreland Fold and Thrust Belt, among which a few have analyzed these processes at kilometric scale (Malavieille et al., 1993; Nalpas et al., 1999; Barrier et al., 2002; Pichot and Nalpas, 2009). The influence of syn-deformation sedimentation and erosion on the structural evolution of FFTB has been clearly demonstrated. Here, we propose to go further in this approach by the study of a more complex system with a double decollement level. The natural study case is the Bolivian sub-Andean thrust and fold belt, which present all the required criteria, such as the double decollement level. A set of analogue models performed under a CT-scan have been used to test the influence of several parameters on a fold and thrust belt system, among which: (i) the spatial variation of the sediment input, (ii) the spatial variation of the erosion rate, (iii) the relative distribution of sedimentation between foreland and hinterland. These experiments led to the following observations:

1. The upper decollement level acts as a decoupling level in case of increased sedimentation rate: it results in the verticalization of the shallower part (above the upper decollement level), while the deeper parts are not impacted.
2. Similarly, the increase of the erosion rate involves the uplift of the deeper part (below the upper decollement level), whereas the shallower parts are not impacted.
3. A high sedimentation rate in the foreland involves a fault and fold vergence reversal, followed by a back-thrusting of the shallower part.
4. A high sedimentation rate in the hinterland favours thrust development toward the foreland in the shallower parts.

1. Introduction

Several studies have shown the influence of surface processes on the structural evolution of fold and thrust belt systems, both at the scale of the lithosphere and of thrust belt systems, mainly by analogue modeling (Cobbold et al., 1993; Malavieille et al., 1993; Baby et al., 1995; Storti and et McClay, 1995; Tondji Biyo, 1995; Mugnier et al., 1997; Chemenda et al., 2000; Diraison et al., 2000; Koyi et al., 2000; Leturmy et al., 2000; Nieuwland et al., 2000; Storti et al., 2000; Bonini, 2001; Smit et al., 2003). Among them, several studies already tried to analyze the relative importance of controlling parameters such as erosion, sedimentation, decollement coupling efficiency and dip, and ratio between ductile and brittle layer at the scale of unitary compressive structures (Tondji Biyo, 1995; Nalpas et al., 1999; Casas et al., 2001; Barrier et al., 2002; Nalpas et al., 2003; Gestain et al., 2004; Pichot and Nalpas.,

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http://dx.doi.org/10.1016/j.jsg.2016.05.009

2009; Vidal-Royo et al., 2011; Barrier et al., 2013; Driehaus et al., 2014). In particular, these studies demonstrated the fundamental role played both by syn-kinematic sedimentation and erosion on the evolution of geological structures during compression. However, single decollement systems are quite rare: most of the time, the presence of several decollement levels within the stratigraphic pile tends to isolate several deformational systems partly to totally decoupled from each other, depending on various parameters and external factors such as sedimentation and/or erosion, deformation rate, and rheological contrast magnitude (e.g. Couzens-Schultz et al., 2003). Although two or three prekinematic decollement levels are quite common, such as observed in the Zagros fold-and-thrust belt (Verges et al., 2011), the Bolivian subandean belt (Labaume et al., 2001), and the Rocky Mountains (e.g. Lebel et al., 1996), relatively few studies focused on the impact of these parameters (e.g. Couzens-Schultz et al., 2003; Pichot and Nalpas, 2009; Driehaus et al., 2014).

These studies showed that deformation is strongly dependent on sedimentation rate: (i) the structures propagate forward with an overall asymmetric shape if the sedimentation is slower than the uplift velocity; (ii) the structures grow vertically and can present vergence inversion at the surface if the sedimentation rate is similar to the uplift velocity; and, (iii) the structures grow vertically with a double vergence at the surface and at depth if the sedimentation rate is higher than the uplift velocity (Barrier et al., 2013; Driehaus et al., 2014). Eventually, if the sedimentation rate is much higher than the tectonic uplift rate, a symmetrical pop-up forms, independent from the internal mechanical stratification. These results showed that the kinematic scenario of the fold development appears to be the first order element that discriminates the various interferences between sedimentation and fold growth.

Following the results obtained by Driehaus et al. (2014) in 2D, the present study aimed to characterize the fold kinematic scenario analysis, in order to properly constrain in 3D and through time the relative importance of internal factors, such as rheological stratigraphy and kinematic boundaries, upon external forces such as sedimentation and erosion. To fulfill that goal, we propose a set of analogue models imaged with an X-ray CT scanner (Colletta et al., 1991), which allows for a non-destructive 3D and repeated acquisition of the internal model geometry. This approach offers access to the kinematic evolution of the geometries. The experiments were applied to the sub Andean compressive system, resulting in a better understanding of this decoupled system. This geological case is also a strategic petroleum basin and the understanding of the 3D structural evolution is crucial for this area. Due to the geometric complexity of such geological systems Fig. 1, seismic imagery usually cannot provide well-defined images of the deeper part of the folded systems. It is thus crucial to understand the evolution of the superimposed structures in these areas to provide pertinent interpretation and assessments of eventual hydrocarbon resources. As a first approximation, analogue modeling can help to better understand these complex structural domains and especially the relationship between shallow and deep-seated structures.

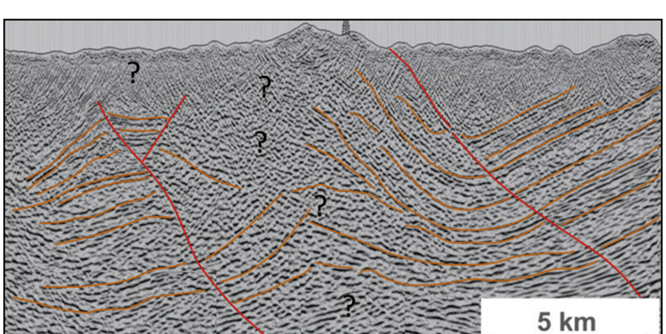

Fig. 1. Example of a seismic profile in the sub-Andean zone. The geometrical complexity does not allow a well-defined seismic imagery.

2. Geological and geographical settings

The southern Sub-Andean Zone (SAZ) of Bolivia, is a Neogene foreland fold and thrust belt, which constitutes the Eastern border of Andes Fig. 2a.

2.1. Sedimentary sequence and mechanical stratigraphy

The SAZ stratigraphy is formed by a thick, mainly siliciclastic, Paleozoic to Quaternary succession developed on top of the Precambrian basement (Sempere et al., 1999; Uba et al., 2005, 2006) Fig. 2b.

The lower part of the Paleozoic succession is marine, with about 4 km of Silurian to Devonian levels including a considerable thickness of marine shales forming the major decoupling levels (the Kirusillas, Icla and Los Monos formations) alternating with sandstones levels (Tarabuco, Santa Rosa, Huamampampa and Iquiri formations; Moretti et al., 2002).

The Subandean Carboniferous to Early Permian cycle is characterized by the deposition of marine to glacial sands and diamictites, indicating a periglacial environment. The carboniferous deposits (Machareti and Mandiyuti groups) have a total thickness of about 2 km, composed mainly of sandstones (Tupambi, Chorro and Escarpment Fms). The overlying sediments are mainly continental, with a few hundred meters of Lower Permian fluvial-eolian sandstones (Cangapi Formation), followed by a few tens of meters of evaporitic Upper Permian carbonates (Vitiacua Formations).

The Lower Triassic anhydrite/gypsum amounts to about 1 km of passing to upper Triassic to Cretaceous fluvial and eolian sandstones (Tacuru Gr.). The Miocene Yecua Formation presents lacustrine facies with local marine influences (Marshall et al., 1993). Above these units, the foreland sequences of Lower and Upper Chaco are composed of distal clastic facies of fluvial plains (with anastomosed fluvial channels) evolving to more proximal facies characterized by conglomeratic beds (Moretti et al., 2002).

2.2. Structural setting

The SAZ is a Neogene, east-verging thrust system that constitutes the Eastern border of Andes with a width of about 150 km. The main thrusts have an average spacing of 15 km with a displacement of several km Fig. 2c. This thrust system involves the Upper Silurian to Quaternary succession, which is about 10 km thick. The main basal decollement level has been defined as located in the Silurian shales (Baby et al., 1993; Colletta et al., 1999), while secondary decollements are located in the Middle Devonian (Icla and Los Monos Formations) and locally in the Carboniferous diamictites (Moretti et al., 2002). Note that Devonian shaly formations are also the source-rocks of the petroleum systems, the maturation of which could have influenced the decollement localization and timing of activity (e.g. Cobbold et al., 2009). Fold and thrust geometries are mainly controlled by lithology and by the decollement levels. Among the sub-andean structure, the Incahuasi trend has the particularity to be west verging, and is offset by at least 1 km to the East (Driehaus et al., 2014). The shallow part of the fold has a west vergence, while the other folds are oriented toward the East Fig. 2c. Driehaus et al. (2014) explained this difference in vergence by the effect of the sediment rate variation.

The development of the structural system started during the