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Research paper

Structural significance of an evaporite formation with lateral stratigraphic heterogeneities (Southeastern Pyrenean Basin, NE Spain)

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ABSTRACT

We run a series of analogue models to study the effect of stratigraphic heterogeneities of an evaporite formation on thin-skinned deformation of the Southeastern Pyrenean Basin (SPB; NE Spain). This basin is characterized by the existence of evaporites, deposited during the Early-Middle Eocene with lateral variations in thickness and lithological composition. These evaporites are distributed in three lithostratigraphic units, known as Serrat Evaporites, Vallfogona and Beuda Gypsum formations and acted as décollement levels, during compressional deformation in the Lutetian. In addition to analogue modeling, we have used field data, detailed geological mapping and key cross-sections supported by seismic and well data to build a new structural interpretation for the SPB. In this interpretation, it is recognized that the basal and upper parts of the Serrat Evaporites acted as the main décollement levels of the so-called Cadí thrust sheet and Serrat unit. A balanced restoration of the basin indicates that thrust faults nucleated at the stratigraphic transition of the Serrat Evaporites (zone with lateral variations of thickness and lithological composition), characterized by a wedge of anhydrite and shale. The analogue models were setup based on information extracted from cross-sections, built in two sectors with different lithology and stratigraphy of the evaporites, and the restored section of the SPB. In these models, deformation preferentially concentrated in areas where thickness change, defined by wedges of the ductile materials, was inbuilt. Based on the structural interpretation and model results, a kinematic evolution of the SPB is proposed. The kinematic model is characterized by the generation of out-of-sequence structures developed due to lateral stratigraphic variations of the Serrat Evaporites. The present work shows a good example of the role of stratigraphic heterogeneities of an evaporite formation which acts as décollement level on structural deformation in a fold-thrust belt. The results of this work have implications for hydrocarbon exploration and are relevant for studying structural geometry and mechanics in shortened evaporite basins.

1. Introduction

Differential loading, displacement along basement faults and/or changes in the thermal gradient drive evaporite rocks buried in sedimentary basins leading to salt flow (e.g., Koyi et al., 1993; Koyi, 1996; Hudec and Jackson, 2007). Irregularities in the basement, such as pre-existing normal faults or topographic highs, lead to salt deformation (e.g., Koyi et al., 1993; Stewart and Coward, 1995; Rubinat et al., 2013; Warsitzka et al., 2015). The role of stratigraphic irregularities of evaporite formations on salt deformation has paid less attention. However, the presence of lateral heterogeneities in the stratigraphic framework (zones with thickness and lithological composition variations attributed to palaeographical belts) has been reported from several evaporite basins (e.g., Ortí, 1974; Richter-Bernburg, 1985; Sarg, 2001; Warren, 2006).

The role of evaporites on the structural evolution in fold-thrust belts dominated by thin-skinned deformation has been studied by different methods including analogue and numerical modeling

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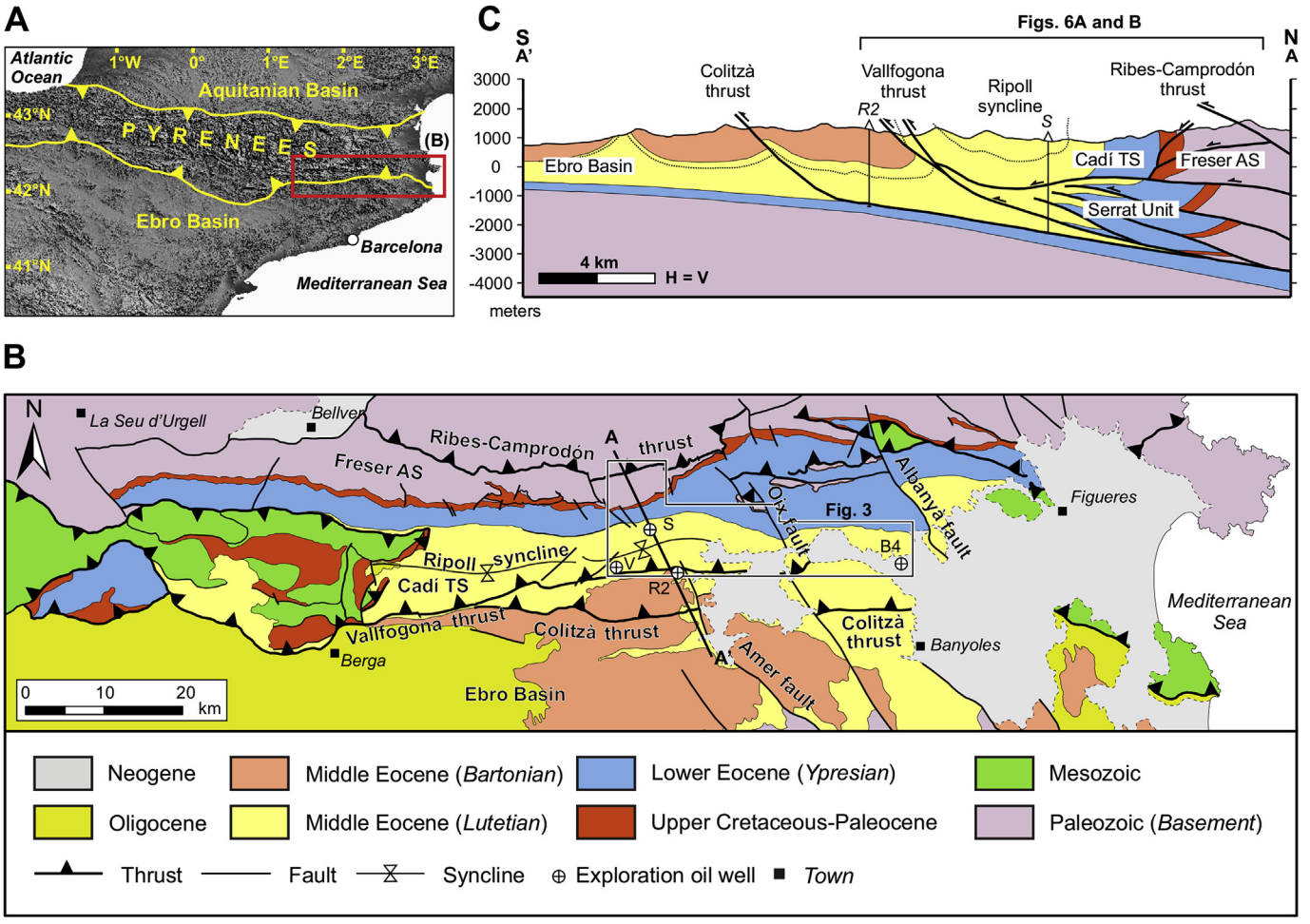

Fig. 1. Geological setting. **A,** Location of the Southeastern Pyrenean Basin (rectangle) in NE Spain (image from Google Earth). **B,** Geological map of the Southeastern Pyrenean Basin (modified from Carrillo et al., 2014) showing thrust sheets (TS), antiformal stacks (AS) and other structural features, and sectors. Rectangle indicates the location of the study area (shown in Fig. 3). Bold line corresponds to the structural cross-section A-A′ shown in **C**. Exploration oil wells: Vallfogona-1 (V), Serrat-1 (S), Riudaura-2 (R2) and Besalú-4 (B4) were drilled by *Sociedad de Exploración de Petróleos Españoles S.A.* (SEPSA), *Unión Texas España Inc.* (UTE), *Sociedad de Investigación de Petróleos S.A.* (SIPSA), and *Prohidro, S.A.*. **C,** Representative structural cross-section A-A' (see location in **B**) of the Southeastern Pyrenean Basin indicating the location of the seismic profile UTE-85-101 (presented in Fig. 6A), structural domains (rectangles) and main structural features (based on Bello et al., 2008).

(e.g., Koyi, 1988; Cobbold et al., 1989; McClay, 1989; Liu et al., 1992; Letouzey et al., 1995; Ge et al., 1997; Cotton and Koyi, 2000; Costa and Vendeville, 2002; Smit et al., 2003; Nilfouroushan et al., 2013). However, many previous modeling studies have assumed homogenous stratigraphic frameworks of evaporite formations (layers with constant thickness and composition). Only a few studies (Cotton and Koyi, 2000; Bahroudi and Koyi, 2003; Koyi and Sans, 2006; Bonini, 2001; Stockmal et al., 2007; Albertz et al., 2010; Albertz and Beaumont, 2010) have accounted for the effect of lateral irregularities in the stratigraphy on the structural evolution of shortened basins.

The Lower and Middle Eocene succession of the Southeastern Pyrenean Basin (SPB; Figs. 1 and 2), NE Spain, consists of an assemblage of carbonate, evaporite and detrital sediments, highly deformed by thin-skinned shortening, displaying lateral heterogeneities in the stratigraphic framework (Martínez et al., 1989, 1997; Vergés, 1993; Carrillo et al., 2014). The evaporites are distributed in the following lithostratigraphic units, from older to younger: Serrat Evaporites; Vallfogona Formation; and Beuda Gypsum Formation (e.g., Martínez et al., 2000; Carrillo et al., 2014). Thus, this area constitutes an ideal example to investigate the role of lateral heterogeneities in the decollement horizon on the structural deformation. The area has been the target of unsuccessful oil exploration during 1970's and 1980's, and constituted an exploration challenge for *CEPSA* Oil Company in 2007. Previous works in this area addressing the role of the evaporites on the deformation style have come to different conclusions about the structural model. Two independent interpretations of stratigraphic locations have been proposed to have acted as decollements: (1) situated in the top of the Beuda Gypsum Formation (Muñoz et al., 1986; Vergés and Martínez, 1988; Martínez et al., 1989; Vergés, 1993; Muñoz et al., 1994; Vergés et al., 1994; Martínez et al., 1997; Bello et al., 2008); and (2) located in the Serrat Evaporites (Martínez et al., 2000; Puig et al., 2003; Pallí et al., 2011; Carrillo et al., 2014; Martínez et al., 2015). However, the second interpretation has been recognized from un-balanced cross-sections. As such, a paleogeographical detachment distribution does not exist. Limited subsurface data, complex structural configuration, which is partly related to the presence of evaporite layers, and the petrophysical properties of rock salt contributing to a poor seismic imaging are some of the reasons for the different conclusions.

In this study, we explore the effect of lateral rheological irregularities in evaporite formations, which act as detachment levels, on the structural style of salt basins. We use results of a series of