Tectono-sedimentary evolution of transverse extensional faults in a foreland basin: Response to changes in tectonic plate processes

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Abstract

Late Paleocene to Middle Eocene strata in the easternmost part of the Southern Pyrenees, up to 4 km thick, provide information on tectono-sedimentary evolution of faults transversal to the Pyrenean chain. To know how changes in tectonic plate processes control the structural evolution of transverse faults and the synchronous thickness and lithological distribution of sedimentary strata in a foreland basin, field observations, interpretation of 2D seismic lines tied to lithostratigraphic data of exploration wells and gravity modelling constrains were carried out. This resulted in the following two tectono-sedimentary phases in a foreland basin: first phase, dominated by transverse extensional faulting, synchronous with deposition of marine carbonates (ca. 57 to 51 Ma); and second phase, characterized by transverse contractional faulting, coeval to accumulation of marine and transitional siliciclastics (51 to 44 Ma). During the first phase, Iberia and Adria were moving to the east and west respectively. Therefore, lithospheric flexure in the easternmost part of the Iberian plate was developed due to that Sardinia was over-thrusting Iberia. Consequently, activation of E-dipping normal faults was generated giving rise to thick-deep and thin-shallow carbonate platform deposits across the hanging walls and footwalls of the transverse structures. During the second phase, a shearing interaction between Iberia and Sardinia prevailed re-activating the transverse faults as contractional structures generating thin-shelf and thick-submarine fan deposits across the hanging walls and footwalls of the transverse structures. In the transition between the first and second phases, evaporitic conditions dominated in the basin suggesting a tectonic control on basin marine restriction. The results of our study demonstrate how thickness and lithology distribution, controlled by transverse faulting in a compressional regimen, are influenced by phases related to processes affecting motions and interactions between tectonic plates and continental blocks.

KEYWORDS

evaporites, foreland basins, Iberia, Pyrenees, Sardinia, transverse faults
1 | INTRODUCTION

The activation of structures perpendicular (transverse) to the trend of foredeep bulges in foreland basins has been widely documented. The most common are strike-slip faults whose generation has been attributed to lateral ramps of thrust sheets and tear displacements from both pre- and early-orogenic structures (e.g. Bahroudi & Koyi, 2004; Hubbard, 1999; Khan, 2002; McDougall & Khan, 1990; Morley et al., 2009; Muñoz et al., 2013; Şengör, 1990; Sylvester, 1988; Turner, Cosgrove, & Liu, 2010). By contrast, relatively few studies have documented the development and evolution of transverse extensional faults (Bianca, Monaco, Tortorici, & Cernobori, 1999; Billi, Porreca, Faccenna, & Mattei, 2006; Doglioni, 1995; Gutscher et al., 2015; Tărăpoancă, Bertotti, Matenco, Dinu, & Cloetingh, 2003; Tavani, Vignaroli, & Parente, 2015; Torelli, Grasso, Mazzoldi, & Peis, 1998). The generation of transverse extensional faults in a foredeep bulge can be explained by two mechanisms: (a) along strike stretching (Doglioni, 1995; Zhao & Jacobi, 1997) and (b) non-cylindrical forebulges (Billi et al., 2006). In the second mechanism, bending foreland lithosphere is partly surrounded by two orogenic salients. By contrast, the first mechanism has been described using only one orogenic salient.

Several of the previous studies on transverse extensional faults discuss the change in stress directions during a single compressional event (periods of less than 20 Ma). However, the way in which changes in tectonic plate processes control the structural evolution of transverse faults and the synchronous thickness and lithological distribution of sedimentary strata in a foreland basin has yet to be considered. Addressing this issue should be relevant to consider the tectono-sedimentary evolution of transverse faults as key to establish kinematic histories of complex compressional zones. These histories are useful to better explain the present-day activity of seismic and volcanic regions with more than one orogenic salient; such as the Mediterranean region. The tectono-sedimentary evolution of transverse faults can also be used for understanding hydrocarbon and geothermal systems, as it can influence the distribution of thickness of source rocks by the generation of transverse depozones; as well as the quality of reservoirs and fluid migration by the formation of fractures and favouring pathways through these faults.

The Paleocene to Eocene succession of the easternmost part of the southern Pyrenees (Figure 1a) provides an opportunity to investigate how multiphase transverse faulting in a foreland basin controls thickness and lithology distribution during tectonic plate processes. This area was located along the north-eastern margin of the Iberian Plate, which experienced continental collision with Eurasia, Corsica and Sardinia during the Eocene (Figure 1b) (Advokaat et al., 2014; Andreani, Loget, Rangin, & Pichon, 2010; Bestani, Espurt, Lamarche, Bellier, & Hollender, 2016; Lacombe & Jolivet, 2005). In the South-eastern Pyrenees, NNW-SSE striking faults are present (Figure 2a), transverse to the main W-E trend of this chain. These faults were active during the Early Eocene; interpreted as normal faulting, coeval to the Pyrenean compression (Estévez, 1970; Martínez et al., 1994; Santisteban & Taberner, 1979). However, there is still considerable uncertainty about the structural evolution, role on the stratigraphy and regional importance of these transverse faults.

In this study, we use a robust unpublished seismic reflection and well data set for the South-eastern Pyrenees in conjunction with field observations to: (a) characterize a foreland basin structure; (b) establish relations between transverse faults and thickness and lithology distributions through time and (c) record tectonic events. The South-eastern Pyrenees has been widely studied as a result of oil exploration. However, the number of boreholes is low and the quality of seismic data is poor due to the structural complexity and the existence of evaporite units (halite and anhydrite) with high-density contrasts (Figures 2b and 3). Therefore, a gravity analysis is integrated with the structural and lithostratigraphic data becoming a significant tool for validating the geological results. The aim of this work is to show how changes in tectonic plate motions and interactions control the structural evolution of transverse faults and the synchronous thickness and lithological distribution of sedimentary strata in a foreland basin. To achieve this, we study the relationship among transverse faults, thickness and lithology distributions through time with the geodynamic evolution of Iberia, Sardinia and Adria. By recording part of the geodynamic history of the Western Mediterranean region, we contribute to the knowledge of transverse extensional faults in foreland basins; specifically on 4-D structural and sedimentary evolution.
GEOLOGICAL SETTING

2.1 Geodynamical evolution

The present-day configuration of the eastern Pyrenees is the result of varying tectonic interactions among Adria, Africa, Eurasia, Iberia, Corsica and Sardinia (Figure 1b) in five tectonic stages: (a) Late Carboniferous to Permian shearing stage, developing WNW-ESE and NW-SE striking wrench joints and faults (e.g. Edel, Schulmann, Lexa, Diraison, & Géraud, 2015; Vegas & Banda, 1982); (b) Early Triassic to Early Cretaceous extensional stage, with the reactivation of the previous structures as normal faults (e.g. Le Pichon & Barbier, 1987; Malod & Mauffret, 1990); (c) Late Cretaceous to Early Miocene continental collision stage, with fault inversion and generation of fold-and-thrust belts with foreland basins (e.g. Lacombe & Jolivet, 2005; Muñoz, 1992); (d) Miocene to Pliocene extensional stage, developing normal faults parallel to the eastern coast of Spain and formation of extensional basins (e.g. Gisbert, Cai, & Gimeno, 2019; Martí, Mitjavila, Roca, & Aparicio, 1992) and (e) present-day compressional stage, with strike-slip and reverse faulting (Goula et al., 1999; Jurado, 1996).

2.2 Sedimentary record

The South-eastern Pyrenees sedimentary succession ranges in age from Triassic to Pliocene and overlies a Paleozoic basement of granite and metamorphic rocks (Figures 2 and 3) (Fleta, Escuer, Vergés, Pujadas, & Martínez, 1994; Martínez et al., 1994; Muñoz et al., 1994; Vergés, 1993; Vergés & Burbank, 1996). During the early episodes of the continental collision, the sedimentary environments were characterized by non- and shallow-marine deposition. From the Early to Late Eocene, marine facies prevailed through an Atlantic Ocean connection. However, a period of isolation from the sea (not disconnect) from 50 to 46 Ma created conditions for the deposition of marine evaporites (Puigdefàbregas, Muñoz, & Marzo, 1986; Puigdefàbregas, Muñoz, & Vergés, 1992; Vergés, 1993; Vergés & Burbank, 1996).

For the purpose of this study, the most significant lithostratigraphic units are those of the Late Paleocene as well as the Early and Middle Eocene ages, which form a sedimentary cover up to at least 2,600 m in thickness (Figure 3). The Late Paleocene to Early Eocene sequence is comprised of carbonates with a middle siliciclastic unit referred to as the Coroners Formation. Overlaying this carbonate sequence is a substantial evaporite formation, known as the Serrat Evaporites, which closely marks
the boundary between the Early and Middle Eocene. The units deposited before the Serrat Evaporites are referred to herein as the Presalt group. Above these evaporites is the Vallfogona Formation, a unit dominated by siliciclastics and carbonates, and an upper discontinuous second evaporite unit known as the Beuda Gypsum Formation. Collectively, the Vallfogona and Beuda Formations will be referred to as the Suprasalt group. The stratigraphic sequence overlying this group is the Bellmunt sequence, comprised of siliciclastic units (Busquets, 1981; Calvet, Playà, Giménez-Montsant, & Permanyer, 2007; Carrillo, 2009; Carrillo, Rosell, & Ortí, 2014; Gimènez-Montsant & Salas, 1997; Martínez, Rivero, & Casas, 1997; Martínez et al., 2000; Puig et al., 2003; Puigdefábregas et al., 1986, 1992).

2.3 | Structural features

The lithostratigraphic units are divided into two main structural zones: the autochthonous zone to the south and the allochthonous zone to the north. The boundary between these two zones is marked by the Middle-to-Late Eocene Vallfogona thrust (Figure 2a,b), a north-dipping frontal thrust (Cruzet et al., 2018; Muñoz, Martínez, & Vergés, 1986; Ramos, Busquets, & Vergés, 2002).

The autochthonous zone contains stratigraphic successions ranging from the Paleozoic (basement) to the Oligocene (Figure 2). The Ebro and Empordà basins are part of the autochthonous zone and are gently deformed by W-E trending fold and thrusts and NNW-SSE and N-S striking faults (Bello et al., 2008; Fleta et al., 1994; Martínez et al., 1994, 2000; Mató et al., 1996; Pujadas, Casas, Muñoz, & Sábat, 1989; Vergés, 1993).

The allochthonous zone is divided into two tectonic units known as upper and lower thrust sheets. The upper thrust sheets are located to the most western and eastern parts (Western and Eastern Upper Thrust sheets) of the South-eastern Pyrenees (Figure 2a), and are formed of sedimentary rocks ranging from Triassic to Late Eocene ages that were displaced between the Paleocene and Late Eocene (e.g. Martínez, Vergés, & Muñoz, ...
The lower thrust sheets are characterized by the following subunits: the Cadí thrust sheet, whose major structure is a W-E trending fold known as Ripoll syncline; and the Serrat unit, underlying the Cadí thrust sheet, bounded by both a floor-and-roof thrust (e.g. Bello et al., 2008; Martínez et al., 1997; Muñoz et al., 1986; Souquet et al., 1975). Several studies have described three stratigraphic locations for regional décollement levels: the lower décollement, situated in the Late Cretaceous-Paleocene rocks (Muñoz et al., 1986; Pujadas et al., 1989); the middle décollement, located in the Early Eocene units (Martínez et al., 1994; Muñoz et al., 1986) and the upper décollement, situated in the Serrat Evaporites (Carrillo, Koyi, & Nilfouroushan, 2017).

The Cadí thrust sheet deforms stratigraphic successions ranging from the Paleozoic (basement) to the Oligocene. This structural unit, displaced from the Middle to Late Eocene, is limited to the north by a regional backstop which was active before the Late Eocene (Figure 2b) (Martínez, Vergés, Clavell, 1988; Pujadas et al., 1989; Vergés, 1993; Vergés & Martínez, 1988).
Both the autochthonous and allochthonous zones within the study area are affected by three major east-dipping faults (Figure 2a) (Martínez et al., 2000, 1994; Muñoz et al., 1994; Pallí, Roqué, & Costa, 2011). In this study, from west to east, these faults are labelled as Western transverse fault (WTF), Central transverse fault (CTF) and Eastern transverse fault (ETF). It has been interpreted that some of these faults were generated as joints during the Late Carboniferous to Permian shearing stage and have been active since the Early Eocene (Estévez, 1970; Goula et al., 1999; Martínez et al., 1994; Santisteban & Taberner, 1979; Saula et al., 1994).

### DATA SET AND METHODS

#### 3.1 Data set

This study uses 24 prestack time-migrated 2-D seismic reflection profiles (Figure 4a) oriented N-S (perpendicular to the
main structural trend) and W-E (parallel to the main structural trend). These profiles were acquired in 1985 by Uniòn Texas España Inc. and reprocessed by CEPSA. The seismic lines are presented in two-way time (TWT), having a sample rate of 4 ms and a record length of 6 s. An estimated average interval velocity of the sedimentary cover of ca. 4,850 m/s is derived from checkshot data from wells. Although the frequency of the peak amplitude in the time-frequency gathers is nowadays not available, considering the source (dynamite) and the frequency of the geophones (10 Hz) we can assume that the dominant frequency is about 30 Hz. This means that the vertical resolution of the seismic lines is of the order of 40 m. To reflect the relations between transverse faults and thickness and lithology distributions through time, structural and stratigraphic features observed are herein described using seconds in TWT, and meters considering this velocity and applying the velocities shown in Table 1 respectively.

Our study incorporates eight exploration wells (Ampurdan-2, Banyoles-2, Besalú-4, Bestrecà-1, Riudaura-1, Riudaura-2, Serrat-1 and Vallfogona-1 in Figure 4) which were drilled by different companies (Sociedad de Exploración de Petróleos Españoles S.A., Uniòn Texas España Inc., Sociedad de Investigación de Petróleos S.A. and Prohidro, S.A.) between 1960 and 1992. Borehole information contains electrical log records (gamma ray, sonic, spontaneous potential, resistivity, bulk density and neutron), dip-meter, vertical seismic profiles (VSP) and around 14.5 km of combined lithologic records based on cores and cuttings. In addition, lithological descriptions for the exploration well/S43, as reported by Vidal-Pardal (1954), were considered.

Field descriptions and measurements (stratigraphic and structural features) were collected during field campaigns. This information enabled the updating of previous geological maps (Martínez et al., 2000, 1994; Mató et al., 1996; Muñoz et al., 1994; Pi et al., 2000) and the generation of eight key lithological sections (sections 1 to 8) in the Cadí thrust sheet (Figure 4b). Lithological information from the Serrat-1 and Bestrecà-1 wells was used to complete two of these sections (sections 2 and 4 in Figure 4b respectively).

A detailed gravity survey was conducted with a total of 844 data points measured (Figure 4a) with a Lacoste-Romberg gravity meter, model G831, and referred to the IGSN-71 through the Spanish Gravity Net. Spatial positioning and height of the stations were obtained from global positioning systems (GPS) and benchmarks with an elevation precision of ±0.1 m. The new gravity measurements were integrated with data from previous surveys (Martínez et al., 1997; Rivero, 1993; Rivero, Pinto, & Casas, 2002).

### 3.2 Methodology

#### 3.2.1 Structural and stratigraphic framework

Four main and relevant horizons were interpreted from all seismic profiles based on relationships obtained from surface and subsurface stratigraphy, VSP and synthetic seismograms (Figure 5). These horizons are as following: (a) boundary between the Basement and overlying sedimentary cover; (b) top of the Presalt group; (c) top of the Serrat Evaporites and (d) top of the Suprasalt group. Another useful surface that provides a stratigraphic control of tectonic events through the time is the top of the Corones Formation, which was used to differentiate the Presalt group into two sub-groups: the Lower Presalt and the Upper Presalt. To match the structural interpretation between the autochthonous and allochthonous zones, 2-D and 3-D surface horizons and fault restorations were performed. According to Carrillo et al. (2017), a shortening of 30% and 15% of the Cadí thrust sheet and the

| Stratigraphy     | Lithology                               | Velocity (m/s) | Density (g/cm³) |
|------------------|-----------------------------------------|----------------|----------------|
| Bellmunt sequence| Conglomerates, sandstones and marls     | 3,000–4,900    | 2.45–2.60      |
| Suprasalt group  | Siltstone, sandstone, limestone, dolostone and anhydrite | 4,700–4,900 | 2.72 |
| Serrat Evaporites| Anhydrite, dolostone, limestone and marl | 5,300–5,700 | 2.83 |
|                  | Anhydrite                               | 6,000–6,100    | 2.90 |
|                  | Shale and anhydrite                      | 4,600          | 2.70 |
|                  | Salt                                     | 4,300          | 2.10 |
| Presalt group    | Limestone and dolostone                 | 5,100–5,600    | 2.67 |
|                  | Shale, marl and limestone                | 4,900          | 2.63 |
| Basement         | Granite                                  | 5,500          | 2.64 |
|                  | Schist, sandstone and limestone          | 5,500          | 2.72 |

*Extracted from previous works (Carrillo et al., 2014; Martínez et al., 1997; Rivero et al., 2001).*
CARRILLO et al.

structural Serrat unit, respectively, was taking into account for these restorations.

To highlight fault growth in 3-D and evaluate the impact of the transverse structures on sediment thickness in time and space, isochron and isopach maps (Figures 6 and 7) and a lithostratigraphic well correlation (Figure 8a) of the main horizons were generated based on seismic interpretation and surface mapping. In the case of the Suprasalt group and its overburden (the Bellmunt sequence), interval velocity is well constrained in the Cadi thrust sheet and the Empordà Basin, and it was converted from time to depth. An average velocity of 3,900 m/s, which corresponds to the average velocity of this group and

FIGURE 5 Key sections (see Figure 4b for locations) illustrating seismic lines (above) and geoseismic sections (below). Triangles, situated on the tops, indicate intersections with other lines and sections. In the seismic lines, lithostratigraphic markers from exploration wells and the location of detailed lines and sections (rectangles in [c] and [d]) are displayed. In the geoseismic sections, the main structures and their relation with the lithostratigraphic units at the present day are shown on the basis of the lithostratigraphic markers, seismic lines and surface information. (a) Section across the Ebro Basin showing the Western transverse fault (WTF). (b) Section across central parts of the autochthonous and allochthonous zones illustrating the WTF and the Central transverse fault (CTF). Note that, in the allochthonous zone, the CTF has a reverse movement. (c) Section across the Empordà Basin where the Eastern transverse fault (ETF) is shown. (d and e) Sections across northern parts of the autochthonous and allochthonous zones illustrating the WTF and the CTF. Note that, in the allochthonous zone of e, the WTF has a reverse movement. CTF, Central transverse fault; WTF, Western transverse fault
overburden (Table 1), was used for this conversion. To identify the impact of transverse structures from field evidence, the eight lithological sections were correlated with a W-E orientation (Figure 8b). Observations from detailed seismic profiles and outcrops (Figure 9) were incorporated into our study, supporting the structural and stratigraphic interpretations.

3.2.2 | Gravity modelling

All the combined gravity data were reduced using the classical formulae of the Bouguer anomaly, where a series of corrections were applied to eliminate the non-geological causes related to gravity variations, including topographic correction. The Bouguer anomaly values were then interpolated by kriging to a 0.5 km × 0.5 km square grid and contoured. As the Bouguer anomaly map integrates the effect of both long- and short-wavelength components, the regional factor was removed from the Bouguer anomaly to obtain a residual anomaly map. This last map was assimilated to a second-order surface whose orientation is consistent with the gravity map of the Pyrenees (Casas, Kearey, Rivero, & Adam, 1997).

To understand residual gravity anomalies and constrain the structural and stratigraphic interpretations, three representative cross-sections were selected and converted from time (in TWT) to depth (Figure 10). The lithologies and interval velocities used for the conversion are listed in Table 1. The residual gravities of these sections were calculated, obtaining inversion models and compared with the measured ones (from the residual gravity map). The densities, assumed for the calculated gravities (Table 1), were extracted from previous works (Carrillo et al., 2014; Martínez et al., 1997; Rivero, Vilas, Pinto, & Casas, 2001).
3.2.3 | Basin and regional framework

The isopach maps were integrated with the stratigraphic correlations and results of the detailed seismic and outcrop interpretations as well as the results documented in previous works to produce three novel paleogeographic maps (Figure 11). These maps correspond to tectono-sedimentary stage models. Each map shows structural features and depositional lithofacies, integrating both the autochthonous and allochthonous zones and accounting for the fore-mentioned shortenings established by Carrillo et al. (2017).

The paleogeographic maps were compared with regional tectonic studies to identify relationships between thickness and lithological distributions of sedimentary strata, influenced by transverse faults, and tectonic plate processes, such as Iberia and Sardinia. To illustrate these relationships, we constructed a transorogenic (350-km-long) cross-section at the scale of the lithosphere (Figure 12). This section shows the geodynamic evolution of Iberia and Sardinia during part of the continental collision stage (Late Paleocene to Middle Eocene), based on previous works, and the tectono-sedimentary features obtained in this study. Finally, to highlight the contribution of our work, a comparison between the tectono-sedimentary evolution of the studied transverse faults and similar structures in other regions was achieved.

4 | STRUCTURE

In this study, it is observed that the major transverse structures affect the Basement and sedimentary succession ranging from the Presalt group to the Bellmunt sequence in both the autochthonous and allochthonous zones with a high of at least
FIGURE 7  Isopach maps in the autochthonous zone for the Presalt group and the Serrat Evaporites (a and b), in time (0.05 s TWT counter interval), and the autochthonous and allochthonous zones for the Suprasalt group (c), in thickness (100 m counter interval), illustrating the main faults (black and dotted white lines), the present-day location of the Vallfogona thrust (red lines) and exploration wells (labelled circles). Exploration wells: A2, Ampurdan-2; B1, Bestrecà-1; B4, Besalú-4; R1, Riudaura-1; R2, Riudaura-2; S1, Serrat-1; V1, Vallfogona-1
2.00 s TWT (ca. 4,850 m) (Figures 4b and 5). In the case of the WTF, the upper fault tip is located up to the lower part of the Bellmunt sequence (Figure 5a,b). These faults divide the study area into structural blocks (Figure 6), with footwalls and hanging walls as well as secondary structures which are irrelevant in this study. To understand fault growth and thickness
variations through the time, a description of the present-day structural features is presented in the following sections.

4.1 | Transverse faults

4.1.1 | Western transverse fault (WTF)

In the Ebro Basin, the WTF is located eastward of the Riudaura-1 well (Figure 4b). Here, this structure has a maximum throw of 0.45 s (ca. 1,100 m) at the top Basement with a normal geometry (Figure 5a). Based on a 3-D geometry of the seismic horizons, it is observed that this structure continues north below the Vallfogona thrust with a maximum throw at the top Basement of 0.83 s (ca. 2,010 m) and a normal geometry (Figure 6a). In the autochthonous zone, the length of the WTF is at least of 15 km.

In the Cadí thrust sheet, a significant NNW-SSE fault, exposed in the northwest region of the study area (Martínez, Carrillo, Tallada, & Copons, 2015; Muñoz et al., 1994), has been described in previous works. Based on restorations, this fault links to the WTF in the autochthonous zone. Here, this fault has a reverse and dextral movement with a throw at the top Serrat Evaporites of 0.15 s (ca. 360 m). In the northern part of the Cadí thrust sheet, the WTF steps westward and displays a normal kinematic sense (Figure 5d,e).

4.1.2 | Central transverse fault (CTF)

In a similar manner to the WTF, the CTF in the allochthonous zone fits with an ENE-dipping fault below the Vallfogona thrust (Figures 5d and 6a). This second fault corresponds to the CTF in the autochthonous zone having a normal geometry and throw at the top Basement of up to 0.54 s (ca. 1,310), which decreases northward. In the autochthonous zone, the length of the CTF is at least of 5 km.

In the Cadí thrust sheet, the CTF is superimposed by a NNW-SSE trending anticline with a length of at least of 12 km (Figures 5b and 6b). This anticline affects the stratigraphic successions ranging between the Presalt group and the Bellmunt sequence, including the sequences of the structural Serrat unit. Geometrically, the fold has a low curvature and its west limb is steeper than the east limb. In the western limb, the CTF is observed with a reverse movement and a throw at the top Serrat Evaporites of 0.15 s (ca. 360 m). In the northern part of the Cadí thrust sheet, the CTF steps westward and displays a normal kinematic sense (Figure 5d,e).

4.1.3 | Eastern transverse fault (ETF)

In the northern part of the ETF, the structure displays a reverse displacement of horizons in the autochthonous zone with a throw at the top Basement of 0.58 s (ca. 1,410 m) (Figure 6a). To the south, this fault has a normal geometry with a maximum throw of 0.88 s (ca. 2,135 m) (Figure 5c).
FIGURE 10  Two-dimensional inversion gravity models (calculated) versus the measured residual gravity (above) in three key sections (below). Triangles, situated on the tops, indicate intersections with other models. In the key sections, the main structures and their relation with lithologies at the present day are shown. Location of the Central model (a), Eastern model (b) and Northern model (c) correspond to the position of Figure 5b-d (see Figure 3b) respectively. CTF, Central transverse fault; ETF, Eastern transverse fault; WTF, Western transverse fault.
However, this throw decreases to 0.39 s (ca. 950 m) in the most southern part. The ETF has a length of at least of 16 km.

4.2 Structural blocks

All the structural blocks in the study area contain low relief (<0.13 s depth; ca. 315 m) basement folds and faults. In the autochthonous zone, the footwall block of the WTF is mainly characterized by a NW-verging monocline (Figure 6a). By contrast, both the footwall and hanging wall blocks of the CTF present W-verging half-grabens. The hanging wall block of the ETF contains a S-verging graben monocline and an E-W trending blind fold thrust, extending almost until the ETF (Figure 5c).

In the Cadí thrust sheet, the footwall of the WTF shows the geometry of the Ripoll syncline with a horizontal fold hinge (Figure 6b). Between the WTF and the CTF, the Serrat Evaporites are affected by a NNW-SEE trending depression (Figure 5d). Moreover, in the structural Serrat unit, an evaporite dome is noted in the north-eastern sector of the related block.

From the CTF to the ETF, two structural areas are recognized: the west side with a depression and the east side with a high.

5 Thickness and lithological distribution

Thickness and lithology variations in the lithostratigraphic units are identified in both the autochthonous and allochthonous zones (Figure 5). These distributions vary markedly adjacent to the transverse faults as well as the low relief basement folds and faults (Figures 7 and 8). The variations are described separately for the Presalt group, the Serrat Evaporites and the Suprasalt group.

5.1 Presalt group

In the autochthonous zone, the thickness of the Presalt group increases across the footwalls to the hanging walls of the transverse faults (Figure 7a). In the footwall of the WTF, a
thickening of this group to the north-western sector is observed, varying from 0.14 to 0.32 s (ca. 370–840 m) thick. In the footwall of the CTF, a depocenter is recognized adjacent the WTF. This depocenter has a maximum thickness of 0.51 s (ca. 1,340), which dramatically decreases southward to 0.18 s where the throw of the WTF is less (Figure 6a). Toward the CTF, the thickness is reduced to 0.10 s (ca. 260 m). In the hanging wall of the CTF, the Presalt strata thickness is 0.39 s (ca. 1,020 m), which decreases slightly to the centre of the block. In the north-eastern sector of this block, a depocenter of up to 0.38 s thick is noted on an axial trace of a SW-NE trending basement syncline. In the southern sector, the Ampurdan-2 well crossed the entire Presalt Group (441 m thick), on a structural high (Figure 8a). In the hanging wall of the ETF, from outcrop the Presalt thickness is 2,200 m (stratigraphic section 8, Figure 8b). The greatest subsurface thickness in the study area (up to 1.10 s; ca. 2,670 m) is observed within the northern and central sectors of this block (Figures 5c and 7a). However, this thickness estimate is affected by structural thickening (up to ca. 30%), related to a blind fold-thrust (Figure 5c). The thickness decreases towards the southern sector of the block, where the throw of the ETF is less (Figure 6a).

In the Cadí thrust sheet, the thickness of the Lower Presalt increases greatly across the CTF and ETF from the footwall to hanging wall (Figure 8b). The same occurs for the Upper Presalt across the ETF; conversely, the thickness of the Upper Presalt decreases across the CTF. The structural block between the WTF and the CTF displays westward thickening of the Presalt group from 1,340 to 1,980 m and 1,110 to 1,340 m for the structural block between the CTF and ETF.

The thinnest (<500 m thick) successions of the Presalt group are dominated by about 80% of limestones and 20% of marls and sandstone in both the Ebro and Empordà basins and the allochthonous zone (Figure 8). On the contrary, the thickest (>500 m thick) successions are formed of 50% marls and shales and 50% of limestones and sandstones.

5.2 Serrat Evaporites

In the autochthonous zone, the thickness of the Serrat Evaporites increases across the footwalls to hanging walls of the CTF and in the southern part of the ETF (Figures 5b and 7b). In the footwall block of the WTF, the average thickness of the Serrat Evaporites is 0.20 s (ca. 520 m). However, the thickness increases to 0.27 s along the Serrat Evaporites-Vallfogona thrust contact, probably due to structural thickening (salt tectonics). The footwall of the CTF shows a peculiar E-W
trending “salt” wall with thicknesses up to 0.34 s (ca. 885 m) below the Vallfogona thrust (Figure 6a). To the north and south of this wall, the evaporitic succession is thinnest (Figure 5b,d) with, locally, low values of 0.05 s (ca. 130 m) (“salt” welds). In the footwall block of the ETF, the Serrat Evaporites unit thickens from 0.1 s (ca. 260 m) thick in the central region to 0.25 s (ca. 650 m) thick towards the CTF. In the south-eastern sector of this block, near the contact between the Serrat Evaporites and the Vallfogona thrust, the thickness is around 0.29 s (ca. 750 m). However, eastward of the Besalú-4 well, the thickness decreases to 0.07 s (ca. 180 m) on a basement high (Figure 5c).

The unit thicknesses in the Ampuradan-2, S-43 and Banyoles-2 wells are 240, 160 and 220 m respectively (Figure 8a). In the hanging wall of the ETF, the evaporites are not recognized outcropping northward (section 8 in Figure 8b), where the ETF has a reverse geometry (Figure 6a). On the other hand, to the south, a thin (0.07 s thick) succession of the Serrat Evaporites is recognized with erosional truncations (Figure 9a). This succession increases in thickness southward, up to 0.37 s (ca. 960 m) thick, where a significant depocenter is present.

In the allochthonous zone, different areas of prominent thickness of the Serrat Evaporites are observed (Figure 5b,d). In the Cadí thrust sheet, these areas are located in the north limb of the Ripoll syncline, westward between the WTF and CTF, with at least 0.17 s (300 m thick; Figure 8b), and in the eastern part between the CTF and ETF, at least 0.20 s (ca. 520 m) thick. By contrast, thin (<100 m thick) successions of the Serrat Evaporites are recognized eastward of the footwalls related to the WTF and CTF. In the structural Serrat unit, an area with a marked thickness of at least 0.78 s (ca. 2,030 m) is observed on the footwall of the WTF (Figure 5e). This thickness decreases progressively in the footwall of the CTF. In the anticline superimposing this structure, another area with a significant thickness of at least 0.51 s (ca. 1,330 m) is noted (Figure 5b).

The lithology distribution of the Serrat Evaporites has the following features: (a) in the Ebro Basin, anhydrite and carbonate layers dominate the structural highs (Figure 8a); (b) in the structural Serrat unit, in agreement with Carrillo et al. (2014), anhydrite and shale prevail between the WTF and CTF in the north limb of the Ripoll syncline; and (c) in the Cadí thrust sheet, successions of anhydrite with a minor content of salt are present in the footwalls of the transverse faults (Vallfogona-1 well; Figure 5b in Carrillo et al., 2017), while salt with minor content of anhydrite are observed in the hanging walls (Serrat-1 well; section 2 in Figure 8b).

5.3 Suprasalt group

In the autochthonous zone, the thickness of the Suprasalt group increases from the footwall to hanging wall across both the WTF and ETF (Figures 5a and 7c). In the footwall of the WTF, 100 m of the Suprasalt group was measured in the Riudaura-1 well. Adjacent the WTF hanging wall, a thickness up to 0.36 s (ca. 860 m) is identified (Figure 5b). Just east of the CTF, within the CTF hanging wall, this group reaches at least 0.25 s (ca. 600 m). This thickness decreases eastward, adjacent the ETF, ranging from 80 to 150 m thick (Figure 8a). In the hanging wall of the ETF, the Suprasalt group displays up to 220 m thick in the northern part (Figure 8b).

In the northern limb of the Ripoll syncline in the Cadí thrust sheet, the thickness of the Suprasalt group decreases from the footwalls to hanging walls across the WTF and ETF (Figure 8b). By contrast, the thickness increases across the faults on the synclinal southern limb (Figure 9b). Therefore, in the north-eastern and south-western parts of the related structural blocks, depocenters ranging from 500 to 1,000 m thick for the Suprasalt group are identified (Figure 7c). While, in the north-western and south-eastern parts, the thickness decreases abruptly with values lower than 500 m. Seismic reflectors of the Suprasalt group onlapping the Serrat Evaporites are recognized in the south-western depocenter towards the transverse faults (Figure 9b).

The thinnest (up to 250 m thick) successions of the Suprasalt group are mainly dominated by carbonate, siltstone and sulphate layers (Figure 8). These successions are identified in the Ebro and Empordà basins as well as the local eastern part of the Cadí thrust sheet. By contrast, the thickest (>250 m thick) successions are formed of siltstone, sandstone and sulphate layers.

6 GRAVITY CONSTRAINTS

In the residual gravity map, values ranges from 13 to −10 mGal. A series of significant anomalies and variations on residual gravity with NNW-SSE, NW-SE and NE-SW directions are observed. In the inversion models (Figure 10), part of these variations are located around the transverse faults. The models are referred to herein as “Central model” (Figure 10a), related to Figure 5b, “Eastern model” (Figure 10b), for Figure 5c, and “Northern model” (Figure 10c), linked to Figure 5d. While small variations in the thicknesses and densities used in the models can render similar residual gravity trends, no alternative structural interpretation has been found that matches the information available.

6.1 Central model

In the Central model (Figure 10a), a positive residual anomaly of up to 4 mGal is identified in the westernmost
sector. We relate this anomaly to the existence of a 1.8-km-thick deposit of pure anhydrite (>80% in anhydrite content with an average density of 2.90 g/cm³) of the Serrat Evaporites, forming part of a relative thin (up to 3.0 km thick) sedimentary cover. Residual gravity decreases to −1 mGal at the axis of the Ripoll syncline, indicating a thickening (up to 4.1 km) of this sedimentary cover and thinning of the anhydrite deposit. Residual gravity increases up to 1 mGal at the CTF, signifying a thin sedimentary cover with thickening of the anhydrite deposit. From the CTF towards the Vallfogona thrust, residual gravity initially decreases to −1 mGal, however, continuing east it increases to a positive anomaly of up to 5 mGal. The negative value is attributed to a salt body (2.10 g/cm³) up to 0.8 km thick in the structural Serrat unit. The positive anomaly is associated with thickening (up to 2.1 km) of the anhydrite deposit within a thin (up to 2.5 km thick) sedimentary cover. Eastward of the Vallfogona thrust, a negative residual anomaly of up to −8 mGal is recognized. We relate this anomaly to the following three features: (a) presence of the thinnest (0.7 km thick) sedimentary cover; (b) low thickness (<0.4 km thick) of the anhydrite deposit and (c) thickening of siliciclastics (2.45–2.60 g/cm³) of the Bellmunt sequence.

6.2 | Eastern model

In the Eastern model (Figure 10b), between the Ampurdan-2 well and the intersection point with Figure 10a, the residual gravity gently reduces from −7 to −9 mGal. These negative values are associated with the same three features listed for the easternmost section of the Central model. These facts, combined with the Ampurdan-2 lithologic descriptions (Figure 8a), suggest a change in the basement lithology, from a high to low concentration of schist and increment of granite (2.72 and 2.64 g/cm³ respectively). From the Central model intersection point to the hanging wall of the ETF, the residual gravity rises abruptly up to −3 mGal. This change is mainly due to two features: (a) a variation in both lithology and thickness of the Serrat Evaporites, from anhydrite and carbonate (2.83 g/cm³) at −0.4 km thick to pure anhydrite at −1.0 km thick; and (b) a variation in lithology of the Basement, from granite to schist. Towards the north-eastern end of the Eastern model, residual gravity increases up to −2 mGal due to reduced thickness of the siliciclastic Bellmunt sequence.

6.3 | Northern model

In the Northern model (Figure 10c), from southeast to northwest, the residual gravity increases from 0 to 4 mGal in a NW direction. This positive trend is attributed to the existence of a thick deposit (1.0 km) of pure anhydrite in the frontal part of the structural Serrat unit. Passing northeast from the Cadi thrust sheet to the CTF, residual gravity reduces to −8 mGal, indicating a decrease in anhydrite content in the passage towards a more shale and salt prone section in the structural Serrat unit. A salt dome was added to the model to explain the lowest residual gravity point. Continuing northeast, the residual gravity rises to −5 mGal, suggesting a thick deposit (1.2 km) of pure anhydrite below the Vallfogona thrust. Residual gravity values then drop up to −8 mGal, which is associated with a reduction in anhydrite thickness.

7 | TECTONO-SEDIMENTARY EVOLUTION OF THE TRANSVERSE FAULTS

We propose three paleogeographic maps for the Late Paleocene to Middle Eocene tectono-sedimentary evolution of the main transverse faults addressed in this study (WTF, CTF and ETF) (Figure 11). In addition, these maps include the evolution of N, NNE, NW and NE dipping faults also identified in the study area. The N and NNE dipping faults, located in the northern and north-eastern parts of the study area, have been interpreted in previous works (Martínez et al., 1989; Pujadas et al., 1989). The maps are synchronous to the sedimentation of the Presalt group, Serrat Evaporites and Suprasalt group, corresponding to the following sedimentary stages: Stage 1 (Figure 11a), Late Paleocene to Early Eocene (57 to 51 Ma); Stage 2 (Figure 11b), Early to Middle Eocene (51 to 49 Ma); and Stage 3 (Figure 11c), Middle Eocene (49 to 44). The maps emphasize: (a) basin topography of the structural blocks; and (b) the relationships among this topography, lithology and thickness.

7.1 | Stage 1: Late Paleocene to Early Eocene (57 to 51 Ma)

Thickening of the Presalt strata across the footwalls to the hanging walls of the transverse faults (Figures 7a and 8) suggests that these structures worked as normal faults during Stage 1 (Figure 11a). This fact is in agreement with Estévez (1970) for the ETF. Southward thinning of the strata along these structures indicates changes in throw.

Based on the relationships between thickness distribution, as controlled by extensional transverse faulting, and lithology of the Presalt strata (Figures 7a and 8), the following tectono-sedimentary features are interpreted for the present stage: limestones, deposited in structural highs (footwalls); and shales and marls, deposited in structural depressions (hanging walls) (Figure 11a). In agreement with previous works (Giménez-Montsant & Salas, 1997; Martínez et al., 1988),
the shale and marl correspond to deep platform environments, and the limestone to shallow platform. In turn, this study interprets that NNW-SSE depositional–environmental belts were formed within each of the structural blocks, characterized by deep platform environments to the west and shallow platform environments to the east. According to Giménez-Montsant and Salas (1997), the north-eastern part of the study area was a shallow detrital environment, attributed to a delta plain deposited on an uplifted eastern margin.

### 7.2 Stage 2: Early to Middle Eocene (51 to 49 Ma)

During the second stage, a westward thickening of the Serrat Evaporites between the WTF and CTF in the Cadí thrust sheet (Figure 8b) suggests that normal faulting was active in the northern portion of the WTF (Figure 11b). Determining topographic and tectonic configuration along the southern portion of the WTF is problematic, due to the high degree of present-day deformation observed for the Serrat Evaporites along this structure (Figure 7b). However, normal faulting is also proposed for the southern sectors of the CTF and ETF as they demonstrate the expected stratigraphic thickening across the footwall to the hanging wall blocks in the autochthonous zone (Figure 10). On the other hand, the northward thinning along the ETF hanging wall and the unconformities within the Serrat Evaporites (Figure 9a) indicate contractional faulting along the northern portion of the ETF. In the case of the salt dome modelled in the structural Serrat unit between the WTF and CTF in the Cadí thrust sheet (Figure 8b) suggests that normal faulting was active in the northern portion of the ETF (Figure 11b). The structural evolution of the transverse faults and the tectono-sedimentary features worked as normal faults during Stage 3 (Figure 11c). However, northern and north-western thinning of the units within the same blocks (Figure 8b) indicates contractional faulting along the northern portions of the transverse structures. In the case of the ETF, the erosional truncations of the Suprasalt group on the Serrat Evaporites in the northern sector of the Empordà Basin (Figure 9a) suggest that the contractional zone migrated southward from that in Stage 2, and was located further south than the contractional zones of the WTF and CTF in Stage 3.

Based on the relationships between lithology of the Suprasalt strata (Figure 8) and thickness distribution, as controlled by transverse faulting, the following tectono-sedimentary features are interpreted for the current stage: carbonate, siltstone and sulphate layers, deposited in structural highs (footwalls); and siltstone, sandstone and sulphate layers, deposited in structural depressions (hanging walls) (Figure 11a). In agreement with previous works (Carrillo et al., 2014; Costa, 1989), the carbonate, siltstone and sulphate layers correspond to shelves, and the siltstone, sandstone and sulphate layers to slope/submarine fans. Thus, in this study, it is interpreted that slope/submarine fans concentrated in the northern and south-western parts of the structural blocks.

### 7.3 Stage 3: Middle Eocene (49 to 44 Ma)

Thickening of the Suprasalt strata across the footwalls to the hanging walls of the transverse faults in the autochthonous zone and the southern part of the Cadí thrust sheet (Figure 7c) suggests that the southern portion of these structures worked as normal faults during Stage 3. However, northern and north-western thinning of the units within the same blocks (Figure 8b) indicates contractional faulting along the northern portions of the transverse structures. In the case of the ETF, the erosional truncations of the Suprasalt group on the Serrat Evaporites in the northern sector of the Empordà Basin (Figure 9a) suggest that the contractional zone migrated southward from that in Stage 2, and was located further south than the contractional zones of the WTF and CTF in Stage 3.

The results described above, collaborated with descriptions of eastern Pyrenees tectonic processes, open a discussion on how changes in tectonic plate motions and interactions control the structural evolution of transverse faults and the synchronous thickness and lithological distribution of sedimentary strata in a foreland basin.

The structural evolution of the transverse faults and the synchronous thickness and lithology distribution across these structures, as observed in this work (Figure 11), indicates a progressive change from stretching to contractional mechanisms migrating from north to south along faults and east to west across structural blocks. This change occurred during the ending of the Early Eocene (ca. 51 Ma) as a response of tectonic processes affecting Iberia and Sardinia. To evaluate this response, we present a cross-section (Figure 12) which assumes the following two points: (a) Sardinia and Corsica were an independent continental block, not a part of Iberia; and (b) during the Eocene, the southernmost part of Sardinia was tectonically interacting with the easternmost part of Iberia. These points are in agreement with previous works (Advokaat et al., 2014; Andreani et al., 2010; Bestani
et al., 2016; Horner & Lowrie, 1981; Lacombe & Jolivet, 2005).

The present-day thickness of the Iberian continental crust is characterized by eastward thinning, from ca. 45 km in the central Pyrenees to ca. 20 km in the Empordà Basin (Chevrot et al., 2018). This thinning is due to the Miocene to Pliocene extensional stage, which displaced Sardinia with a counterclockwise rotation to the present-day position (e.g. Roca, Sans, Cabrera, & Marzo, 1999). The two continental blocks of Sardinia and Corsica have a maximum crustal thickness of 34 km (Egger, Demartin, Ansorge, Banda, & Maistrello, 1988), and they thin up to 25 km along the margins (Gailler, Klingelhofer, Olivet, Aslanian, & Sardinia-group, 2009; Prada et al., 2013). According to Bestani et al. (2016), the south-eastern part of Eurasia and Corsica had maximum crustal thickness of 60 km during the Eocene. Therefore, in this study, it is assumed that during the same epoch, the easternmost part of the Iberian as well as the Sardinian crust would have been thicker than the present day, between 45 and 60 km.

According to previous works (Macchiavelli et al., 2017; Malusà, Danisšť, & Kuhlemann, 2016), two tectonic phases related to motions of Adria and Iberia, with respect to Eurasia, are distinguished from the Late Paleocene to Middle Eocene. These phases are illustrated in Figure 12, where the first phase takes place from 57 to 51 Ma and a second phase between 51 and 44 Ma. The relationships between these phases and the tectono-sedimentary evolution of the South-eastern Pyrenees and southern part of Sardinia are discussed below.

### 8.1.1 First phase (57 to 51 Ma)

During the first phase, Iberia was moving east and Adria to the west, relative to Eurasia (Macchiavelli et al., 2017; Malusà et al., 2016). Consequently, it is known that during the Early Eocene, Sardinia and Corsica were over-thrusting Iberia and Eurasia forming an active N-S striking mountain range (Figure 12a) (Andreani et al., 2010; Bestani et al., 2016; Lacombe & Jolivet, 2005). It is assumed in this study that the boundary between the Iberian plate and the Sardinian block was marked by a main thrust known as the present-day Northern Balearic Fracture Zone (NBFZ; Figure 1a).

In the Sardinian block, we identify three domains which prevailed during the first phase, from west to east: (a) a high-relief thrust system, verging to the east and deforming basement units and a sedimentary Mesozoic cover; (b) a Tethyan-influenced marine piggy-back basin and (c) a basement high with a sedimentary Mesozoic cover (Figure 12a). Apatite U-Th/He (AHe) with cooling ages between 80 and 57 Ma in the southernmost part of Sardinia, analysed by Malusà et al. (2016), and E-verging thrusts affecting Mesozoic series (Barca & Costamagna, 1997) support the existence of the first domain. To the north, previous works (Carmignani, Funedda, Oggiano, & Pasci, 2004; Costamagna & Schäfer, 2017) recognize Early Eocene shallow marine carbonate deposits indicating the influence from the Tethys sea within the second domain. In the central-east of Sardinia, thermochronological interpretations by Zattin, Massar, and Dieni (2008) suggest uplifting from 140 Ma to Oligocene, supporting the basement high of the last domain.

In the Iberian plate, we also recognize three domains during the first phase, from east to west: (a) a high-relief W-verging thrust system, deforming basement units and a sedimentary Mesozoic cover; (b) an Atlantic-influence marine foreland basin controlled by N-S striking normal faults and (c) a low-relief thrust system, verging to the east and involving sedimentary Mesozoic cover (Figure 12a). West verging structures involving metamorphic and Mesozoic units have been well-documented (e.g. Carreras, 2001; Druguet, 2001; Fleta et al., 1994), supporting the existence of the first domain. We propose that during the first phase a load and lithospheric flexure in the easternmost part of the Iberian plate developed due to the Sardinian over-thrusting. Consequently, activation of E-dipping normal faults for both pre- and early orogenic structures was generated, giving rise to thick/deep and thin/shallow carbonate platform deposits across the hanging walls and footwalls of the transverse structures. Also, a forebulge transversal to an active W-E Pyrenean range was formed in the central part of this basin. The paleogeographic features of our Stage 1 (Figure 11a) are consistent with this proposal. Apatite fissions tracks (AFT) with cooling ages between 59 and 48 Ma for Mesozoic units in the Western Upper Thrust Sheet (Figure 2a), documented in Rushlow, Barnes, Ehlers, and Vergés (2013), suggest the low relief in the last Iberian domain.

### 8.1.2 Second phase (51 to 44 Ma)

During the second phase, relative to Eurasia, Iberia and Adria were displacing to the northwest and north respectively (Figure 12b) (Macchiavelli et al., 2017; Malusà et al., 2016). Therefore, a transpressive stress regimen dominated between Iberia and Sardinia (Andreani et al., 2010; Lacombe & Jolivet, 2005), potentially through the NBFZ.

In the Sardinian block, molasse facies (alluvial fan and fluvial systems) in the south, documented by Costamagna and Schäfer (2017) with a Middle Eocene age, suggest that the uplifting of the Sardinian high-relief thrust system persisted, and the piggy-back basin disconnected from the Tethys sea (Figure 12b). In the basement high domain, Middle Eocene deformation affected the Mesozoic cover
with minor fold and thrusts (Arragoni, Maggi, Cianfarra, & Salvini, 2016).

In the Iberian plate, syn-orogenic conglomerates in the frontal parts of the Eastern and Western upper thrust sheets (Martínez et al., 1988; Pi et al., 2000), indicate that the high- and low-relief thrust systems continued their uplifting to at least the Late Eocene (Figure 12b). A change from extensional to contractional kinematic of the transverse faults occurred in the northern part of the foreland basin, giving rise to thin/shelf deposits in the hanging walls as it is observed in our Stages 2 and 3 (Figure 11b,c). By contrast, thick/submarine fan deposits were generated in the footwalls. We interpret that the structural change from extensional to contractional was due to the new displacement of Iberia to the northwest, where the active Pyrenean chain was acting as backstop. The east-to-west migration of contraction is consistent with the existence of Eulerian counter-clockwise poles to the central part of Iberia (Tavani et al., 2018 and referred herein). The transition between the first and second phases is also marked by a lithological change from carbonates (Presalt Group) to evaporites (Serrat Evaporites and the Suprasalt Group) and siliciclastics (Suprasalt Group) in the foreland basin suggesting a tectonic control on basin marine restriction and sedimentary conditions.

### 8.2 Comparisons with other regions

Geometries and stratigraphic variations through transverse faulting in foreland basins have been reported in the central and southern Apennines (Doglioni, 1995; Tavani et al., 2015), the Eastern Maghrebides (Bianca et al., 1999; Billi et al., 2006; Gutscher et al., 2015; Torelli et al., 1998) and the Carpathian Bend Zone (Tărăpoancă et al., 2003). All these examples acted with two stages of different stress direction: a first extensional stage; and a subsequently reverse and/or strike-slip motion (e.g. Gutscher et al., 2015; Tărăpoancă et al., 2003; Tavani et al., 2015). The main tectonic and stratigraphic features of these foreland basins are highlighted and compared with our case study.

In the Apennines, Tavani et al. (2015) have provided a kinematic evolution of a fault system transversal to a paleo-subducting front. The same authors have interpreted that the transverse extensional faulting was attributed as a response of a syncline arching and flexure of a subducted plate forming a non-cylindrical forebulge. The sedimentary succession deposited during the motion of the fault system is only formed of siliciclastics. Fault-throws at the prefaulting horizons and synchronous stratigraphic thickness have not been reported in the Apennines.

In the Carpathian Bend Zone, Tărăpoancă et al. (2003) have shown foreland deposits within hanging walls of faults transversal to a thrust front. This work displays thickness variations, although it is based only on seismic data.

In the Eastern Maghrebides, Torelli et al. (1998) have recognized a stratigraphic record deposited coevally with normal faulting transversal to the Maghrebian Thrust Belt. A forebulge, transversal to this front, has also been identified (Bianca et al., 1999; Billi et al., 2006; Torelli et al., 1998). According to Billi et al. (2006), the normal faults were developed due to a flexure of a subducted plate associated with a lateral loading effect by a growing accretionary wedge. Thickness variations in 2D across the faults and a diversity of lithologies have been recognized in the related foreland basin (Hyblean basin; Torelli et al., 1998). However, this information is based on off-shore subsurface data.

From a tectonic point of view, we consider that the generation of the transverse extensional faults in the Eastern Maghrebides (described above) is analogue to the studied faults in this work. Furthermore, again similarly to the Eastern Maghrebides, the South-eastern Pyrenees underwent lateral loading from an additional orogenic salient (the Sardinian block; Figure 12a) forming flexural extension. By contrast, the cases from the Apennines and the Carpathian Bend Zone were controlled by a single orogenic salient in an along-strike stretching setting.

Our case study in the South-eastern Pyrenees provides the complete structural, stratigraphic and lithologic features related to a tectono-sedimentary evolution of transverse extensional faults in a compressional regimen. Here, we have an on-shore case which is supported by field, seismic and well data. Moreover, thickness distribution patterns and lithology variations (carbonates, evaporites and siliciclastics) during the structural evolution are recognized. In Tavani et al. (2015), the orientation of the fault dips and the impact of the structural evolution on thickness and lithology distribution remains uncertain. In Tărăpoancă et al. (2003), the relationships between lithology variations and structural evolution of transverse faults, supported by field and/or well evidences, have not been provided. In the Eastern Maghrebides, field examples have not been reported yet. All of these remaining features make the South-eastern Pyrenees an exceptional area to understand the 4-D structural and sedimentary evolution of transverse extensional faults in foreland basins.

### 9 Conclusions

Based on the analysis of Late Paleocene to Middle Eocene sedimentation patterns of the South-eastern Pyrenees and data documented in previous works, the principal conclusions of this study, are as follows:
1. Two main tectono-sedimentary phases can be distinguished: (a) first phase with deep and shallow marine carbonate accumulation controlled by extensional faulting, transverse to an active Pyrenean chain, synchronously to east displacement of Iberia and frontal collision of this plate with Sardinia (ca. 57 to 51 Ma); and (b) second phase with marine evaporitic and siliciclastic deposition influenced by re-activation of the transverse structures as contractional faults coevally to northwest motion of Iberia and transpressive stress regimen between Iberia and Sardinia (ca. 51 to 44 Ma).

2. Our study reveals how the tectono-sedimentary evolution of transverse faults in foreland basins record changes on motions and interactions of tectonic plates and continental blocks. These changes have an influence on structural evolution of transverse faults and the synchronous thickness and lithology distributions. Moreover, this work highlights the importance to analyse relationships between stratigraphic sequences, affected by transverse faults in orogenic chains, and tectonic processes as key to understanding kinematic histories of complex compressional and/or subduction zones.

3. The tectonic origin of transverse extensional faults in the South-eastern Pyrenees is similar to the Eastern Maghrebides where a lateral loading occurred presenting two orogenic salients. The South-eastern Pyrenees is an exceptional area to understand the structural evolution of transverse extensional faults active by bending foreland lithosphere. It provides field and subsurface evidences where thickness and lithology distributions are observed through the time as a response to the evolution of these structures. Moreover, the Late Paleocene to Middle Eocene stratigraphic record of this easternmost part of Iberia contributes to better understanding the complex geodynamic history of the Western Mediterranean region.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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