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Reconstructing the Iberian Salt-Bearing Rifted Margin of the Southern Pyrenees: Insights From the Organyà Basin

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Key Points:

- Reinterpretation of the Organyà Basin indicates occurrence of a large and continuous salt tectonics province in the South-Central Pyrenees
- Late Jurassic early salt mobilization followed by Early Cretaceous passive diapirism and diapir reactivation from late Campanian
- The restored 65 km wide salt-bearing passive margin indicates asymmetrical Iberia-Eurasia conjugate margins

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Abstract Reinterpretation of the Organyà Basin, based on new detailed field observations and subsurface data, emphasizes the key contribution of Upper Triassic evaporites in the tectono-sedimentary evolution of the South-Central Pyrenees. Results are integrated in a 65-km long restored cross-section through the Serres Marginals, Montsec and eastern Organyà salt-related depocenters. The reconstructed part of the Jurassic–Cretaceous northern Iberian salt-rich rifted margin shows a template characterized by inherited Permo-Triassic basement normal faults and an initial salt thickness of 0.7 km to the south and 1.5 km to the north. The Organyà Basin is part of the South Pyrenean Diapiric Province, a large system of salt related depocenters and minibasins, that is limited to the north by the more than 120-km long Senterada salt wall complex separating the supra-salt and sub-salt domains in the Southern Pyrenees. Three main stages of diapiric activity are recognized along the northern Iberian margin from Asturias to the Eastern Pyrenees: a Jurassic early salt mobilization; a latest Jurassic–middle Albian main diapiric evolution associated with rifting; and a Campanian–Miocene diapiric reactivation during basin inversion that produced salt welds and thrust welds and translated the salt province some 60 km to the south.

1. Introduction

Fold-thrust belts generally result from the inversion of rifted or passive margins, and the study and interpretation of these terrains require a comprehensive understanding of the inherited extensional structures and their influence on subsequent structuration of the compressional belt. This is particularly true for fold-thrust belts formed along former salt-bearing margins where the presence and mobilization of thick evaporite accumulations strongly controls the evolution and heterogeneity of the original sedimentary basins (e.g., Giles & Rowan, 2012; Jackson & Hudec, 2017; Rowan, 2014; Rowan & Vendeville, 2006) as well as localization and style of compressive structures (Callot et al., 2007; Graham et al., 2012; Hudec & Jackson, 2007; Letouzey et al., 1995; Saura et al., 2014; Soto et al., 2017; Vergés et al., 2019).

The Pyrenees contains a large number of well exposed and easily accessible localities that present excellent opportunities to characterize and understand the tectono-sedimentary evolution of inverted salt-bearing rifted margins. The importance of the widespread thick Triassic evaporites on the evolution of the northern Iberian and Eurasian margins has been documented since the 1940's (e.g., Badillo Larrieta, 1982; Brinkmann & Lögters, 1968; Ríos, 1948) but fell out of vogue in the 1980s and 1990s when concepts of thrust tectonics became dominant. In recent years however, following the lessons learned from the study of well documented examples of salt tectonics from offshore seismic data, a growing number of works documented typical salt-tectonics structures in several areas along the mountain range (e.g., Bodego & Agirrezabala, 2013; Burrel & Teixell, 2021; Cámara & Flinch, 2017; Canérot et al., 2005; Ducoux et al., 2019; Ferrer et al., 2008, 2012; Ford & Vergés, 2021; Jammes et al., 2010; Lagabrielle et al., 2010; López-Horgue et al., 2010; Masini et al., 2014; Poprawski et al., 2014; Quintà & Tavani, 2012; Saspiturry et al., 2019; Saura et al., 2016; Vergés et al., 2019; Zamora et al., 2017).

In the South-Central Pyrenees, the importance of Jurassic to Late Cretaceous salt tectonics has received increasing attention in recent investigations that unambiguously demonstrate the role of diapiric processes in constraining the Mesozoic tectono-sedimentary evolution of the area, including those at: Cotiella (López-Mir et al., 2015; McClay et al., 2004; Ramos et al., 2020), Sopeira and Sant Gervàs (Burrel, 2020; Gannaway Dalton et al., 2022; López-Gómez et al., 2019; Muñoz et al., 2018; Saura et al., 2016), and Upper Pedraforca (Saura et al., 2016). This collection of relatively small basins, each containing several kilometres of salt-controlled sediments, defines a

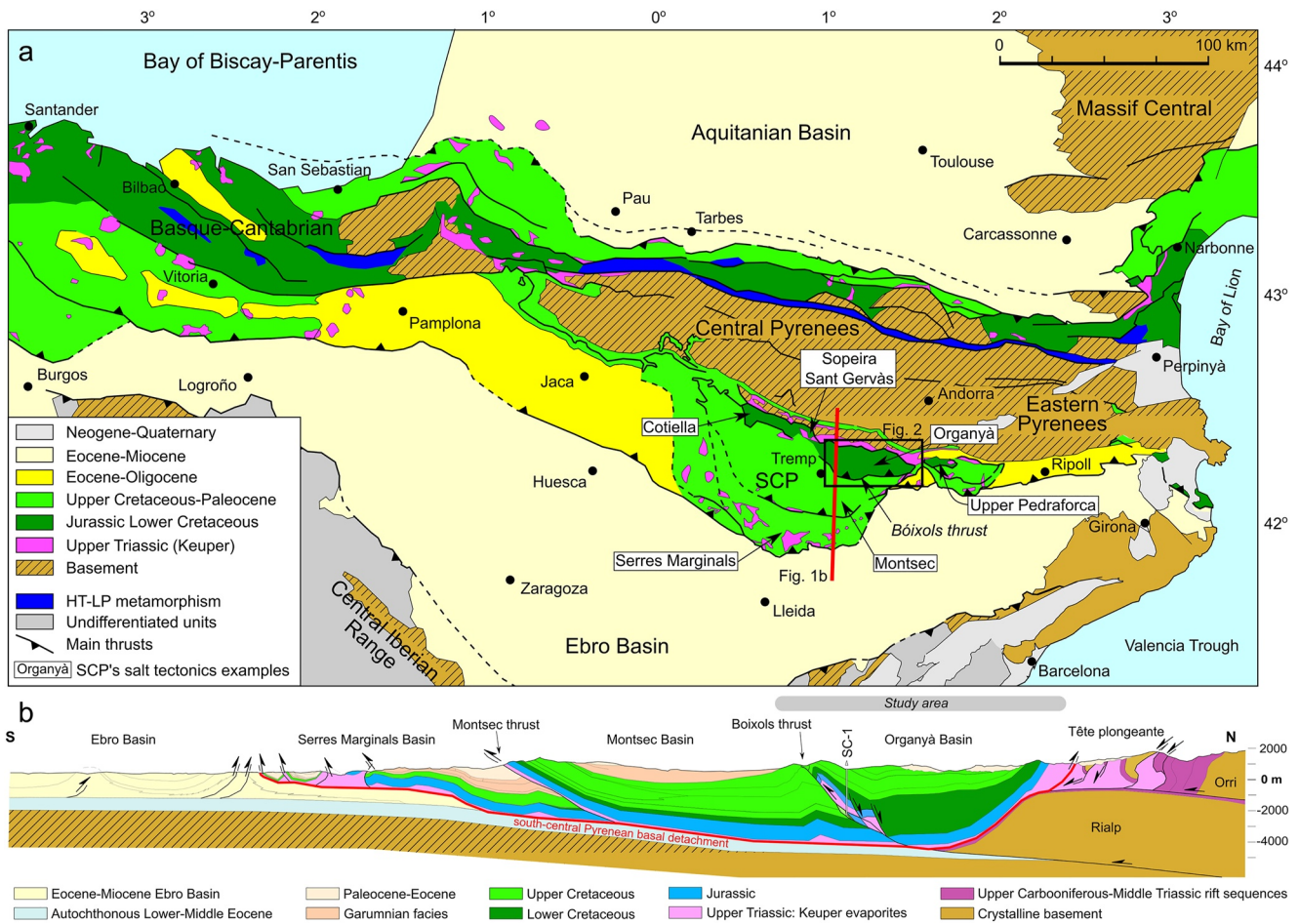


Figure 1. (a) Simplified geological map of the Pyrenees (SCP = South-Central Pyrenees). Red line: trace of regional cross-section represented in panel b. Black hollow box: study area and more detailed map of Figure 2. (b) Regional geological cross-section through the South-Central Pyrenees constructed from surface and a range of subsurface well, seismic and geophysical data (modified after Vergés, 1993). SC-1 is the location of the Sant Corneli-1 well. Note the arcuate southerly extension of the fold and thrust belt in the South-Central Pyrenees (SCP) that coincides with diapiric structures soled onto Triassic salt.

diapiric domain, named as Diapiric Province in Southern Pyrenees (Saura et al., 2016) and Senterada Salt Province (Burrell, 2020; Burrell et al., 2021), that stretches at least 120 km parallel to the fold and thrust belt.

The 560 km² Organyà Basin, located in the Boixols thrust sheet between the Sopeira-Sant Gervàs to the west and Upper Pedraforca diapiric structures to the east, represents the largest continuous area with Jurassic to Upper Cretaceous stratigraphy exposed in the South-Central Pyrenees (Figure 1). As the target of many academic and industry studies and training courses for decades, the Organyà Basin has been represented in several cross-sections where it is typically interpreted as a half graben bounded by a north-dipping normal fault system rooted in the Paleozoic basement (e.g., Berástegui et al., 1990; Bond & McClay, 1995; Déramond et al., 1993; García-Senz, 2002; Garrido-Megías & Ríos Aragués, 1972; Lagabrielle et al., 2010; Losantos et al., 1988; Mencos et al., 2011, 2015; Muñoz, 1992; Muñoz et al., 2018; Specht et al., 1991; Tavani et al., 2011; Vergés, 1993). While there is a general agreement that inherited extensional structures exerted a strong control during the inversion of the basin, the inferred geometry of the Early Cretaceous graben and fault system vary from one author to another. The Early Cretaceous Organyà Basin has been represented as a rollover-type basin associated with a north dipping listric fault (Bond & McClay, 1995), a ramp syncline over a flat-ramp-flat listric fault (Berástegui et al., 1990), a half-graben bounded by high-angle normal faults (García-Senz, 2002; Vergés, 1993), or a hanging wall syncline controlled by salt mobilization and a forced/fault-propagation fold (Mencos et al., 2015). Although these structural models provide a reasonable large-scale interpretation of surface and subsurface data (i.e., asymmetry of the basin, onlapping and backstepping of Aptian carbonate platforms over eroded and basinward tilted Jurassic strata), important tectono-sedimentary relationships observed in key areas of the basin remain unresolved and the

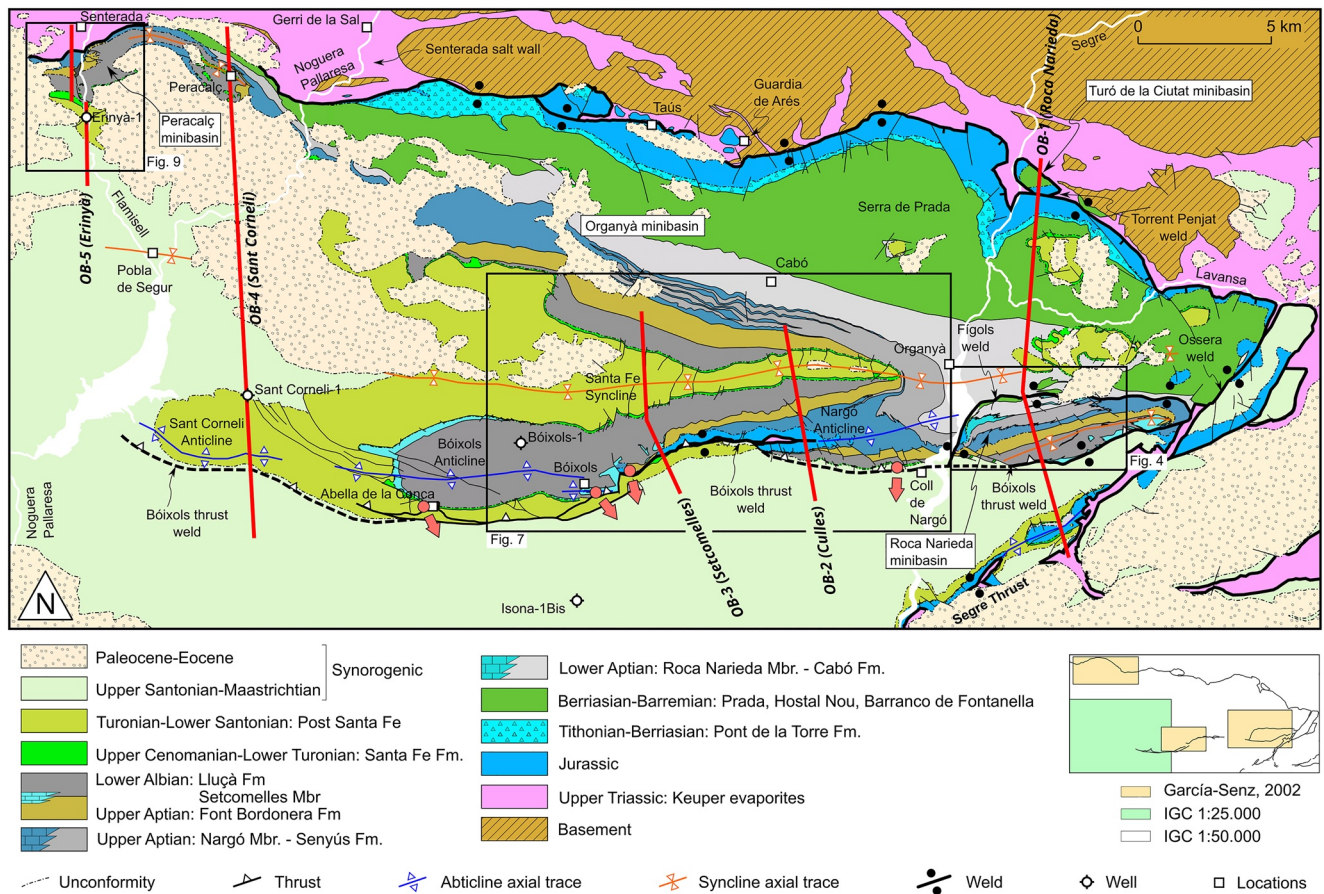


Figure 2. Organyà Basin simplified geological map (reinterpreted after García-Senz, 2002, 1:25,000 and 1:50,000 geological maps published by the Institut Geologic de Catalunya). Red arrows indicate the compressional transport direction as deduced from S-C structures observed in thrust faults and stepped slickensides of strike-slip faults (Cruset et al., 2020; Muñoz-López et al., 2020; Nardini et al., 2019; Tavani et al., 2011). Red dots indicate the sampling locations for dating the movement along the Bóixols thrust. Red lines indicate the traces of the cross-sections presented in this work. Black hollow boxes indicate more detailed maps presented in the following sections (Figures 4, 7 and 9).

discontinuous but relatively frequent occurrence of remnants of Late Triassic evaporites are generally overlooked. In fact, none of the models incorporate the role of salt tectonics on the tectono-sedimentary evolution of the basin and as such are unable to fully represent and integrate the complex structural pattern, the distribution and geometry of carbonate platforms and the migration of sedimentary depocenters that are present in surface and subsurface data. Only recently, have some of the stratal geometries within the Lower Cretaceous sequence along the margins of the Organyà Basin been interpreted as halokinetic in nature (Burrel, 2020; Martín-Chivelet, Floquet, et al., 2019; Martín-Chivelet, López-Gómez et al., 2019) and has the contact between the Organyà Basin and the large outcrops of Keuper evaporites in the Senterada area, previously described as a backthrust (Muñoz, 1992), been reinterpreted as a diapiric contact (Burrel, 2020; Martín-Chivelet, Floquet, et al., 2019).

In this contribution, well-defined Early Cretaceous halokinetic patterns are described and analyzed to provide a new salt tectonics interpretation of the entire Organyà Basin. The new interpretation is based on the integration of fieldwork data and remote sensing mapping from selected outcrops with the large number of already published structural, stratigraphic and biostratigraphic studies from this area. We describe key areas for the characterization of the halokinetic structures and halokinetic depositional sequences and summarize these data through the construction of two N-S oriented balanced cross-sections in which the complexities of the halokinetic sedimentary sequences are constrained by surface and subsurface structural data.

The Organyà Basin contains up to 4,260 m fill of Jurassic to Lower Cretaceous strata, and is bounded and subdivided into four asymmetric minibasins (Organyà, Roca Narieda, Turó de la Ciutat, and Peracalç) by salt pillows and salt walls with a dominant E-W trend. We discuss the role of Triassic evaporites on the geometries

and tectono-sedimentary evolution of these minibasins and the role of halokinetic structures on the inversion of the Organyà Basin during Alpine compression. We also discuss the significance of the Organyà Basin within the northern Iberian margin along the Pyrenean Trough by comparing it to other regional halokinetic sequences.

2. South-Central Pyrenees Geological Setting and Organyà Basin Overview

The Pyrenees are a doubly verging fold and thrust belt orogen resulting from the inversion of the Iberian-Eurasian plate boundary and partial subduction of the Iberian plate from late Santonian to middle Miocene times (Campanyà et al., 2012; Chevrot et al., 2014; Choukroune & Team, 1989; Muñoz, 1992; Pedreira et al., 2003; Roest & Srivastava, 1991; Rosenbaum et al., 2002; Roure et al., 1989; Sibuet et al., 2004; Teixell & Muñoz, 2000; Vergés et al., 2002). Large parts of the Iberian and Eurasian pre-compressive passive margins are preserved and exposed in the fold and thrust belts that flank the Axial Zone of the Pyrenees to the north and south. These areas record the transition from rifting and passive margin development (Triassic through the Late Cretaceous) to Alpine compression and basin inversion (Late Cretaceous through the Miocene).

The Triassic-lower Santonian pre-orogenic sediments were deposited during a prolonged and polyphasic rifting phase that eventually led to the exhumation of sub-continental mantle during late Aptian-Cenomanian along the North Pyrenean Zone (e.g., Clerc et al., 2014; Jammes et al., 2009, 2010; Lagabrielle & Bodinier, 2008; Lagabrielle et al., 2010; Tugend et al., 2014).

In the South-Central Pyrenees, tectonic inversion transported the Mesozoic cover southwards above a basal detachment within the Upper Triassic evaporites and thrust it over the slightly deformed sediments of the Ebro foreland basin (Garrido-Megías & Ríos Aragüés, 1972; Muñoz, 1992; Muñoz et al., 2018; Séguret, 1972; Teixell & Muñoz, 2000; Vergés, 1993). The South-Central Pyrenean Unit (after Séguret, 1972), separated into the Bóixols, Montsec and Serres Marginals imbricated thrust sheets, is interpreted to represent a large portion of the Iberian margin sedimentary cover (e.g., Muñoz, 1992; Vergés, 1993). The emplacement ages of these thrust sheets are late Santonian for the Bóixols thrust, early middle Eocene for the Montsec and Eocene-Oligocene for the Serres Marginals (e.g., Arbués et al., 1996; Ardèvol et al., 2000; Beaumont et al., 2000; Cámara & Klimowitz, 1985; Cruset et al., 2020; Garcés et al., 2020; Garrido-Megías & Ríos Aragüés, 1972; Grool et al., 2018; Simó, 1985; Vergés et al., 2002) (Figure 1b). As commonly observed in other inverted salt-bearing margins (Soto et al., 2017), the diapiric structures described along the South-Central Pyrenees have been tightened and welded, and the halokinetic depositional sequences have been steepened along the flanks of squeezed salt stocks and salt walls hindering their recognition until recently (e.g., López-Mir et al., 2015; McClay et al., 2004; Saura et al., 2016).

The inverted Organyà Basin is today exposed in the Bóixols thrust sheet. To the north, the thrust sheet is limited by the Senterada salt wall that is represented by an almost continuous outcrop of Triassic evaporites between the Mesozoic cover and the Paleozoic basement of the Axial Zone. To the south, the Bóixols thrust separates the thick pre-orogenic sedimentary sequences of the Organyà Basin from the relatively thin stratigraphy of the Montsec and Serres Marginals thrust sheets (Figure 2) (e.g., Berástegui et al., 1990; Garrido-Megías & Ríos Aragüés, 1972; Lanaja et al., 1987; Simó, 1985, 1989).

Large-scale structures generated during the inversion of the Organyà Basin include the Santa Fe syncline, and the Bóixols and Sant Corneli anticlines that grew on the hanging wall of the Bóixols thrust. These folds share a regional tilt to the west and follow the general E-W trend of the pre-orogenic structures and heterogeneities (e.g., Berástegui et al., 1990; García-Senz, 2002; Mencos et al., 2015). The Bóixols thrust, that is only locally exposed at surface, has been interpreted to invert and short-cut through the footwall of the inferred major Early Cretaceous north-dipping normal faults bounding the Organyà Basin to the south (Bond & McClay, 1995; García-Senz, 2002; Mencos et al., 2015; Muñoz et al., 2018; Tavani et al., 2011; Vergés, 1993). The tectonic transport direction of the Bóixols thrust sheet ranges between N-141E° and N-182E° as determined through the analysis of S-C planes along the Bóixols thrust and/or through the analysis of the orientation of strike-slip faults and conjugate vein systems in four localities (Coll de Nargó, Setcomelles, Bóixols and Abella de la Conca) (Figure 2) (Cruset et al., 2020; Muñoz-López et al., 2020; Nardini et al., 2019; Tavani et al., 2011). U-Pb dating of fracture-filling calcite and Ar-Ar dating of illites on fault planes associated with the tectonic movement along the Bóixols thrust provide ages ranging between 71 and 36.5 Ma (Figure 2) (Cruset et al., 2020; Haines, 2008; Muñoz-López et al., 2022). These ages indicate that the Bóixols thrust was at least active during Maastrichtian and middle-late Eocene times, while the upper Santonian-Campanian Herbasavina Formation and younger syn-orogenic deposits

wedging against the southern limb of the Sant Corneli anticline indicate beginning of folding at late Santonian (Arbués et al., 1996).

The Organyà Basin, whose current extent is about 45 km long and 6–18 km wide, is asymmetric with a Jurassic-Lower Cretaceous sedimentary succession that is roughly 4.5 km thick in the NE, along the Segre river valley, and decreases to the west and south where, along the Bóixols thrust, it is locally less than 0.5 km thick. The profound thickness and facies variability observed across the basin has been previously associated to an Early Cretaceous rifting phase and development of major north dipping normal faults bounding the basin to the south and linked to the opening of the Bay of Biscay and North Atlantic Ocean (e.g., Berástegui et al., 1990; Bond & McClay, 1995; García-Senz, 2002; Garrido-Megías, 1973; Mencos et al., 2015; Muñoz et al., 2018; Souquet, 1984; Vergés, 1993).

The entire structure of the Organyà Basin is tilted westward above the Segre oblique thrust ramp (Vergés, 2003). As a result, the Late Jurassic-Early Cretaceous halokinetic structures are progressively less exposed moving from the Eastern Organyà Basin to the Central and Western Organyà Basin where Late Cretaceous–Paleocene pre-growth and growth sedimentary successions dominate.

3. Organyà Basin Stratigraphy

The Organyà Basin stratigraphic record is remarkable in terms of its heterogeneity, and rapid changes in facies, thickness and stratal relationships. Figure 3 is a generalized composite stratigraphic column that summarizes the information obtained from different locations and published sources. However, it is important to realize that many of the units shown have limited extent and very variable upper and lower contacts with other stratigraphic units and basin-bounding structures. The stratigraphic column provides maximum measured thicknesses. Within the Organyà Basin, all Jurassic and Upper Cretaceous formations can locally be absent due to either erosion or no deposition along the flanks of diapiric structures, thus constituting halokinetic depositional sequences (Giles & Rowan, 2012).

Triassic strata overlie Palaeozoic basement and are represented by typical facies of the alpine realm: clastic red beds (Buntsandstein), limestones and dolomites (Muschelkalk), and marls and evaporites (Keuper) (Berástegui et al., 1990; Cámara & Flinch, 2017). These deposits are found along the northern margin of the basin, in the core of the Bóixols-Sant Corneli anticline (Sant Corneli-1 well) and to the south along the Bóixols thrust (Figure 2).

In the Organyà Basin Jurassic strata crop out along its northern boundary, west of the Noguera Pallaresa river gorge, and to the south in sparse smaller outcrops along the Bóixols thrust. Jurassic strata are dominantly represented by limestones, dolostones and evaporites interpreted to have been deposited in restricted to open marine environments (Garrido-Megías & Ríos Aragüés, 1972). Regionally they thin toward the south and west having maximum measured thicknesses (c. 800 m) along the Segre river valley (Garrido-Megías & Ríos Aragüés, 1972). These rocks are often interpreted to have been deposited in a relatively stable and continuous basin that developed after the Permo-Triassic rifting episode and before the Early Cretaceous rifting phase (e.g., Berástegui et al., 1990; Choukroune et al., 1973; Curnelle et al., 1982; García-Senz, 2002; López-Mir et al., 2015; Puigdefàbregas & Souquet, 1986). However, local thickness changes, the occurrence of several breccias with reworked Triassic and Jurassic rocks, and intra-Jurassic unconformities (Delmas et al., 1971; García-Senz, 2002; Garrido-Megías & Ríos Aragüés, 1972) imply a tectonically unstable sea bottom throughout the Jurassic.

The Lower Cretaceous strata record dramatic thickness and facies changes across the South-Central Pyrenees and are interpreted to reflect the main phase of rifting that dissected the Jurassic basin into smaller basins (e.g., Garrido-Megías & Ríos Aragüés, 1972). In the Organyà Basin, the Lower Cretaceous succession records a maximum thickness along the Segre river valley (3,230 m). It onlaps and pinches-out to the south against eroded Jurassic strata in the core of the Bóixols-Nargó anticline (Figure 2). South of the Bóixols thrust, the Lower Cretaceous is generally thin or absent, and locally transgressive Santonian siliciclastic deposits lie directly on the eroded Jurassic strata (García-Senz, 2002). The base of the Lower Cretaceous succession is a discontinuous and variably thick (0–150 m) massive polygenetic carbonate breccia (Pont de la Torre Formation; Latest Jurassic to Berriasian in age) that unconformably overlays eroded Jurassic strata. The breccia consists of angular limestone, dolomite and anhydrite clasts of up to 70 cm in size. It is interpreted as debris flow deposits related to sub-marine fault escarpments (Berástegui et al., 1990; Caus et al., 1990; García-Senz, 2002). The breccia is overlain by the Berriasian regressive marls and limestones belonging to the Barranc de Fontanella Fm. whose distribution in

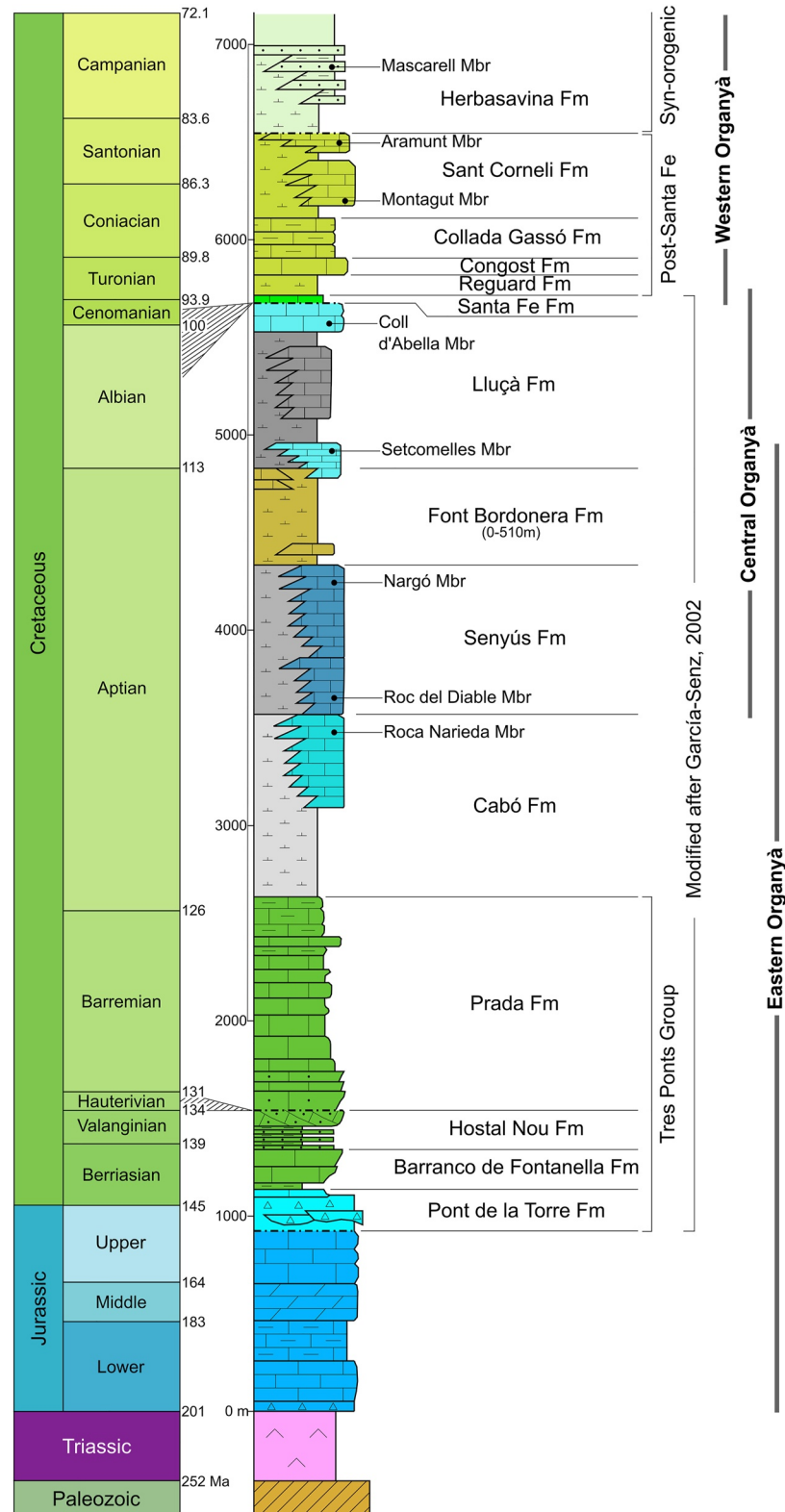


Figure 3. The stratigraphy is extremely variable across the basin with rapid lateral changes in thickness and facies. This is a simplified and composite stratigraphic column of the Organyà Basin that summarizes the information obtained from different locations and published sources (García-Senz, 2002).

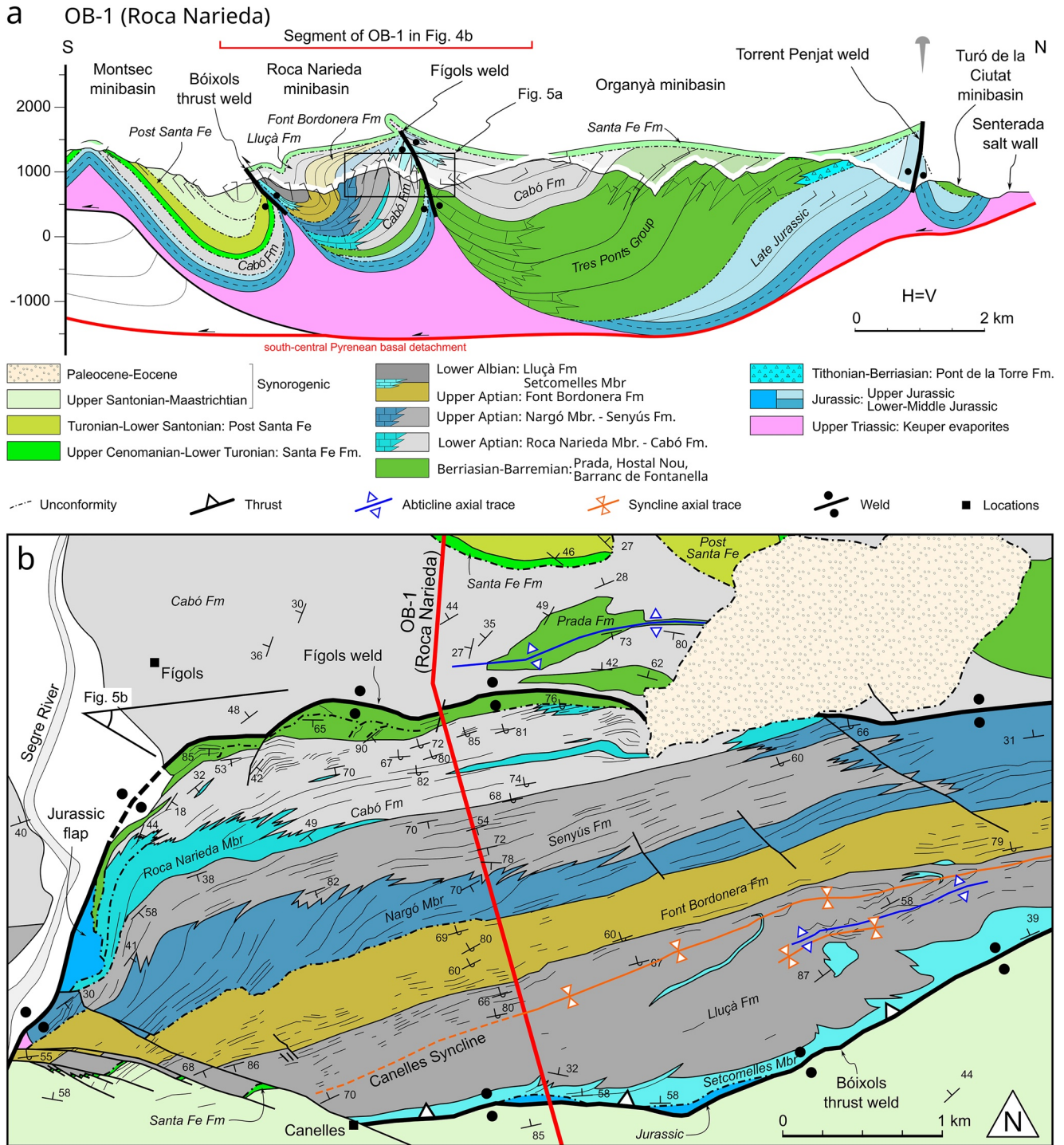


Figure 4. (a) OB-1 (Roca Narieda) cross-section through the Eastern Organyà Basin. Black hollow box: area covered by the field photo in Figure 5a. (b) Detailed geological map of the Roca Narieda minibasin. Red line: trace of the OB-1 (Roca Narieda) cross-section.

thickness and facies is heterogeneous. Locally it sits directly on Jurassic rocks. The Valanginian Hostal Nou Formation is a mixed carbonate-siliciclastic system deposited in a coastal environment with deltas and lagoons. A regional unconformity formed during the uppermost Valanginian-lower Barremian hiatus marks the base of the Barremian Prada Formation that was deposited in a very shallow basin with numerous local subaerial exposure and erosional surfaces (Bernaus et al., 2000). In contrast, along the Bóixols thrust only the top of the formation is

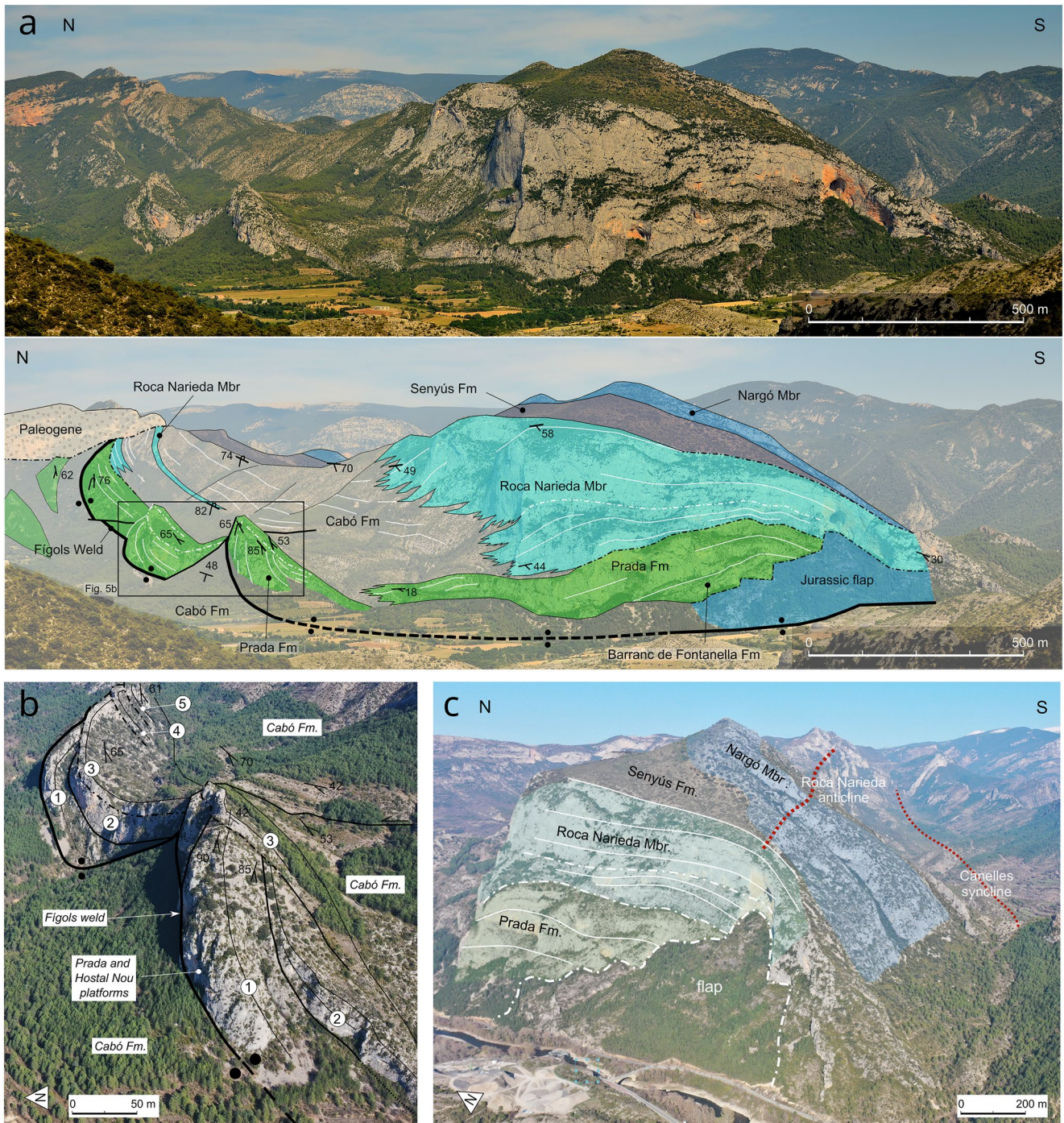


Figure 5. Roca Narieda minibasin field photos. (a) Image and interpretation of the Roca Narieda minibasin. Black hollow box: location of the close-up view of panel (b) Detail of the carbonate platforms along the Figols salt weld. (c) Aerial view of Roca Narieda and Canyelles syncline.

present and unconformably overlies Jurassic rocks (García-Senz, 2002). The Aptian-Albian time interval records an increase in accommodation and deepening of the basin with development of relatively narrow carbonate platforms along the northern (Peracalç) and southern (Bóixols, Roca Narieda areas) basin margins and abrupt lateral facies changes toward the center of the basin where deposition was dominated by deep water marls. Along the Bóixols thrust a clear basinward tilting of the platforms forces progressively younger platforms to backstep and onlap Jurassic rocks (Berástegui et al., 1990; García-Senz, 2002). The Aptian-Albian stratigraphy is up to

c. 1,500 m thick, and is divided into limestone and marl strata of the Cabó, Senyús, Font Bordonera and Lluçà formations (from bottom to top).

Strata from the late Albian and early Cenomanian are missing throughout the Organyà Basin and the upper Cenomanian-lower Turonian carbonate platform of the Santa Fe Formation unconformably overlies the Lower Cretaceous north of the Santa Fe syncline showing up to 40 degrees of angular discordance, while it sits on top of the Lluçà Formation to the south, along the Bóixols thrust (Figure 2). This regional unconformity has been recognized since the 1960's (Garrido-Megías, 1973; Peybernès, 1976; Rosell, 1967; Souquet, 1967) but its origin is still debated and three main interpretations have been proposed: (a) break-up unconformity (Berástegui et al., 1990); (b) erosion following activity along a listric fault during the Jurassic and Early Cretaceous (Simó, 1985); and (c) uplift and erosion due to an early compression (García-Senz, 2002). The Upper Cretaceous Santa Fe Formation is a relatively thin carbonate unit that extends across the entire South-Central Pyrenees region with little variation in thickness and facies. It lies above an unconformity that records the end of rifting and a period of regional uplift and erosion. The pre-orogenic sequence is completed by a series of upper Turonian-lower Santonian aggrading and backstepping carbonate platforms interpreted to have been deposited during a period of post-rift thermal subsidence (Berástegui et al., 1990; García-Senz, 2002; Simó, 1989).

4. Approach and Methods

In the following three sections we present and discuss key surface and subsurface data and observations that support our new salt tectonic interpretation of the basin. We summarize these data in a set of N-S cross-sections, two of which are balanced and restored. This study is based on the integration of previous studies, geological maps, and exploration wells with our own remote sensing mapping constrained by fieldwork and drone image interpretation.

All published maps and associated dips were digitized and integrated with remote sensing geological interpretation and with 433 bedding dips the majority of which are from satellite-derived 3D models with some from drone-derived 3D models. Fieldwork was focused in key areas of the basin: (a) the Segre river valley and the Roca Narieda areas in the eastern Organyà Basin; (b) the Bóixols, Setcomelles and Culles areas in the central Organyà Basin; and (c) the Flamisell and Noguera Pallaresa river gorges, the Cérvoles and Peracalç areas and the Sant Corneli anticline in the western Organyà Basin. A total of 329 dips were measured in the field. Surface data were integrated with subsurface data from 6 exploration wells (from east to west): Isona-1Bis, Boixols-1, Comiols-1, Sant-Corneli-1, Erinyà-1 and Tamurcia-1.

While the northern margin of the Organyà Basin is nearly continuously exposed and crossed by several deep river gorges (Flamisell, Noguera Pallaresa, and Segre), the geometry and deep stratigraphic levels of the southern margin are only exposed in the eastern and central portions of the basin, in the Roca Narieda and Bóixols-Nargó areas respectively. First, we describe data and observations along the Segre River whose gorge provides spectacular exposures of the geometries characterizing the northern and southern margins of the basin, and we summarize them in a N-S cross-section running east of the river. The Bóixols-Nargó area provides a unique opportunity to understand the lateral variability of the southern margin that is key to interpreting subsurface data in the Sant Corneli area. Finally, we describe surface and subsurface data from the western portion of the basin where continuous exposures of the Jurassic-Lower Cretaceous stratigraphic record along the Flamisell and Noguera Pallaresa gorges is combined with data from the Erinyà-1 and Sant Corneli-1 wells and integrated into a second balanced and restored N-S cross-section across the basin.

N-S cross-sections were restored step-by-step to validate the proposed geometries and interpretations, and to assess the role of Upper Triassic evaporites and basement faulting in the tectono-sedimentary evolution of the Organyà Basin. In salt tectonics, out of section motion and erosion at surface have the potential to dramatically change the cross-sectional area of salt and supra-salt units through time thus requiring thorough 3D modeling to fully capture the evolution of the mobile unit and the minibasins. However, in this case, given the small amount of available subsurface data, 3D modeling and restoration would require major assumptions regarding the lateral continuity of the structures and their geometry thus nullifying the benefits of a 3D modeling approach. Therefore, structural modeling was performed in 2D only and it was limited to areas with good exposures and abundant surface data. The cross-sections were built and restored making use of the modeling software Move from Petroleum Experts and edited with a vector graphic freeware. Restoration of supra-salt units was based on line length

and area balancing and preservation of the halokinetic depositional geometries, while restoration of the mobile evaporitic unit was based on area balancing only (e.g., Najafi et al., 2018; Rowan & Ratliff, 2012). Because we had no data to constrain either out of section salt motion or erosion at surface, we preferred to assume a constant salt area in cross-section reconstructions, at least through the Late-Jurassic-Early Cretaceous extensional phase, thus minimizing original salt thickness. This approach also provided constraints for the interpretation of the pre-halokinetic geometry of sub-salt units and the reactivation of basement faults during Late Jurassic-Early Cretaceous.

5. Eastern Organyà Basin Salt-Related Structure and Evolution

The eastern Organyà Basin is divided in three salt-related minibasins, named the Turó de la Ciutat, Organyà, and Roca Narieda from north to south. The minibasins show dramatic thickness and facies changes and are limited by the roughly E-W trending Torrent Penjat and Fígols salt welds (Figure 2).

5.1. The Turó de la Ciutat Minibasin

The Turó de la Ciutat minibasin, of which only a small part is preserved, is bounded by the Senterada salt wall to the north and by the Torrent Penjat salt weld to the south. The Torrent Penjat salt weld, underlain by Keuper evaporites, juxtaposes the Jurassic strata of the Turó de la Ciutat and Organyà minibasins with opposite dip directions. The Jurassic beds are overturned to steeply dipping toward the north along the northern flank of the salt weld while they dip moderately toward the south along its southern flank (Figure 4a). The Turó de la Ciutat minibasin is characterized by a condensed Jurassic-Lower Cretaceous stratigraphy. The Lower Jurassic succession is capped by a hardground and overlain by only a few meters of upper Bathonian lutite and Kimmeridgian dolomite and limestone (García-Senz, 2002; Garrido-Megías & Ríos Aragüés, 1972). The overlying Tithonian-lower Berriasian Pont de la Torre breccia laterally thins toward the northern basin margin and eventually pinches out, and the basal Cretaceous angular unconformity juxtaposes the Berriasian Barranc de Fontanella Formation directly onto the Kimmeridgian limestones (García-Senz, 2002).

5.2. The Organyà Minibasin

The asymmetric and west plunging Organyà minibasin is filled with up to 4,260 m of Jurassic-Lower Aptian strata that are exposed at the eastern termination of the Santa Fe syncline (Figure 4). The thick Jurassic succession is gently to steeply dipping to the south and regionally capped by the basal Cretaceous unconformity. Above it, breccias of the Pont de la Torre Formation record instability in the northern flank of the Organyà minibasin through Tithonian and early Berriasian stages. Above this breccia there are nearly 2,000 m of Berriasian-earliest Aptian carbonate deposits belonging to the Tres Ponts Group, followed by at least 800 m of marly deposits of the Cabó Formation that constitutes the uppermost stratigraphic unit on the northern flank of the Organyà minibasin.

Upper Aptian to upper Albian strata are not exposed along the Eastern Organyà OB-1 cross-section but they are found further west along the Santa Fe syncline and Bóixols anticline. We assumed that Upper Aptian units could be projected in the cross-section below the Cenomanian carbonates (Figure 4a). Cenomanian limestone of the Santa Fe Formation truncates the entire northern flank of the Organyà minibasin cutting through about 2,500 m of stratigraphy from the Cabó Formation (Lower Aptian) to the top of the Hostal Nou Formation (Valanginian) (García-Senz, 2002). The significant southward tilting (up to 43° angular unconformity according to Martín-Chivelet, Floquet, et al., 2019) and erosion of the Organyà minibasin predates the widely documented late Santonian onset of compression, therefore they should be related to other geodynamic processes. The southern flank of the Organyà minibasin parallels the Fígols salt weld that juxtaposes steeply northward dipping marls belonging to the lower Aptian Cabó Formation of the Organyà minibasin against overturned to steeply southward dipping limestone and marls of the Barremian-upper Aptian Prada, Cabó and Senyús formations of the Roca Narieda minibasin.

5.3. The Roca Narieda Minibasin

The Roca Narieda minibasin is relatively small and elongated. It is bounded to the east by the Ossera weld (Figure 2), to the north and west by the Fígols weld and to the south by the Bóixols thrust weld (Figure 4). Halokinetic activity

is recorded throughout the Lower Cretaceous stratigraphy that is exposed along the flanks of the Bóixols and Fígols salt welds. The aggrading and backstepping stratal geometries of the Barremian-upper Aptian Prada, Roca Narieda and Nargó carbonate platforms, spectacularly exposed along the Roca Narieda cliff, thin toward the south and west and rapidly transition into distal marls northeastward toward the center of the minibasin (Berástegui et al., 1990; García-Senz, 2002). The transgressive surfaces separating these backstepping carbonate platforms are characterized by updip erosion and downdip flooding indicating a progressive and significant NE tilting of the substrate along the Bóixols salt weld. Along the SSW-NNE segment of the Fígols salt weld, the moderately dipping Berriasian-Barremian Barranc de Fontanella and Prada formations directly onlap onto Jurassic dolomites that parallel the salt weld (Berástegui et al., 1990; García-Senz, 2002; Martín-Chivelet, Floquet, et al., 2019). To the south, the upper Aptian-Albian Font Bordonera and Lluçà formations are exposed in the overturned Canelles syncline and the lower Albian Setcomelles Member onlaps directly onto eroded Jurassic carbonates along the Bóixols thrust weld (Figure 5). These observations indicate that the carbonate platforms characterizing the halokinetic depositional sequences of the Roca Narieda minibasin record long lasting syn-sedimentary instabilities around the margins of the salt-related structure since at least the Berriasian and up to the early Albian (c. 30 Myr).

The northern flank of the Roca Narieda minibasin is represented by a long E-W trending ridge that, from west to east, consists of a series of carbonate platforms belonging to the Valanginian-Barremian Hostal Nou and Prada formations, and the middle Aptian Roca Narieda and Nargó members. To the west, five carbonate platforms of the Hostal Nou and Prada formations are differentiated (labeled 1 to 5 from oldest to youngest in Figure 5b). These carbonate platforms dip to the south but approaching the ridge they become subvertical to overturned defining wedges thinning toward the Fígols salt weld.

The geometric relationships between these five platforms are best exposed SW of the Fígols village in two outcrops showing the same stratigraphy, but separated by a NE-SW striking fault that quickly loses its horizontal displacement within the marls of the Cabó Formation. The oldest platform 1 is onlapped by platform 2 and forms a hook that terminates against a local unconformity at the base of platform 3. These three halokinetic depositional sequences are repeated to the east of the fault where two younger depositional sequences (platforms 4 and 5) can be mapped above platform 3. The relatively abrupt down-dip termination of platform 1 at the bottom of the ridge on both outcrops is interpreted as a lateral transition to deeper marls toward the center of the minibasin.

Further east, clinoforms belonging to the Roca Narieda Member carbonate platform and marls of the Cabó Formation onlap the Prada Formation confirming a syn-depositional south to southwest tilting of the northern flank of the Roca Narieda minibasin along the Fígols salt weld. These halokinetic patterns indicate that the Fígols salt wall was already a depositional high at least from Berriasian to early Aptian time (c. 15 Myr).

Previous studies have interpreted the Torrent Penjat and Fígols lineaments as inverted and buttressed basement-rooted high-angle normal faults separating the thick Jurassic-Lower Cretaceous successions of the Organyà Basin (Bóixols thrust sheet) from the condensed stratigraphy deposited on their footwalls (García-Senz, 2002; Vergés, 1993). However, Martín-Chivelet, Floquet, et al. (2019) have suggested that the paleostructures observed below the Santa Fe unconformity might follow older salt structures that pushed and arched the sediments into anticlines during Early Cretaceous extension. The observed geometries, such as the progressive and synchronous basinward tilting and backstepping of the Lower Cretaceous carbonate platforms bordering the Fígols and Bóixols welds, the highly aggrading clinoforms, and the rapid transition from shelf carbonates into basinal marls, are typical of depositional halokinetic sequences. We therefore interpret the Roca Narieda minibasin to represent a narrow fast-subsiding salt-related depocenter whose margins were characterized by shallow marine conditions and a highly unstable substrate. In this context, the Jurassic unit exposed along the Segre River is interpreted as a potential flap on the eastern side of the NNE segment of the Fígols salt weld. This NNE segment of the Fígols salt weld, previously interpreted as a transfer fault (Martín-Chivelet, López-Gómez et al., 2019), explains the abrupt change in basin geometry and stratigraphy between the Roca Narieda and Nargó areas across the Segre valley.

5.4. Eastern Organyà Basin Cross-Sections

The N-S cross-section through the Eastern Organyà Basin is the result of the integration of all available structural and stratigraphic data and observations (OB-1 in Figures 2, 4 and 6). It was tested and validated by step-by-step backward and forward restoration. We constructed the restoration in 5 steps from the Middle Jurassic to the Cenomanian (Figure 6). To build this cross-section we tested several scenarios for the geometry and evolution of the sub-salt domain: (a) no basement extensional faulting; (b) Permo-Triassic normal faulting only; (c) Late

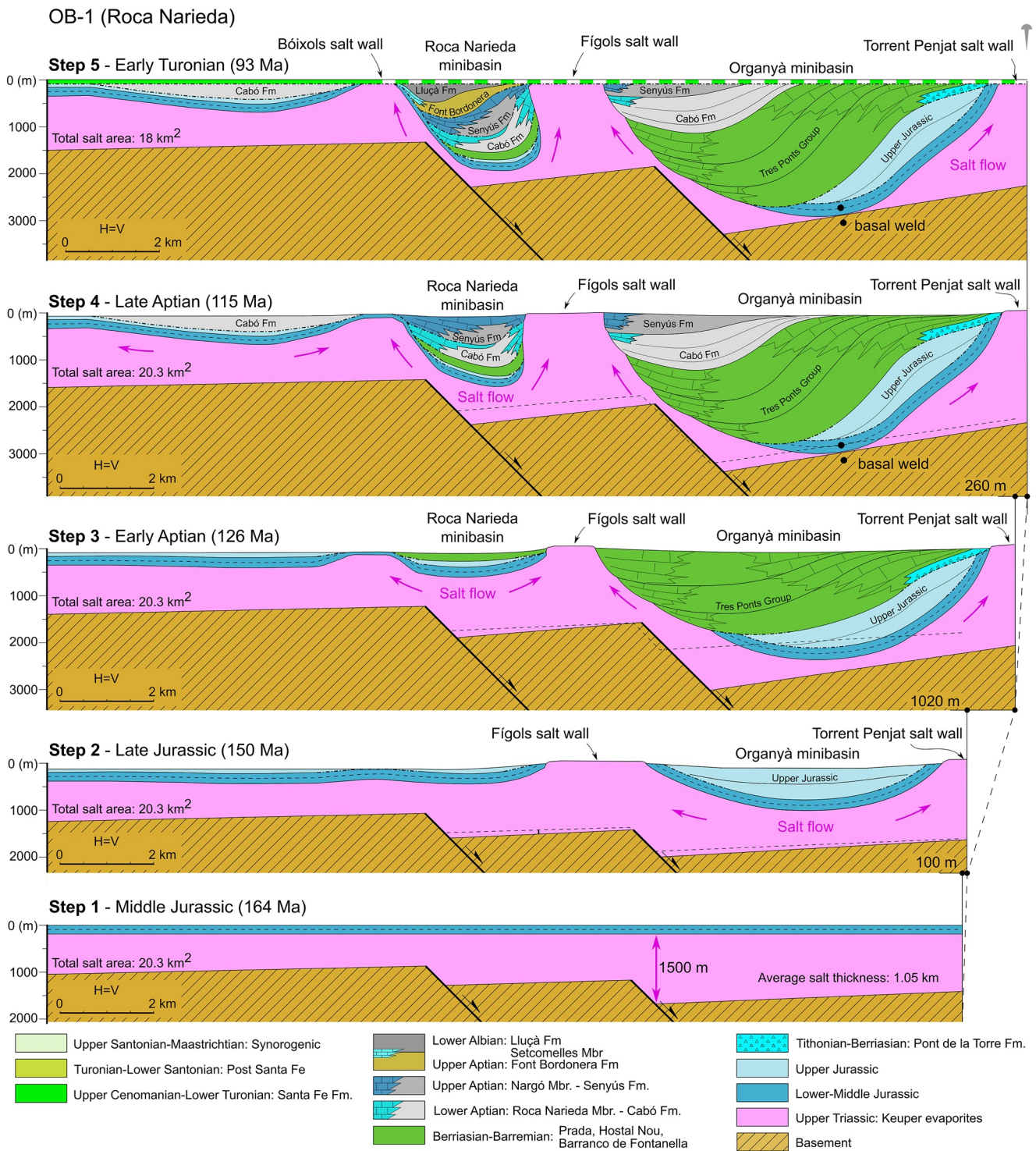


Figure 6. Step-by-step restoration of the OB-1 (Roca Narieda; Figure 4a) cross-section through the Eastern Organyà Basin.

Jurassic-Early Cretaceous normal faulting only; (d) Late Jurassic-Early Cretaceous reactivation of Permo-Triassic normal faults. The first two scenarios were discarded as they would imply large original salt thickness (up to ca. 3 km). The fourth scenario (Late Jurassic-Early Cretaceous reactivation of Permo-Triassic rift-related normal faults) was preferred to the third scenario as it better fits the Permo-Triassic evolution of the region and because it minimizes the original Upper Triassic salt thickness in the Montsec thrust sheet.

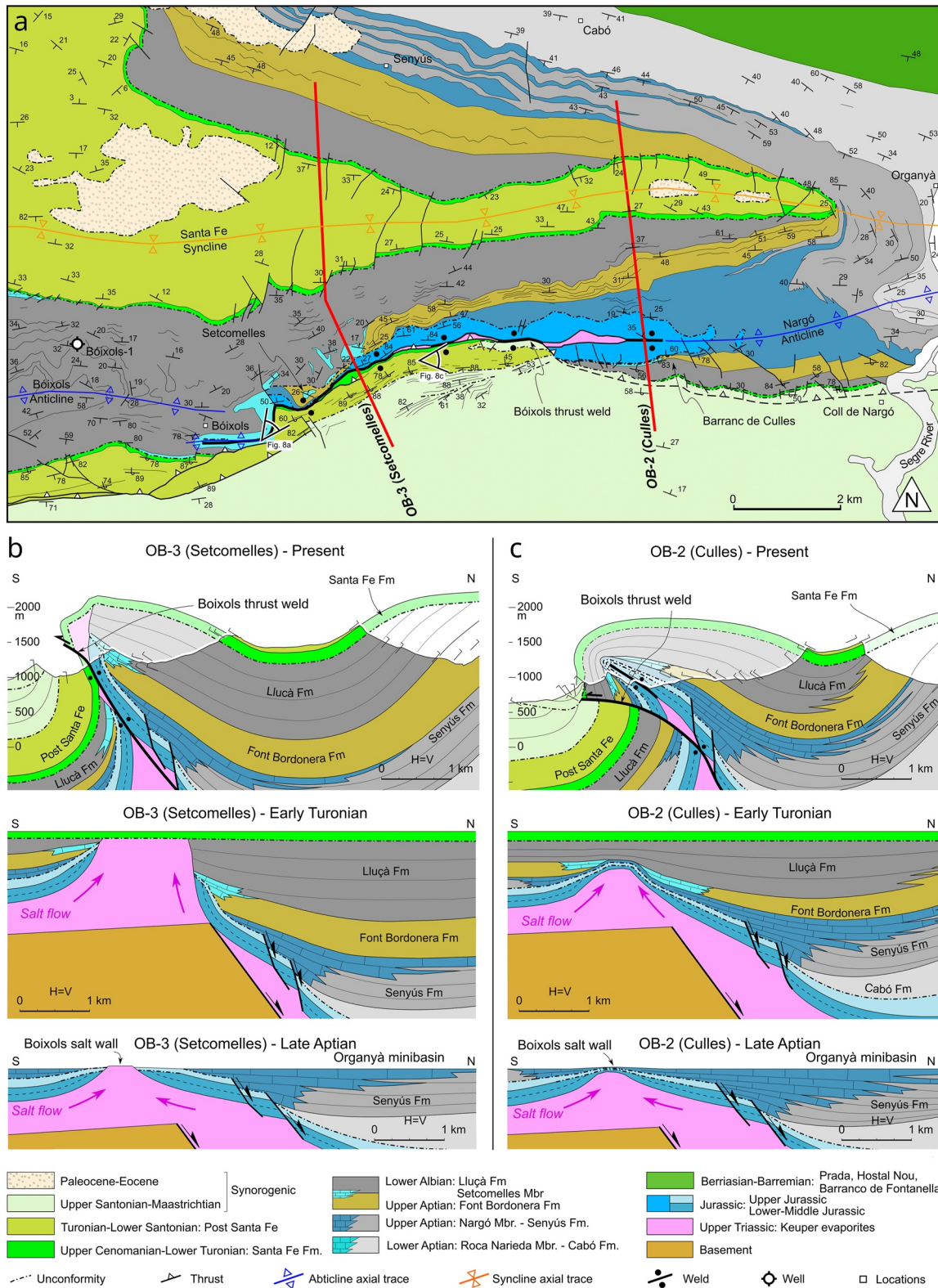


Figure 7. (a) Central Organyà Basin detailed geological map (reinterpreted after García-Senz (2002), 1:25.000 and 1:50.000 geological maps published by the Institut Geologic de Catalunya). Red lines: traces of the OB-2 (Culles) and OB-3 (Setcomelles) cross-sections. (b) Balanced and restored cross-section through Setcomelles (OB-3). (c) Balanced and restored cross-section through Culles (OB-2).

- Step 1.** was set at the end of Middle Jurassic (164 Ma), just before the onset of halokinetic movement observed in the Organyà Basin. The length of the restored section is 19.5 km and corresponds to the restored length of the pre-halokinetic Lower-Middle Jurassic strata that measure a constant thickness of about 220 m throughout the basin. After testing several geometries, a faulted top basement with roughly 4.8% Late Triassic extension and a variable thickness of the evaporites between 0.72 and 1.5 km was assumed to minimize evaporite area and Jurassic-Early Cretaceous extension. With the above assumptions, the total cross-sectional area of the evaporites is 20.3 km² and it is preserved from step 1 to 4.
- Step 2.** corresponds to the end of Late Jurassic (150 Ma). The length of the restored section is 19.6 km. Changes in thicknesses measured in halokinetic depositional units indicate that diapiric movements started to develop both the Fígols and Torrent Penjat salt walls that bound and separate the Organyà and Turó de la Ciutat minibasins. The thickness of the Upper Jurassic varies greatly from 690 m in the center of the Organyà minibasin to a few meters south of the Fígols salt wall and nearly zero meters close to the other salt walls. Basement fault displacement is required to accommodate minibasin subsidence while preserving salt volume. From step 1 to step 2, total fault throw is 130 m giving an extension of about 100 m (0.5%). Following analogue models (e.g., Dooley et al., 2005), we assume that diapirs localized above the immediate footwall of active basement normal faults.
- Step 3.** corresponds to the base of early Aptian (126 Ma). The length of the restored section is 20.62 km. The thickness of the Tres Ponts Group ranges between 0 in the south to roughly 2,500 m in the Organyà minibasin, while it is relatively thin in the Roca Narieda minibasin. The thickness of the halokinetic sequences filling the Organyà minibasin requires a significant offset along the normal basement faults to maintain a constant salt area and to provide the required accommodation for the accumulated sediment. From step 2 to step 3 normal faulting in the basement produced a maximum vertical offset of 900 m (the majority of which is accommodated by the northern fault) and 1,020 m of extension (5.7% cumulative post salt extension; 5.2% relative extension between steps 2 and 3). The salt walls separating the minibasins have been rising since the Late Jurassic and are fed by salt withdrawal from below the sinking minibasins. The rapid subsidence of the Organyà minibasin amplifies this process with potential evaporites extrusion along the Torrent Penjat salt wall.
- Step 4.** corresponds to late Aptian (115 Ma). The length of the restored section is 20.88 km. The Aptian Nargó and Roca Narieda platforms and equivalent basinal marl of the Senyús and Cabó formations are 330 m thick south of the Bóixols salt wall and are up to 1.3 km thick in the Roca Narieda and Organyà minibasins. There is a clear shift of the depocenters toward the south with increasing subsidence in the Roca Narieda minibasin. The Organyà minibasin weld onto the underlying sub-salt halting the subsidence of the minibasin. To balance the area of the Keuper evaporites, a maximum cumulative throw of 310 m is required (mostly accommodated by the southern fault), and the extension is 260 m between steps 3 and 4 (7.1% cumulative post-salt extension; 1.3% relative extension between steps 3 and 4).
- Step 5.** represents the early Turonian (93 Ma) and shows a restored section length of 20.88 km. The thickness of the upper Aptian-Albian succession preserved below the Cenomanian unconformity is variable with subsidence that continues to focus into the Roca Narieda minibasin. The maximum thickness, up to 1 km, occurs in the Roca Narieda minibasin, while strata of this age are absent in the Organyà minibasin. The Roca Narieda minibasin weld, or very nearly weld, onto the underlying sub-salt slowing the subsidence of the minibasins and halting the halokinetic processes, allowing the relatively thin upper Cenomanian-lower Turonian Santa Fe platform to develop across the basin. The amount of tectonic subsidence and extension required to balance the section is close to zero.
- Step 6.** represents the present-day geometry as constrained by surface data and cross-section balancing and restoration, and for the basal thrust we used the geometry inferred in Vergés (1993) (Figure 4a). The section length is 13.3 km and the estimated salt cross-sectional area projected from regional cross-sections from Vergés (1993) is approximately 6.9 km². The final volume of the Keuper evaporites represents only a small part of the presumed original salt volume that is required to accommodate the measured thickness of the halokinetic sequences filling the minibasins. A comparison with step 5 yields an internal shortening of 7.6 km (36%) and a loss of 13.4 km² of salt-bearing rocks (66%). This loss is the result of compression and has large uncertainties related to the construction of the section at depth. If confirmed, the large loss of evaporites was produced during inversion of the margin and associated folding and thrusting of the Mesozoic cover over a regional detachment at the Keuper level. Most probably a large part of the missing salt volume remained in the footwall of the South-Central Pyrenean basal thrust. However, the inversion

of salt-bearing margins commonly produces significant salt expulsion with generation of salt canopies and salt glaciers in the foreland syn-orogenic basins (e.g., Harrison & Jackson, 2014; Hearon IV et al., 2015; Kergaravat et al., 2016). In this case, part of this volume could have also moved for great distances toward the front of the South-Pyrenean thrust system below the Montsec and Serres Marginals thrust sheets where large amounts of evaporites are still preserved and where syn-orogenic halokinetic sequences have been documented by Burrel (2020) and Burrel and Teixell (2021) and modeled by Hudec et al. (2021). If our reconstruction is correct, excluding the large basal detachment, the inversion and shortening of the Mesozoic cover of the Organyà Basin is mostly accommodated by diapir squeezing and folding and involves only minor thrusting concentrated in the reactivation of welded salt walls.

6. Central Organyà Basin Salt-Related Structure Across the Bóixols Thrust-Weld

The central part of the Organyà Basin has been represented in several of the available regional and local cross-sections. The main and more evident structures of this area are the Bóixols thrust that bounds the basin and homonymous thrust sheet to the south and the associated Bóixols-Nargó hanging wall anticline.

In the central part of the Organyà Basin, we describe the southern margin of the highly asymmetric Organyà minibasin whose axis is roughly located along the hinge of the Santa Fe syncline and whose northern and southern boundaries are represented by the Senterada salt wall and the Bóixols thrust weld respectively. The Bóixols thrust weld is only exposed south of Setcomelles where thin and discontinuous remnants of Keuper evaporites separate the gently dipping backlimb of the Bóixols-Nargó anticline from its steeply dipping to overturned forelimb. Outside this area, the Bóixols thrust weld is not exposed at surface and its hanging wall is preserved on the forelimb of the Bóixols-Nargó anticline (Figure 7).

The halokinetic depositional succession belonging to the southern flank of the Organyà minibasin is continuously exposed along the gently dipping backlimb of the Bóixols-Nargó anticline. Here, the thick Tithonian-lower Aptian stratigraphy exposed on the northern flank of the Organyà minibasin is absent and upper Aptian-Albian rocks progressively onlap onto eroded and more steeply dipping Jurassic strata from east to west. This geometric relationship between the Lower Cretaceous halokinetic sequence and Jurassic strata is particularly well exposed in the Setcomelles cross-section (OB-3 in Figure 7) where the gently dipping upper Aptian-lower Albian Setcomelles platform directly onlaps onto nearly vertical and eroded Jurassic strata (Figure 8a). The platform consists of two backstepping units separated by an angular unconformity that indicates progressive northward tilting of the strata resulting in a wedge-shaped Setcomelles outcrop that thins toward the south (Berástegui et al., 1990; García-Senz, 2002; Schöllhorn, 1992).

On the southern flank of the Bóixols-Nargó anticline, Jurassic and Lower Cretaceous rocks are only exposed in the Bóixols area and in the eastern portion of the structure where the hanging wall of the Bóixols thrust weld is still preserved. Where present, the Lower Cretaceous stratigraphy of the southern flank is much thinner than its equivalent of the northern flank. This asymmetry is particularly evident in the Barranc de Culles cross-section where the thick Albian Lluçà marls exposed on the northern flank of the Bóixols-Nargó anticline (nearly 900 m) measure less than 300 m on the southern flank. In this area, the Setcomelles platform is nearly vertical and onlaps onto overturned and eroded upper Aptian and Jurassic rocks. This geometry, together with the sedimentary breccia that marks the rapid transition of the Setcomelles platform into Font Bordonera marls indicates that the upper Aptian-lower Albian platform grew onto a highly unstable substrate that progressively rotated toward the south.

When the two N-S cross-sections running through the central and eastern portion of the Bóixols-Nargó anticline are restored to the early Turonian and late Aptian (Figures 7b and 7c), the dramatic thickness difference and the opposing onlap geometries observed in the two flanks of the anticline indicate that, throughout at least late Aptian-early Albian, the two flanks represented distinct depositional basins separated by an elongated diapiric structure: the Bóixols salt wall/anticline. However, the beginning of the halokinetic activity can be dated back to the base of Kimmeridgian according to the onlap geometries and condensed sequences described by Martín-Chivelet, López-Gómez et al. (2019). The two halokinetic minibasins, the Organyà minibasin to the north (this work) and the Montsec minibasin to the south (Burrel, 2020; Burrel & Teixell, 2021; Hudec et al., 2021), were characterized by highly unstable margins and very different subsidence rates. The onlap geometry of upper Aptian-lower Albian platforms also indicate that the Bóixols salt wall was laterally discontinuous and plunging to the east where the Jurassic units and the Nargó member are continuous across the flanks of the structure.

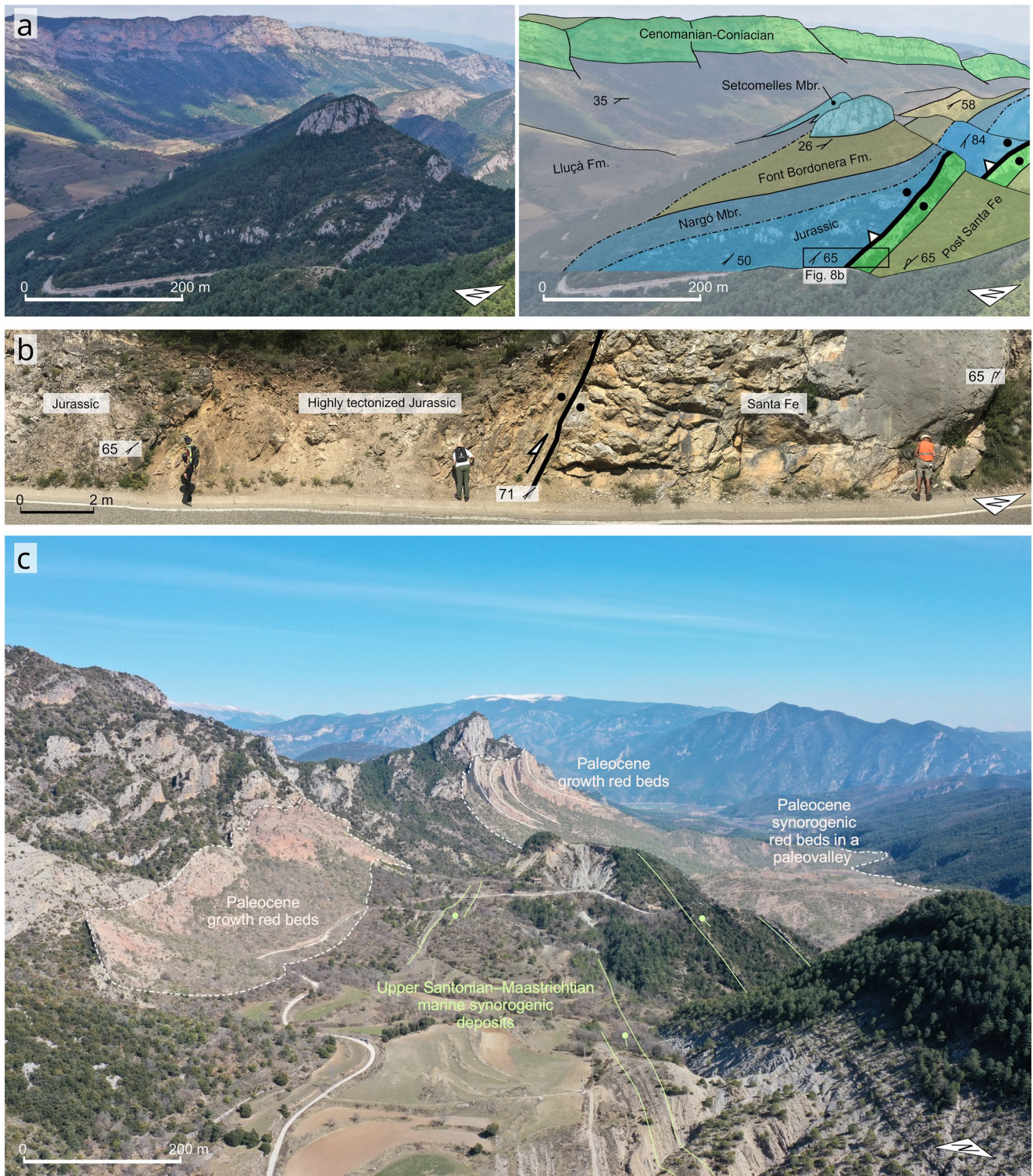


Figure 8. (a) Aerial view and interpretation of the Bóixols thrust weld at Setcomelles (cross-section OB-3). (b) Close-up view of the Bóixols thrust weld at Setcomelles. (c) Aerial view of the Herbasavina synorogenic deposits and Paleocene growth strata associated to the Bóixols thrust weld between cross-sections OB-2 and OB-3.

The thickness difference between the Organyà and Montsec minibasins, as demonstrated by the Comiols-1 and Isona-1Bis wells (Burrel, 2020; Burrel & Teixell, 2021; Hudec et al., 2021), together with the dominant E-W orientation of the Bóixols salt wall, suggest that the Bóixols salt wall developed atop reactivated E-W basement normal faults. Analogue models show that reactivated basement normal faults might strongly control the geometry and location of extensional diapiric structures that are typically observed on the footwall of the normal fault (e.g., Dooley et al., 2005; Granado et al., 2021; Koyi et al., 1993; Moragas et al., 2017; Warsitzka et al., 2021). In some of the models, synthetic normal faults develop within the supra-salt strata to help accommodate the different subsidence rate between the margin of the minibasin, located mostly above the basement footwall, and the center of the minibasin, located above the basement hanging wall (e.g., Dooley et al., 2005). A similar geometry is expected on the southern flank of the Organyà minibasin and it might explain the marked stratigraphic difference observed between the two flanks of the Organyà minibasin (Figure 7). The juxtaposition of Jurassic and upper Cenomanian-lower Turonian rocks along the core of the Bóixols-Nargó anticline, previously interpreted as the surface expression of a major thrust (e.g., Bond & McClay, 1995; García-Senz, 2002; Mencos et al., 2015; Vergés, 1993), is thus reinterpreted as the welding of the southern flank of the Organyà minibasin with the roof of the salt wall during inversion of the basin and squeezing of the diapiric structure (Figure 8b). This weld represents the western continuation of the Bóixols thrust weld located east of the Segre River and discussed in the previous Eastern Organyà Basin section. The two diapiric structures, although not visibly connected at surface, separate the thick Organyà Basin to the north from the condensed Montsec basin to the south. The Central Organyà Basin thus offers a unique opportunity to understand the geometry and lateral stratigraphic variability of the southern margin of the Organyà Basin and provides a model to guide the interpretation of subsurface data in the Western Organyà Basin.

7. Western Organyà Basin Salt-Related Structure Across the Sant Corneli Anticline

In the Western Organyà Basin, Upper Jurassic-Lower Cretaceous halokinetic depositional sequences are only exposed along the Senterada salt wall that bounds the basin to the north. The entire Jurassic and Lower Cretaceous stratigraphy is also penetrated by the Erinyà-1 well located c. 3 km south of the Senterada salt wall along the Flamisell river valley (Figure 9). To the south, the Sant Corneli anticline exposes Santonian or younger rocks but a condensed Jurassic-Lower Cretaceous sequence is penetrated by the Sant Corneli-1 well that is located in the backlimb of the anticline (Figure 2). We will first describe the northern part of the basin where the Flamisell and Noguera Pallaresa river gorges provide excellent exposures of the Lower Cretaceous stratigraphy and then we will combine these observations with sub-surface data from the Erinyà-1 and Sant Corneli-1 wells to build a balanced and restored cross-section through the Western Organyà Basin.

7.1. The Peracalç Minibasin

The large outcrop of Keuper evaporites in the Senterada area has been recently interpreted as part of a large diapiric structure, the Senterada salt wall, that bounds the Lower Cretaceous Organyà Basin to the north (Burrel, 2020; Martín-Chivelet, Floquet, et al., 2019; Martín-Chivelet, López-Gómez et al., 2019). The halokinetic activity of this diapiric structure is recorded in the Barremian-Albian depositional sequences that are spectacularly exposed along the Flamisell and Noguera Pallaresa river gorges. The diapiric contact between the Lower Cretaceous stratigraphy of the Organyà Basin and the Keuper evaporites of the Senterada salt wall, previously interpreted as the expression of the northward-directed Morreres backthrust (Berástegui et al., 1990; Bond & McClay, 1995; García-Senz, 2002; Muñoz, 1992), is overturned along both transects. The overlying Lower Cretaceous stratigraphy consists of a series of sedimentary wedges thinning toward the salt wall and separated by angular unconformities that indicate a progressive and significant basinward tilting of the substrate along the Senterada salt wall. These geometries are particularly well exposed along the Flamisell river valley (Figure 9). Here, the upper Aptian Nargó platform is in contact with the Keuper evaporites. The platform top is karstified and eroded (Berástegui et al., 1990; García-Senz, 2002) and it is overlapped by a condensed section of the Font Bordonera Formation that pinches out toward the north (Puigcerver area). The top of the Font Bordonera is characterized by a hardground overlaid by glauconite-rich marls of the Lluçà Formation (Berástegui et al., 1990; García-Senz, 2002). The Albian marls of the Lluçà Formation locally contain sedimentary breccias with clasts belonging to the same formation and, close to the top, gypsum, red mudstones and ophites belonging to the Keuper (García-Senz, 2002).

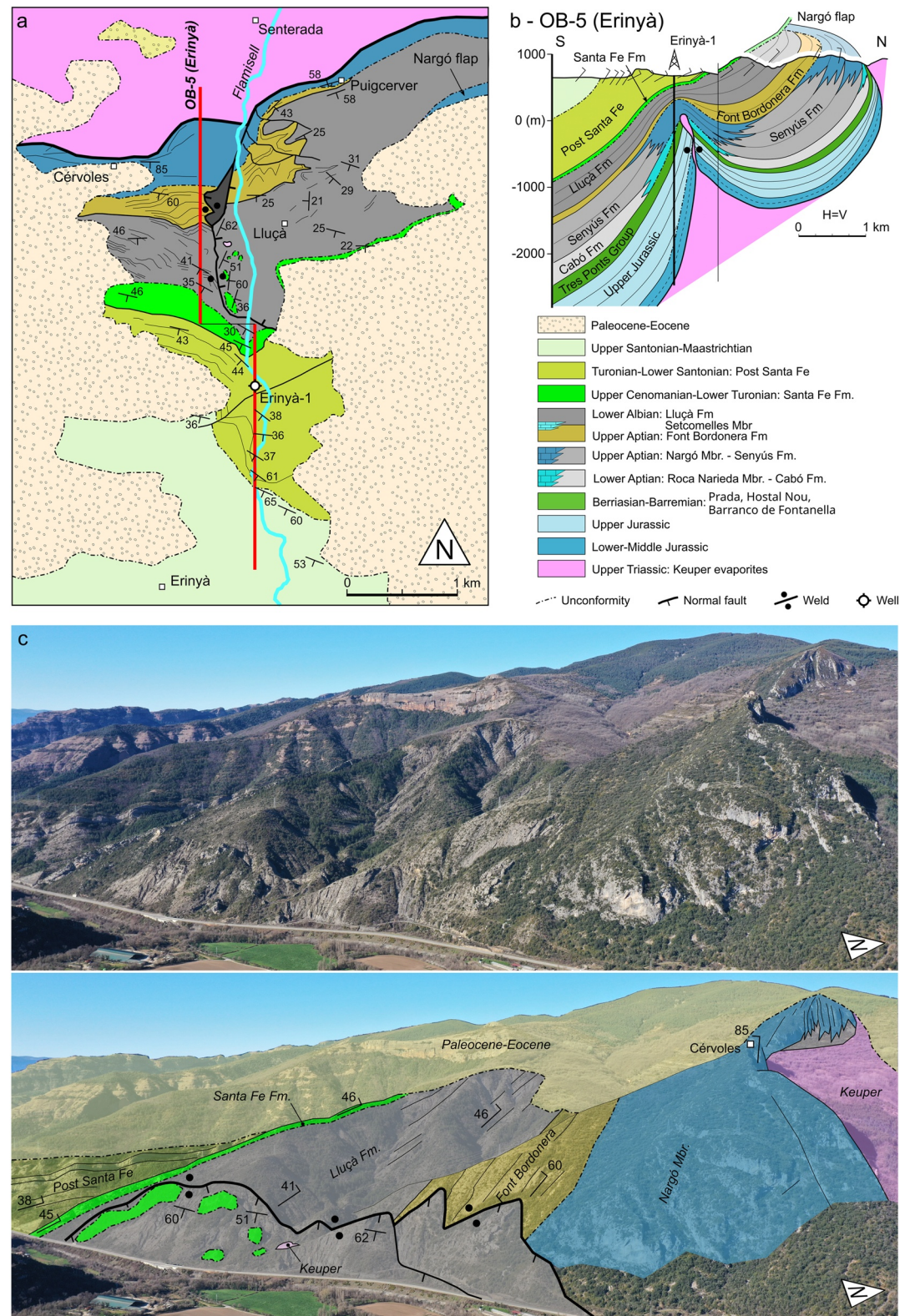


Figure 9. Halokinetic geometries in the Cérvoles-Erinyà area, western Organyà Basin. (a) Geological map modified after García-Senz (2002). Red lines: trace of the OB-5 (Erinyà) cross-section. (b) OB-5 (Erinyà) cross-section. (c) Drone photo of the western side of the Flamisell river (top) and its geological interpretation (bottom).

All these observations indicate that halokinetic movements promoted shallow water deposition and highly mobile substrate along the Senterada salt wall throughout Barremian-Albian time. The redeposited Triassic rocks found toward the top of the Lluçà Formation have been previously interpreted as a salt sheet derived from the Senterada salt wall (Burrel et al., 2021). Certainly, the flap of Nargó mapped along the eastern side of the Flamisell valley suggests an acceleration of the subsidence during early Albian time that eventually led to salt extrusion along the Senterada salt wall. The halokinetic depositional sequence adjacent to the Senterada salt wall filled a fast-subsiding and narrow minibasin oriented parallel to the main diapiric structure: the Peracalç minibasin (Figure 2). The southern boundary of this minibasin is not exposed at surface but it must be located somewhere between the Erinyà-1 well, that penetrates a condensed Aptian-Albian succession, and the exposed Santa Fe platform to the north (Figure 9a). Previous studies have interpreted these sudden thickness and facies changes as the expression of a syn-depositional north-dipping high-angle normal fault (Berástegui et al., 1990; García-Senz, 2002; Garrido-Megías & Ríos Aragüés, 1972). However, the halokinetic geometries observed along the Senterada salt wall favor a salt tectonic reinterpretation of this basin boundary that could be either represented by a listric normal fault detached within Upper Triassic evaporites, as proposed by Burrel (2020), or as a narrow salt wall separating the Peracalç minibasin to the north from the larger Organyà minibasin to the south (Figure 9b). We favor a salt wall solution because of the size similarity between the Peracalç and the Roca Narieda minibasins, and because the listric normal fault option would generate a less realistic extremely narrow and deep basin. Along the Flamisell valley, the Lower Cretaceous strata and the upper Cenomanian-lower Turonian Santa Fe Fm. are offset by and change attitude along a roughly N-S structure that we tentatively interpret as a weld/normal fault possibly related to the collapse of a minor N-S salt wall/anticline (Figure 9c).

7.2. The Sant Corneli Anticline

Further south, where the Lower Cretaceous stratigraphy is not exposed, the E-W trending Sant Corneli anticline represents the western continuation of the broader Bóixols anticline that is cored by a thick Lower Cretaceous succession. The western termination of the Sant Corneli anticline plunges rapidly westwards below Santonian-Maastrichtian synorogenic deposits (Figure 2).

The Sant Corneli anticline is characterized by a moderately dipping backlimb and a nearly vertical forelimb, and it exposes platform to basinal facies of the upper Coniacian-lower Santonian Sant Corneli Formation (Figure 10).

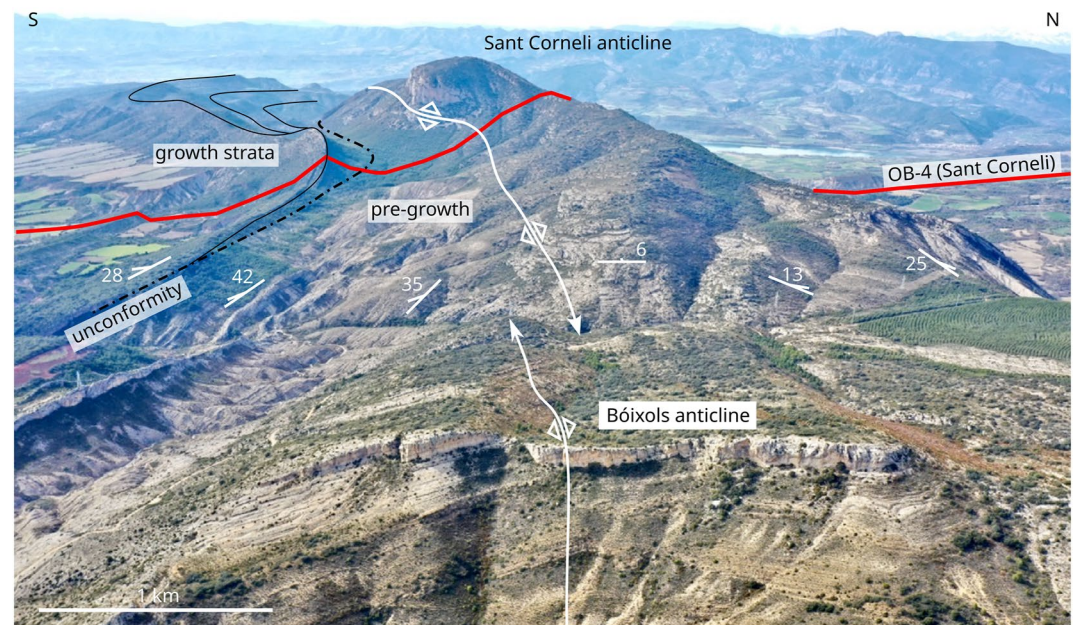


Figure 10. Drone photo, looking toward the west, of the Sant Corneli anticline and western termination of the Bóixols anticline. The red line indicates the trace of the OB-4 (Sant Corneli) cross-section (see Figure 2 for location) through the Western Organyà Basin.

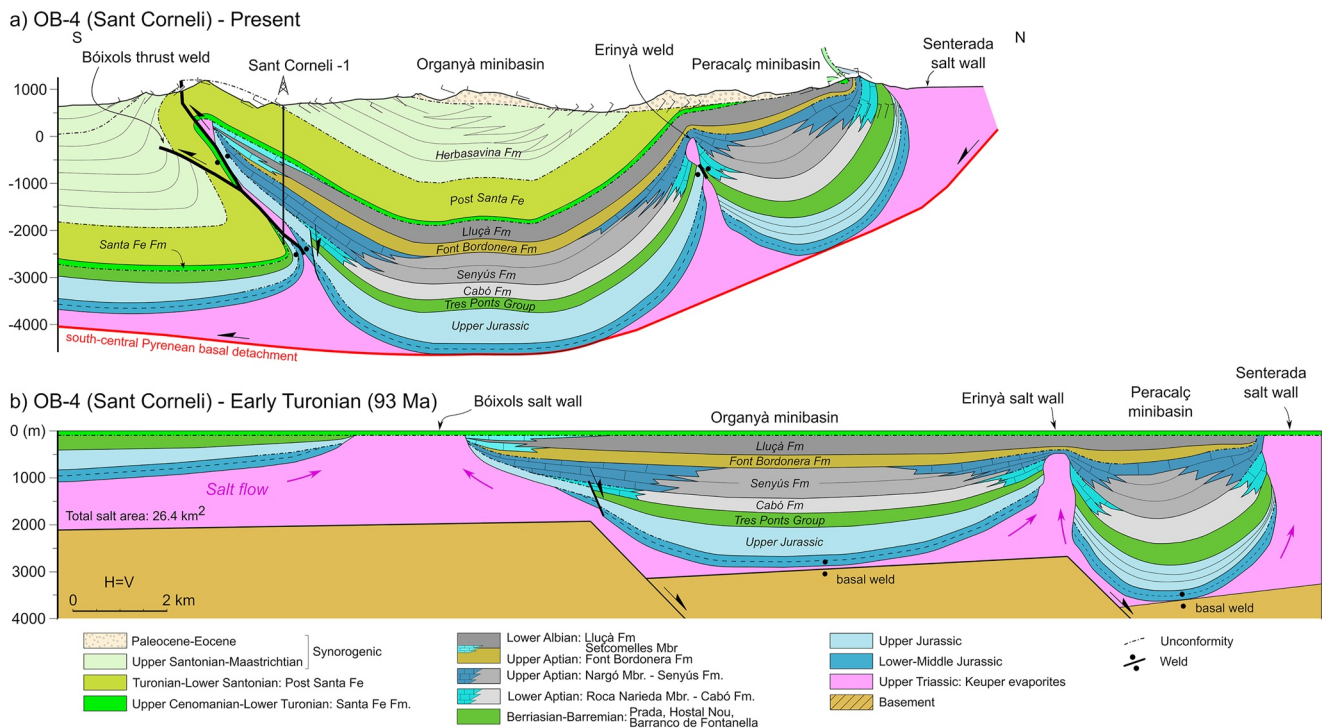


Figure 11. OB-4 (Sant Corneli) balanced and restored cross-section through the Western Organyà Basin.

The upper Santonian-Campanian Herbasavina Formation and younger syn-orogenic deposits wedge against the southern limb of the anticline and fill a growth syncline that dates the beginning of folding at late Santonian (Arbués et al., 1996). Important constraints on the Early Cretaceous configuration of the Organyà Basin are provided by the Sant Corneli-1 well that intercepts roughly 1,000 m of upper Aptian-Albian limestones lying directly on Upper Jurassic rocks. Available well data do not allow the nature of this contact to be established but using the exposures along the core of the Bóixols anticline as an analogue, it is interpreted as an angular unconformity. Below the Jurassic, and after 347 m of Upper Triassic evaporites, the well penetrates a very condensed section of overturned beds composed of Jurassic strata, the Berriasian-Barremian Tres Ponts Group and the upper Cenomanian-lower Turonian Santa Fe Formation. The Jurassic-Lower Cretaceous stratigraphy of the Sant Corneli anticline backlimb is practically identical to the stratigraphy exposed along the southern flank of the Organyà minibasin in the Central Organyà Basin. The Sant Corneli-1 well does not encounter Aptian and Albian stratigraphy below the Upper Triassic evaporites. This stratigraphy, although much more condensed, is comparable to the stratigraphy exposed in the Montsec range and penetrated by the Comiols-1 and Isona-1B is wells to the south (Figure 2). We propose that the thickness and stratigraphic changes recorded between the two flanks of the Sant Corneli anticline indicate that these represent two distinct Early Cretaceous depocenters separated by a depositional high. In continuity to what is observed in the Central Organyà Basin, the depositional high separating the two basins is interpreted as a salt wall that was active from at least Late Jurassic to Albian times and that has been subsequently squeezed and welded to form the Sant Corneli anticline. The salt weld in the core of the Sant Corneli anticline therefore represents the continuation to the west of the Bóixols thrust weld. The geometries observed and reconstructed along the Flamisell river gorge and for the Sant Corneli Anticline have been projected and combined into a balanced and restored N-S cross-section that runs through the Peracalç village and the Sant Corneli-1 well (OB-4 in Figure 11).

8. Discussion

In this section we discuss the restoration of sub-salt and supra-salt domains in the South-Central-Pyrenees, the timing of the Organyà Basin in the frame of the large diapiric province located along the Iberian-Eurasian plate boundary and their implications on the debated Iberian-Eurasian plate boundary configuration.

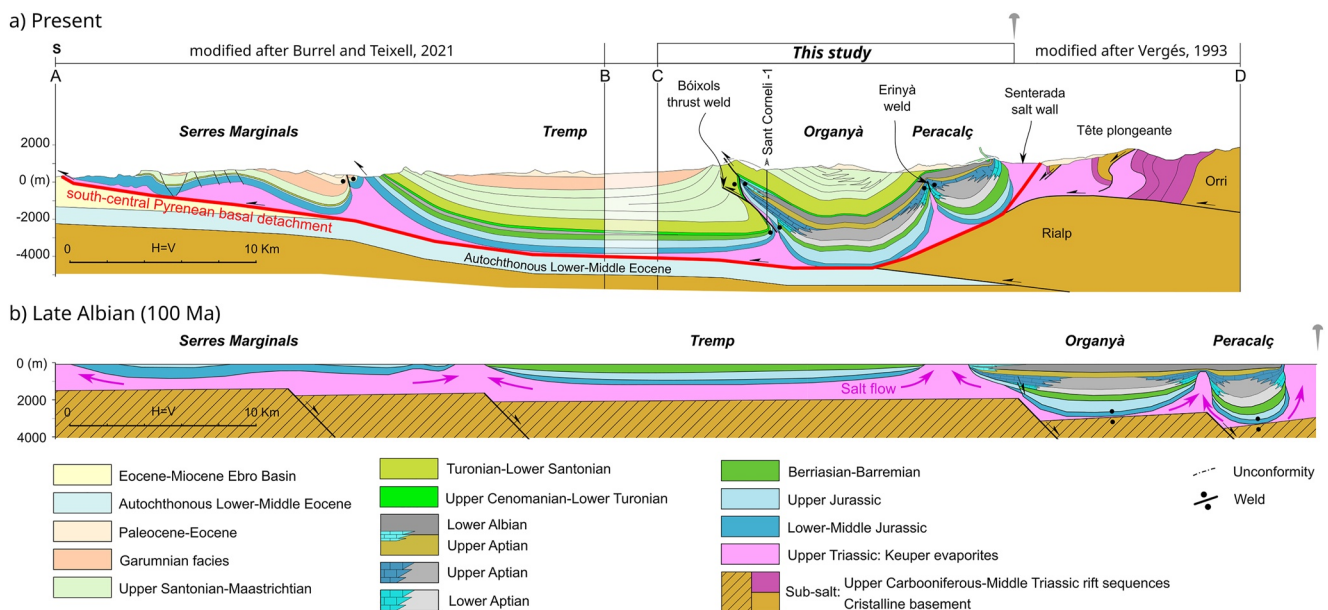


Figure 12. (a) Regional cross-section through the Sant Corneli anticline. The cross-section combines the results of this study with the recent new interpretation of the Serres Marginals and Montsec area by Burrell and Teixell (2021) and the regional cross-section from Vergés (1993). (b) Cross-section restored to late Albian (100 Ma).

8.1. Restoring Supra-Salt and Sub-Salt Domains of the Iberian Rifted Margin

The widespread occurrence of diapiric structures within the South-Central Pyrenees (e.g., Serres Marginals, Montsec, Organyà Basin, Pedraforca, Cotiella, Turbón, Sopeira), to the south of the Senterada salt province, leads to the recognition of a more than 120 km strike-parallel salt-rich domain whose tectono-sedimentary evolution has been profoundly influenced by salt tectonics since at least the Late Jurassic (Figure 1). The complex network of dominantly E-W and N-S oriented diapiric features defines a polygonal array of diachronous supra-salt minibasins typical of diapiric provinces such as the Gulf of Mexico and the Flinders Ranges in Australia (e.g., Rowan & Vendeville, 2006).

Sub-salt units, exposed north of the Senterada salt wall, comprise Uppermost Carboniferous, Permian and Lower Triassic strata that were deposited in half grabens above Variscan basement. These units now lie on the leading edge of the Axial Zone antiformal stack in complex compressional inverted structures (e.g., Têtes plongeantes and Orri thrust sheets on Figure 12; e.g., Saura & Teixell, 2006; Séguret, 1972).

Supra-salt strata of the South-Central Pyrenees allochthonous units have been transported southwards above the Upper Triassic basal detachment and no longer overlie their original substratum. The restoration of presented composite regional cross-section, provides a minimum original width of 60 km for the Iberian margin (Figure 12). This reconstruction would place the Organyà Basin (Bóixols thrust sheet) about 50 km north of its current position. The thickness of the supra-salt minibasins increases toward the north from the Serres Marginals to Montsec to the Organyà Basin suggesting an increase of the original salt thickness as well as greater subsidence and crustal thinning of the rifted margin toward the north.

The localization of diapir growth above and in the immediate footwall of active normal faults, as represented in our model, has been commonly reported in other inverted salt-bearing rifted margins (e.g., Martín-Martín et al., 2016; Saura et al., 2014; Teixell et al., 2017; Vergés et al., 2020) including the Pyrenees and the Bay of Biscay (e.g., Cámara, 2017; Canérot et al., 2005; López-Horgue et al., 2010; Martín-Chivelet, López-Gómez et al., 2019; Poprawski et al., 2014; Quintà et al., 2012). Similar salt-related margin configurations have also been reproduced in numerical and analogue models (e.g., Dooley et al., 2005; Granado et al., 2021; Koyi et al., 1993; Moragas et al., 2017; Schultz-Ela & Jackson, 1996; Vendeville & Jackson, 1992).

The proposed interpretation of the Organyà Basin also requires a review of the geometry and style of the tectonic inversion of this area. As widely recognized, the Triassic evaporites acted as an excellent detachment level between the Jurassic–Cretaceous sedimentary cover and the Paleozoic basement during Alpine shortening (e.g., Ford

et al., 2022). The Organyà Basin was transported over more than 50 km to the south on the south-central Pyrenean basal detachment (e.g., Muñoz, 1992; Muñoz et al., 2018; Vergés, 1993). The two proposed N-S cross-sections through the Roca Narieda and Sant Corneli areas indicate that, beside the large displacement recorded along the basal detachment, the supra-salt section of the Organyà thrust sheet accommodated only a relatively small internal shortening of 8.3–8.6 km (ca. 31%–39%). In contrast to previous models based on thrust tectonics, thrusting seems to be limited and mostly concentrated into the reactivation of salt welds while diapir squeezing and folding account for >85% of the total internal shortening.

8.2. Timing of Diapirism Along the Iberia-Europe Plate Boundary

In the last two decades, a revitalized interest in salt tectonics has generated a large number of detailed studies and the recognition of halokinetic structures from outcrops and seismic data in the main basins along the Iberian-Eurasia rift system: (a) Asturian Basin (e.g., Cadenas & Fernández-Viejo, 2017; Zamora et al., 2017); (b) Basque-Cantabrian Basin (e.g., Badillo Larrieta, 1982; Bodego & Agirrezabala, 2013; Bodego et al., 2018; Cámara, 2017; Hernaiz Huerta & Solé Pont, 2000; López-Horgue et al., 2010; Poprawski et al., 2014, 2016; Quintà et al., 2012; Roca et al., 2011, 2021; Serrano & Martínez del Olmo, 1990; Ábalos et al., 2003); (c) South-Central Pyrenees (Burrel & Teixell, 2021; Gannaway Dalton et al., 2022; López-Mir et al., 2015; Martín-Chivelet, López-Gómez et al., 2019; McClay et al., 2004; Saura et al., 2016); (d) Bay of Biscay-Parentis basins (e.g., Ferrer et al., 2012; Jammes et al., 2010; Roca et al., 2011); (e) Arzacq and Mauléon basins of the northwest Pyrenees (e.g., Canérot et al., 2005; Issautier et al., 2020; Labaume & Teixell, 2020; Masini et al., 2014); and (f) NE Pyrenees (Crémades et al., 2021; Ford & Vergés, 2021). Despite each diapiric structure and minibasin being characterized by unique timing at a high resolution, three main stages of diapiric activity can be recognized: (a) Early Late Jurassic early salt mobilization; (b) Latest Jurassic–early Santonian widespread passive diapirism; (c) base Campanian-Miocene diapir rejuvenation (Figure 13).

Early salt mobilization along the Iberian margin is recorded from Early to Late Jurassic in various depocenters (Figure 13). In the Organyà Basin, the onset of halokinetic activity is recorded at the base Kimmeridgian angular unconformity as recognized in the Taús area. In this locality, a polygenetic breccia unconformably overlies a hard-ground developed on the top of the Aalenian strata (Delmas et al., 1971; Garrido-Megías & Ríos Aragüés, 1972). The dolomite breccia was originally dated as Middle Jurassic (Peybernès, 1968), but the presence of *Pseudocyclammina jaccardi* (*Alveosepta jaccardi*) at its base indicates a late Oxfordian-Kimmeridgian age (e.g., Delmas et al., 1971; Garrido-Megías & Ríos Aragüés, 1972; Maync, 1960; Pélissié et al., 1984). The unconformity records a period of instability along the northern flank of the Organyà minibasin and also corresponds to a change from open to restricted marine depositional conditions (Delmas et al., 1971; Garrido-Megías & Ríos Aragüés, 1972) suggesting that the diapiric structures rapidly modified the paleogeography of the area and influenced depocenter geometry and sedimentary facies distributions. Late Jurassic halokinetic activity has also been reported along the northern flank of the Montsec minibasin by Martín-Chivelet, López-Gómez et al. (2019). These authors interpret the local absence of the thick Bathonian-Oxfordian deposits (Isona-1Bis well), and the onlap of Berriasian-Barremian strata onto a thin and southward tilted Jurassic substratum as evidence for the development of a large salt pillow on the footwall of the main basement fault bounding the Organyà Basin to the south.

The principal period of passive diapirism across the Iberian margin occurred during Early Cretaceous. During this period, and despite the uniqueness of each diapiric structure, all sedimentary basins along the Pyrenean Trough recorded extensive diapirism, increased subsidence, and the deposition of thick mixed carbonate-siliciclastic depositional sequences (e.g., Badillo Larrieta, 1982; Burrel & Teixell, 2021; Hernaiz Huerta & Solé Pont, 2000; Labaume & Teixell, 2020; López-Horgue et al., 2010; Saura et al., 2016; Serrano & Martínez del Olmo, 1990; Vergés, 1993; Zamora et al., 2017). The activity of main diapirs in the Organyà minibasin also continued throughout the Early Cretaceous, and up to the mid Cenomanian Santa Fe unconformity. The overlying upper Cenomanian-lower Turonian post-rift Santa Fe carbonate platform records an important basin-scale period of reduced subsidence (see Figure 1) and the end of the most significant halokinetic activity in the Organyà Basin (see Figure 6). However, facies changes and progradation directions observed in the upper Turonian-lower Santonian carbonate platforms exposed along the Sant Corneli and Bóixols anticlines suggest that salt movements continued up to late Santonian.

Finally, the closure of the Iberia-Eurasia rift system and the inversion of rifted basins along the Pyrenean Trough, that started at base Campanian, triggered a widespread rejuvenation of diapiric structures that continued up to

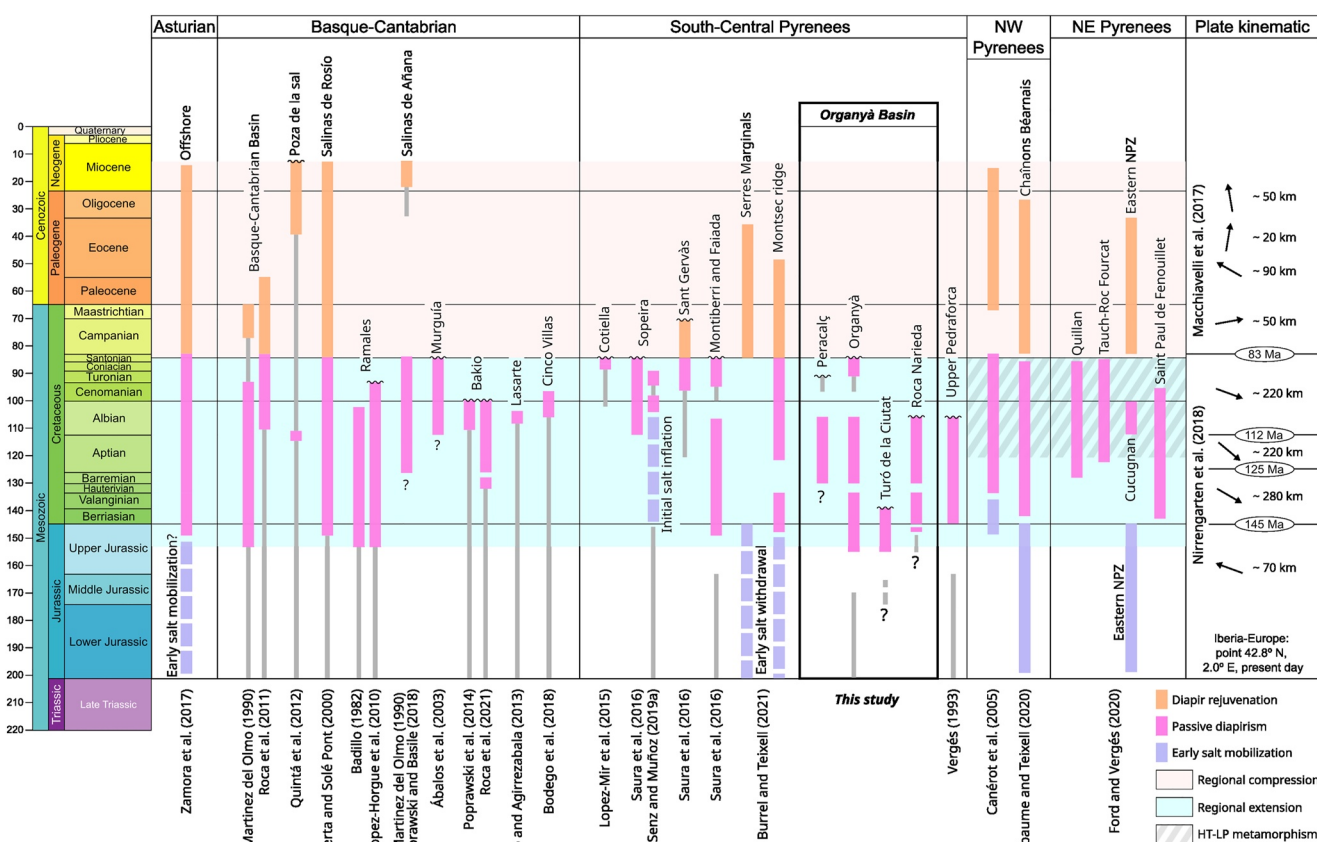


Figure 13. Timing of halokinetic movements along the Pyrenean Trough. Black hollow box indicates the results of this study.

middle Miocene (Burrell & Teixell, 2021; Gannaway Dalton et al., 2022; Poprawski & Basile, 2018; Quintà et al., 2012; Roca et al., 2011; Saura et al., 2016; Serrano & Martínez del Olmo, 1990; Zamora et al., 2017). In fact, only few diapiric structures are clearly sealed by pre-orogenic strata or not rejuvenated during compression (e.g., Lasarte, Cinco Villas), while several examples preserve synorogenic halokinetic depositional sequences, in the Asturian Basin (Zamora et al., 2017) and in the Basque-Cantabrian Basin (e.g., Poza de la Sal, Salinas de Rosío, Salinas de Añana, Salinas de Oro and Estella diapir, among others) (e.g., Hernaiz Huerta & Solé Pont, 2000; Larrasoana et al., 2003; Poprawski & Basile, 2018; Quintà et al., 2012; Roca et al., 2011; Serrano & Martínez del Olmo, 1990). Syn-compression halokinetic depositional sequences are also preserved along the South-Central Pyrenees with good examples in Cotiella, Sopeira, Sant Gervàs, Serres Marginals and Montsec (Burrell & Teixell, 2021; Gannaway Dalton et al., 2022; López-Mir et al., 2015; McClay et al., 2004; Saura et al., 2016). Uppermost Cretaceous and Paleocene syntectonic units also occur along the front of the inverted Organyà Basin (e.g., Arbués et al., 1996; Simó, 1985). However, the level of exposure makes it difficult to determine if they represent compressional growth strata, halokinetic depositional sequences or a combination of the two.

Despite the numerous works dedicated to unraveling the evolution of the Iberia-Eurasia plate boundary and the recent advances in plate tectonic reconstructions, the geometry and kinematics of this plate boundary are still debated. The main models proposed so far can be divided in two groups with regards to the relative movement of the Iberian plate during the Jurassic and Early Cretaceous. In the first group, the Bay of Biscay opened in a left-lateral or transtensive manner with little rotation of Iberia (e.g., Olivet, 1996; Olivet et al., 1984) whereas in the second group the Bay of Biscay opened scissor-like with coeval counterclockwise rotation of Iberia and subduction of a Neotethys oceanic realm below the present Ebro Basin (e.g., Sibuet et al., 2004; Srivastava, Schouten, et al., 1990). Recently, more complex models integrate non-rigid plates and/or a number of small continental blocks with deformation accommodated along multiple boundaries between Eurasia and Iberia (e.g.,

Angrand et al., 2020; Asti et al., 2022; Nirrengarten et al., 2018; Tugend et al., 2015). Regardless of the adopted plate geometry and kinematics, all models propose similar positions for the Iberian plate with respect to North America and Europe at the Triassic–Jurassic boundary (pre-Jurassic rifting), and at 83.5 Ma (pre-Late Cretaceous convergence). The Late Cretaceous position is well-constrained by Anomaly 34 in the Southern North Atlantic (Rosenbaum et al., 2002; Srivastava et al., 1990; Vissers & Meijer, 2012) and it is supported by the new Southern North Atlantic isochron map from Macchiavelli et al. (2017). The inferred sinistral drift of Iberia of ~720 km, considered a maximum drift distance according to Nirrengarten et al. (2018), took place mainly during the Cretaceous between 150–140 and 90–83.5 Ma giving mean rates of ~9.0 mm/yr. The documented thick halokinetic sequences along the Iberian and Eurasian margins are synchronous to the large sinistral translation of Iberia with respect to Europe thus suggesting a link between diapirism and transtensional plate movement as already discussed for the NE Pyrenees (Ford & Vergés, 2021). Diapiric growth during Early Cretaceous has been also proposed for the Maestrat Basin in the Iberian Ranges (Vergés et al., 2020), potentially confirming either localized accommodation of transtensional deformation along the Iberian Range or diffuse transtension across north Iberia. However, the efficient decoupling between supra-salt and sub-salt structures in the Organyà Basin, as documented in this contribution, prevents clear identification of sub-salt lineaments and the potential roles of strike-slip or pure shear mechanisms along the Iberian–Eurasian boundary during Late Jurassic–Early Cretaceous rifting.

9. Conclusions

The 4.3 km thick Organyà Basin, along the northern South-Central Pyrenees, is reinterpreted stressing both the initial contribution of Upper Triassic salt mobilization during the Jurassic and Early Cretaceous rifting and its implications for the style of compressive structures associated to the Alpine inversion of the basin.

Within the salt-related Organyà Basin, distinctive halokinetic depositional sequences involving prograding and aggrading carbonate platform systems, infilled the Organyà, Roca Narieda, Turó de la Ciutat and Peracalç minibasins that were limited by dominantly E-W and N-S salt walls.

The Organyà Basin belongs to the South Pyrenean Diapiric Province that also includes the Upper Pedraforca unit to the east and the Sopeira-Sant Gervàs and Cotiella units to the west. This diapiric province is limited to the north by the 120-km long Senterada salt wall complex that formed an ample part of the northern margin of Iberia during most of the Mesozoic.

In the Eastern Organyà Basin, where salt-related evolution is best identified, the carbonate platforms of the Roca Narieda minibasin record a long-lasting halokinetic evolution at least from the Berriasian to the Early Albian (ca. 30 Myr). The minibasin is limited by the Fígols weld to the north and west and by the Bóixols thrust weld to the south.

A 5-stage evolutionary model of the Eastern Organyà Basin has been constructed along a N-S cross-section from end Middle Jurassic to early Turonian times. The volume of required Upper Triassic salt has been minimized by assuming a minor reactivation of pre-existing Permo-Triassic normal faults resulting in an initial thickness of salt between 0.7 km to the south of the Roca Narieda minibasin and 1.5 km to the north.

The front of the Bóixols thrust sheet developed along the Bóixols salt wall that was squeezed and displacement to the south as a thrust weld during Late Cretaceous shortening. This structural reactivation is well characterized in the Eastern Organyà Basin but becomes more complex toward the west where the better preservation of pre-growth and growth depositional sequences masks the salt-related signature along the Bóixols and Sant Corneli anticline.

During Alpine compression, the Organyà Basin was fully decoupled from its Paleozoic basement and transported southwards above the South Pyrenean thrust system using Upper Triassic salt as basal detachment level. Above the detachment, compression was mostly accommodated by diapir squeezing, salt wall welding and associated folding. In contrast to previously adopted thrust tectonics models, in our interpretation thrusting only accounted for less than 15% of the recorded internal shortening.

The three main periods of diapiric activity in the Organyà Basin can be recognized within multiple depocenters along the whole northern Iberian margin from Asturias to the Eastern Pyrenees: (a) Jurassic early salt mobilization; (b) latest Jurassic–middle Albian main diapiric activity which could continue to the late Santonian; and (c) diapir reactivation starting at base Campanian time.

The widespread and long-lasting diapiric activity of the second period developed in both margins of the Pyrenean Trough and may be related to the general transtensional motion of Iberia over about 60 Myr during the opening of the Southern North Atlantic Ocean.

Data Availability Statement

Dips measured in the field (329) and extracted from virtual outcrops (433) are available in this in-text data citation reference: Casini et al. (2022). Reconstructing the Iberian salt-bearing rifted margin of the Southern Pyrenees: insights from the Organyà Basin (dataset). The dataset is open access to anybody (Public Domain Mark (PD)) and can be found at: DOI: <https://doi.org/10.20350/digitalCSIC/14862>; URL: <http://hdl.handle.net/10261/285257>. Part of the geological maps, dips and stratigraphic column used in this work were digitized and modified from García-Senz (2002). The PhD thesis is available at: <http://diposit.ub.edu/dspace/handle/2445/34901>. Part of the geological maps and dips used in this work were digitized and modified from the following ICGC 1:25.000 maps: Aramunt 252-2-2 (66-22); Isona 290-2-1 (66-23); Tremp 252-1-2 (65-22); Vilamitjana 290-1-1 (65-23). The maps are available both in GeoPDF and Shape file formats from the ICGC web page at: <https://www.icgc.cat/Administracio-i-empresa/Descarregues/Cartografia-geologica-i-geotematica/Cartografia-geologica-GT-I-Mapa-geologic-1-25.000> (Muñoz et al., 2009, 2010; Pi et al., 2001, 2004). Part of the geological maps and dips used in this work were digitized and modified from the following ICGC 1:50.000 maps: 04_Alt Urgell; 23_Noguera; 25_Pallars Jussà. The maps are available in GeoPDF format from the ICGC web page at: <https://www.icgc.cat/Administracio-i-empresa/Descarregues/Cartografia-geologica-i-geotematica/Cartografia-geologica-Mapa-geologic-comarcal-1-50.000/Mapa-geologic-comarcal-de-Catalunya-1-50.000>. The whole dataset of ICGC 1:50.000 maps is also available in Shape format from the ICGC web page at: <https://www.icgc.cat/Administracio-i-empresa/Descarregues/Cartografia-geologica-i-geotematica/Cartografia-geologica-Mapa-geologic-comarcal-1-50.000> (Institut Cartogràfic i Geològic de Catalunya, 2006, 2007a, 2007b). Part of the remote sensing geological mapping was performed on GoogleEarth pro available at: <https://www.google.com/intl/en/earth/versions/> (Google, 2022).

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