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RESEARCH ARTICLE

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Key Points:

- We show the evolution of the Mesozoic Columbrets Basin located SW of the Valencia Trough
- We describe the Mesozoic evolution of one of the main Cenozoic western Mediterranean basins
- We illustrate the complex interaction between extreme crustal thinning and prerift salt level for the evolution of hyperextended basins

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Extreme Mesozoic Crustal Thinning in the Eastern Iberia Margin: The Example of the Columbrets Basin (Valencia Trough)

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Abstract Eastern Iberia preserves a complex succession of Mesozoic rifts partly or completely inverted during the Late Cretaceous and Cenozoic in relation with Africa-Eurasia convergence. Notably, the Valencia Trough, classically viewed as part of the Cenozoic West Mediterranean basins, preserves in its southwestern part a thick Mesozoic succession (locally ≈ 10 km thick) over a highly thinned continental basement (locally only ≈ 3.5 km thick). This subbasin, referred to as the Columbrets Basin, represents a Late Jurassic-Early Cretaceous hyperextended rift basin weakly overprinted by subsequent events. Its initial configuration is well preserved allowing us to unravel its 3-D architecture and tectonostratigraphic evolution in the frame of the Mesozoic evolution of eastern Iberia. The Columbrets Basin benefits from an extensive data set combining high-resolution seismic reflection profiles, drill holes, seismic refraction data, and expanding spread profiles. The interactions between halokinesis, involving the Upper Triassic salt, and extensional deformation controlled the architecture of the Mesozoic basin. The thick uppermost Triassic to Cretaceous succession displays a large-scale “syncline” shape, progressively stretched and dismembered toward the basin borders. We propose that the SE border of the basin is characterized by a large extensional detachment fault acting at crustal scale and interacting locally with the Upper Triassic décollement. This extensional structure accommodates the exhumation of the continental basement and part of the crustal thinning. Eventually, our results highlight the complex interaction between extreme crustal thinning and occurrence of a prerift salt level for the deformation style and tectonostratigraphic evolution of hyperextended rift basins.

1. Introduction

The Valencia Trough, located between the Iberian Peninsula and the Balearic Promontory, is generally considered as one of the western Mediterranean Cenozoic extensional basins. These basins developed during the late Oligocene to middle Miocene in relation with the southeastward slab retreat of the Maghreb-ian-West Ligurian Tethys subduction (e.g., Etheve et al., 2016; Jolivet & Faccenna, 2000; Maillard & Mauffret, 1999; Rehault et al., 1984; Roca et al., 1999; Séranne, 1999). This tectonic history is often interpreted as the main event that shaped the present-day crustal architecture of the Valencia Trough, characterized by a shallow Moho depth, reaching locally 8–10 km at the transition with the Liguro-Provençal basin (Ayala et al., 2015; Mauffret et al., 1992; Torne et al., 1992).

The Valencia Trough is surrounded by the Iberian Chain, the Catalan Coastal Ranges, and the Betic-Balearic orogenic system, recording a complex and polyphased Mesozoic to Cenozoic evolution (Figure 1). To the west, the Iberian Chain and the Catalan Coastal Ranges represent Paleogene intracontinental belts (Guimerà & Álvaro, 1990), related to the inversion of Late Jurassic to Early Cretaceous rift basins (Álvaro et al., 1979; Gaspar-Escribano et al., 2004; Salas et al., 2001). To the southeast, the Valencia Trough is partly overprinted and deformed by a northwest directed middle Miocene fold-and-thrust belt belonging to the external Betic orogen (De Ruig, 1992; Maillard & Mauffret, 1999; Roca & Desegaulx, 1992; Roca et al., 2004; Vergés & Fernández, 2012).

While the Cenozoic infill of the Valencia Trough has been extensively described, seismic profiles across its SW part revealed a thick Mesozoic succession (~ 10 km) particularly well imaged in the so-called Columbrets

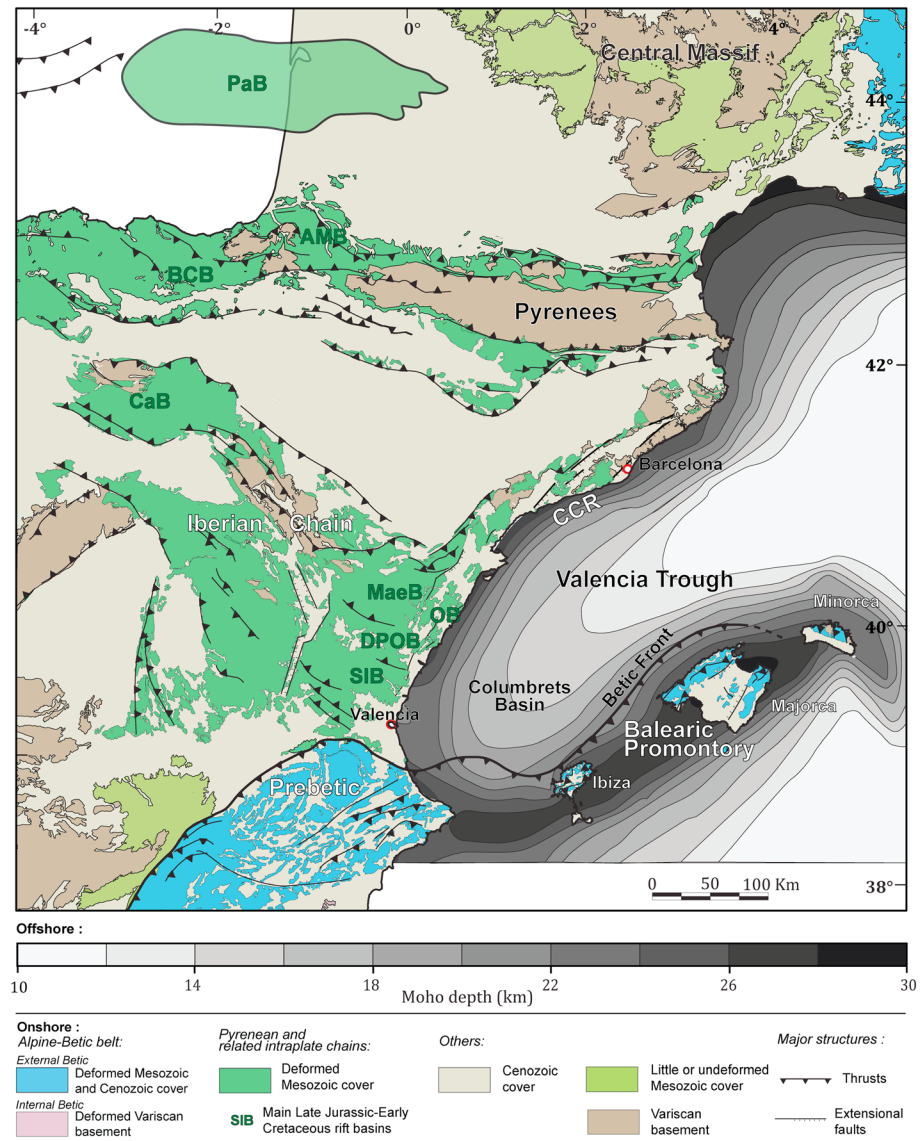


Figure 1. Tectonic map of eastern Iberian Peninsula and adjoining offshore Mediterranean areas highlighting the critical position of the Valencia Trough at the junction of Pyrenean-related intraplate chains (Iberian Chain and Catalan Coastal Ranges) and the younger Betic orogen. Moho depth is taken from Ayala et al. (2003). CaB = Cameros Basin; MaeB = Maestrat Basin; DPOB = Desert de les Palmes Basin; SIB = South Iberian Basin; OB = Orpesa Basin; PaB = Parentis Basin; AMB = Arzacq-Mauleon Basin; BCB = Basque-Cantabrian Basin; CCR = Catalan Coastal Ranges.

Basin. The imaged Mesozoic succession consists of Jurassic to Cretaceous sedimentary rocks above an Upper Triassic evaporite sequence overlying an extremely thinned continental basement (Ayala et al., 2015; Maillard et al., 1992; Roca, 1996). The Upper Triassic evaporites are notably involved in salt diapirism in the southern Iberian paleomargin (i.e., Betic domain) (Martínez del Olmo, 1996; Moissenet, 1985) and represent the main décollement in eastern Iberia. Altogether, these observations indicate that the present-day crustal architecture of the Valencia Trough is not only simply resulting from the West Mediterranean Cenozoic evolution but also records a previous history including Mesozoic extension and Paleogene compression. This study aims to unravel the architecture and Mesozoic to Paleogene evolution of the Columbrets Basin and its place in the eastern Iberia framework.

The Columbrets Basin benefits of high-quality seismic reflection coverage, local drillings, expanding spread profiles (ESP), and refraction data (e.g., Dañobeitia et al., 1992; Lanaja, 1987; Mauffret et al., 1992; Roca, 1996; Torne et al., 1992). Well data and correlations together with onshore field observations and seismic

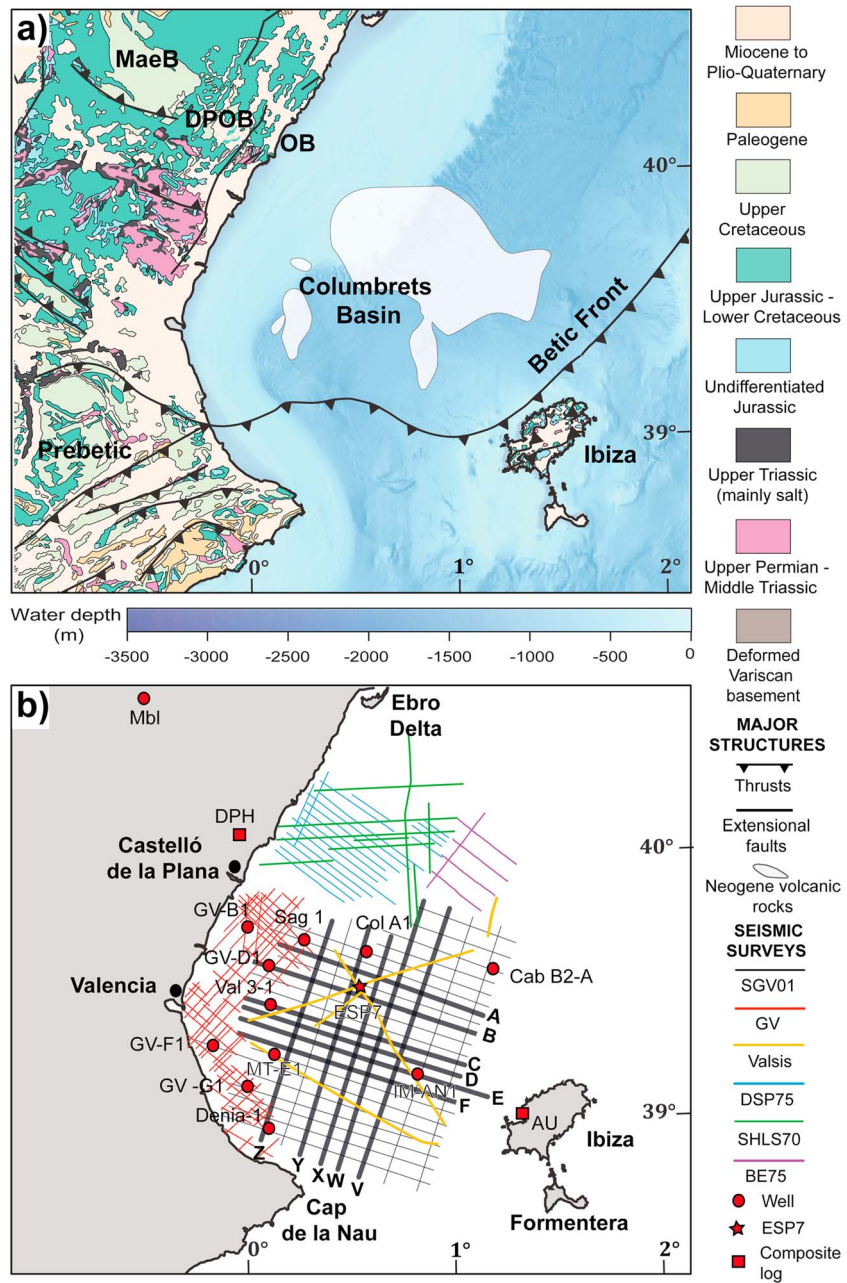


Figure 2. (a) Geological map of the offshore areas surrounding the SW part of the Valencia Trough after (Instituto Geológico y Minero de España (IGME), 1994) with the offshore location of the Upper Triassic salt bodies and main Neogene volcanic edifices. The bathymetry is after www.emodnet.eu/bathymetry. (b) Map showing the location of the seismic surveys, drill holes, and ESP data used in this study; SGV01 seismic profiles represented with a thicker line correspond to the ones included in the paper. (Profile A: SGV01-107; Profile B: SGV01-109; Profile C: SGV01-112; Profile D: SGV01-113; Profile E: SGV01-114; Profile F: SGV01-115; Profile Z: SGV01-201; Profile Y: SGV01-203; Profile X: SGV01-204; Profile W: SGV01-205; Profile V: SGV01-206).

stratigraphy allow us to describe in detail the basin fill stratigraphy. Additional NW-SE and NE-SW seismic reflection sections illustrate the spatial evolution of the basin architecture. Thickness variations of different basin fill units are analyzed using isochore maps built from the interpreted boundaries in the seismic profiles. The new data presented in this work document the Mesozoic tectonosedimentary evolution of the Columbrets Basin, as part of the eastern Iberian margin, as it experienced only little reactivation during

subsequent Cenozoic compressional and extensional events. These results enable us to highlight the role of the Mesozoic history in shaping the present-day architecture of the Valencia Trough with potential implications for the pre-Cenozoic history of other West Mediterranean basins, as the Gulf of Lion or Provençal basins. More generally, our conclusions provide new key observations on the formation of hyperextended rift basins with prekinematic salt among which the Late Jurassic to Early Cretaceous rift basins observed within and around Iberia.

2. Geological Setting

2.1. The Tectonosedimentary Evolution of Eastern Iberia

From the late Paleozoic onward, eastern Iberia recorded a succession of extensional and compressional events. In particular, the extensional events were associated with the formation of rift basins characterized by different ages and degree of crustal thinning and strong lateral thickness variations of their sedimentary infill (Figures 1 and 2). These deformations affected a Paleozoic substratum consisting of pre-Permian sediments moderately deformed and generally weakly to unmetamorphosed during the Variscan orogeny associated with magmatic intrusions during the late Paleozoic (Martinez-Catalán et al., 2007). From the Permian to the Santonian, a long period of extension occurred characterized by several rift events in relation with the opening of both the Tethys and Atlantic Oceans. In the Valencia Trough and its close surroundings, three major rift events are recognized that are separated by periods of relative tectonic quiescence.

The first one, Late Permian to Early Triassic in age, was characterized by a diffuse extension leading to the formation of a set of small intracontinental extensional basins forming two rift systems: (1) a NW-SE system, localized on the present-day Iberian Chain and (2) a NNE-SSW system, following the Valencia Trough (Arche & López-Gómez, 1996; Vargas et al., 2009). These basins were mainly filled by red siliciclastic continental deposits (e.g., Buntsandstein facies), which were upsection replaced by postrift shallow marine carbonates with minor evaporite and continental detrital interbeds (Muschelkalk facies) (e.g., Vargas et al., 2009, and references therein) (Figure 3).

The second rift event, mainly Late Triassic-Middle Jurassic in age, was linked to the opening of the Alpine-Ligurian Tethys expressed essentially in the Betic realm, which represent the Iberian paleomargin of this oceanic domain (Frizon de Lamotte et al., 2011; Jiménez-Munt et al., 2010; Schettino & Turco, 2011). In the study area, this event was mainly recorded in the SE part of the Iberian Chain (i.e., the Desert de les Palmes area, Figures 1 and 2) and was characterized by extensional faulting, strong thickness variations of the sedimentary succession (Figure 3) and syntectonic unconformities (Aurell et al., 1992; Roca et al., 1994). The associated sedimentary record shows relatively thick evaporitic succession (mainly anhydrite and halite) with frequent continental detrital and shallow platform dolostone interbeds (Ortí et al., 2017). This last shallow water platform became predominant from Rhaetian times grading upsection into limestone and marly successions of Sinemurian to Middle Jurassic age. Because of their constant thickness and associated subsidence analyses, the upper part of these successions has been interpreted as deposited in a postrift tectonic setting relatively to the second rift event (Salas et al., 2001; Vargas et al., 2009).

The third and last Mesozoic rift event started in the late Oxfordian and lasted until the middle Albian (Nebot & Guimerà, 2016; Salas et al., 2001). It eventually led to the opening of the Bay of Biscay and to hyperextension in the Pyrenean rift system, interpreted as a failed attempt of the individualization of the Iberian plate (Tugend et al., 2015). This event resulted in the formation of large intraplate extensional basins in the Iberian domain and Valencia Trough (e.g., Caméros, Maestrat, Columbrets, and South Iberian Basins; Figures 1 and 2) (Maillard et al., 1992; Roca, 2001; Roca & Guimerà, 1992; Salas & Casas, 1993; Salas et al., 2001). In addition, a renewed crustal stretching in the proximal parts of the South Iberian passive margin was also evidenced (Vilas et al., 2003). These basins recorded important crustal thinning while filled up by thick (5–8 km) Late Jurassic to Early Cretaceous successions (Roca, 1996; Salas et al., 2001). These synrift successions are essentially made by platform carbonates that grade basinward into deep water marls and rhythmites. Locally, in the basin margins, they include also fluvial to deltaic detrital interbeds of Barremian age. Unconformably overlying these successions, the late Albian detrital sandstones (Utrillas Formation) and the Upper Cretaceous carbonates recorded a thermal subsidence linked to the postrift stage that followed this third rift event (e.g., Nebot & Guimerà, 2016; Salas et al., 2001).

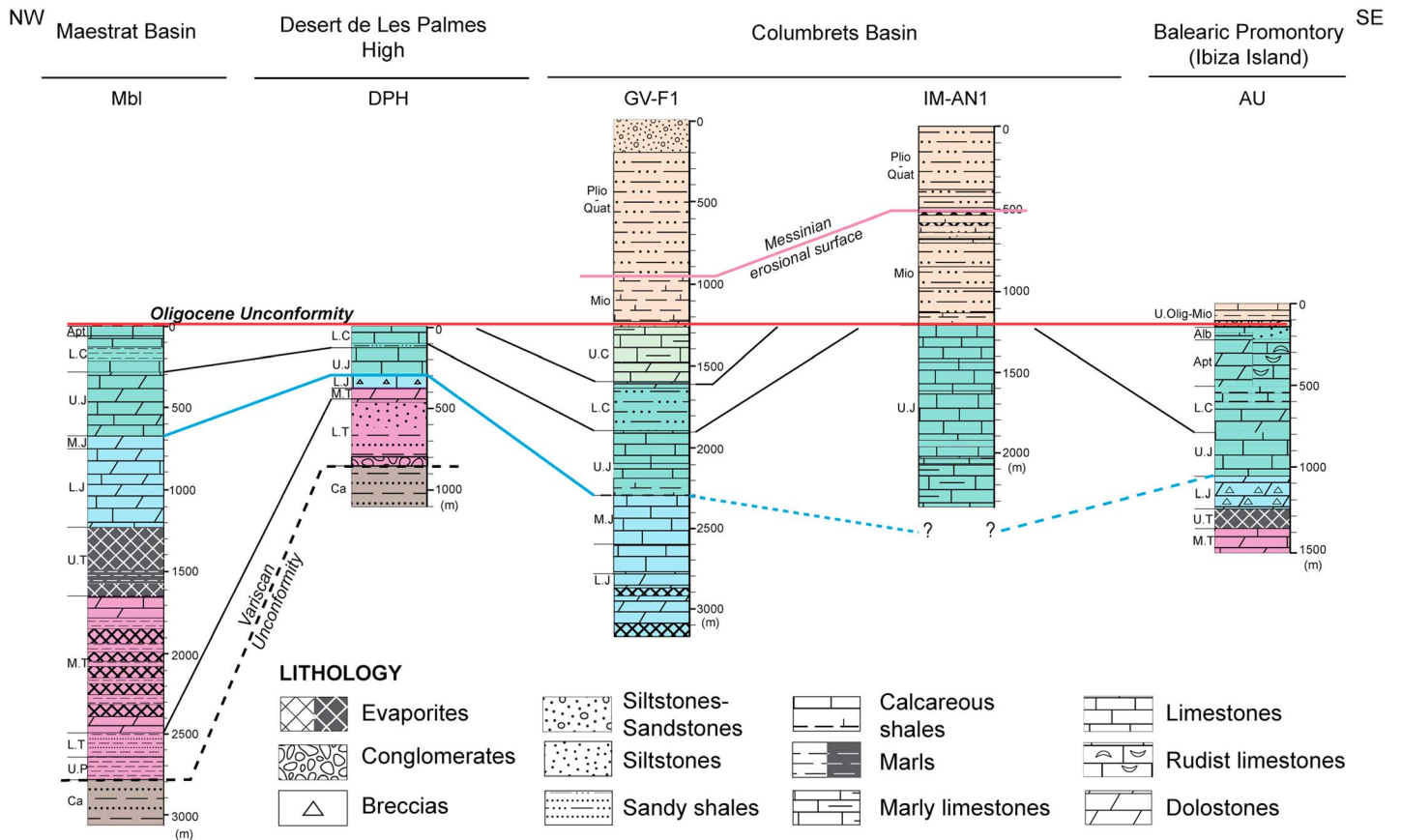


Figure 3. Stratigraphic logs documenting the thickness and lithological variations of the Mesozoic successions across the SW part of the Valencia Trough. Logs after Salas and Casas (1993) for the Maestrat Basin; Roca et al. (1994) for the Les Palmes High; Roca (1996) for wells of Golfo de Valencia F-1, Ibiza Marino An-1; and Etheve et al. (2016) for the northwestern part of the Ibiza Island. The location of the stratigraphic logs is indicated in Figure 2b. Ca = Carboniferous (Variscan substratum); U.P = Upper Permian; L.T = Lower Triassic; M.T = Middle Triassic; U.T = Upper Triassic; L.J = Lower Jurassic; M.J = Middle Jurassic; U.J = Upper Jurassic; L.C = Lower Cretaceous; Apt = Aptian; Alb = Albian; U.C = Upper Cretaceous; U.Olig = Upper Oligocene; Mio = Miocene; Plio-Quat = Pliocene to Quaternary.

The onset of the convergence between Africa and Eurasia at Santonian times entailed a radical change in the tectonosedimentary evolution of the area. The extensional tectonic regime that prevailed was replaced by a succession of compressional and extensional deformational stages (e.g., Álvaro et al., 1979; Roca, 2001; Roca et al., 2004; Salas et al., 2001; Vergés & Sàbat, 1999). From Santonian to early Eocene, this change of geodynamic context led to the formation of some minor unconformities (Azéma, 1977; Guerrero et al., 2014; Ramos-Guerreo et al., 1989; Salas et al., 2001). During late Eocene to Oligocene, a major compressional event led to the inversion of former Mesozoic extensional basins. This inversion resulted in the formation of the intraplate Iberian Chain and Catalan Coastal Ranges and finally the formation of a major regional unconformity (the so-called “Oligocene unconformity” (O.U.)) in the Valencia Trough, Balearic Promontory, and eastern Prebetic domain (Gaspar-Escribano et al., 2004; Geel, 1995; Guimerà & Álvaro, 1990; Sàbat et al., 2011; Soler et al., 1983) (Figure 3). This compressional deformation is also interpreted as the main phase of the Pyrenean orogeny (Muñoz, 2002; Vergés & García-Senz, 2001; Vergés et al., 2002). It was followed by a late Oligocene to middle Miocene extensional event in relation with the complex interaction between the European Cenozoic rift system (Dèzes et al., 2004; Séranne, 1999; Vegas et al., 1979) and the Maghrebian-Ligurian Tethys slab rollback (Auzende et al., 1973; Boccaletti & Guazzone, 1974; Etheve et al., 2016; Jolivet et al., 2015; Roca et al., 1999). This extension triggered the formation of the Liguro-Provençal and Algerian basins as well as the Valencia Trough. In its northeastern parts, the development of the Cenozoic Valencia Trough was associated with the motion of large extensional faults (with displacements >5 km; Roca et al., 1999) that reactivated previous Paleogene compressional and Mesozoic extensional faults (Fontboté, 1954; Gaspar-Escribano et al., 2004). In contrast, southwest of the Valencia Trough (our study area) evidence for

extensional faults are minor and diffuse while the connection with its northeastern part remains poorly constrained (Maillard & Mauffret, 1993; Pellen et al., 2016; Roca & Guimerà, 1992).

The accommodation space generated in the Valencia Trough from the late Oligocene onward was filled by up to a 2–6 km thick pile of sediments (e.g., Ayala et al., 2015). This basin infill consists of uppermost Oligocene–lower Miocene platform carbonates and massive conglomerates that grade upsection, to lower-middle Miocene marls and limestones, and middle Miocene to recent basinward prograding clastic deposits (Clavell & Berástegui, 1991; Roca et al., 1999; Soler et al., 1983). These last deposits outline the presence of a major internal unconformity with thin continental detrital bodies and evaporites that record the Mediterranean Messinian event (Escutia & Maldonado, 1992; Maillard et al., 2006; Martínez del Olmo & Megías, 1991; Stampfli & Höcker, 1989; Urgeles et al., 2011).

It is worth noting that extension in the Valencia Trough occurred just before and/or synchronously with the buildup of the compressional Betic orogen (Fontboté et al., 1990; Vergés & Sàbat, 1999). This orogen grew southeast of the Valencia Trough and affected its southeastern parts during the early-middle Miocene. This compressional deformation is well expressed by a thin- or thick-skinned fold-and-thrust system cropping out in Ibiza and Majorca Islands (Balearic Promontory) and Eastern Betics (Etheve et al., 2016; Sàbat et al., 2011). Eventually, this complex evolution was associated with a significant magmatic activity in and around the Valencia Trough that can be divided into two main distinct phases: (1) a late Oligocene to Serravallian calc alkaline and (2) a Tortonian to Present alkaline volcanic activity (Martí et al., 1992).

2.2. The Crustal and Lithospheric Architecture of the Valencia Trough

The crustal and lithospheric architecture of the Valencia Trough is well known from the extensive geophysical investigations carried out by the oil industry and academic institutions. These studies reveal that the basin is floored by thin crust and lithosphere. (See Ayala et al., 2015, for a review.) However, the two margins of the Trough are showing a contrasted crustal thickness passing from 30 to 36 km thick in the Iberia mainland (Gómez-Ortiz et al., 2011; Vidal et al., 1997) to 23–25 km in the Balearic Promontory (Ayala et al., 2015, 1996; Dañobeitia et al., 1992; Torne et al., 1992; Vidal et al., 1998). The continental crust is thinner in the present-day Valencia Trough axis where the Moho depth passes from 23–25 km in the SW to 8–12 km in the NE (Ayala et al., 2015, 2003; Torne et al., 1996) (Figure 1). Assuming the bottom of the Cenozoic basin infill as the top of the “crust” in the Valencia Trough, a stretching factor (β) of 1.8–3.2 was estimated (Collier et al., 1994; Negredo et al., 1999; Watts & Torné, 1992). Nevertheless, this stretching factor did not consider the thick Mesozoic cover imaged in the Columbrets Basin. Indeed, the ESP and seismic data show that the continental crust (i.e., pre-Mesozoic basement) is only 4–5 km thick beneath the Columbrets Basin (Mauffret et al., 1992; Torne et al., 1992) implying a much larger crustal stretching.

In the Valencia Trough area, the continental crust is generally characterized by a highly reflective lower crust. Notably, this reflective zone is close to 16 km thick in the unextended Iberian Peninsula (Gallart et al., 1994; Sàbat et al., 1997) while it thins toward the axis of the trough becoming only 1–2 km thick or even absent (Torne et al., 1992). The decrease of this reflective zone within the trough was related to the development of ductile shear zones that thinned the lower crust (Sàbat et al., 1997).

Below, the lithosphere-asthenosphere boundary is also interpreted as being relatively shallow based on 3-D gravity and geoid modeling (Ayala et al., 1996, 2003; Carballo et al., 2015; Roca et al., 2004; Zeyen & Fernández, 1994). Following the review of Ayala et al. (2015), it is inferred to be at 60–65 km depth along the SW-NE axis of the Valencia Trough deepening to 80–90 km under the Iberian Peninsula and 65–70 km beneath the Balearic Promontory. One of the most distinctive features of the Valencia Trough is the anomalous low P wave velocities of its uppermost mantle (7.6–7.8 km s⁻¹; Dañobeitia et al., 1992; Gallart et al., 1990; Watts et al., 1990). This anomaly was attributed to a moderate serpentinization of the lithospheric mantle (Carballo et al., 2015) although other origins such as seismic anisotropies or partial meltings have also been proposed (e.g., Collier et al., 1994; Díaz et al., 2013).

3. Data and Methodology

The data sets used in this work are indicated in Figure 2b. They are composed of industrial and previously published academic surveys (e.g., VALSIS-II experiment, Mauffret et al., 1992; Maillard et al., 1992). Seismic interpretations (Figures 5–9) and isochore maps (Figure 10) across the Columbrets Basin are based on the

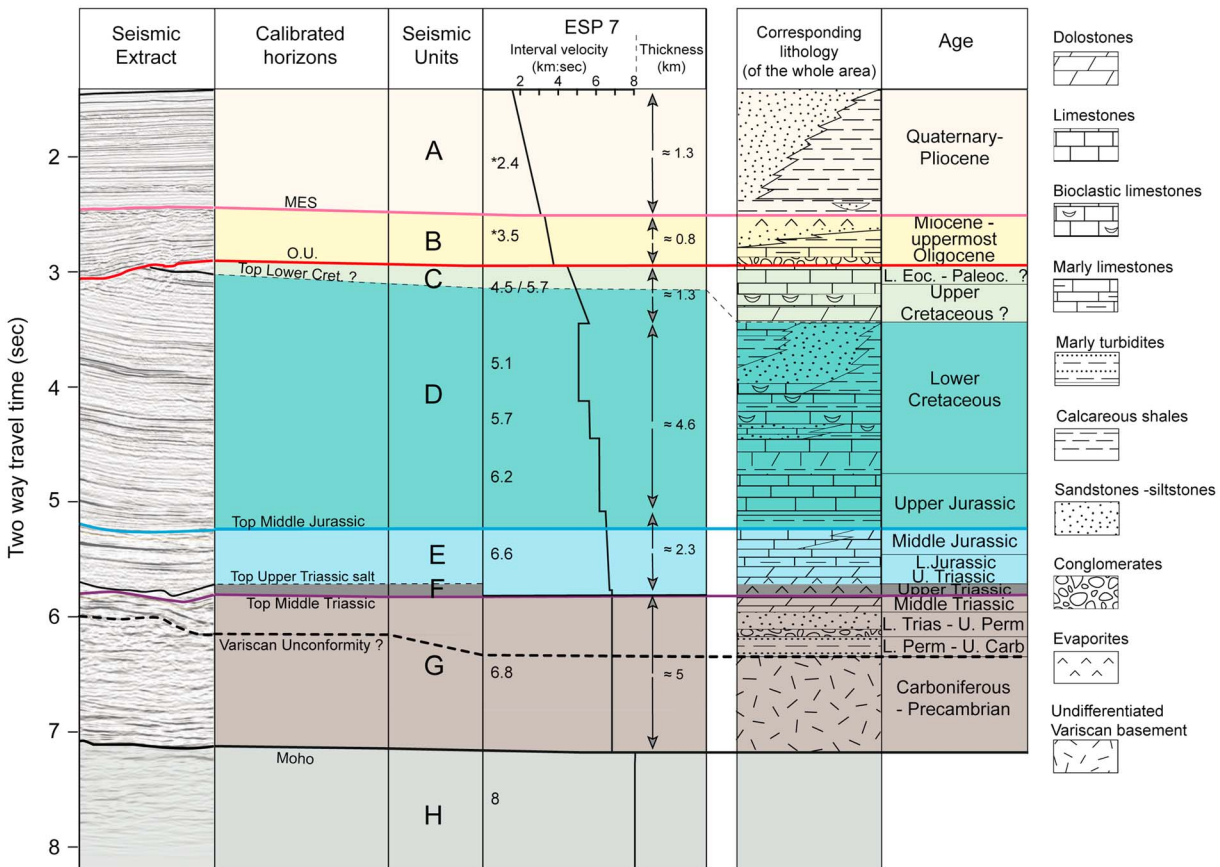


Figure 4. Definition of the seismic units used in this study. The seismic extract comes from the SGV01-109 (Profile B in Figure 2), and the ESP data corresponds to the ESP-7 of Torne et al. (1992) located nearby. See profile, extract, and ESP localizations in Figures 2 and 6. The correlation between the seismic facies and lithologies and ages is based on well data combined with onshore observations.

industrial SGV-01 seismic reflection data locally completed by adjacent surveys. Reflection seismic surveys are combined with ESPs acquired during the VALSIS-II experiment in 1988 in the Valencia Through (Pascal et al., 1992; Torne et al., 1992). Offshore and onshore industrial wells (>10, Lanaja, 1987, Figure 3) located on the borders of the Columbrets Basin (Figure 2b) are used for calibrations. Two composite wells constructed from field stratigraphic sections were added (DPH and AU, respectively, based on Roca et al., 1994; Etheve et al., 2016, Figure 2b). In addition, these data sets were completed by onshore geological observations from the adjacent Iberian Peninsula and Balearic Promontory (Figure 2a).

In detail, the identification of seismic units across the basin is based on (1) variations of seismic facies throughout the profiles, (2) P wave velocity information from the ESP-7 (Dañobeitia et al., 1992; Torne et al., 1992), and (3) identification of major unconformities observed in wells and seismic reflection profiles (Figures 2–4). Eventually, the link between the seismic facies and lithologies/ages is inferred from well calibration. However, where well data were insufficient, in particular, in the central and/or deeper parts of the basin, correlations have been deduced from analogies with onshore adjacent reactivated Mesozoic basins (e.g., Maestrat basin and Prebetic domain) (Figure 2a).

4. Definition of Seismic Units at the Columbrets Basin Area

Seven main seismic units labeled from A to H (Figure 4) have been defined in the Columbrets Basin. The definition of the different units is primarily based on well calibration with seismic reflection sections, explaining the local misfit with the ESP data (Figure 4).

4.1. Present to Upper Oligocene Succession (Units A and B)

This succession is a part of the Cenozoic filling of the Valencia Trough, extensively studied since the 1970s (e.g., Clavell & Berástegui, 1991; Maillard et al., 1992; Pellen et al., 2016; Roca et al., 1999; Soler et al., 1983).

The Unit A is generally characterized by continuous parallel flat-lying reflectors of moderate to high amplitudes that present general progradation geometry toward the basin, close to the present-day shelf of the Iberian Peninsula (see Figures 5–9). With an average P wave velocity of 2.4 km s^{-1} based on the ESP-7 (Torne et al., 1992), this unit consists of terrigenous shelf-talus system formed by sandstones, shales, and marls as indicated by several industrial wells (Figures 3 and 4).

The limit between units A and B is highlighted by a strong and irregular high-amplitude reflection that truncates the underlying reflectors, while in the deepest part of the basin it is covered by a thin system of chaotic and imbricated seismic bodies. These bodies and the high-amplitude reflection have been associated to the Messinian Salinity Crisis (Lofi et al., 2011; Maillard & Mauffret, 2013; Martínez del Olmo & Megias, 1991). Specifically, the high-amplitude reflection is correlated with the subaerial unconformity described in the literature as the Messinian erosional surface (Bache et al., 2012; Lofi et al., 2011).

Beneath this boundary, the sedimentary Unit B displays low- to high-amplitude reflections generally associated with horizontal geometries passing locally downsection to a transparent or chaotic pattern (see Figures 4, 5, and 7). Based on extensive drilling, the Unit B has been inferred to be late Oligocene to late Miocene in age. It includes uppermost Oligocene to lower Burdigalian continental terrigenous sediments to marine platform carbonates, upper Burdigalian to Langhian marine platform carbonates and marls, and Serravallian to lower Messinian terrigenous shelf-talus progradational deposits (Clavell & Berástegui, 1991; Lanaja, 1987; Martínez del Olmo, 1996; Roca & Desegaulx, 1992; Soler et al., 1983).

In seismic reflection profiles, prominent seamounts were related to large volcanic edifices associated with layered high-amplitude reflections attributed to lava flows (Maillard & Mauffret, 1993; Martí et al., 1992). This widespread volcanic activity appears to be contemporaneous with the deposition of both units A and B.

4.2. Lower Eocene to Upper Triassic Succession (Units C–F)

The top of the lower Eocene to Upper Triassic succession is marked by an irregular high-amplitude reflector that clearly truncates the underlying reflective units and is overlapped by the basal deposits of the Unit B (Figures 4, 5, and 7). It corresponds to a major regional unconformity dated as late Eocene to earliest Miocene (Clavell & Berástegui, 1991; Soler et al., 1983; Stoekinger, 1976) present in the whole Valencia Trough and surrounding onshore areas. This major unconformity is referred to as Oligocene Unconformity (O.U) throughout this study.

Below this unconformity, a reflective package mostly Mesozoic in age, overlies the so-called “acoustic basement” (described in details in the next section). These units C–F are essentially composed of Upper Triassic to Upper Cretaceous sediments although we cannot exclude the local occurrence of Paleocene to Eocene deposits (Soler et al., 1983). Nevertheless, for the sake of simplicity, it will be referred to in the following as the Mesozoic succession.

The reflectivity pattern of this so-called Mesozoic succession is not constant and changes laterally and vertically (Figures 4, 5, and 7). We distinguish five superposed units with a well-differentiated seismic signature. The stratigraphic calibration of these seismic units in the central part of the basin remains difficult. Indeed, most of the drilled wells either sampled the uppermost part of the Mesozoic succession or were located on the margins of the Columbrets Basin with distinct seismic facies and occurrence of faults preventing any detailed correlations (Figures 5 and 7).

The Unit C is generally strongly eroded by the O.U. and is only present close to the depocenter of the Columbrets Basin and in some isolated areas of its margins. Seismically, it consists of a rather transparent facies with diffuse and discontinuous reflectors of moderate amplitude limited at their base by a marked and continuous high-amplitude reflector (Figures 4, 5, and 7). The precise age of this unit is poorly constrained as no wells have sampled it. The seismic calibration associated with available wells in the Columbrets Basin margins enables us to propose a post-Aptian age for this unit. The strong reflector located at the base of Unit C suggests a significant lithological change in agreement with the ESP-7 (Torne et al., 1992), showing a downward increase of the seismic velocity (Figure 4). We suggest that the base of the Unit C corresponds to the boundary between

the Cenomanian-Turonian dolostones and the Senonian marls and limestones based on analogies with the onshore Upper Cretaceous stratigraphy (Azéma et al., 1979; De Ruig, 1992; Martin-Chivelet et al., 2002) and observations from the well Golfo de Valencia F-1 where the Upper Cretaceous succession is almost complete (Lanaja, 1987; Roca, 1996). As shown in the Golfo de Valencia F-1 well logs (Roca, 1996), this boundary separates a Senonian interval (i.e., Coniacian to Campanian) with frequent velocity changes from a Cenomanian-Turonian interval with a relatively constant higher seismic velocity. Assuming this proposed age for the lower boundary, the Unit C may include Senonian to possible lower Eocene deposits in less eroded areas.

The Unit D corresponds to an alternation of reflective, continuous, and high-amplitude reflectors with more transparent and diffuse packages (Figures 4, 5, and 7). This unit shows major thickness variations, passing from less than 0.5 s two-way traveltime (TWT) in the margins to ~2.5 s TWT in the Columbrets Basin depocenter (Figure 6). As the rest of Mesozoic units, the drilled wells only sampled the basin margins at the top of Miocene topographic highs (e.g., Golfo de Valencia F-1, Columbretes A-1, and Cabriel B2-A). Based on these well data and on the comparison between the seismic facies and the onshore stratigraphy (Iberian Peninsula and Balearic islands), this unit is dated as Late Jurassic to Cenomanian-Turonian (Late Cretaceous) and can be divided into four subunits:

1. An upper subunit formed by relative transparent facies with a high seismic velocity (5.7 km s^{-1} in the ESP-7; Figure 4) that can be correlated with the Cenomanian-Turonian dolostones.
2. A middle-upper reflective subunit of lower seismic velocity (5.1 km s^{-1} in the ESP-7; Figure 4) characterized by high-amplitude reflectors becoming diffuse upward. As in the Prebetics (Escosa et al., 2016) where a similar seismic unit is dated by some wells, it is interpreted as middle Albian-early Cenomanian in age consisting of poorly lithified sandstones that grade upward to shales and limestones and basinward to marls with some sandstone interbeds.
3. A middle-lower subunit again relatively transparent with some reflectors of moderate to high amplitude becoming more frequent in the basin margins (see Figures 5 and 7). With a slightly higher seismic velocity ($5.7\text{--}6.2 \text{ km s}^{-1}$ in the ESP-7; Figure 4), this subunit is correlated with the Hauterivian-lower Albian successions recognized both onshore and in the wells Golfo de Valencia F-1 and Columbretes A-1. These successions are made by platform marls and bioclastic limestones (Urgonian facies) and, in their middle to lower parts (Hauterivian-lower Aptian), grade toward the basin margins to deltaic/fluvial sandstones and shales (Weald facies). This sedimentary succession is consistent with the distribution of the “transparent” and “reflective” seismic facies present in this subunit.
4. A lower unit again very reflective with some continuous and high-amplitude reflectors interlayered with transparent units (Figures 4–8). This subunit is drilled by the Ibiza Marino An-1 and Golfo de Valencia F-1 wells and corresponds to the Upper Jurassic-Berriasian consisting of platform to hemipelagic limestones and marly limestones with marly interbeds.

The Unit E is well identifiable in seismic reflection profile. It corresponds to a quite transparent package with some continuous low-frequency and high-amplitude reflectors that are more frequent in the upper part of the unit. The thickness of the unit through the seismic sections is generally constant despite some local variations. Based on well data and onshore observations combined with seismic correlation, the unit may correspond to uppermost Triassic to early Lower Jurassic massive dolostones and anhydrites that grade upward to late Lower to Middle Jurassic limestones and dolostones with some minor marly interbeds (Roca, 1996, Figure 3). According to this lithological composition, the Unit E exhibits a relatively fast internal velocity (6.6 km s^{-1} ; Torne et al., 1992).

Finally, the Unit F corresponds to a chaotic seismic facies that passes laterally to quite continuous reflectors with a very high amplitude. This unit forms isolated bodies showing typical salt-related geometries such as diapirs, pillows ridges, or welds (Figures 7 and 8). The roof of some of these diapir shape bodies has been drilled in the SW margin of the Columbrets Basin (Lanaja, 1987, e.g., Denia-1, see Figure 2 for location) consisting of Upper Triassic evaporites (Keuper facies). In detail, the Upper Triassic evaporites consist of a layered sequence formed by halite with layers of anhydrite, dolostone, and terrigenous sediments that became predominant westward (De Torres & Sanchez, 1990; Ortí, 1974).

4.3. Middle Triassic to Moho: The “Acoustic” Basement

The Unit G is defined as the acoustic basement bracketed by the above described Mesozoic units and the Moho. In this work, the term acoustic basement defines a composite unit with an internal structure

characterized by variable seismic signatures (likely corresponding to different lithologies) that can be interpreted locally but cannot be easily correlated over large distances.

This unit includes three intervals with a different seismic signature: an upper thin and discontinuous level integrated by high-frequency, high-amplitude reflectors; a thick intermediate level with a chaotic seismic facies and rare short reflectors; and, finally, a lower reflective level formed by discontinuous and moderate to high-amplitude reflectors.

The reflective upper level consists of nearly horizontal layers with a noticeable acoustic impedance difference. Based on the onshore sedimentary record (Arche & López-Gómez, 1996; Roca et al., 1994; Vargas et al., 2009), it probably corresponds to an alternation of slightly deformed detrital, carbonate, volcanic, and evaporite layers belonging to the Permian to Middle Triassic. The intermediate layer is interpreted as the middle-upper crust characterized by a velocity of 5.9–6.4 km/s (Torne et al., 1992) measured in the Columbrets Basin margins. As suggested from well data in the closest Iberian Peninsula (Bartrina et al., 1990; Gallart et al., 1994; Lanaja, 1987), it likely corresponds to the Variscan basement. The lower reflective layer has a higher velocity (6.4–7.0 km/s; Torne et al., 1992; Vidal et al., 1998) and is consistent with lower crust. The base of this interval is characterized by a sudden increase of the seismic velocity from 6.8 to 7.8–8 km s⁻¹ (Torne et al., 1992) corresponding to a very high amplitude reflector located at ~7–7.5 s TWT, interpreted as the Moho. The Moho is well observed beneath the basin, although locally discontinuous and vanishing close to the Balearic Promontory (Figures 4–8).

5. The Columbrets Basin: A Mesozoic Hyperextended Basin

By using seismic sections of the SGV-01 survey combined with well data and previous geophysical information (e.g., Maillard et al., 1992; Torne et al., 1992) we investigate the SW part of the Valencia Trough and, in particular, the architecture of the Mesozoic Columbrets Basin. Seismic profiles used in this study have NW and NE trends that are partly oblique to the main structures recognized in the area both onshore and offshore (Maillard et al., 1992; Roca, 1996; Vera, 2004). The NW trending sections (named respectively A to F, Figures 5 and 6) show extensional structures that formed in relation with the Mesozoic Iberian margin. In contrast, the NE trending ones (named respectively Z to V, Figures 7 and 8) illustrate the southeast offshore extension of the Iberian Chain and the Betic thrust-and-fold belt and associated salt structures. The NW and NE trending seismic sections combined with the interpretations of previously published surveys are the main data set used for the creation of the isochore maps shown in Figure 10.

The analysis of seismic sections (Figures 5–9) illustrates the post late Oligocene history of the southwestern part of the Valencia Trough showing the geometry of Present to upper Oligocene sedimentary basin infill. Unconformably overlying the folded Mesozoic units, this Tertiary basin infill was affected by a compressional deformation at the southern part of the study area where it is involved in a thin-skinned fold-and-thrust system with reactivated salt diapiric structures (Figures 7 and 8). The northern edge of this system, middle Miocene in age, is interpreted to represent the Betic front that depicts a large WNW trending bend in our study area, connecting the Eastern Prebetics and Ibiza thrust fronts (Figures 1, 2, and 10). North of this front, the uppermost Oligocene to present-day fill of the Valencia Trough is practically undeformed. This succession shows a rather constant thickness and is predominantly horizontal, only deformed by few listric extensional faults and smooth folds (Figures 7 and 8). Thus, despite the Neogene extensional to compressional events and local magmatism, the Mesozoic architecture of the Columbrets Basin is still remarkably preserved and imaged.

5.1. Architecture of the Mesozoic Columbrets Basin

We illustrate the general 3-D architecture of the Mesozoic Columbrets Basin based on the seismic profiles shown in Figures 5–9 and the isochore and structural maps in Figure 10. Beneath the O.U., the Mesozoic reflective succession and underlying acoustic basement display contrasting deformation style separated by a key horizon corresponding to the Upper Triassic layered evaporite sequence.

Along the seismic profiles, the Upper Triassic-Cretaceous succession (possibly including lower Eocene sediments locally) displays a NE plunging “syncline” shape (Figures 5–10). The height and width of the syncline is not constant. The maximum width is observed close to the NE edge of study area (Figure 6, Profile A) and decreases gradually to the SW (Figure 6, Profile F), where the syncline almost disappears.

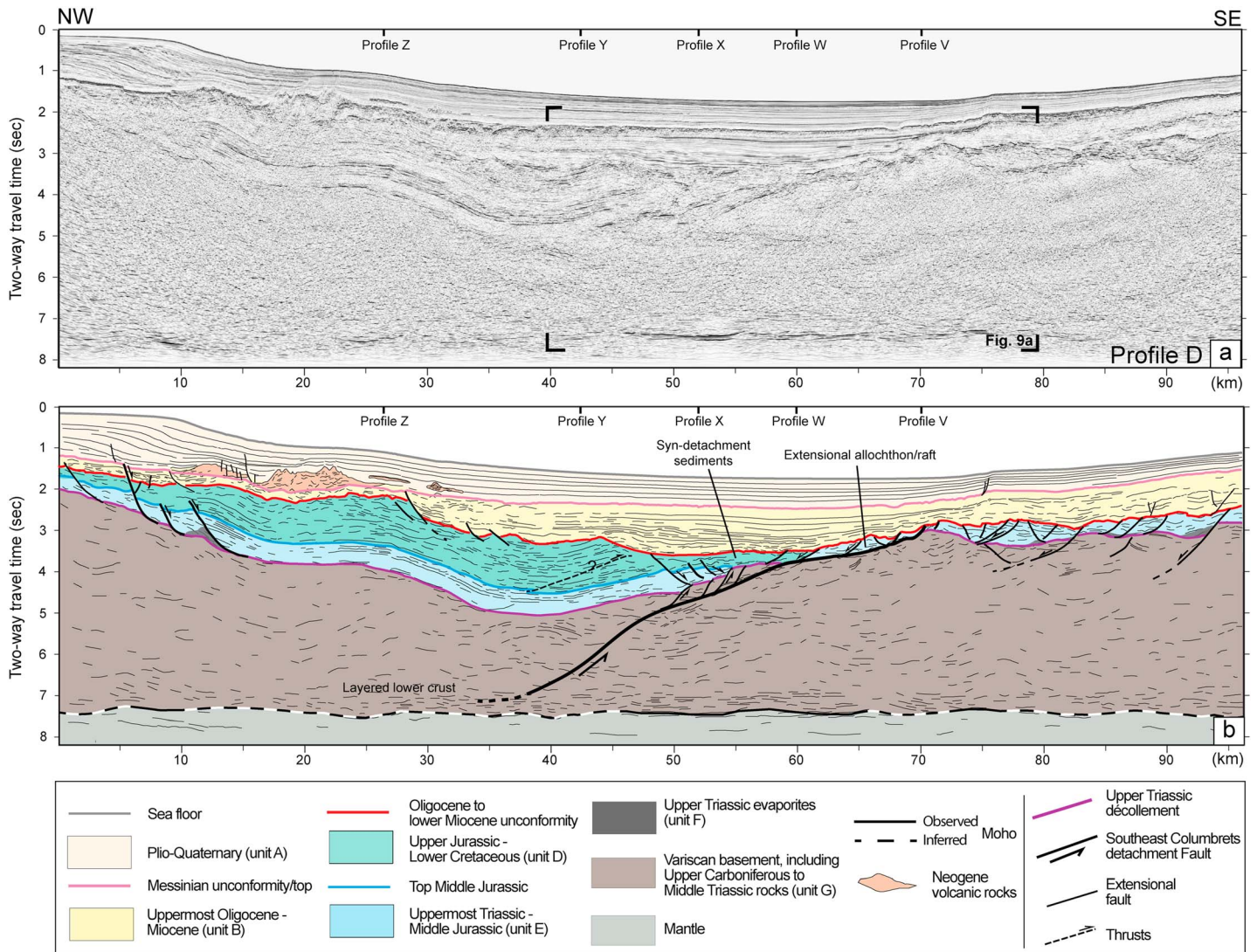


Figure 5. NW trending seismic Profile D across the Columbrets Basin. (a) Time migrated seismic reflection profile (SGV01-113) with the location of the close-up shown in Figures 9a and 9b) (b) Line drawing and proposed interpretation. The location of the seismic profile is indicated in Figure 2b.

Along NW trending profiles, the syncline is roughly asymmetric separating the basin into two distinct domains well illustrated in Profile D (Figure 5). The NW limb appears longer characterized by a relatively continuous Mesozoic succession. In contrast, this succession seems discontinuous and shorter in the SE limb. The hinge of the syncline is lying directly above the thinnest part of the acoustic basement where Mesozoic sediments show a coherent and continuous sequence without major angular unconformity (Figure 6). Along NE trending profiles, the syncline shape is less expressed. The thick Mesozoic succession and the Upper Triassic level are again overlying an extremely thin acoustic basement showing a general tilting toward the NE (Profiles X and Y Figures 7 and 8). Continuing in this direction, the architecture remains difficult to characterize, while the seismic signal becomes blurred, likely related to salt-inflated structures (Figure 9c).

The Mesozoic succession shows a gradual north-northwestward thickness increase associated with the widening of the basin, correlated with a decrease of the acoustic basement thickness in the same direction (Figures 6 and 8). The isochore maps show that the thickest Mesozoic sequence developed directly above the thinnest acoustic basement. A direct correlation between the crustal thickness and the depocenter of the Upper Triassic-Cretaceous sediments is, therefore, emphasized. On the maps of the Figure 10, the

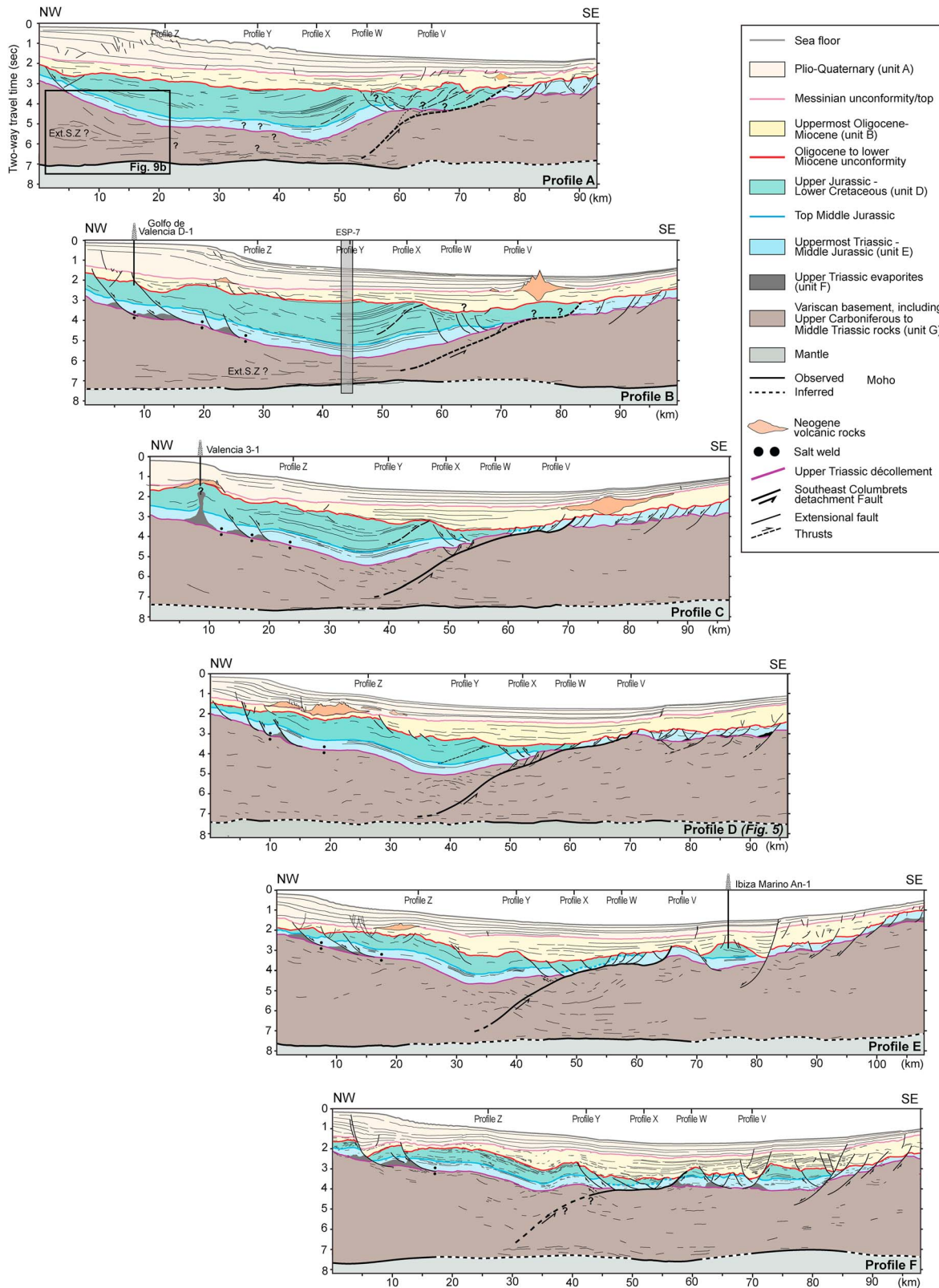


Figure 6. Interpreted line drawings of NW trending reflection seismic profiles of the SGV survey showing the transversal variations of the crustal structure of the southwestern Valencia Trough, from NE to SW. Note that, southwestward, decreases the crustal thinning as well as the thickness of the Upper Jurassic-Cretaceous infilling of the Mesozoic Columbrets Basin. The NW margin of the Profiles A and B are characterized by many intra-acoustic basement reflectors possibly representing extensional shear zones (Ext.S.Z). The location of the represented seismic profiles is indicated in Figure 2b.

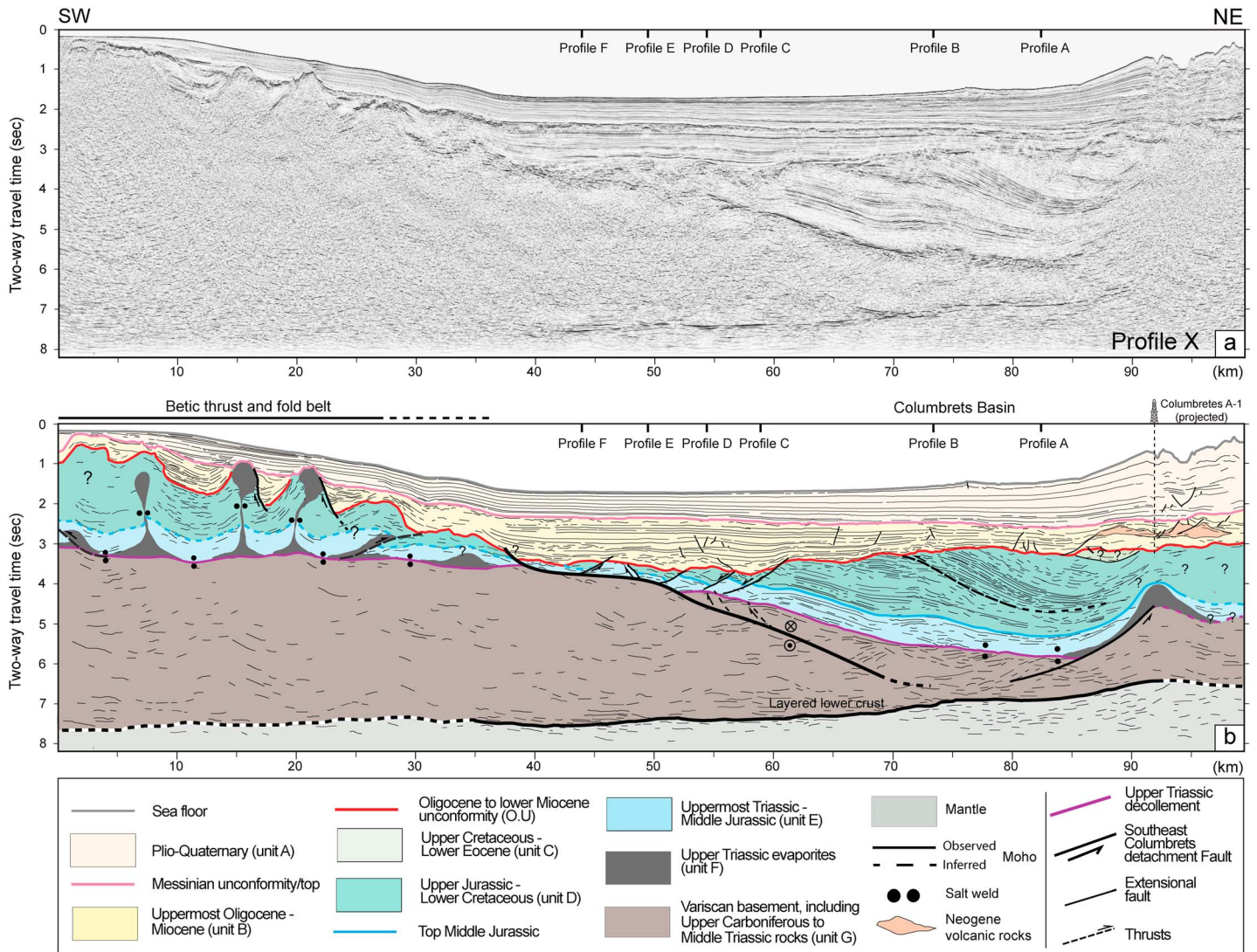


Figure 7. NE trending seismic Profile X across the Columbrets Basin and northern edge of the Betic fold-and-thrust belt. (a) Time migrated seismic reflection profile (SGV01-204). (b) Line drawing and proposed interpretation. The location of the seismic profile is indicated in Figure 2b.

thinner acoustic basement together with the thicker Mesozoic succession describes a general elliptical shape with a long axis oriented ENE-WSW (Figure 10) localized in the NW part of the Columbrets Basin.

In detail, along series of NW trending 2-D seismic profiles across the basin (Figure 6) and considering a velocity of 6.8 km s^{-1} based on ESP-7 of Torne et al. (1992), the acoustic basement at the hinge of the syncline is passing from a thickness of 12 km (3.5 s TWT) in the SW to 3.5 km (1 s TWT) to the NE. Above, the Mesozoic succession ranges from a thickness of 1 s TWT to 3 s TWT (Figure 6), although these values only represent a minimum estimates due to erosion occurring before the O.U. The distinct units forming the Mesozoic succession also show contrasting thicknesses. The Unit E corresponding to uppermost Triassic to Middle Jurassic sediments roughly defines an isopach package ($\approx 0.5\text{--}0.6 \text{ s TWT}$) except from local variations possibly related to salt activity and extensional faulting as observed on the NE part of the basin (Figures 7, 8, and 9c). Just above, the Unit D rests conformably over and shows significant thickness variations. Although, the erosion associated with the O.U. prevents any exact knowledge of the thickness of the Unit D, a general increase is observed from the SW to the NE passing from 0.5 s TWT to 2.5 s TWT. In contrast, its thickness decreases gradually toward the Iberian mainland and Balearic Promontory. Based on the well calibrations, the most significant thickness variations seem to be expressed in the Lower Cretaceous package.

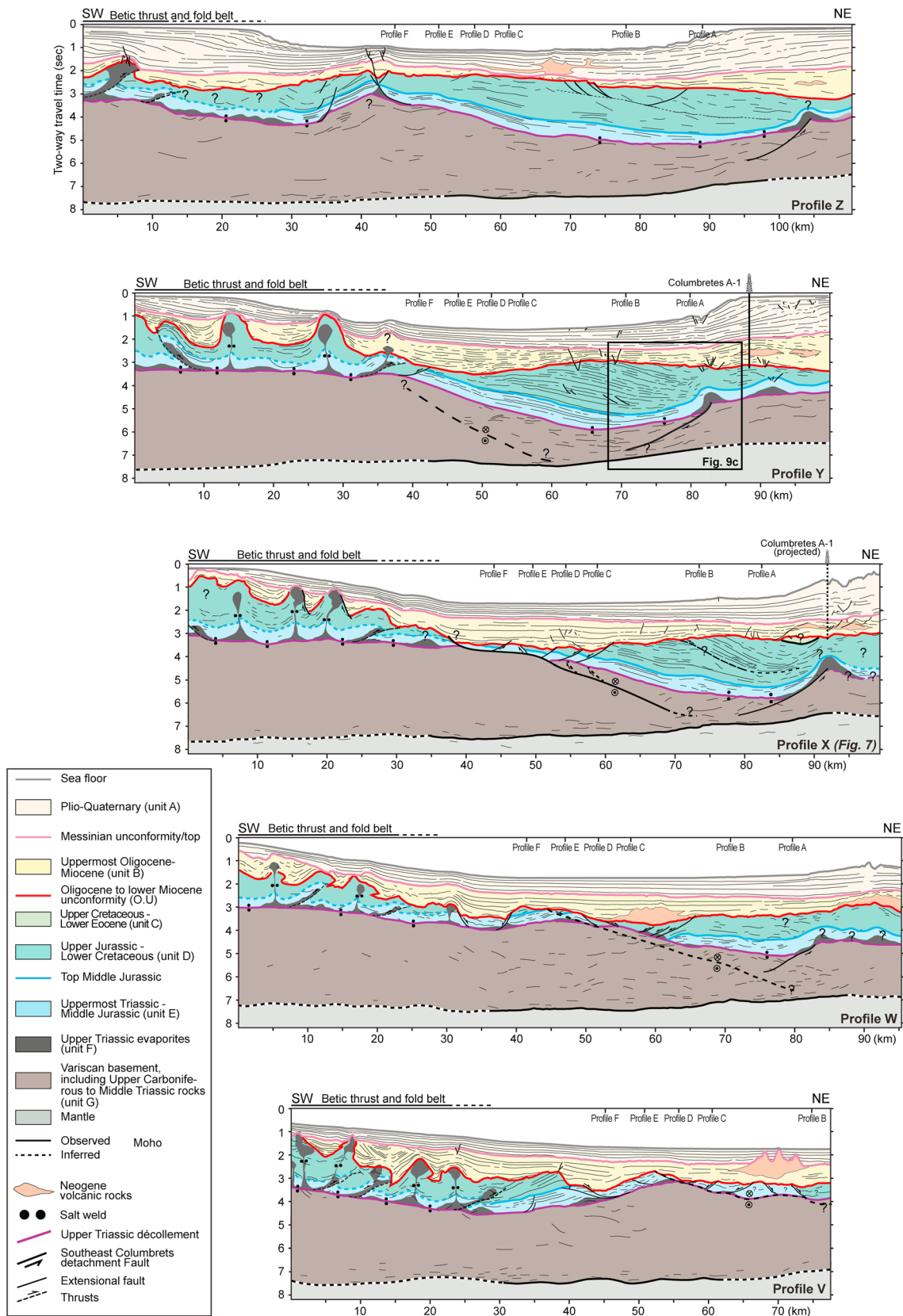


Figure 8. Interpreted line drawings of NE trending reflection seismic profiles of the SGV01 survey showing the longitudinal variations of the crustal structure of the southwestern Valencia Trough, from NW to SE. The location of the figured seismic profiles is indicated in Figure 2b.

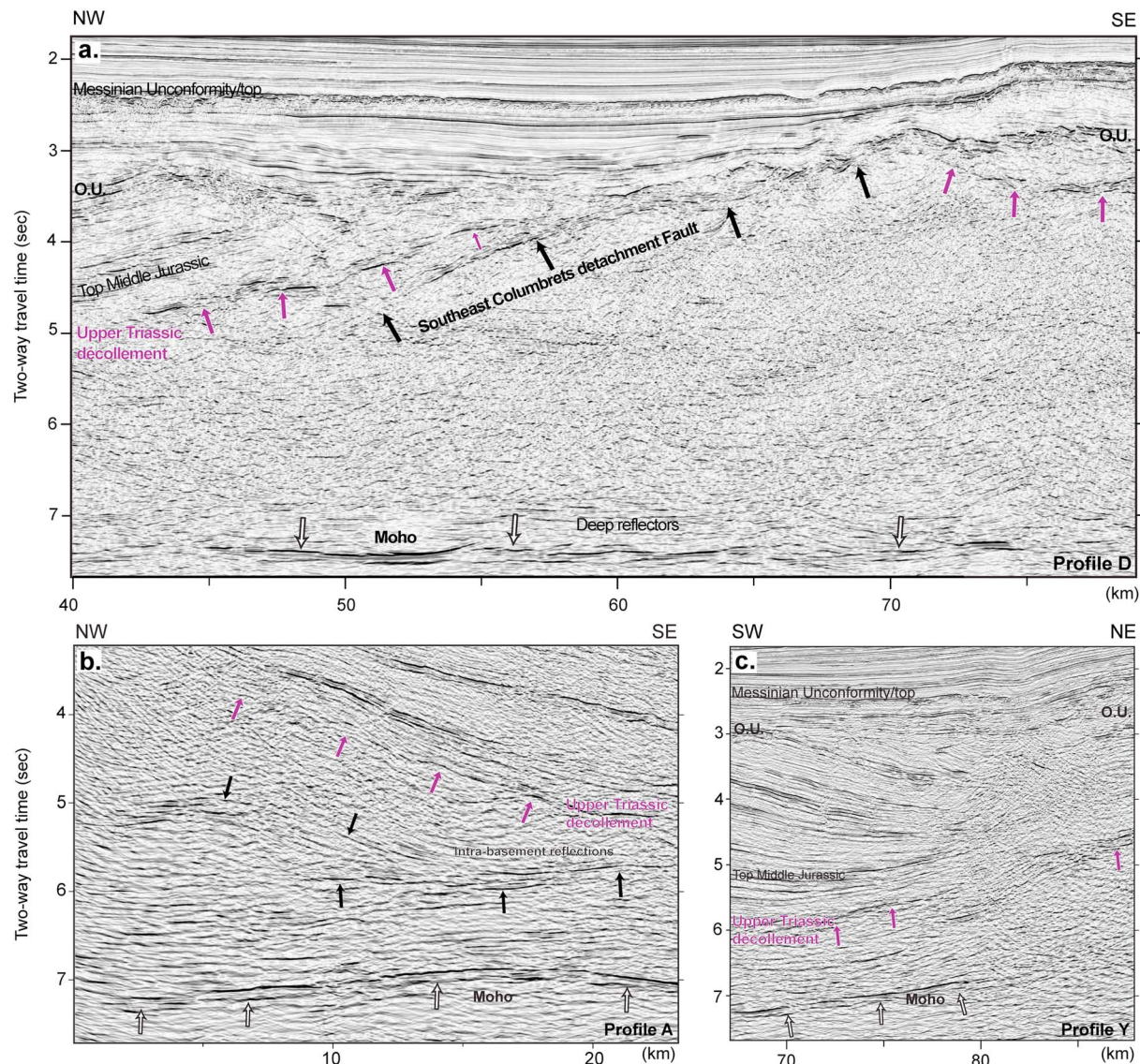


Figure 9. (a) Close-up of the seismic Profile D (SGV01-113) showing the interpreted Southeast Columbrets detachment fault (black arrows) offsetting the Upper Triassic decollement (purple arrows). The location of the close-up is indicated in Figure 5. (b) Close-up of the seismic Profile A (SGV01-107) highlighting intrabasement reflections representing possible extensional structures. The location of the close-up is indicated in Figure 6. (c) Close-up of the seismic Profile Y (SGV01-203) showing a general thinning of the sedimentary package toward the NE in relation with salt-related structures. The location of the close-up is indicated in Figure 8.

5.2. Mesozoic Extensional Structures in the Columbrets Basin

The Mesozoic succession and acoustic basement display contrasted deformation style in the Columbrets Basin. Intriguingly, the main depocenter of the Mesozoic succession located in the syncline hinge (Profiles A–C Figure 6) appears devoid of visible extensional faults. Evidence for extensional deformation affecting the Mesozoic succession is essentially observed in the basin margins. Notably, in the NW and SE parts of the Profiles A to F (Figure 6), the Upper Triassic to Middle Jurassic sediments (Unit E) form typical raft structures apparently fragmented by a succession of extensional faults that root in the Upper Triassic level. These observations suggest that the Upper Triassic level represents a major décollement horizon throughout the entire area.

As well documented in the NW trending profile and notably in Profile D, a major structural change occurs in the basin at the southeastern termination of the syncline (Figures 5 and 9a) related to termination of the thick

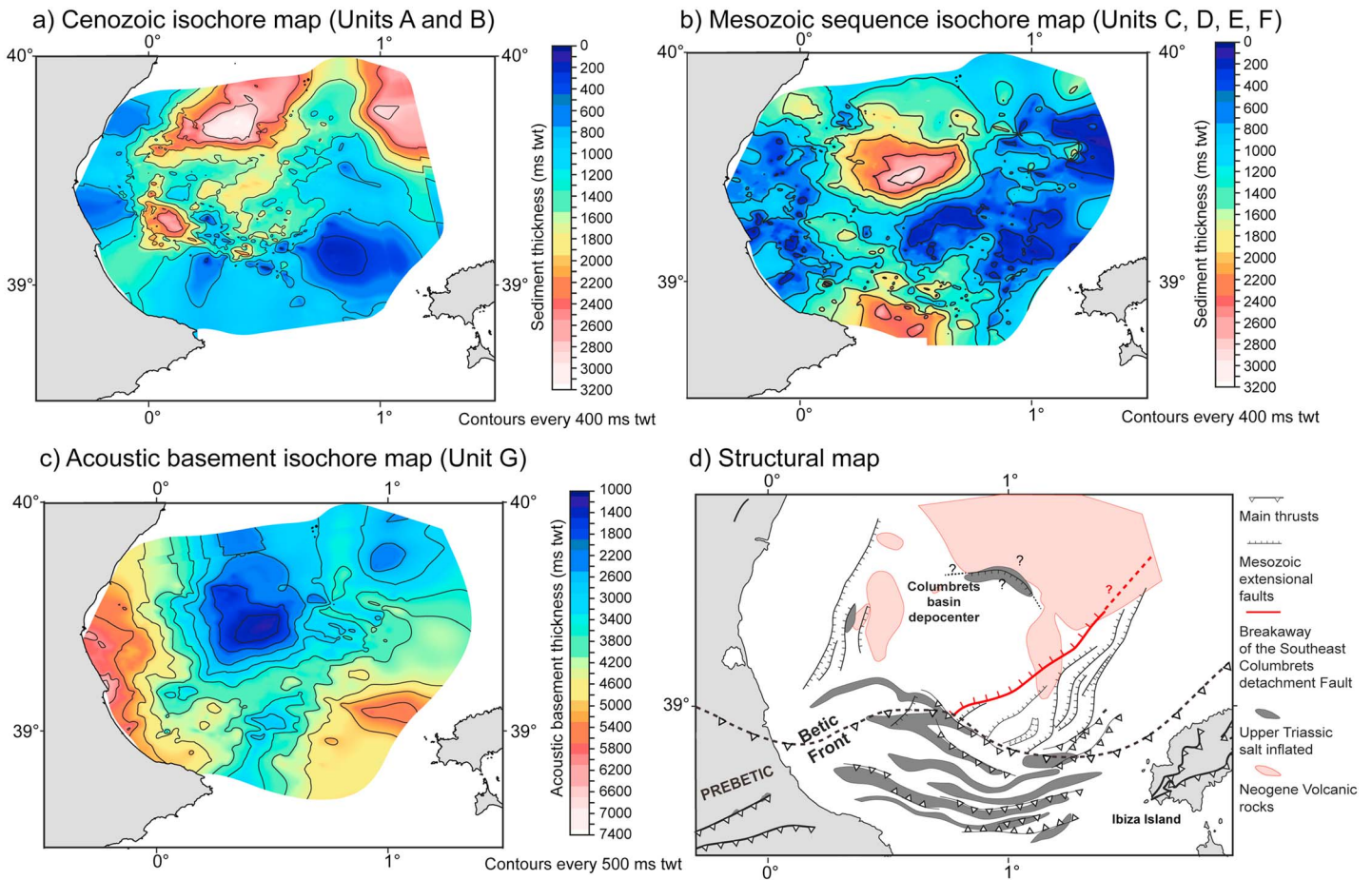


Figure 10. (a) Isochore TWT maps of the Cenozoic Valencia Trough basin infill (Units A and B), (b) the uppermost Triassic-lower Eocene (?) sedimentary cover (Units C–F), (c) and the acoustic basement (Unit G) interpolated from the used 2-D seismic data set. (d) A structural sketch map derived from the interpretation of the seismic data set.

Mesozoic succession at ~50 km distance. This termination is inferred to be associated with high-angle SE dipping extensional faults affecting the Unit E and rooting in the Upper Triassic décollement (Figures 5 and 9a). From 50 to 70 km, two main reflectors can be observed dipping toward the NW and merging together at about 60 km (Figure 9a). The upper reflector corresponds to the base of the Upper Triassic décollement and is interpreted as decoupling the Mesozoic succession from the acoustic basement. Notably, this reflector stops against the lower reflector from ~60 to 70 km (Figure 9a). In contrast, the lower reflector corresponds to an intra-acoustic basement reflector gradually disappearing at depth toward the NW while rising and being in direct contact with discontinuous remnants of the Mesozoic cover toward the SE (Figure 9a). Therefore, this lower reflector accommodates the exhumation of the acoustic basement and is interpreted as a major low-angle crustal-scale extensional fault hereafter named the Southeast Columbrets Detachment. This configuration may account for the lateral termination and dismembering of the uppermost Triassic to Middle Jurassic cover (Unit E) interpreted as extensional allochthons/raft either over the Upper Triassic décollement or directly over the detachment fault. Locally, Late Jurassic to Early Cretaceous sediments, characterized by downlap geometries, seem to be lying directly over the acoustic basement suggesting that they might have been deposited during the activity of the Southeast Columbrets detachment fault (Figures 6 and 9a Profiles A–D). At ~70 km in Profile D, the Upper Triassic décollement is crosscut by the detachment possibly defining the breakaway of this structure, overlain by the O.U. and the flat-lying Upper Oligocene to Quaternary sediments (Figures 5 and 9a). At the southeastern end of the profile, the Mesozoic cover is thinner (~0.5 s TWT) and only few remnants of the Unit E and possibly D are preserved. They are dissected by extensional faults rooting

either in the Upper Triassic décollement or directly into the acoustic basement. These extensional faults are generally sealed by the O.U. through the whole Columbrets Basin; locally, only some of them affect also the Cenozoic cover. Such relationships, associated with the Upper Triassic to Middle Jurassic rafts observed in the NW part of the profiles, confirm the Late Jurassic to Early Cretaceous age of the major extensional deformation in the Columbrets Basin.

This structural pattern changes from the SW to the NE. In the SW part, in Profile F (Figure 6), where the acoustic basement is thicker and the Mesozoic sequence thinner, the previously described syncline shape remains poorly expressed, with a wavelength of ~10 km. The sediments from the E and D units are strongly affected by extensional faults rooting either in the Upper Triassic décollement or in the NW dipping Southeast Columbrets detachment Fault present in the SE limb of the syncline.

Toward the NE, in Profiles D to A (Figure 6), the asymmetry of the basin is well illustrated, with the individualization of the NW and SE domains exhibiting similar geometries to the one previously defined in Section D (Figure 9a). At the termination of the continuous Mesozoic cover (~50 to 60 km, Figure 9a), in the hanging wall of the detachment fault, anticlinal geometries developed. They are locally associated with SE dipping extensional faults. There, the Upper Triassic décollement appears locally offset as a possible result of extensional faults dipping in the opposite direction, that is, toward the NW (Figures 5, 6, and 9a).

In Profiles D to A (Figure 6), the acoustic basement is interpreted as being exhumed and possibly directly overlain by the Upper Jurassic to Lower Cretaceous of the Unit D. Local remnants of stretched uppermost Triassic to Middle Jurassic deposits (Unit E) are inferred and interpreted to form extensional allochthons or rafts associated with a succession of extensional faults on the hanging wall of the Southeast Columbrets detachment Fault. Unfortunately, the characterization of the detachment fault on the northeastward profiles (Profiles A and B) is hampered by the presence of Neogene volcanic edifices and subsequent compressional deformation.

These seismic observations combined with the isochore maps highlight a general ENE trend of Mesozoic extensional structures, including the Southeast Columbrets detachment fault and associated minor extensional faults (Figure 10). These results suggest a NW-SE (present-day coordinates) main direction of stretching in the Mesozoic Columbrets Basin.

Extensional structures offsetting the acoustic basement beneath the Upper Triassic décollement are rare or hardly visible. Locally, just below the Upper Triassic décollement, reflectors interpreted as Middle Triassic to Permian sediments display complex geometries being tilted and possibly affected by extensional faults (e.g., Profile D, Figure 5). In addition, many intra-acoustic basement reflectors are observed in seismic profiles within the acoustic basement, and especially in lower crustal levels. Locally, they display sigmoidal shapes (Profiles A from ~0 to 20 km and B from ~30 to 40 km, Figures 6 and 9b) possibly representing intrabasement extensional shear zones accommodating part of the extreme extension inferred for the acoustic basement.

Eventually, it is worth noting that some seismic sections (Profiles A and B in Figure 6) document a local overprinting of the Southeast Columbrets detachment fault by compressional structures especially at the NE part of the basin. The latter are generally sealed by O.U. suggesting a pre-upper Oligocene to middle Miocene age of this compressional deformation.

5.3. Salt Tectonic-Related Structures

Across the Columbrets Basin a wide range of distinct salt-related structures are observed. They are distributed and visible in the basin margins essentially in the SW and the NE parts of the study area (Figures 5–10). In the SW termination of the seismic profiles (Figures 7 and 8), these salt-related structures are squeezed by the Betic middle Miocene compressional deformation. Despite the blurring of seismic imaging, salt walls, detached anticlines, and diapirs are suggested based on first-order observations combined with neighboring onshore area analogies (e.g., De Ruig, 1992; Roca et al., 2013; Rubinat et al., 2013). This late evolution masks the initial geometry of the salt-related structures. Nevertheless, locally along the edges of these structures sedimentary wedges of Jurassic to Cretaceous sediments are inferred (Profiles X and Y, Figure 8). Such geometries suggest that major salt-related structures were already active during the Mesozoic (Figure 8).

Further north, in the parts of the Columbrets Basin that are not affected by the Betic orogen overprint, Mesozoic salt-related structures are rather frequent but they often appear overprinted by upper Oligocene

to Miocene and Plio-Quaternary extensional reactivations (Profiles E and F). Such situation is displayed on Profile E, at Ibiza Marino An-1 well area (Figure 6). Here the O.U. and overlying sediments form a “turtle-back” structure bounded by two listric Upper Oligocene-Quaternary extensional faults (Etheve et al., 2016). Based on the restoration of the Mesozoic succession geometry prior to these late extensional reactivations, combined with well calibrations and the overall architecture of the basin, the following information is inferred. (1) Salt-related movements started in Middle Jurassic as shown by the unconformity between units E and D (Figure 7). (2) Salt-related movements continued during the Late Jurassic to Early Cretaceous, as the sediments of Unit D show similar geometries, and (3) salt-related movements mostly finished before the O.U.; however, they may locally continue until Present time, triggered by extensional structures or gravity-driven movements.

On the Profiles X at 85 km (Figure 7) and Y at 80 km (Figure 9c), a general thinning of the sedimentary package and gradual onlapping of Lower Jurassic to Upper Cretaceous sediments is reported toward the NE. This geometry suggests the occurrence of a salt dome cored by Upper Triassic evaporites. Salt was likely mobilized soon after its deposition already during the Early Jurassic to explain the observed geometry along the flanks of salt structures. In spite of the poor seismic imaging, a SW dipping extensional fault is inferred in this area. The occurrence of such a fault is based on Columbrets AN-1 well (see localization on Figures 2 and 8) showing that the drilled Lower Cretaceous sediments are structurally higher than in the SW part of the basin. This part of the basin is likely characterized by a salt inflated body in the hanging wall of an extensional fault. Upsection, the roughly horizontal arrangement of the O.U. as well as of the overlying sediments above this salt ridge denotes that the salt inflation ceased before the Oligocene. Consequently, the base of the thick uppermost Triassic to Cretaceous succession at the central part of the Columbrets Basin corresponds to a primary salt weld.

6. Discussion

The aim of the following discussion is twofold: (1) integrate the tectonosedimentary evolution of the Columbrets Basin in the frame of eastern Iberia and (2) address the mechanisms controlling the observed extreme crustal thinning and the interactions with halokinesis.

6.1. The Mesozoic Tectonosedimentary Evolution of the Columbrets Basin and Its Integration in the Frame of Eastern Iberia

6.1.1. The Permian to Middle Jurassic period

During the Permian to Middle Triassic a broadly distributed extension with formation of rift basins, filled by fluvial to shallow marine sediments, developed in the adjacent onshore Iberian Peninsula and Balearic Promontory (e.g., Arche & López-Gómez, 1996; Vargas et al., 2009). Triassic sediments were sampled in several wells across the Columbrets Basin (e.g., Cabriel B2-A, Figure 2). The complex pattern of reflectors observed in Profile D (Figure 5) seems to indicate local thickness variations underneath the Upper Triassic décollement representing possible candidates for Permian to Early Triassic rift basins. However, evidence for such a rift event in the Columbrets Basin remains difficult to characterize due to the poor seismic imaging below the Upper Triassic décollement. Based on previous studies and on the β factors estimated in surrounding areas (~ 1.2 , Arche & López-Gómez, 1996; Vargas et al., 2009), such rift basins were likely only related to a weak crustal thinning in eastern Iberia and in the Columbrets Basin (Figure 11a).

Generally, this period of diffuse extension was followed by evaporitic sedimentation during the Upper Triassic in eastern Iberia and notably in the study area. Such deposits were locally associated with thick salt deposits (e.g., Ortí et al., 2017) playing a major role on the subsequent evolution of the basin.

The overlying Lower to Middle Jurassic sediments show a relatively constant thickness in the Columbrets Basin, although local thickness variations are observed near salt-related structures and interpreted as related to the early movement of the Upper Triassic salt (Profiles Y and X, Figures 7, 8, and 9c). These sediments, deposited in a general shallow-marine environment based on well data, are interpreted to record a period of tectonic quiescence with a slow subsidence regime documented in the whole eastern Iberia (Roca et al., 1994; Salas & Casas, 1993). In contrast, the margins of the southeastern Iberian Peninsula record various amplitude and distribution of extensional tectonic in relation with the opening of the Tethys Ream. In particular, the “Desert de les Palmes” area preserves the occurrence of Upper Triassic to Lower Jurassic NE-SW trending extensional faults dipping toward the NW (Roca et al., 1994) (Figures 1–3 and 11a). Low

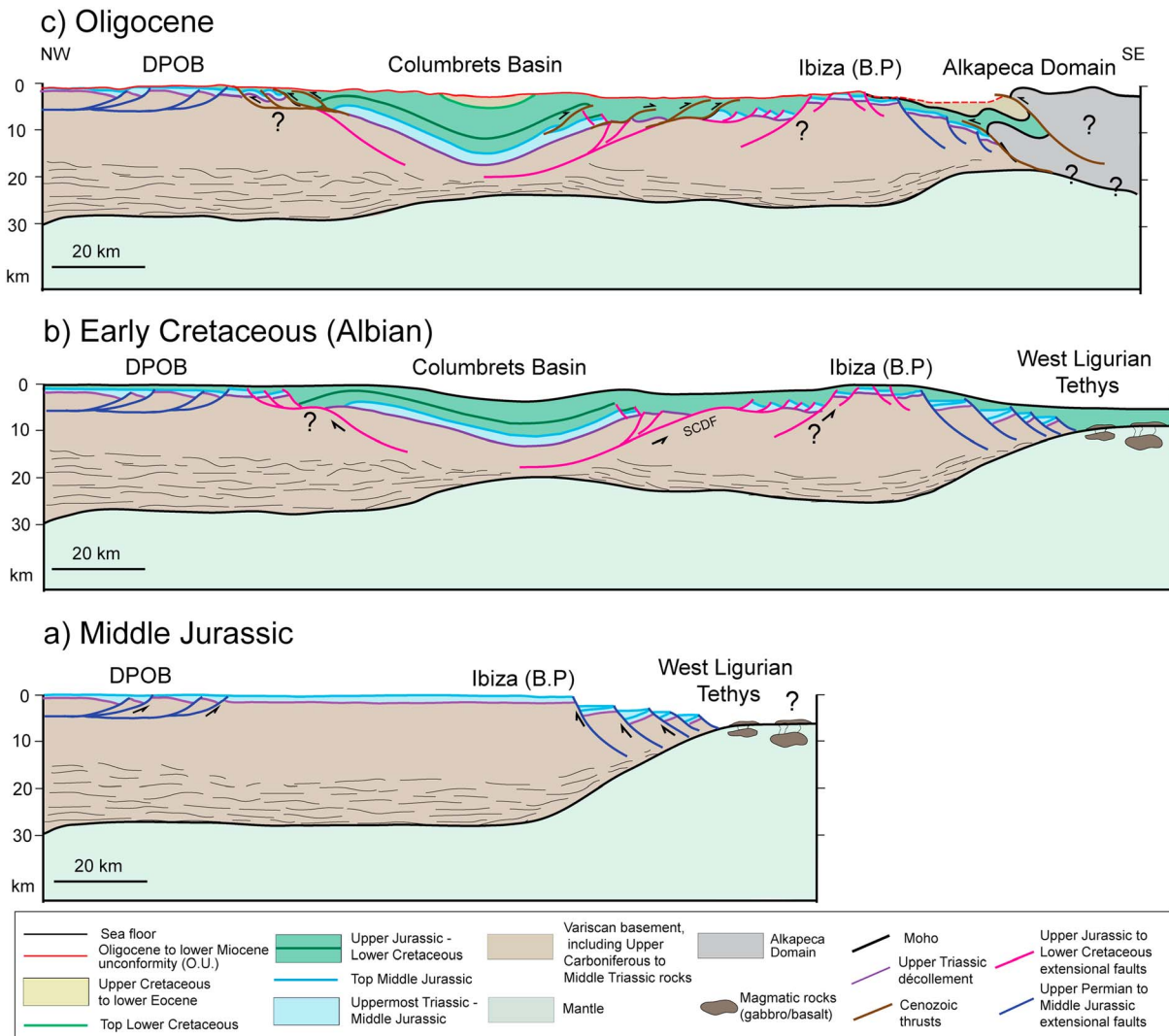


Figure 11. Crustal-scale cross-section from the Iberian Peninsula (SE of the Iberian Chain) to the Algerian Basin across the SW part of the Valencia Trough and Balearic Promontory. From bottom to top: at (a) at Middle Jurassic time, after Lower Jurassic extension, (b) at Early Cretaceous time, after hyperextension, and at (c) Oligocene time, after Early Cenozoic compression. Comparing the sections, it is evident that the present-day crustal structure is mainly Mesozoic in origin, and the Cenozoic structure of the area is strongly controlled by the Mesozoic extensional faults that have been both inverted positively and negatively. SCDF = Southeast Columbrets detachment Fault.

stretching factors are estimated for this area based on restored cross sections (Roca et al., 1994). In contrast, extensional deformation significantly increases toward the Betic domain where a succession of crustal blocks bounded by SE dipping extensional faults are described (Figure 11a). This rift event is poorly documented in the Balearic Promontory. The associated sedimentary record is relatively thin (<1 km thick in the Columbrets Basin) and associated with a change in sedimentary facies at the Lower-Middle Jurassic transition with a local erosional unconformity (Álvaro et al., 1989; Azéma et al., 1979; Bourrouilh, 1983; Fourcade et al., 1982; Sàbat et al., 2011). An Early Jurassic extensional event is reported in Majorca (Gelabert et al., 1992) although any further precise characterization is precluded due to subsequent Cenozoic overprints. In general, the Early to Middle Jurassic evolution of the eastern part of the Balearic promontory remains poorly constrained. Large-scale paleogeographic restorations (e.g., Dercourt et al., 2000; Handy et al., 2010; Roca et al., 2004; Vergés & Sàbat, 1999) include the Balearic Promontory as a part of the eastern Iberian passive margin of the West Ligurian Tethys (Figure 11a). Based on the relatively limited tectonic record, it was likely located in the proximal part of this margin.

6.1.2. The Late Jurassic to Early Cretaceous Period

This period is interpreted as the main rift phase related to the extreme thinning of the Columbrets Basin notably associated with the development of the Southeast Columbrets detachment fault (Figure 11b). This hypothesis is supported by several observations.

Although, the Columbrets Basin and surrounding areas underwent evidence of rifting during the Permian to Middle Triassic, the available data suggest that this event was associated with only minor crustal thinning as discussed above. This hypothesis is confirmed by the relatively constant and minor/moderate thickness of the uppermost Triassic to Middle Jurassic succession generally deposited in shallow marine environments in the overall study area. In contrast, the thinnest part of the acoustic basement of the Columbrets Basin is directly overlaid by the thickest Upper Jurassic-Lower Cretaceous successions. The deposition of the latter was controlled by extensional structures as indicated by their overall geometry and thickness variations. Finally, the Cenozoic rift event in our area is characterized by a lack of evidence for large extensional structures. The stretching factors deduced from the latest Oligocene-Neogene extensional faults imaged on seismic sections only range from 1.09 to 1.26 (Roca & Desegaulx, 1992). Furthermore, this extension is counterbalanced partially or totally by the shortening recorded in the compressional structures developed at the same time or after in other parts of the study area.

The Columbrets Basin shows a general ENE trend (Figures 10 and 11b), similar to the predominant trend of the Late Jurassic-Early Cretaceous extensional structures observed in the Prebetics southwest of the study area (De Ruig, 1992) and in the Catalan Coastal Ranges further to the northwest (Baqueés et al., 2012; Salas, 1987). However, the NW margin of the Columbrets Basin is characterized by the interference between two main trends of extension respectively ENE-WSW and NW-SE as documented onshore south of Maestrat Basin in the Orpesa subbasin area (Figure 1; Salas et al., 2001; Liesa et al., 2006). This set of NW trending Late Jurassic-Early Cretaceous structures continues onshore to the Northwest forming the Aragonese and Castillian branches of the intraplate Iberian rift system (Álvaro et al., 1979; Salas et al., 2001).

At a larger scale, the Columbrets Basin appears as a new “element” of the Late Jurassic to Early Cretaceous rift systems related to the northward propagation of the southern North Atlantic (e.g., Boillot & Malod, 1988; Olivet, 1996; Srivastava et al., 1990) and the formation of the Bay of Biscay rifted margins (Thinon et al., 2003; Tugend et al., 2015). Several rift basins of this age are also developed between the European and Iberian plates including the Basque-Cantabrian (Pedreira et al., 2007; Rat, 1988), Pyrenean (Jammes et al., 2009; Lagabrielle & Bodinier, 2008; Lagabrielle et al., 2010) rift systems and even intra-Iberia such as Prebetics (Castro et al., 2008; De Ruig, 1992; Granier & Perthuisot, 2009), Catalan Coastal Ranges (Gaspar-Escribano et al., 2004; Roca et al., 1999; Roca & Guimerà, 1992), Cameros (Casas et al., 2009; Omodeo Salé et al., 2014), and Mastreat basins (Campos-Soto et al., 2016; Salas et al., 2001).

6.1.3. The Late Cretaceous to Oligocene-Early Miocene Period

The Upper Cretaceous infill of the Columbrets Basin is only partly preserved due to significant uplift and erosion before the O.U. precluding any detailed analysis. However, in the adjacent Iberian Chain, this period has been traditionally interpreted as recording a postrift stage with minor evidence of tectonic activity (Hanne et al., 2003; Salas et al., 2001). In contrast, in the adjacent eastern Prebetics extensional faulting was still active coevally with the growth and collapse of diapiric structures (De Ruig, 1992; Martín-Chivelet et al., 2002). In the Columbrets Basin, a pre-O.U. compressional deformation is observed (Figure 11c). This deformation is essentially localized along the margins of the basin and shows roughly NE-SW trends. Compressional structures observed in the NE part of the basin (Profile A, Figure 6) are interpreted as reactivating previous Mesozoic structures such as the Southeast Columbrets detachment fault. Similar structures are also inferred on the opposite margin of the basin toward the Iberian Peninsula although not imaged on the seismic sections. However, the inversion of former Mesozoic structures has been recently documented in the adjacent Maestrat Basin located onshore of the Columbrets Basin (Nebot & Guimerà, 2016) (Figure 11c). This compressional event was associated with the regional uplift of the Columbrets Basin leading to the so-called O.U. Similar Paleogene-early Miocene inversion of former Mesozoic rift basins is well documented within or at the margins of the Iberian plate and specifically in the surroundings of the study area (Iberian Chain, Prebetic domain, and Balearic Promontory). During the same period, the Iberian passive margin, east of the Columbrets Basin, is strongly deformed in relation with the subduction of the West Ligurian Tethys and the possible accretion of a narrow microcontinent, the so-called Alkapecca block (e.g., Handy et al., 2010) (Figure 11c).

6.2. Mechanism of Crustal Thinning of the Columbrets Basin and Relationships With Prekinematic Salt

Based on our results, we suggest that the Columbrets Basin underwent extreme crustal thinning processes (“hyperextension”) during the Late Jurassic to Early Cretaceous (Figure 11b). Notably, this basin is characterized by several striking features such as (1) a strong partitioning of the deformation style between the Mesozoic succession and the acoustic basement accommodated along the Upper Triassic décollement, (2) an apparent discrepancy between the imaged extensional faults and the amount of crustal thinning, and (3) a lack of clear synrift geometry throughout the whole basin.

The Columbrets Basin provides one of the rare examples where the interactions between prekinematic salt (Upper Triassic in age in this study) and hyperextension can be investigated. Only few studies focused on this topic (e.g., Ferrer et al., 2012; Jammes et al., 2010; Lagabrielle et al., 2010; Rowan, 2014), in spite of the ubiquitous occurrence of this Upper Triassic salt décollement level in rift basins in western Europe (e.g., Cameros, Parentis, Basque–Cantabrian, or Mauléon basins) as well as in some of the Atlantic rifted margins. The architecture of salt-related structures evolved across the Columbrets Basin from the center to the basin margins and also from north to south. We suggest that these variations are controlled by (1) the initial configuration of the Upper Triassic layered evaporite sequence (thickness and composition as well as proportion, distribution of the salt); (2) the lateral changes of the overburden thickness; and (3) the nature and amount of the overburden and subsalt extensional stretching. From this point of view, the architecture of the Columbrets Basin shares many similarities with other basins presenting a syncline geometry like the Parentis or Cameros basins (e.g., Bois & Gariel, 1994; Ferrer et al., 2012; Jammes et al., 2010; Mas et al., 2004).

The center of the Columbrets Basin, where the thickest Mesozoic succession occurs, is characterized by the relative absence of salt-related structures. In this area, the thick Mesozoic sedimentary pile might have triggered an important overburden enhancing salt migration toward the margins of the basin and the formation of a weld in its central part (Figures 6 and 8). In contrast, salt-related structures located on the basin margins are generally characterized by a thin-skinned extensional deformation associated with salt-related structures that led to the stretching of the Mesozoic cover with the formation of a succession of rafts (Figures 5 and 6). This configuration differs from the mode of raft formation that are developed in a postrift setting where they are triggered by gravitational failure as shown for example along the South Atlantic margins (e.g., Duval et al., 1992). In our case, the formation of rafts was likely associated with a crustal-scale stretching and not due to gravitational failure processes as already inferred in the Parentis and North Pyrenean basins (e.g., Clerc et al., 2016; Clerc & Lagabrielle, 2014; Jammes et al., 2010).

In addition to this thin-skinned deformation affecting mostly the Mesozoic cover, the Columbrets Basin recorded a significant thinning of the acoustic basement and hence continental crust to about 3.5 km (considering an average velocity of 6.8 km/s). However, across the basin, the thick-skinned extensional structures recognized on seismic sections cannot account for this extreme thinning. Indeed, the Southeast Columbrets detachment fault is only characterized by a displacement of 10 to 15 km, based on the offset of the Upper Triassic décollement inferred from our seismic interpretations. Therefore, this structure is unable to accommodate this extreme crustal thinning alone. Such a discrepancy between the recognized extensional structures on seismic data and the amount of crustal thinning is reported from many hyperextended rift basins worldwide, and the related processes remain under discussion (e.g., Kuszniir & Karner, 2007; Reston, 2007).

In particular, our seismic sections show a significant lack of extension of the Lower to Middle Jurassic prerift cover (Unit E) with respect to the severely thinned continental basement. Indeed, apart from the Southeast Columbrets detachment fault and the extensional faults with only minor to moderate displacements described in the basin margins, the prerift unit can be traced confidently across its central part (Figure 11b). Additional important extensional structures affecting the prerift cover are, therefore, expected. Such structures may occur either near the Iberian Peninsula or Balearic Promontory or both, outside the extent of our seismic sections (Figure 11b). In the present stage and with the available data, the exact location of such structures remains unclear.

These observations question the structures and the processes accommodating the extreme thinning of the continental crust in the Columbrets Basin. Intrabasement reflectivity is observed on seismic sections but is often difficult to interpret in detail. Part of this reflectivity (e.g., Profiles A and B, Figures 6 and 9b) may represent intrabasement extensional shear zones partially accommodating the observed crustal thinning.

In particular, lower crustal levels are characterized by a highly reflective and layered package. The origin of the layering remains a matter of debate. Watts et al. (1990) concluded that this layering must predate the Neogene rifting event. Similar layering of lower crustal levels is reported from many seismic profiles across western Europe and has been associated to a magmatic underplating and high-temperature metamorphism related to a late Paleozoic post-Variscan stage (Rey, 1993). Previous studies (Ayala et al., 2015, and references therein) emphasized a significant thinning from 9–10 to 1–2 km of this lower crustal reflective package from the margins to the center of the Columbrets Basin. These thickness variations may suggest the occurrence of large-scale boudinage of the continental crust, as recently suggested by Duretz et al. (2016) based on numerical modeling experiments and interpreted on seismic sections (e.g., Clerc et al., 2015). Despite the extreme crustal thinning, mantle exhumation is not evidenced in the Columbrets Basin.

We suggest that the general architecture and evolution of the basin is controlled by a complex interaction between several decoupling horizons as illustrated by the apparent complex geometry of the Southeast Columbrets detachment fault (Figures 5 and 11b). The hanging wall of the detachment fault is associated on the one hand with the fragmentation and dismembering of the prerift Mesozoic cover resulting in the development of extensional allochthones and rafts and on the other hand with the suggested deposition of syndetachment sedimentary sequences. In these settings (e.g., from ~60 to 70 km, Figure 9a), the top basement detachment fault coincides with the Upper Triassic décollement. The detachment fault is interpreted to root at depth where the reflective package is observed within the acoustic basement (Figures 5, 7, and 9a). We suggest that the overall complex geometry of the detachment fault, characterized by several flats and ramps, is related to the occurrence of two main decoupling horizons: the Upper Triassic salt décollement and the top of the lower crust. The presence of these decoupling horizons might have triggered a spatial partitioning of the extensional deformation between the Mesozoic cover and the underlying continental basement. The extension of the prerift Mesozoic cover is evidenced at the basin margins, whereas the main crustal thinning is focused at its center where the thickest Late Jurassic to Early Cretaceous sediments were deposited. We suggest that this deformation style may explain the first-order syncline shape of the basin and absence of typical synrift geometries in the overlying sediments.

7. Conclusions

The Columbrets Basin, in the SE part of the Valencia Trough, is characterized by a hyperthinned basement (≈ 3.5 km thick at its minimum) filled by thick Mesozoic sediments (reaching locally ~ 10 km) poorly inverted during the Paleogene and unconformably overlain by Upper Oligocene to recent deposits. We suggest that this basin results from an extreme crustal thinning during the Late Jurassic to Early Cretaceous and was not related, as classically proposed, to the extensional processes linked to the Cenozoic opening of the western Mediterranean basins. Based on high-resolution NW-SE and NE-SW oriented seismic reflection profiles, seismic refraction, ESP and drill hole data, we draw the following conclusions:

1. The Columbrets Basin represents a Late Jurassic to Early Cretaceous hyperextended rift basin characterized by an extremely thin continental basement associated with a thick Mesozoic sequence. From SW to NE, the Upper Jurassic to Lower Cretaceous succession shows a gradual increase of the sedimentary thickness together with a decrease of the acoustic basement thickness evidencing a major rifting phase during this period. The Mesozoic rift-related architecture of the basin is preserved despite Cenozoic overprints consisting in a succession of compressional and extensional events.
2. The general architecture of the Columbrets Basin shows contrasted deformation styles between the Mesozoic succession and acoustic basement controlled by the so-called Upper Triassic décollement. At first order, the Mesozoic basin exposes a general syncline shape together with a significant asymmetry well illustrated on NW-SE profiles. This asymmetry can be related to the activity of a low-angle crustal-scale extensional fault (the Southeast Columbrets detachment fault) contributing to the dismembering of the Mesozoic cover. This detachment is interpreted to root at middle to lower crustal levels and partly accommodates the thinning of the continental crust. This extensional structure alone cannot account for the observed extreme crustal thinning. Additional extensional structures, along the margins of the Columbrets Basin, are inferred.
3. The Columbrets Basin is integrated in the frame of the Mesozoic evolution of the eastern Iberia preserving a complex Mesozoic succession of rift events. The NNE-SSW trending extensional structures recorded in

the Basin are similar to those recorded onshore in the Desert de les Palmes and in the southern part of Maestrat Basin. Thanks to its limited inversion, the Columbrets Basin represents a key element for our understanding of the tectonic processes that shaped the Iberian Plate and surrounding areas during the Upper Jurassic to Lower Cretaceous. This basin may represent, to first order, an analog of Cameros, Parentis and North-Pyrenean basins that were at various degree reactivated and inverted.

4. Finally, the Columbrets Basin documents the complex interaction between hyperextension processes and prekinematic Upper Triassic evaporites. In the SE, the Southeast Columbrets detachment fault interacts with the Upper Triassic décollement associated with the formation of rafts. In the NW, a major salt-related structure is documented showing a polyphase evolution from Early Jurassic to Late Cretaceous. Important salt movements are inferred during the Late Jurassic to Early Cretaceous. Finally, these results highlight the critical role of decoupling horizons such as the intrabasement horizons or Upper Triassic décollement, on the architecture and evolution of rift basins.

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