Tectono-sedimentary evolution of Jurassic–Cretaceous diapiric structures: Miravete anticline, Maestrat Basin, Spain

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Abstract
Integration of extensive fieldwork, remote sensing mapping and 3D models from high-quality drone photographs relates tectonics and sedimentation to define the Jurassic–early Albian diapiric evolution of the N–S Miravete anticline, the NW-SE Castel de Cabra anticline and the NW-SE Cañada Vellida ridge in the Maestrat Basin (Iberian Ranges, Spain). The pre shortening diapiric structures are defined by well-exposed and unambiguous halokinetic geometries such as hooks and flaps, salt walls and collapse normal faults. These were developed on Triassic salt-bearing deposits, previously misinterpreted because they were hidden and overprinted by the Alpine shortening. The Miravete anticline grew during the Jurassic and Early Cretaceous and was rejuvenated during Cenozoic shortening. Its evolution is separated into four halokinetic stages, including the latest Alpine compression. Regionally, the well-exposed Castel de Cabra salt anticline and Cañada Vellida salt wall confirm the widespread Jurassic and Early Cretaceous diapiric evolution of the Maestrat Basin. The NE flank of the Cañada Vellida salt wall is characterized by hook patterns and by a 500-m-long thin Upper Jurassic carbonates defining an upturned flap, inferred as the roof of the salt wall before NE-directed salt extrusion. A regional E-W cross section through the Ababuj, Miravete and Cañada-Benatanduz anticlines shows typical geometries of salt-related rift basins, partly decoupled from basement faults. These structures could form a broader diapiric region still to be investigated. In this section, the Camarillas and Fortanete minibasins displayed well-developed bowl geometries at the onset of shortening. The most active period of diapiric growth in the Maestrat Basin occurred during the Early Cretaceous, which is also recorded in the Eastern Betics, Asturias and Basque-Cantabrian basins. This period coincides with the peak of eastward drift of the Iberian microplate, with speeds of 20 mm/year. The transtensional regime is interpreted to have played a role in diapiric development.
1 | INTRODUCTION

In the decades preceding the 1980s, salt tectonic interpretations were commonly invoked in many fold and thrust belts worldwide, in which large masses of salt-bearing rocks disrupted the regional tectonic grain. These regional studies resulted in the compilation of salt tectonic activity within the Tethys realm (reviews in Hudec & Jackson, 2007; Letouzey et al., 1995). The overwhelming application of thrust tectonic geometries and kinematics in fold and thrust belts beginning in the 1980s (examples in McClay, 1992; McClay and Price, 1981) modified previous interpretations of diapirism, but emphasized the influence of salt detachments (pre- and syn-compression) as essential elements of the geometry of thrust systems.

Extensive interpretation of excellent quality seismic lines from salt-influenced continental margins mostly along the North Sea, Gulf of Mexico, Brazil and Angola (Davison et al., 2000; Stewart & Coward, 1995), studies of exceptional field examples (e.g. La Popa Basin in Mexico; Giles & Lawton, 2002; Giles & Rowan, 2012) and profuse analogue modelling (e.g. Brun & Fort, 2011; Jackson & Vendeville, 1994; Vendeville & Jackson, 1992) have demonstrated the importance of salt tectonics in fold and thrust belts, and constitute the basis of a solid geometric and kinematic compendium of salt-related tectonics that can be applied elsewhere (e.g. Jackson & Hudec, 2017; Soto, Flinch, & Tari, 2017).

The Mesozoic domains of the Iberian plate contain large outcrops of Upper Triassic salt-bearing deposits (e.g. Escavy, Herrero, & Arribas, 2012; Ortí, Pérez-López, & Salvany, 2017; Rodríguez-Fernández & Oliveira, 2014), a number of which were interpreted as diapiric. Recently, an increasing number of salt-related structures were re-interpreted in the various Iberian fold and thrust belts as indicated by red circles in Figure 1 and discussed in Vergés et al. (2019). These include the Basque-Cantabrian Basin (1–4: Bodego & Agirrezabala, 2013; López-Horgue et al., 2010; Poprawski et al., 2014; Poprawski, Basile, Jaillard, Gaudin, & Lopez, 2016; Quintà, Tavani, & Roca, 2012), the Pyrenees (5–9: Canérot, Hudec, & Rockenbauch, 2005; Jammes, Tiberi, & Manatschal, 2010; Lopez-Mir, Anton Muñoz, & García Senz, 2014; McClay, Muñoz, & García-Senz, 2004; Saura, Ardevol i Oró, Teixell, & Vergés, 2016), the Iberian Range (10: Canérot, 1991), the Betics (11–16: Escosa, Roca, & Ferrer, 2018; Martínez del Olmo et al., 2015; Pedrera, Marín-Lechado, Galindo-Zaldívar, & García-Lobón, 2014; Soto et al., 2017; Soto & Flinch, 2017), the Algarve Basin (17, 18: Ramos, Fernández, 2018).

FIGURE 1 | a) Pre-breakup reconstruction of Pangea in the Early Triassic (modified from Lawver, Dalziel, Norton, & Gahagan, 2009; Moulin, Aslanian, & Unternehm, 2010). (b) Late Triassic palaeogeographic map of the western Neotethys area (modified from Dercourt, Gaetani, & Vrielynck, 2000; Martin-Rojas et al., 2009; Ortí et al., 2017). (c) Simplified geological map of Iberia with position of the Maestrat Basin and location of the main salt diapirs growing during the Mesozoic with most recent references (red circles). 1: Laredo and Pondra diapirs (López-Horgue et al., 2010); 2: Poza de la Sal diapir (Quintà et al., 2012); 3: Bakio diapir (Poprawski et al., 2014, 2016); 4: Lasarte sub-basin salt controlled basin (Bodego & Agirrezabala, 2013; Bodego, Iriarte, López-Horgue, & Álvarez, 2018); 5–7: Gaujacq and Ossun diapirs (Canérot et al., 2005); 8: Maultéon basin diapirs (Jammes et al., 2010); 9: Cotiella extensional salt area (McClay et al., 2004); 9: Sopieira and Sant Gervás diapirs (Saura et al., 2016); 10: Villahermosa del Rio diapir (Canérot, 1991); 11: Parcent diapir (Pedrera et al., 2014); 12: Altea diapir (Pedrera et al., 2014; Martínez del Olmo et al., 2015); 13, 14: Finestrat and Elda diapirs (Martínez del Olmo et al., 2015); 15: Jumilla diapirs (Escosa et al., 2018); 16: Western Betics (Soto & Flinch, 2017); 17, 18: Faro and Albuferia diapirs (Ramos et al., 2016); 19, 20: Santa Cruz and Caldas da Rainha diapirs (Alves et al., 2003; Pena do Reis et al., 2017). Iberian Range AB: Aragoneses Branch; Iberian Range CB: Castillan Branch; PB: Parentis Basin; AB: Asturian Basin; AP: As Pontes Basin; ALZ: Asturoccidental-Leonese Zone; CZ: Cantabric Zone; CM: Cantabrian Mountain; CS: Central System; CCR: Catalan Coastal Range; GB: Guadalquivir Basin.

KEYWORDS
Iberian Ranges, Jurassic–Early Cretaceous halokinetic depositional sequences, Maestrat Basin, Miravete salt anticline, salt walls, salt-welds, Triassic diapirism

Highlights
- The Miravete anticline grew for tens of millions of years during the Jurassic and Early Cretaceous periods.
- Peak diapirism began in Hettangian-Barremian ages with coeval western diapir flank collapse and salt extrusion.
- Early Aptian W-prograding carbonate platforms might relate to the N-S growth of the Miravete salt wall.
- Upturned flap in Cañada-Vellida salt wall confirms the diapiric history of the Maestrat Basin.
- Early Cretaceous increase of Iberia eastward drift could trigger diapirism in many of Iberian rifted basins.
Terrinha, & Muñoz, 2016) and the Lusitanian basin (19, 20: Alves, Gawthorpe, Hunt, & Monteiro, 2003; Peno dos Reis, et al. 2017).

The Iberian Range formed from the inversion of the Mesozoic Maestrat intraplate rift basin (e.g. Guimerà, Mas, & Alonso, 2004; Salas & Casas, 1993), in which widespread
unconformities within the Jurassic and Lower Cretaceous successions were traditionally interpreted in terms of syn-rift to post-rift differential subsidence between fault-bounded tectonic domains (Aurell et al., 1992; Campos, Aurell, & Casas, 1996; Guimerà, 1988; Liesa, Soria, Meléndez, & Meléndez, 2006; Roca & Guimerà, 1992; Roca, Guimerà, & Salas, 1994; San Román & Aurell, 1992). The only previously documented examples of halokinesis within the Maestrat Basin are a diapir located in the Penyagolosa block near Villahermosa del Río village and in Lucena del Cid, north of Castelló (Canérot, 1989, 1991; Trell, Canérot, & Martin, 1979) (see location in Figure 1). However, in a recent reappraisal of seismic and well data of the Maestrat Basin, Nebot and Guimerà (2016a, 2016b) clearly document the migration of Middle Triassic salt as a consequence of a Cenozoic detachment, promoting the development of salt pillows in the subsurface.

In this contribution, we explore the hypothesis that Triassic salt-bearing layers of the Maestrat Basin flowed soon after their deposition producing diapirism, well before the Late Cretaceous onset of regional contraction (e.g. Macchiavelli et al., 2017; Martín-Chivelet & Chacón, 2007). We focused our study on the vicinity of the Miravete anticline, a N–S trending structure, that has been classically interpreted as a fold related to the Cenozoic compression despite its trend subparallel to the direction of tectonic shortening (Simón, 2004). This region of the Maestrat Basin, especially to the north of the Miravete anticline, has very complex fold patterns composed of sets of anticlines and synclines with different and sometimes orthogonal trends that were interpreted as superposed buckle folds (Simón, 2004). However, in the Miravete region, Triassic rocks form long and narrow outcrops along anticline axes or rectilinear faults trending either NW-SE or N-S. These salt-bearing rocks are associated with Jurassic and Lower Cretaceous depositional sequences characterized by multiple intraformational unconformities, sedimentary wedges, complex facies patterns, stratal onlaps and outward progradation of carbonate platform systems, usually associated with rifting. In the Miravete anticline, the high quality and continuous exposure of this fold led to the publication of numerous stratigraphic studies that are used to build a detailed thickness, facies and age interpretations providing a very detailed framework for our study (Bover-Arnal et al., 2010; Bover-Arnal, Pascual-Cebrian, Skelton, Gili, & Salas, 2015; Embry et al., 2010; García et al., 2014; Meléndez, Liesa, Soria, & Meléndez, 2009; Navarrete et al., 2014; Navarrete, Rodríguez-López, Liesa, Soria, & Veloso, 2013; Peropadre, Liesa, & Meléndez, 2013; Vennin & Aurell, 2001).

We established the interplay between tectonics and sedimentation in the Miravete salt anticline (Figure 2) through numerous field campaigns (mostly during years 2015 and 2016), remote sensing and high-quality photography to build drone-derived virtual outcrop models. Once the contributions of halokinesis in Miravete anticline were established, we extended the study to other nearby structures where we collected additional data that confirmed the fundamental role of salt movement prior to the onset of Alpine contraction (Castel de Cabra salt anticline and Cañada Vellida and Pancrudo salt walls, Figure 2). These additional studies corroborate that the Maestrat Basin in the southeastern Iberian Range is a newly identified diapiric province. In this region we identify masked halokinetic structures of early diapirism that influenced the local deposition, but were then significantly overprinted by later contraction. Nevertheless, this study is particularly restricted to the Jurassic and Early Cretaceous evolution of diapirc structures in the analysed region well before Alpine compression.

2 | GEOLOGICAL SETTING: THE MAESTRAT BASIN

The NW-SE trending Iberian Range is interpreted as an intraplate chain resulting from the Alpine inversion of the Late Permian to Mesozoic NW-SE Iberian rift system and of the nearly coeval NE-SW Catalan rift system (Guimerà, Rivero, Salas, & Casas, 2016; Salas & Casas, 1993; Salas et al., 2001). The Iberian Range comprises the northeastern Aragonese branch and the southwestern Castilian branch, predominantly containing Cretaceous and Jurassic depocentres respectively (Figure 1). The Aragonese branch is connected with the almost orthogonal Catalan Coastal Ranges, whereas the Castilian branch is linked to the NE domain of the External Betics.

The Late Permian to Mesozoic extensional Iberian system is a failed rift, which reactivated the previous Hercynian tectonic grain and formed during the opening of the Central and North Atlantic basins in the early stages of the break-up of Pangea (e.g. Quesada and Oliveira, 2020; Salas et al., 2001; Stampfli & Borel, 2002). The Betic and Catalan rift systems formed along a roughly NE-SW trend during the development of the Ligurian-Tethys oceanic basins (e.g. Galán-Abellán et al., 2013; Scibetta & Turco, 2011). The evolution of the Iberian Rift was characterized by two main extensional stages: Late Permian to Late Triassic and late Oxfonian to late Albian according to numerous studies (e.g. Capote, Muñoz, Simón, Liesa, & Arlegui, 2002; Salas et al., 2001; Vargas et al., 2009). During the first rift stage, Upper Permian continental deposits and Triassic strata of typical Germanic facies accumulated in approximately NW-SE trending fault-bounded depressions (Arche & López-Gómez, 1999, 2005; Benito, 2005). These deposits include two principal Triassic salt layers, one in the middle Muschelkalk unit and another in the Keuper unit (Nebot & Guimerà, 2016; Ortí et al., 2017). After the first rifting stage, Jurassic shallow-water platforms developed in an epeiric sea that connected southwards to the Tethys oceanic domain (Alnaghah, Bádenas, Pomar, Aurell, & Morsilli, 2013; Aurell, Bádenas, Ipas, & Ramajo, 2010;
A second rifting stage occurred from Late Jurassic to Early Cretaceous, coeval with the opening of the southern segment of the North Atlantic, between Iberia and Newfoundland, and the opening of the Bay of Biscay (Alvaro, Capote, & Vegas, 1979; Capote et al., 2002; Salas & Casas, 1993; Van Wees, Arche, Beijdorff, López-Gómez, & Cloetingh, 1998). During this second rifting stage the Jurassic carbonate platforms were broken-up and newly formed faults defined individual basins, namely the Cameros, Maestrat and Columbrets basins, which were characterized by independent subsidence and stratigraphic histories (Etheve et al., 2018; Salas et al., 2001). More recently, in Martín-Chivelet et al. (2019) have distinguished a Neocomian (late Berriasian–Hauterivian) post-rift phase between rifting cycles of Late Jurassic and Barremian–early Albian ages during the Late Jurassic–Early Cretaceous extension of the Maestrat Basin.

This study focused on the western Maestrat Basin (Figure 2), which is limited to the south by NW–SE Iberian-trending normal faults, and to the north by a system of approximately E–W south dipping normal faults (Nebot & Guimerà, 2016; Salas et al., 2001). The position and orientation of these basin-bounding structures, and that of subsidiary faults within the basin, controlled the thickness of Cretaceous deposits (Liesa, Soria, Meléndez, & Meléndez, 2006; Navarrete et al., 2013) and influenced the formation of thrust ramps and fold belts during later tectonic inversion (Liesa & Simón, 2009; Simón, 2004).

Folds in the Maestrat Basin, including the Miravete anticline, are traditionally assumed to be the consequence of basin inversion during the Alpine compression triggered by the
roughly N-S convergence between Africa and Europe (e.g. Capote et al., 2002; Guimerà, 1984; Guimerà et al., 2004; Nebot & Guimerà, 2016; Salas & Casas, 1993; Simón, 2004). The N-S to NNE-SSW shortening direction is documented north of the Miravete anticline, where a NW-SE sinuous belt of salt-cored anticlines and exposures of Triassic deposits are interpreted as the frontal part of a N-directed thrust sheet (Utrillas thrust; Simón & Liesa, 2011). This thrust sheet detaches above either the middle Muschelkalk evaporites in its northern part (Maestrat Basement Thrust, Nebot & Guimerà, 2016) or Upper Triassic evaporites (Liesa, Casas, & Simón, 2018). The E–W trending structures of Camarillas and Jorcas thrusts and the El Morrón box-fold in the western flank of the Miravete anticline grew according to the N-S direction of shortening (Figure 4).

The total shortening along a NNE-SSW profile of the Iberian Ranges was estimated as 20.5% (Guimerà, Salas, Vergés, & Casas, 1996; Salas et al., 2001) across the Maestrat Basin, and 26% near the Cameros Basin (Guimerà et al., 2004). De Vicente et al. (2009) provided a similar 20% shortening for the Castilian Branch only. Consequently, structures oblique or subparallel to the main direction of shortening are expected to give shortening values lower than 20%. In any event, fold superposition is observed in the study area and a relative chronology was established where E-W to ENE-WSW trending folds and thrusts (assumed as Early Miocene age) overprinted earlier N-S to NNW-SSE trending folds (assumed as Eocene–Oligocene age; Simón, 2004; Figure 2).

3 | THE MIRAVETE SALT ANTICLINE

The Miravete anticline, located in the Galve sub-basin that was open towards the Tethys (Salas and Guimerà, 1996), was previously interpreted as resulting from the inversion of the roughly N–S trending westward-dipping Miravete normal fault (Liesa et al., 2006). The greater thickness of Lower Cretaceous formations observed on the western limb of the anticline was attributed to the larger accommodation space in the hangingwall of the normal fault. Non-balanced published cross sections of the anticline are included in the Villarluengo map sheet, 1:50,000 scale (MAGNA geological map; Gautier, 1979), and in articles by Simón (2004) and Liesa et al. (2018). In order to demonstrate that the Miravete anticline developed as an early diapiric structure during the Jurassic and Early Cretaceous, which was never mentioned in previously published studies, we first provide general stratigraphic and structural descriptions of the anticline.

3.1 | Stratigraphy of the Miravete anticline

The sedimentary and stratigraphic framework of the Miravete anticline (Figure 3) is based on detailed studies by Canérot, Cugny, Pardo, Salas, and Villena (1982), Liesa et al. (2006), Liesa et al. (2018), Gómez and Fernández-López (2006), Bover-Arnal, Salas, Moreno Bedmar, and Bitzer (2009), Bover-Arnal, Salas, Guimerà, and Moreno-Bedmar (2014); Bover-Arnal et al. (2010, 2015, 2016), Embry et al. (2010), Peropadre et al. (2013), Aurell et al. (2016) and Navarrete et al. (2013, 2014). Strata range from Triassic to poorly dated Cenozoic ages, and are arranged herein into six sedimentary units related to different age-based tectono-sedimentary phases linked to the evolution of the Galve sub-basin.

The Upper Triassic deposits (sedimentary unit 1 in Figure 3) comprise red clays with secondary gypsum that contains bipyramidal quartz crystals which are attributed to diagenetic replacement of anhydrite crystals (Querol et al., 1992). These sediments are locally accompanied by red shales, evaporites and dolostones of Middle Triassic age, (e.g. Cañada Vellida area; Figure 2). In the Miravete anticline, Triassic strata weather easily and only crop out in the core of the anticline (Figures 2 and 3), where they are highly deformed by regional and local tectonic stresses. Although difficult to calculate, the local thicknesses of Upper Triassic along the anticline are 20–30 m thick and might disappear laterally. In the subsurface, however, Upper Triassic evaporite deposits in the Maestrat Basin reach thicknesses up to 250 m, whereas Middle Triassic Muschelkalk units range up to 600 m, locally forming salt structures with larger thicknesses at depth towards the NNE of the Miravete salt anticline (Nebot & Guimerà, 2016 and references therein).

Jurassic strata (sedimentary unit 2 in Figure 3) are composed of shallow carbonate platform sediments ranging in age from the Hettangian to the Tithonian. In the Miravete area, Liesa et al. (2006) differentiate eight Jurassic sedimentary lithostratigraphic units composed of shallow marine to transitional carbonates. Flanking the Miravete anticline, however, the Jurassic record is relatively thin, incomplete, and contains numerous angular unconformities. According to Liesa et al. (2006), Liesa et al. (2018) and thicknesses by Gautier (1979), the preserved part of the Early Jurassic succession corresponds to the Cortes de Tajuña (50 m) and Cuevas Labradas (60 m) formations (Hettangian to Pliensbachian in age), the Late Jurassic includes the Loriguilla (100–200 m) and Higuéelas (60–70 m) formations (Oxfordian–Kimmeridgian) and the uppermost part is the Tithonian–Berriasian Villar del Arzobispo Fm. showing a maximum of 250 m of thickness. A stratigraphic gap ranging from the earliest Berriasian to Hauterivian times (Salas et al., 2001) is recorded in the Miravete area as an unconformable boundary between the Villar del Arzobispo Fm. and the Hauterivian El Castellar Fm., and represents a major marine regression. Recently, Aurell et al. (2016, 2019) characterized three new formations (Cedrillas, Aguilar de Alfambra and Galve) along the latest Kimmeridgian–Berriasian succession of the Galve sub-basin, and proposed to restrict the Villar del Arzobispo Fm. to the València Basin (Aurell et al., 2019).
Furthermore, Aurell et al. (2019) placed the intra-rift Berriasian to Hauterivian unconformity between the Berriasian Galve Fm. and the Hauterivian El Castellar Fm. However, this paper follows the Jurassic stratigraphy mapped by Liesa et al. (2006), Liesa et al. (2018).

Sedimentary unit 3 comprises the El Castellar, Camarillas, Artoles and Morella lithostratigraphic units and spans the Hauterivian to late Barremian interval (Figure 3). The El Castellar Fm. (Hauterivian to Barremian) was deposited in alluvial plain, palustrine, and lacustrine environments (Liesa et al., 2006; Meléndez et al., 2009; Navarrete et al., 2013), and consists of sandstone, mudstone and limestone facies that show rapid lateral variations with distance from the anticline crest and its faults (Liesa et al., 2006). Recently, the continental Galve Formation has been defined and recognized in the strata of the Galve sub-basin (Aurell et al., 2016, 2019). The Galve Formation is equivalent to the basal El Castellar Formation as mapped in this study, suggesting the regional Berriasian unconformity may occur within this unit as well. The Camarillas Fm. (in the Weald facies, Figure 3) is composed of discontinuous lenses of cross-bedded fluvial sandstone encased in reddish floodplain mudstone (Bover-Arnal et al., 2016; Canérot et al., 1982; Embry et al., 2010; Navarrete et al., 2013, 2014). Both the El Castellar and Camarillas formations record variations in occurrence, thickness and facies around the Jurassic core of the anticline, suggesting that their deposition was strongly influenced by an actively growing topographic high (Miravete anticline) at the time of deposition, resulting in facies partitioning. In addition, these units contain internal unconformities and erosional surfaces. The Artoles Fm. (early to late Barremian according to Bover-Arnal et al., 2016) is composed of alternating green marl and bioclastic limestone rich in benthic foraminifera and oysters suggesting very shallow marine to transitional environments (Vennin & Aurell, 2001). It has more consistent thickness and facies distribution patterns around the anticline compared to the El Castellar and Camarillas formations. The last lithostratigraphic unit of sedimentary unit 3, the upper Barremian Morella Fm., is composed of red mudstone and sandstone, and is interpreted as having formed in tidal flat and high energy fluvial environments (Bover-Arnal et al., 2016; Salas, 1987). Bover-Arnal et al.
(2010) noted that the Morella Fm. is more developed on the western flank of the anticline, where it unconformably rests on the Artoles Fm.

Above the Morella Fm., sedimentary environments became fully marine and are composed of mostly carbonate platform strata towards the top of the Xert Fm. (latest Barremian in age). The Xert Fm. is characterized by a sandy and marl-dominated basal part that changes vertically into carbonate strata containing coated grains, green algae and benthic foraminifera (Bover-Arnal et al., 2010; Embry et al., 2010; Vennin & Aurell, 2001). This unit marks the base of Urgonian facies in the Miravete region (sedimentary unit 4 in Figure 3). In addition, the Xert Fm. is thicker and contains deeper facies on the western compared to the eastern flank (Bover-Arnal et al., 2010). These observations indicate that subsidence was greater on the western than on the eastern flank during deposition of sedimentary unit 4. The top of the Xert Fm. contains chondrodontid bivalves and miliolid foraminifera suggesting a pronounced shallowing of relative sea level, although no direct evidence for subaerial exposure has been recognized.

The Xert Fm. marks the beginning of a major, Tethyan-wide, transgression, which culminated with deposition of the overlying Forcall Fm. The Forcall is interpreted as basin to slope deposits, and is mainly composed of marls, marly limestones, limestones and storm-induced turbidites. This unit is dated as early Aptian based on ammonite occurrences, and includes the Oceanic Anoxic Event 1a (Bover-Arnal, Salas, Martín-Closas, Schlagnitweit, & Moreno-Bedmar, 2011, 2016; Moreno-Bedmar et al., 2009, 2010). The uppermost part of the Forcall Fm. passes laterally and is overlain by the Villarroya de los Pinares Fm. (upper part of sedimentary unit 4; Figure 3), which is composed of coral, rudist-dominated floatstones and rudstones deposited in carbonate platform shelf and slope environments during the late early Aptian (Bover-Arnal et al., 2009, 2010, 2015). The facies are thicker and shallower on the eastern flank of the anticline, whereas they thin and transition laterally into basinal deposits at the Las Mingachas location on the western flank (Bover-Arnal et al., 2009, 2010), suggesting that subsidence continued to be greater on the western flank during the late early Aptian (Figure 8a). A regionally recognized exposure surface characterized by local incision and karst dissolution occurs near the top of the Villarroya Fm., indicating a significant fall in relative sea level during the latest early Aptian (Bover-Arnal et al., 2009, 2015, 2016). Alternatively, Peropadre et al. (2013) identify as many as six erosional surfaces within this interval, and interpret a complex drainage system recording southward and westward flow, coeval to the development of the Villarroya carbonate platform. These authors interpreted a partial tectonic control for sea-level changes, but favoured a mainly eustatic origin to develop these unconformities. Moreover, on the western flank of the Miravete anticline, the top of the Villarroya de los Pinares Formation is locally not preserved due to recent erosion (Bover-Arnal et al., 2010).

The lower part of sedimentary unit 5 contains the late Aptian Benassal Fm. This latter lithostratigraphic unit is arranged into two transgressive-regressive sequences (Bover-Arnal et al., 2010, 2016; Embry et al., 2010). The transgressive parts are made up of marls and marly limestones with orbitolinids and gastropods, whereas the regressive units correspond to platform carbonates rich in rudists and corals (Figure 3). The top of the Benassal Formation is characterized by sand-grade silicilastic input (Figure 3). The first transgressive–regressive sequence of the Benassal Fm. shows similar facies and thickness patterns on both sides of the anticline. The second transgressive–regressive sequence likewise shows similar facies patterns on either side of the anticline but is thinner on the western side as a result of later Palaeogene erosion. Furthermore, the lithostratigraphic units of sedimentary units 4 and 5 also show a progressive thickness increase and a deepening of the sedimentary environments from north to south at the scale of the sub-basin (Bover-Arnal et al., 2010; Embry et al., 2010; Vennin & Aurell, 2001).

Above the Benassal Formation, the sedimentary succession records an unconformity and a transition back to transitional and continental facies, which belong to the Escucha and Utrillas Fms. (Figure 3). The Escucha and Utrillas Fms. are Alban-earliest Cenomanian in age (Canérot et al., 1982). They are composed of coal-bearing deltaic deposits that change vertically into fluvial and locally aeolian sandstone (Querol et al., 1992; Rodríguez-López, Meléndez, Soria, & De Boer, 2009).

The overlying Cenomanian to Maastrichtian sedimentary record (Late Cretaceous in Figure 3) consists of shallow marine carbonates and fine siliciclastic strata with gypsum and lacustrine limestone (Canérot, 1991; Gil, Carenas, Segura, Hidalgo, & García, 2004). The Late Cretaceous formations are only preserved on the eastern flank of the Miravete anticline, having been eroded from the west flank before deposition of Palaeogene red beds. An unconformity associated with a major relative sea level drop at the end of the Maastrichtian marks the top of sedimentary unit 5.

The youngest deposits exposed in the study area correspond to Palaeogene alluvial to lacustrine conglomerate, sandstones and shales (sedimentary unit 6 in Figure 3). This succession, was inferred to range from earliest Palaeocene to
Miocene in age and was grouped into six tectono-sedimentary units bounded by unconformities associated with successive Alpine compressional events (González & Guimerà, 1993; Simón, 2004). Recently, K-Ar isotopic dating of illites from clay gouges near the SE front of the Iberian Ranges (Río Grío Fault) provided three groups of absolute ages, for the first time in the study area (Aldega et al., 2019). The Río Grío Fault system was active during Permian-Triassic and Late Jurassic (Mesozoic rifting phases) and then recorded the compression stages during Campanian (72 Ma) and middle Eocene (43 Ma).

3.2 | Present geometry of the Miravete anticline and of surrounding structures

The Miravete anticline is a 16-km long, almost N-S trending fold that reaches 20 km in length when coupled with the Campos anticline to the north (Gautier, 1979; Figure 2). The northward transition from the Miravete anticline to the Campos anticline is across the ESE-WNW trending Cobatillas thrust, producing a local verticalization of the anticline plunge (Figure 2; Simón & Liesa, 2011). The Campos anticline is embedded in the large ESE-WNW trending Aliaga synclinorium, which is filled with a thick, coarse succession of Palaeogene growth strata. The Miravete anticline also preserves its southern periclinal termination (Figures 4 and 5a) while along its central segment is characterized by a complex, discontinuous and parallel to the axis normal fault system that collapsed its western flank. At a regional scale, the Miravete anticline is bounded by two relatively broad synclines: the N-S trending Camarillas syncline to the west and the NNW-SSE trending Fortanete syncline to the east (Figure 2).

The core of the Miravete anticline, delineated by the Keuper, Jurassic, and Lower Cretaceous to the mid Barremian (Artoles Fm.) part of the succession, shows a tight geometry especially along its central sector (Figure 4). The southern sector displays an easterly verging crestal domain within the Jurassic and Lower Cretaceous El Castellar Formation (Figure 5a). The central sector of the anticline, recognizable by the Remenderuelas–Camarillas normal fault system, locally exposes the Triassic succession along its core (Figures 4a and 5b). Where the Triassic is missing, different subvertical to overturned Jurassic–Barremian successions of the two limbs of the Miravete anticline are juxtaposed. Finally, in the northern sector, close to the Aliaga village (Figure 2), the anticline preserves its Jurassic crestal domain. The northern sector of the Miravete anticline was folded across the E–W trending La Olla monocline,

**FIGURE 5** Two drone pictures showing the structure of the Miravete anticline: (a) view to the south of the southern termination of the Miravete anticline delineated by the Villarroya Aptian carbonate platform smoothly rounded and east-vergent with a very steep eastern limb; and (b) view to the north of the central sector of the Miravete fold, cored by Triassic and Jurassic rocks displaying halokinetic features and exposing Cretaceous successions on both flanks (see location in Figure 4)
resulting in a steep northward fold plunge of 70–80° and an almost circular, an outstanding subvertical fold closure (Simón, 2004). The Remenderuelas–Camarillas normal faults were previously described by Liesa (2006) and Navarrete et al. (2013, 2014) as a set of listric normal faults compartmentalizing the NNW-SSE trending Galve graben, a local sub-basin of the Maestrat Basin.

4 | EARLY JURASSIC TO APYAN GROWTH OF THE MIRAVETE SALT ANTICLINE

In this section, we describe in greater detail the tectono-sedimentary relationships along the core of the Miravete anticline from the Lower Jurassic through the lower Aptian Villarroya de los Pinares Formation. This section is supported by the collection of a large amount of structural data (2,400 dips), from field and remote sensing datasets, to better constrain the tectonic and sedimentary relations. 3D geomodels were made for the region of Las Mingachas using high-quality images acquired with drones, where carbonate platforms of the Villarroya de los Pinares Formation, from late early Aptian age, display several progradational bedsets in a hard-to-reach cliff. The entire sedimentary succession, showing abundant evidence of growth of the Miravete anticline, which we interpret to be related to salt tectonics, is examined in the following Sections 4.1–4.3.

4.1 | Jurassic salt anticline (salt mobilization)

The Jurassic to earliest Cretaceous structural evolution of the Miravete salt anticline is best illustrated in the central sector of the anticline at the Peña de las Higueras locality (Figure 6). At this outcrop, the core of the anticline is characterized by subvertical Jurassic carbonate formations with an eastward stratigraphic polarity and a reduced total thickness compared to regional. These Jurassic sequences are in contact with steeply westward-dipping El Castellar and Camarillas formations along the western flank of the anticline. The contact between these two opposing successions is sharp and steeply east-dipping (079/84°), showing subparallel flanks and was previously interpreted as a thrust fault since the thick Jurassic carbonates seem to thrust above the subvertical to overturned alluvial and lacustrine strata of the El Castellar Formation (Gautier, 1979; Liesa et al., 2006).

Interpreting this contact as a simple compressional thrust is not straightforward and it might only be possible thrusting an original west-verging closed fold in which the hanging-wall shows a flat geometry and the footwall displays a ramp geometry and thus involving considerable offset. The lack of any hangingwall ramp at the level of Jurassic carbonate as well as the sudden changes in stratigraphy on both flanks along the central segment of the Miravete anticline (Figure 4), are more compatible with a salt weld interpretation. This diapiric explanation is also sustained by the existence of Jurassic angular unconformities and Lower Cretaceous ones infilled by Camarillas Fm. indicating tectonic activity along the Miravete structure that steepened its flanks generating a pre-compression palaeorelief as described in this section.

Along the eastern flank of the Miravete salt anticline, the Jurassic carbonate succession is >200-m thick and is characterized by two unconformities (Figure 6). The basal part (units 1, 2 and 3 in Figure 6) is composed of thick breccia deposits, attributed to the Jurassic 1, showing evidence of karstic overprint. This interval is truncated by a well-bedded carbonate unit with sparse biota and numerous metre-scale cycles (units 5 and 6), which is attributed to the Jurassic 2. Bedding within this Unit 5 is parallel to the basal unconformity (a in Figure 6). These Lower Jurassic carbonate platforms are truncated towards the top by a high-angle planar erosional surface (b in Figure 6) that cuts down through the stratigraphy and is associated with brecciation, a pink coloration, and reddening of the underlying carbonates. This erosional unconformity is overlapped at a relatively low angle (>10°) by cross-bedded oolitic packstones and grainstones of the uppermost Jurassic Villar del Arzobispo Formation (Figure 6). The subparallel deposition of the Villar del Arzobispo above its basal unconformity indicates previous tilting of the Lower Jurassic carbonate platforms.

The Villar del Arzobispo Formation is truncated by an erosional unconformity onto which the lower Barremian fluvial system of the Camarillas Formation onlaps, filling an observed palaeotopographic relief of more than hundred metres located near the active ridge of the rising Miravete salt wall (Figure 6a). Towards the south, the Hauterivian El Castellar Formation onlaps the top of the Villar del Arzobispo Formation and forms the eastern flank of the salt weld in contact with the west-dipping Jurassic strata (Figure 4). East-dipping Lower Cretaceous Artoles to Utrillas formations are conformable above the Jurassic through Lower Cretaceous Camarillas halokinetic sequence on the eastern flank of the Miravete salt anticline.

The Peña de las Higueras locality (Figure 6) was used to reconstruct the evolution of the eastern flank of the Miravete salt wall by examining variations in bedding attitude of the Jurassic 1 (Lower Jurassic) carbonates and of progressively younger deposits, namely: Jurassic 2; uppermost Jurassic Villar del Arzobispo Formation and lower Barremian fluvial deposits of the Camarillas Formation through time. We applied a sequential restoration, flattening layers above each unconformity to calculate the rotation of layers below it (Figure 6b). The first restoration (unfolding of the Camarillas
FIGURE 6  (a) View to the north of the outcrop of the Miravete west-verging diapiric weld in the Peña de la Higuera that juxtaposes east-dipping Jurassic carbonates (eastern flank) against Early Cretaceous El Castellar strata dipping west (western flank) (see its location in Figure 4). The eastern flank shows multiple unconformities within the Jurassic formations and the Early Cretaceous Camarillas onlapping the Villar del Arzobispo Formation. (b) Dip attitudes of successive formations have been restored to the horizontal to calculate the orientation of the Jurassic 1, through Jurassic 2, Late Jurassic (Villar del Arzobispo Formation) and Lower Barremian (Camarillas Formation) times. The stereoplots show that the Jurassic 1 carbonates attitudes changed orientation significantly over time during successive restoration. (c) Base of Unit 1 composed of fragmented clasts interpreted as a reworked deposit of karstified carbonates. (d) Erosional unconformity affecting peritidal carbonates of Unit 3 with conglomerates marking the transition to the subtidal limestones of Unit 5.
Fm.) involves a rotation of 62° about an axis of 00°–147° producing a Jurassic 1 dip of 101°/21°; the second restoration (unfolding Villar del Arzobispo Fm.) involves a rotation of 26° with an axis rotation of 00°–215° giving a Jurassic 1 dip of 358°/11° and the third and last restoration (unfolding Jurassic 2) needed a rotation of 49° with a rotation axis of 00°–064° resulting in a Jurassic 1 dip of 149°/39°. Summarizing, from older to younger, Jurassic 1 layers were tilted 39° to SSW (before Jurassic 2 time), 11° to N (before Villar del Arzobispo Fm.), and 21° to ESE before the deposition of the Camarillas Formation. These changes in both dip angle and dip direction do not seem to be typical of fault motions in which slightly more systematic rotations are observed.

The unconformity at the top of the Villar del Arzobispo Formation corresponds to a rough surface that bounds the outcrops of Jurassic carbonates. The unconformity shows an angle with the onlapping Camarillas strata in its lower part, whereas it is overlaid by younger Camarillas strata in its upper part and thus constraining its palaeo-height. The flattening of the older onlapping Camarillas strata indicates that the unconformity surface was dipping about 26 degrees towards the ESE as shown in Figure 6b. The present verticalization of flanks occurred during the Palaeogene tightening of the anticline that closed the salt wall along the central sector of the N–S trending Miravete anticline. A potential reverse-slip component for the salt weld is not disregarded, thus representing a thrust-weld (e.g. Rowan, Jackson, & Trudgill, 1999; Figure 6a).

4.2 | Hauterivian–Early Barremian salt wall and its western flank collapse

The Remenderuelas–Camarillas listric extensional fault system characterizes the western flank of the Miravete anticline in its central region (Liesa et al., 2006; Figure 7). The plane of the Remenderuelas–Camarillas extensional fault system is subparallel to the Triassic rocks cropping out in the core of the anticline and cuts through the Jurassic succession (Cortes de Tajuña to Villar del Arzobispo formations). The Hauterivian–Barremian El Castellar continental to transitional deposits are partly coeval with faulting, and the continental Camarillas and shallow marine Artoles formations show both syn- and post-faulting depositional patterns related to displacement on the two large Remenderuelas and Camarillas concave fault planes (location in Figure 4). The geometry of the fault system is described hereinafter from south to north, in the Peña de la Cingla, Mas de Sangüesa and Loma de las Remenderuelas localities (Figure 7, locations in Figure 4).

At the Peña de la Cingla locality the Camarillas fault is well exposed, as shown in the interpreted drone image of Figure 7a. The Lower Jurassic carbonates of the western flank of the Miravete anticline constitute the footwall of the fault that cut the carbonates at a high angle. The fault flattens along the Triassic salt-bearing rocks to the south illustrating its listric geometry (Figure 7a). The hanging-wall of the Camarillas fault contains approximately 80 m of Hauterivian El Castellar Formation. Above it, several hundred metres of Barremian Camarillas strata infill and onlap the hangingwall fault plane showing a slight thickening...
towards the fault, which can define growth strata pattern. Upper Camarillas beds thin and overlie the topmost part of the fault, whereas the upper part of the mid-Barremian Artoles strata show no sign of growth and thus representing post-faulting deposition in this locality (Figure 7a). The El Batán fault (from Liesa et al., 2006) constitutes the southern end of this 2.3-km-long Camarillas depocentre (Figure 4). To the south, the Miravete anticline preserves its complete fold geometry but is heavily faulted at the El Castellar Formation level within the southern sector of plunge domain 3 (Figure 4 for location) although faults are not represented at this scale (see details in Gautier, 1979 and Liesa et al., 2006).

At the Mas de Sangüesa locality, the Remenderuelas fault hangingwall is exposed (as observed in a southward aerial view from drone photography in Figure 7b). The fault hangingwall is composed of Jurassic carbonates, the El Castellar and the basal Camarillas formations. The Hauterivian El Castellar Formation thins southwards and the circa 250-m thick lower part of the early Barremian Camarillas Formation is deposited conformably on the underlying strata. At the Mas de Sangüesa locality, however, a deep incision cuts almost the entire lower Camarillas and is filled with middle Camarillas fluvial deposits onlapping against the walls of the palaeorelief (Figure 7b). The upper part of the Camarillas Formation is continuous, and thus postdates infill of the palaeovalley on the western flank of the Miravete salt anticline. These observations show that collapse of the western flank was coeval with the mostly continental deposition of the El Castellar and Camarillas formations and influenced their facies, thickness distributions and stratigraphic geometries.

At the Loma de las Remenderuelas locality, the Remenderuelas fault is well exposed dipping 055/72° (Figure 7c). Here, Jurassic carbonates and remnants of salt-bearing Upper Triassic rocks form the footwall of the fault. The upper part of the Camarillas Formation onlap the fault and the lower part of the Artoles Formation, above an unconformity, onlap both the Camarillas Formation and the fault plane. The upper marine Artoles Formation unconformably overlies older growth strata and fossilizes the palaeorelief developed during the activity of the Remenderuelas fault.

We interpret the W-dipping Remenderuelas–Camarillas extensional fault system to be related to the collapse of the western flank of the growing Miravete salt anticline or elongated salt weld starting before the deposition of the early Barremian Camarillas Formation. The collapse of the central segment of the anticline could be related to increasing extension or sediment loading (Liesa et al., 2006), or to removal of salt at depth flowing towards the active salt wall.

Reconstructing the evolving topography during growth folding or diapirc structures is always difficult unless growth or halokinetic depositional sequences directly fossilize previous tectonic or erosional features (Burbank & Vergés, 1994). The eastern flank of the Miravete salt anticline at Peña de las Higueras locality (Figure 6a) shows a well-preserved palaeorelief carved in the Jurassic limestones and infilled by non-marine sediments of the El Castellar and Camarillas formations. The Camarillas strata onlap the previously tilted Jurassic units of the eastern flank of the Miravete salt anticline showing relatively constant thickness and an apparent subparallel attitude. Earliest Cretaceous facies distribution along the central segment of the anticline in both the eastern flank (footwall) and the western flank (hangingwall of Remenderuelas–Camarillas fault system) indicate the existence of a variable palaeorelief, defined by steeper Jurassic carbonates. This variable palaeorelief could be explained by deposition along an elongated and relatively narrow salt wall characterized by the collapse of its western flank and by the potential extrusion of salt along its footwall. This palaeotopography was covered by the Camarillas river system, that would eventually traverse the rising Miravete salt wall.

4.3 Late Barremian–Aptian salt anticline growth and effects on carbonate platform distribution

Depositional facies and thickness patterns suggest the Miravete anticline exerted control on sedimentary units throughout the early Aptian, primarily by creating more accommodation (subsidence) on the western flank than the eastern flank (Figure 4). Evidence supporting this conclusion includes: (a) the continental to transitional Morella Formation is thicker in the western flank; (b) the overlying shallow marine carbonates of the Xert Formation record deeper water facies, as well as west-directed progradational geometries away from the crest of the anticline, on its western flank. In the Las Mingachas locality, located on the western limb, near the village of Miravete de la Sierra (Figure 4), Bover-Arnal et al. (2009) described three superposed systems tracts (highstand, lowstand, and transgressive) within the lower Aptian Villarroya de los Pinares platform, preserving clinoforms that we analysed to determine their direction of progradation with respect to their stratigraphic position (Figure 8). This was accomplished using a virtual outcrop model based on high-quality photographs collected by drone photogrammetry. The modelled dip directions of the clinoforms were verified with direct measurements in the field. The results of this analysis show that the clinoforms of the highstand systems tract are prograding towards the SW, whereas those of the subsequent lowstand systems tract prograde towards the SSW, and those of the overlying transgressive systems tract prograde towards the W (Figure 8b,c).
Taking into account that regional platform progradation was southwards, towards the Tethys, analysed platforms prograding roughly towards the west suggest that the Miravete anticline was a bathymetric high that partially controlled the platform architecture, along with relative sea level variations. To verify the potential growth of the Miravete salt anticline during deposition of the upper Barremian–Aptian carbonate platform successions we analysed different published stratigraphic columns in areas relatively away and close to the axis of the Miravete anticline (Figure 9b). The stratigraphic columns of the Barranco de las Calzadas in the eastern flank of Miravete anticline and the Estrecho de la Calzada Vieja (Bover-Arnal et al., 2010) in the western flank are located 1.2 and 0.8 km away from the axis of the anticline respectively (Figure 9b).

Assuming that the Miravete salt anticline was rising during deposition of these units, the thinner Las Cubetas stratigraphic column would represent a relatively proximal position above the crest of the anticline, whereas the other sections along the flanks would correspond to more distal areas away from the creatal domain. Therefore, we have projected and correlated the 279 m thick succession of the Las Cubetas stratigraphic column together with the western flank section (a minimum of 572 m) and the Eastern flank section (547 m thick) stratigraphic columns located in the central part of the anticline (Figure 9b). The comparison shows that all the stratigraphic units, except the Villarroya de los Pinares Formation thin towards the crest of the anticline, indicating amplification of the salt anticline during the late Barremian to Aptian. The Villarroya de los Pinares Formation thins and records deeper facies towards the western flank of the Miravete salt anticline (Bover-Arnal et al., 2010), and is relatively thicker on its eastern flank (Figure 9b). Such a configuration may be explained by lateral facies changes related to carbonate platform production and progradation above the more distal facies of the Forcall Formation on the western flank, as observed in the Las Mingachas locality (Figures 8a and 9b). Alternatively, since carbonate platforms preferentially develop in the photic zone above palaeohighs, they may be relatively thicker above the growing salt structures, as observed in other diapiric examples like the El Gordo diapir in the La Popa Basin (Giles et al., 2008), the Bakio diapir in the Basque-Cantabrian Basin (Poprawski et al., 2016), or on the present margins of the Red Sea (Purkis, Harris, & Ellis, 2012).

4.4 | Reconstruction of the Miravete salt anticline

Although field evidence documents the growth of the Miravete salt anticline from the Early Jurassic until at least the Aptian, the construction of a constrained cross section is not straightforward due to the erosion of the anticline crestal domains, a crucial part of the geological cross section (Figure 9). Therefore, two end-members models are constructed: (a) a buckle fold model overlying an inverted normal fault, fitting the present structural relief difference, with its western flank higher than the eastern one, according to published interpretations (Figure 9a), and (b) a growing salt anticline model during the Jurassic and Early Cretaceous above the same inverted normal fault, as interpreted in this study (Figure 9d).

4.4.1 | Buckle anticline model

The buckle anticline model, was built according to: (a) techniques of balanced cross-sectional construction assuming minimal shortening; (b) a large number of new structural dips measured in the field along the line of the cross section (n = 154) and through remote sensing mapping, along the entire length of the anticline limbs and core; (c) compilation of thickness data extrapolated from our geological map and from previous stratigraphic studies (Bover-Arnal et al., 2009, 2010, 2015, 2016; Embry et al., 2010; Meléndez et al., 2009; Navarrete et al., 2013, 2014; Peropadre et al., 2013) to constrain stratatal thicknesses; and (d) constant thickness for groups of strata across the anticline, except where clear thickness variations were identified in the field or from our stratalt thickness dataset. This model shows a fold amplitude of 1.4 km between its crest and its western flank, whereas increasing to 2.4 km with
Field data and interpretation

Drone-derived virtual outcrop

Sequence stratigraphy model

Adapted from Hunt and Tucker (1992, 1995)
respects to its eastern flank (Figure 9a). Shortening at the base of the Xert Formation is 20% (2 km) in an E–W direction, perpendicular to both the anticline axis and the regional direction of shortening in the Maestran Basin.

4.4.2 Growing salt anticline model

The cross section considering the anticline as a growing salt structure during the Jurassic–Early Cretaceous periods was built using the same general assumptions as the buckle anticline model and identical structural dip and stratal thickness datasets. However, we used four additional constraints by (a) projecting the base of the Xert Formation along a longitudinal section to constrain its position in the intersecting E–W cross section (Figure 9c; see its position in Figure 4); (b) using the thicknesses of the Las Cubetas stratigraphic succession projected from the northern termination of the anticline, as representative of the crestal domain stratigraphy and compared to the equivalent successions in the flanks of the anticline (Figure 9b); (c) drawing appropriate stratal geometries for growing diapiric anticlines above salt walls, when observed in the field and (d) ensuring that the general geometry of the growing salt anticline model replicates the preserved east-vergent southern termination of the anticline (as imaged in Figure 5a).

The longitudinal cross section was constructed using about 200 dip measurements to define 5 plunge domains (Figure 9c). The plunge of domain 1 in the northern termination of the Miravete salt anticline is 70° north due to its north-bending across the ENE–WSW trending Cobatillas thrust (Figures 2 and 4), which produced the verticalization of the anticline termination and the beautiful geological features of smaller folds with subvertical axes near Aliaga as described by Simón (2004). Domains 2 and 3 are plunging 3° and 5° north respectively. Domains 4 and 5 show the southern plunge of the anticline with very similar values of 9° and 8° respectively.

At the intersection between longitudinal and E-W cross sections, the base of the Xert Formation, corresponding to the projected Las Cubetas log, is estimated to lie at an elevation of ~1,690 m asl, in contrast to its position at 2,200 m asl at the anticline model buckle (Figure 9b,c). This stratigraphic succession encompasses the 40-m thick upper Barremian Xert Formation, the early Aptian Forcall and Villarroya de los Pinares formations with thicknesses of 75 and 87 m, respectively, and the latest early–late Aptian Benassal Formation, with a minimum thickness of 77 m (Bover-Arnal et al., 2010). This 279-m-thick Las Cubetas succession is about half the total thickness of the equivalent succession outcropping on the eastern and western flanks of the anticline along the E-W cross section (Estrecho de la Calzada Vieja and Barranco de las Calzadas logs; Figure 9b).

In the growing salt anticline model, the projected position of the base Xert carbonate platform in the E-W cross section does not permit thick preservation of the underlying Hauterivian–Barremian pre-Xert sedimentary units in the core of the anticline (El Castellar, Camarillas, Artoles and Morella formations; Figure 9d). Field observations described earlier show that these steeply dipping pre-Xert sediments onlap against Jurassic platforms (Figure 6), and are wedged towards the Miravete salt weld as observed by an abrupt decrease in dip at the boundary between Artoles and the Morella formations. Above the Xert Formation, the geological cross section is constructed considering the decrease in thickness of Xert, Forcall, Villarroya de los Pinares and Benassal formations using typical growth triangle geometries in both flanks (Figure 9d). This reconstruction is consistent with the interpretation of the Las Mingachas locality where the carbonate platforms of the Villarroya de los Pinares Formation prograded roughly westward and thus outwards from the N–S trending core of the growing Miravete salt anticline (Figure 8). This model shows a fold amplitude of ~0.8 km between its crest and its western flank, whereas increasing to 1.9 km with respect to its eastern flank (Figure 9a). Shortening at the base of the Xert Formation is only 10% (1 km) in an E-W direction; about half the amount of shortening obtained for the buckle anticline model.

An analysis of the well-calibrated cross section provides other important results regarding the variations of the sedimentary thicknesses across the Miravete anticline. From the base of the El Castellar Formation (Hauterivian) to the base of the Benassal Formation (latest early Aptian) the total cumulative sedimentary thickness is 570 m (~30%) greater on the western flank than in the eastern one. If we compare only the El Castellar and Camarillas formations (Hauterivian–early Barremian) it turns out that these units are ~40% thicker in its western flank. As well, an increase in thickness of about...
(a) **Buckle anticline model**

![Diagram](image)

- Camarillas Syncline
- Miravete Anticline
- Fortanete Syncline

(b) **Thickness variation across the Miravete anticline**

- Western flank: Barranco de las Calavacas log
- Crestal domain: Las Cubetas log (projected background)
- Eastern flank: Estrechos de la Calavaca de Veja log

* minimum thickness (bedding or formations represented by a hardground)

** maximum differential structural relief at top/Barranco

- Log thickness (m)
- Xert - Forcall - Villamoya thickness (m)

(c) **Longitudinal cross-section along the Miravete anticline**

- Plunge 348.7°
- Best fit plane

(d) **Growing Jurassic–Early Cretaceous salt anticline model**

- Camarillas Syncline
- Miravete Anticline
- Fortanete Syncline

![Diagram](image)
30% is still determined during deposition of Xert, Forcall and Villarroya de los Pinares carbonate platforms in the western flank of the anticline (Figure 9b). Despite the greatest western flank thicknesses throughout most of the Lower Cretaceous sedimentation, in agreement with the Remenderuelas–Camarillas west-dipping extensional fault system, the configuration of the two flanks currently shows a reverse arrangement. In this way, the base of the Xert Formation is presently located >1,500 m higher in the Camarillas syncline (to the west) than in the Fortanete syncline (to the east), indicating a post-Xert tectonic inversion during the Cenozoic Alpine compression along a west-dipping basement normal fault. The base of the Cenozoic red beds deposited on both flanks of the anticline are located almost at the same elevation but showing the most significant erosive unconformity in the Camarillas syncline cutting down to the basal part of Benassal Formation (Figure 9d). In this paper we associate the 1,500 m of uplift as related to the compressional reactivation of the west-dipping basement normal fault at depth, triggering the east-vergence of the Miravete salt anticline as exposed along its southern termination (Figure 5).

5 | Jurassic and Early–Late Cretaceous Regional Diapiric Structures

In this section, we propose a regional analysis of tectono-sedimentary relationships using published geological maps and fieldwork in order to show evidence of other nearby salt-related structures that followed a similar evolution as the Miravete anticline. The regional evidence for salt-related structures growing from the Early Jurassic to Late Cretaceous includes: well-exposed discordant contacts between salt-bearing rocks and younger strata, unconformities, growth strata and onlap, and typical diapiric patterns like hooks and flaps. Two of the best examples, located at Castel de Cabra and the Cañada Vellida (Figure 2), are described below.

5.1 | Earliest Cretaceous to Aptian Castel de Cabra salt anticline growth

The near E–W trending Castel de Cabra salt anticline, located to the south of the village of Castel de Cabra, is characterized by a narrow strip of Upper Triassic rocks in its core overlain by thick Jurassic carbonates defining an elongated anticline (Figure 10). The sedimentary infill of the adjacent asymmetric syncline to the north, composed of a few hundred metres of lower Barremian to Upper Cretaceous deposits, shows significant thinning of lower Barremian to Aptian, and possibly Albian, strata towards the crest of the Castel de Cabra anticline. The most striking feature is the well-developed Albian unconformity bevelling the crest of the anticline at the base of the Escucha and Utrillas formations. Above the Utrillas Formation, a thin package of Upper Cretaceous carbonates is the youngest preserved deposit within the Castel de Cabra growth syncline (Canérot, Crespo, & Navarro, 1977). This stratigraphic thinning towards the anticline crest indicates that folding and erosion occurred before deposition of the non-marine Albian Escucha-Utrillas succession. The growth of the Castel de Cabra anticline during Early Cretaceous is partially coeval with the diapiric growth of the Miravete salt anticline. A simple structural restoration using the base of the Utrillas Formation as a flat reference level in the Castel de Cabra salt anticline, confirmed an approximately 12° dip of the northern flank of the salt anticline before Albian deposition. This unconformity at the base of the Albian Escucha-Utrillas formations is observed at regional scale in the Maestran Basin above underlying stratigraphy including Upper Triassic evaporites. This observation agrees with the outcrops of two 2-m-thick microconglomerate beds within the Escucha Formation containing bipyramidal quartz (around 35-km northwest of the study area; Querol et al., 1992). According to these authors, these idiomorphic crystals of quartz, showing large and abundant anhydrite inclusions, grew within the Triassic evaporites and their erosion, short transport and deposition, indicate the exposure and dissolution of large volumes of evaporites during Albian period at least.

5.2 | Late Jurassic flap to Aptian passive diapir development along the Cañada Vellida salt wall

The Cañada Vellida NW-SE striking structure, located northeast of the town of Galve, forms an elongated outcrop of Triassic red clay and gypsum in map view, up to 10-km long and a few hundred metres wide (Figure 11; see geological
maps of Villarluengo and Argente; Gautier, 1979; Martín & Canérot, 1977). This structure has been traditionally interpreted as a normal fault bounding the Cretaceous Galve sub-basin (Liesa et al., 2006), inverted in its SE part along the E-W trending Cobatillas thrust (Simón, 2004; Simón & Liesa, 2011) (see location in Figure 2).

The Cañada Vellida structure displays different stratigraphic successions on both sides of the Upper Triassic rocks cropping out along its core (Figure 11). The SW flank contains a thick Lower Jurassic to lower Barremian succession (equivalent to Camarillas Formation) and lacks younger deposits, whereas the NE flank shows a reduced Upper Jurassic to lower Barremian succession followed by a relatively thick upper Barremian to Upper Cretaceous succession (Figure 11). Along the NE flank, the Upper Triassic rocks are in contact with Upper Jurassic through Aptian units indicating a discordant limit. Two salt-related bedding structures within the NE flank of the Cañada Vellida confirms its evolution as a salt wall: a small hook within Lower Cretaceous beds and a large flap of Jurassic carbonates of which only remnants crop out (Figure 11). Along the contact with Upper Triassic salt-bearing rocks, a local intra-upper Barremian to Aptian unconformity is interpreted as a halokinetic hook (Figure 11c). The NE flank of the central part of Cañada Vellida shows a spectacular stratigraphic relationship between small patches of overturned Jurassic carbonate beds that lie unconformably on top of a thick subvertical Barremian–Aptian succession (Figure 11b). The Jurassic beds have overturned dips that vary from 53° SW in the lower part in contact with the Upper Triassic evaporites, to only 17° SW in contact with younger Upper Cretaceous strata. We interpret the thin Jurassic patches as remnants of a large overturned flap against which the younger sediments were onlapping during the infill of the basin to the NE of the Cañada Vellida salt wall. The Cañada Vellida salt wall separated the Galve minibasin to the SW from the Aliaga minibasin to the NE. The present deeper position of the Galve minibasin to the SW, together with the SW-dipping flap on its NE flank, strongly indicates that a large breakout of salt extrusion was NE-directed soon after the deposition of Upper Jurassic carbonate platforms covering the salt wall roof. Lower Cretaceous deposition infilled the SW side of the Aliaga minibasin onlapping against the at least 500-m-long upturned flap. The Jurassic thin carbonate patches forming the flap structure are part of the NE flank of
the Cañada Vellida salt wall and therefore represent the oldest units outcropping along this flank. Their attitude dipping to SW along the contact with Upper Triassic evaporites does not permit to interpret them as remnants of a potential Alpine hangingwall thrust.

The NW-SE elongated structure at Cañada Vellida is interpreted in this study as a salt wall that was active from the uppermost Jurassic to the Albian. Field examples of salt walls, slat-related normal faults, hook and flap structures are described in the Alps (Graham, Jackson, Pilcher, & Kilsdonk, 2012), Pyrenees (Saura et al., 2016), Central High Atlas (Saura et al., 2014) and the Sivas Basin in Turkey (Ringenbach et al., 2013), among others (Rowan, Giles, Hearon, & Fiduk, 2016). Offshore examples, analysed on
seismic profiles, are very common in a large variety of geological settings (Jackson & Hudec, 2017). Described structures at Miravete, Castel de Cabra and Cañada Vellida provide evidence for a regional halokinetic history of Early Jurassic through Albian, and possibly later, but prior to regional Palaeogene compression. This compression tightened most of the pre-existing diapiric structures, including those analysed in this study, as well as rejuvenated others like the Teruel diapir, active during Tortonian–Messinian deposition (e.g. Alonso-Zarza & Calvo, 2000).

6 | DISCUSSION

A model for the integrated halokinetic and stratigraphic evolution of the Miravete anticline, from the Jurassic through Alpine compression extending into the Miocene, is shown in Figure 12. We address the implications of this model, as described for the Miravete salt anticline, Castel de Cabra salt anticline and Cañada Vellida salt wall first, at the scale of the Maestrat Basin, and then at the broader scale of the northeastern margin of the Iberian plate towards its limit with the European plate.

6.1 | Implications of salt tectonics at the Maestrat Basin scale

The diapiric structures described in the Miravete anticline, in the Castel de Cabra and Cañada Vellida localities, evolved prior to Alpine compression, from the Jurassic through late Early Cretaceous and were later reactivated during compression from the Palaeocene through Miocene. The diapiric evolution model of the studied region of the Maestrat Basin has been divided into four different periods and is summarized in Figure 12. The first stage, during the Jurassic, is characterized by the formation of salt anticlines, as described in the La Peña de la Higuera outcrop where Jurassic carbonate strata of different units rotated with unsystematic orientations near the Miravete anticline culmination (Figure 6). The overturned Upper Jurassic carbonates of Cañada Vellida, interpreted as a diapiric flap, indicate that the roof of the anticline during Jurassic time could have been formed by a thin carbonate sequence (Figure 10). The second stage of evolution during the Hauterivian and early Barremian is widely represented in the outcrops along the western flank of the Miravete anticline at Loma de las Remenderuelas, Mas de Sangüesa and Peña de la Cingla (Figure 7). This stage is characterized by the growth of the Miravete salt wall producing differential subsidence, collapse and growth of the Remenderuelas–Camarillas fault system, potential extrusion of salt, and formation of variable palaeorelief along the flanks of the salt wall. The third stage of evolution is less constrained due to lack of direct observations in the Miravete anticline, with the exception of the analysis of the upper lower Albian Las Mingachas carbonate platform progradation directions on the western flank (Figure 8). We interpret this as a period of growth of salt anticline with a thinning of the carbonate halokinetic sequences towards the crest of the anticline. However, the Miravete salt wall growth on the footwall of the Remenderuelas–Camarillas fault system would also be possible until at least the beginning of the Albian, considering the coeval evolution observed in the Castel de Cabra structure (Figure 10) and in the Cañada Vellida (Figure 11). The duration of this stage of salt wall growth would be related to the amount of salt below adjacent synclines, which produced variations in depositional thicknesses and differential ages of primary welding (as described in Fortanete and Aliaga synclines-minibasins). The fourth and last stage of diapiric growth is related to Alpine shortening during which the described diapiric structures were squeezed, welded and thrust (thrust-weld of Miravete anticline, potential salt withdrawal in the Cenozoic Aliaga synclinorium and the Miocene Teruel diapir).

This investigation of the Maestrat basin builds on important advances in salt tectonics over the last decades, beginning in the 1940s through 1980s with studies of the Iberian fold and thrust belt where salt tectonics and halokinetic sequences are preserved, such as in the Pyrenees and Basque-Cantabrian Basin and the Betic Cordillera (e.g. Brinkmann & Logters, 1968; Moseley, Cuttell, Lange, Stevens, & Warbrick, 1981; Ríos, 1948). More recent investigations into the role of salt tectonics, specifically in the large European and North African Permo-Triassic salt basins, illustrate its influence during both extension and subsequent compressional inversion (Soto et al., 2017). The identification of halokinetic depositional sequences (e.g. Giles & Lawton, 2002; Giles & Rowan, 2012), even in regions where no trace of salt-bearing rocks is preserved, has been associated with diapiric structuration, and the age of contemporaneous depositional units determines the timing of salt tectonic-related deformation. Some excellent examples occur in the Western Alps (e.g. Graham et al., 2012), the southern Pyrenees and Basque-Cantabrian Basin (e.g. Bodega & Agirrezabala, 2013; López-Horgue et al., 2010; Lopez-Mir et al., 2014; Poprawski et al., 2016; Saura et al., 2016) and the Central High Atlas (Martín-Martín et al., 2017; Moragas et al., 2017, 2018; Teixell et al., 2017). One of the most significant characteristics of these examples is the lack of extensional faults cutting the post-salt depositional sequences. The lack of extensional faults in the post-salt strata is due to decoupling of the presalt structure (basement) and the post-salt structure. In most cases, the bending of post-salt units after a short phase of extension produces long, narrow grabens that trigger reactive, active and passive diapirism along salt walls (e.g. Dooley & Schreurs, 2012).

By applying these salt tectonic concepts, a new geological cross section has been constructed between the eastern Cañada-Benatanduz and western Ababuj anticlines enclosing the Miravete salt-related anticline in its centre (Figure 13). The geological cross section is constructed using the detailed
Regional observations

**Tenue Miocene diapir**

*Escucha Fm.* bipyramidal quartz microconglomerates

**Castell de Cabra** [Fig. 10] Aptian-Albian unconformity growth syncline, minibasin

**Las Mingachas** [Fig. 8] carbonate prograding platforms

**Cañada Vellida** [Fig. 11] overturned flap, hook

*Loma de las Remenderuelas, Mas de Sangüesa, Peña de la Cingla* [Fig. 7] Remenderuelas-Camarillas fault system

**Peña de la Higuera** [Fig. 6] unconformities

**Stage 1** Salt anticline
Salt wall
salt mobilization

**Stage 2** Salt wall
flank collapse
normal faulting & salt extrusion

**Stage 3** Salt anticline
Salt wall primary welding

**Stage 4** Present
Rejuvenated diapir
squeezing & secondary welding

**FIGURE 12** Schematic model of pre-Cenozoic compression diapiric evolution of the Miravete salt anticline combined with results from Castell de Cabra growth anticline and Cañada Vellida salt wall. During the first stage (Jurassic), the anticline shows thinner platform sequences along its crest. Second stage records the increase of subsidence in the western flank coevally its collapse along the Remenderuelas-Camarillas fault system in its central sector. Potential salt extrusion along the footwall of the fault system occurred as well in the Cañada Vellida salt wall. The third stage of diapiric evolution records both the growth of the salt anticline or salt wall in Miravete and continued extrusive diapirism at Cañada Vellida salt wall. The fourth and last stage occurred during the Alpine shortening, tightening previous diapiric structures.

generalized section across the Miravete anticline and the geological sections from the IGME (1979) geological maps of Villarluengo and Alfambra (Gautier, 1979; Olivé, Godoy, & Moissenet, 1981). The pre-salt basement is cut by a westerly dipping fault located beneath the Miravete anticline, as determined by the presence of thicker Lower Cretaceous strata on its
western flank when restored at the base of Upper Cretaceous strata. The extensional fault system of Remenderuelas–Camarillas could possibly be related in space and time to the basement fault beneath the Miravete anticline at depth, but is not necessarily connected. In fact, in our interpretation, the Remenderuelas–Camarillas fault system is a salt-related growth fault that collapsed the western flank of the Miravete salt wall along its central segment. Excellent examples of similar growth faults are imaged on seismic lines crossing the Horn Graben in the southern North Sea (Nalpas & Brun, 1993), and in the offshore Campos, Santos and Espírito Santo basins on the Brazilian margin (Alves, Cartwright, & Davies, 2009; Demercian, Szatmari, & Cobbold, 1993), among others.

The extensional geometry of this part of the Maestrat Basin is evident after restoration at the base-Upper Cretaceous level. This geometry resembles other preserved salt basins of Europe located away from the Iberia-Africa and Iberia-Europe plate boundaries, which experienced little to no modification by Alpine compression. The depocentre of the SE part of the Iberian Basin is 120- to 140-km wide (Salas et al., 2001; Seillé et al., 2015) and likely includes numerous salt structures that still need to be studied, of which Miravete, Castel de Cabra and Cañada Vellida-Pancrudo, have been identified in this study. Other sedimentary basins developed above Upper Triassic salt show comparable numbers of salt structures with similar geometries. For example the Central Polish Basin is about 140-km wide and contains five central diapiric salt walls and marginal salt anticlines (Krzywiec et al., 2017), and the Central Glückstadt Graben displays a total of eight salt walls in the centre of the graben and salt anticlines along its margins (Warsitzka, Kley, Jähne-Klingberg, & Kukowski, 2016, modified from Baldschuhn, Binot, Fleig, & Kockel, 2001), bounding minibasins which may contain different stratigraphies.

6.2 Diapiric evolution of the Maestrat Basin in the Iberian microplate framework

The halokinetic evolution of the Maestrat Basin shares a similar history with other salt basins in Iberia during the Jurassic
and Early Cretaceous and was possibly influenced by the larger scale Mesozoic and Cenozoic tectonic evolution of the Iberian microplate (Figure 14).

Widespread Upper Triassic salt diapirism was active in most of the extensional basins within the Iberian microplate during the Mesozoic (e.g. Vergés et al., 2019), including: the Basque-Cantabrian Basin (Bodego & Agirrezabala, 2013; López-Horgue et al., 2010; Poprawski et al., 2014, 2016; Quintà et al., 2012), the Pyrenean Basin (Canérot et al., 2005; Jammes et al., 2010; Lopez-Mir et al., 2014; McClay et al., 2004; Saura et al., 2016), the Iberian Basin (Canérot, 1991), the Betic Basin (Martínez del Olmo et al., 2015; Pedrera et al., 2014), the Algarve Basin (Ramos et al., 2016) and the Lusitanian Basin (Alves et al., 2003). In all of these regions, salt tectonics occurred during Jurassic and Early Cretaceous times, and most show evidence for reactivation during Alpine compression starting in the Late Cretaceous and continuing into the Miocene (Figure 14).

From the Late Jurassic to late Early Cretaceous, a major transcurrent-transpressional event has been determined along the Europe-Iberia plate boundary according to Nirrengarten, Manatschal, Tugend, Kuszniir, and Sauter (2018). Late Jurassic–Early Cretaceous extensional rifting reactivated diapirs and listric fault systems in the Basque-Cantabrian and Asturias basins (Cámara, 2017; Zamora, Fleming, & Gallastegui, 2017), the Bay of Biscay (Ferrer, Jackson, Roca, & Rubinat, 2012) and probably also in the South-Central Pyrenees (Cámara & Flinch, 2017; Saura et al., 2016). Diapiric activity seems to have diminished or even completely stopped during the Late Cretaceous in the Maestrat Basin. In contrast, this period corresponds to widespread diapiric activity in other areas of the Iberian Peninsula (Figure 14). In the Pyrenees, the development of listric faults detaching on Triassic evaporates, created raft systems, which were active during the Late Cretaceous up to the onset of inversion associated with the Alpine orogeny (Cámara & Flinch, 2017; López-Mir, Muñoz, & García-Senz, 2015; Saura et al., 2016). In the diapiric areas of the Atlantic, the Basque-Cantabrian and Asturias basins and the Bay of Biscay, both raft tectonics and passive diapirism were active during this period resulting in very well-developed diapiric structures (Cámara, 2017; Ferrer et al., 2012; Zamora et al., 2017).

In the study region, Alpine reactivation of the precompressional diapiric structures is indicated by the Teruel diapir within the Iberian Range, which was active during the Tortonian–Messinian (e.g. Alonso-Zarza & Calvo, 2000). Elsewhere, in the Pyrenean, the Betic-Rif and Iberian fold and thrust belts, the large number of diapir reactivations during Alpine shortening, and their widespread distribution suggests that this phenomenon is regional, and that the role of salt mobilization during the Mesozoic extension was very important. This has been recently established by detailed
tectono-sedimentary studies of high-quality northern Iberian outcrops (e.g. Câmara, 2017; Câmara & Flinch, 2017; Canérot et al., 2005; Ferrer et al., 2012; López-Horgue et al., 2010; López-Mir et al., 2015; Poprawski et al., 2014; Saura et al., 2016; Zamora et al., 2017; among others).

In the large-scale Atlantic-Tethys context, Jurassic opening of the northern domain of the Central Atlantic triggered the southeastward transtensional drift of Africa with respect to Iberia and Europe, forming the highly segmented Ligurian-Tethys ocean and margins. Considering the segmented nature of the Jurassic plate boundary defined by several authors (Frizon de Lamotte et al., 2011; Handy, Schmid, Bousquet, Kissling, & Bernoulli, 2010; Sallarès et al., 2011; Schettino & Turco, 2011; Vergés & Fernàndez, 2012), the NW-SE Iberian-Maestrat Basin can be considered as a transform zone of the Ligurian-Tethys margin limiting the two ENE-WSW margin of the Betics and NE-SW Catalan Coastal Ranges. According to the model of Nirrengarten et al. (2018), the Iberian plate during the Jurassic, is marked by a period of relative tectonic quiescence in the relative movement of the Iberian plate with respect to Europe (Figure 14). This widespread extensional phase ended in the Early Cretaceous, coinciding with the northward propagation of the Mid-Atlantic Ridge across the south Newfoundland-Iberia margin (Nirrengarten et al., 2018). This crucial event triggered the large transtensional motion of Iberia relative to the rest of Europe, with an eastwards movement of the Iberian microplate of about 720 km during Early and Late Cretaceous up to late Santonian at 83.5 Ma. The faster eastwards drift occurred over about 28 Myr from earliest Cretaceous to the earliest Albian at a rate of 20 mm/year, followed by a slower period of drift of 8 mm/year. It is interesting to note the synchronicity of the highest drift motion of the Iberia microplate with the highest diapiric activity in the Maestrat Basin (Figure 14).

7 CONCLUSIONS

A halokinetic model for the origin of the Miravete anticline is the best model for explaining the structural and stratigraphic observations made in the field. Earlier models, based solely on Alpine reactivation of normal faults do not adequately explain the facies distribution patterns, platform progradation directions, formational thickness variations on opposite flanks of the anticline, intraformational unconformities, nor the progressive changes in bed orientation with distance from the anticline core, all of which strongly suggest an actively growing structure from the Jurassic through Early Cretaceous. The following conclusions summarize the proposed halokinetic model and its implications.

1. Widespread diapiric structures are recognized for the first time in the Miravete anticline and surrounding structures as indicated by well-exposed typical salt-related features (salt walls, collapse normal faults, hook and flap geometries), and unambiguous halokinetic depositional sequences that are documented in three examples, indicating protracted salt movement starting during the Jurassic and extending to the Albian at least.

2. The Miravete anticline is interpreted as a diapiric anticline, despite the scarcity of outcrops of Upper Triassic evaporites. The growth of Miravete occurred over tens of millions of years during the Jurassic and especially during the Early Cretaceous. Halokinetic developed in four stages, including the last one related to the Alpine shortening that defines the present shape of the anticline.

3. This halokinetic interpretation is supported by the core of the anticline interpreted as a subvertical salt weld or thrust-weld, separating two steep flanks with opposing orientations and different stratigraphies and ages, which correspond to halokinetic depositional sequences of the Jurassic and Early Cretaceous.

4. The Miravete salt anticline started to grow during the Jurassic, as indicated by thin platform sequences of this age separated by angular unconformities attributed to early salt movement along the central segment of the salt weld (stage 1).

5. During the Hauterivian–Early Barremian, the central sector of the Miravete salt anticline evolved as a salt wall ridge along which the El Castellar and Camarillas deposits onlapped an already developed palaeotopography. This period was also characterized by the collapse of the western flank of the salt anticline along a 10-km-long N-S fault system, west-dipping and subparallel to the edge of the diapir. Potential extrusion of salt along its footwall may occur (stage 2).

6. During the Late Barremian–Aptian times, the anticline evolved as either a salt anticline or as a salt wall influencing the growth of carbonate platforms (Xert, Forcall, Villarroya de los Pinares and Benassal formations) as indicated by the apparent reduction in thickness along the crestal domain. The progradation directions of the Villarroya de los Pinares is at a high angle to the anticline trend indicating that their deposition was influenced by the rising diapiric ridge up to the end of the Albian (stage 3).

7. Regionally, the well-exposed Castel de Cabra salt anticline and Cañada Vellida salt wall diapiric structures confirm the widespread diapirism during the Jurassic and Early Cretaceous in the Maestrat Basin. The NE flank of the Cañada Vellida salt wall is characterized by hook patterns and by a 500-m-long upturned flaps, comprising thin Upper Jurassic carbonates. An incomplete 500-m-thick Lower Cretaceous succession onlaps against the flap during the infilling of the SW flank of the Aliaga minibasin.

8. An E-W trending regional cross section across the Ababuj, Miravete and Cañada-Benatanduz anticlines was
constructed, representing distinctive geometries of salt-related rift basins. The diapiric development and its control on the growth of salt anticlines and diapir walls were significant and partially decoupled from basement faults. The Camarillas and Fortanete minibasins already displayed bowl geometries at the onset of Palaeogene shortening (stage 4).

9. The most active period of diapiric growth in the Maestrat Basin occurred during the Early Cretaceous and this was also recorded in the Eastern Betics, Asturias and Basque-Cantabrian basins. This period coincides with the peak of eastward drift of the Iberian microplate at rates of 20 mm/year, followed by a decreased rate of 8 m/year in earliest Albian time. Deviatoric stresses related to plate kinematics thus possibly playing a role in diapiric evolution.

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DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES
Aldega, L., Viola, G., Casas-Sainz, A., Marcén, M., Román-Berdiel, T., & van der Leij, R. (2019). Unravelling multiple thermo-tectonic events accommodated by crustal-scale faults in northern Iberian Spain: Insights from K-Ar dating of clay gouges. Tectonics, 38(10), 3629–3651. https://doi.org/10.1029/2019TC005585

Alnazghah, M. H., Bádenas, B., Pomar, L., Aurell, M., & Morsilli, M. (2013). Facies heterogeneity at interwell-scale in a carbonate ramp, Upper Jurassic, NE Spain. Marine and Petroleum Geology, 44, 140–163. https://doi.org/10.1016/j.marpetgeo.2013.03.004

Alonso-Zarza, A. M., & Calvo, J. F. (2000). Palustrine sedimentation in an episodically subsiding basin: The Miocene of the northern Teruel Graben (Spain). Palaeogeography, Palaeoclimatology, Palaeoecology, 160(1–2), 1–21. https://doi.org/10.1016/S0031-0182(00)00041-9

Alvaro, M., Capote, R., & Vegas, R. (1979). A model of evolution geotectónica para la Cadena Celtibérica. Acta Geológica Hispánica. Homenaje a Luis Solé i Sabaris, 14, 172–177.

Alves, T. M., Cartwright, J., & Davies, R. J. (2009). Faulting of salt-withdrawal basins during early halokinesis: Effects on the Paleogene Rio Doce Canyon system (Espírito Santo Basin, Brazil). AAPG Bulletin, 93, 617–652. https://doi.org/10.1306/2030908105

Alves, T. M., Gawthorpe, R. L., Hunt, D. W., & Monteiro, J. H. (2003). Post-Jurassic tectono-sedimentary evolution of the Northern Lusitanian Basin (western Iberian margin). Basin Research, 15(2), 227–249. https://doi.org/10.1046/j.1365-2117.2003.00202.x

Arche, A., & López-Gómez, J. (1999). Tectonic and geomorphic controls on the fluvial styles of the Esilda Formation, Middle Triassic, Eastern Spain. Tectonophysics, 315(1–4), 187–207. https://doi.org/10.1016/S0040-1951(99)00291-7

Arche, A., & López-Gómez, J. (2005). Sudden changes in fluvial style across the Permian-Triassic boundary in the eastern Iberian Ranges, Spain: Analysis of possible causes. Palaeogeography, Palaeoclimatology, Palaeoecology, 229(1–2), 104–126. https://doi.org/10.1016/j.palaeo.2005.06.033

Aurell, M., Bádenas, B., Canudo, J. I., Castanera, D., García-Penas, A., Gasca, J. M., … Val, J. (2019). Kimmeridgian-Berriasian stratigraphy and sedimentary evolution of the central Iberian Rift System (NE Spain). Cretaceous Research, 103, 104153. https://doi.org/10.1016/j.cretes.2019.05.011

Aurell, M., Bádenas, B., Gasca, J. M., Canudo, J. I., Liesa, C. L., Soria, A. R., … Najas, L. (2016). Stratigraphy and evolution of the Galve sub-basin (Spain) in the middle Tithonian-early Barremian: Implications for the setting and age of some dinosaur fossil sites. Cretaceous Research, 65, 138–162. https://doi.org/10.1016/j.cretes.2016.04.020

Aurell, M., Bádenas, B., Ipas, J., & Ramajo, J. (2010). Sedimentary evolution of an Upper Jurassic epeiric carbonate ramp, Iberian Basin, NE Spain. Geological Society, London, Special Publications, 329(1), 89–111. https://doi.org/10.1144/SP329.5

Aurell, M., Salas, R., Alonso-Zarza, A. M., Mas, J. R., Roca, R., Meléndez, A., …San Román, J. (1992). Tectónica sin-sedimentaria distensiva en el límite Triásico-Jurásico en la cordillera Ibérica. Actas de Las Sessiones Científicas: III Congreso Geológico de España, 1, 50–54. ISBN 84-600-8132-X.

Bádenas, B., & Aurell, M. (2001). Kimmeridgian palaeogeography and basin evolution of northeastern Iberia. Palaeogeography, Palaeoclimatology, Palaeoecology, 168(3–4), 291–310. https://doi.org/10.1016/S0031-0182(01)00204-8

Baldschuhn, R., Binot, F., Fleig, S., & Kockel, F. (2001). Geotektonischer Atlas von Nordwest-Deutschland und dem deutschen Nordsee- Sektor. Stuttgart, Germany: Schweizerbart Science Publishers, 88 pp.

Benito, M. I., Lohmann, K. C., & Mas, R. (2005). Late Jurassic Paleogeography and Paleoclimate in the Northern Iberian Basin of Spain: Constraints from Diagenetic Records in Reelfal and Continental Carbonates. Journal of Sedimentary Research, 75(1), 82–96. https://doi.org/10.2110/jsr.2005.008
to present day): PLATES Progress Report 325–0509. University of Texas Technical Report, 196, 63.

Letouzey, J., Colletta, B., Vially, R., & Chermette, J. C. (1995). Evolution of salt-related structures in compressional settings. In M. P. A. Jackson, D. C. Roberts, & S. Snelson (Eds.), Salt tectonics: A global perspective: AAPG Memoir 65, 41–60.

Liesa, C. L., Casas, A. M., & Simón, J. L. (2018). La tectónica de inversión en una región intrapacífica: La Cordillera Ibérica. Revista de la Sociedad Geológica de España, 31(2), 23–50.

Liesa, C. L., & Simón, J. L. (2009). Evolution of intraplate stress fields under multiple remote compressions: The case of the Iberian Chain (NE Spain). Tectonophysics, 474(1–2), 144–159. https://doi.org/10.1016/j.tecto.2009.02.002

Liesa, C. L., Soria, A. R., Meléndez, N., & Meléndez, A. (2006). Extensional fault control on the sedimentation patterns in a continental rift basin: El Castellar Formation, Galve sub-basin, Spain. Journal of the Geological Society, 163(3), 487–498. https://doi.org/10.1144/0161-764904-169

López-Horgue, M. A., Iriarte, E., Schröder, S., Fernández-Mendiola, P. A., Caline, B., Corneilhie, H., … Zerti, S. (2010). Structurally controlled hydrothermal dolomites in Albian carbonates of the Asón Valley, Basque Cantabrian Basin, Northern Spain. Marine and Petroleum Geology, 27(5), 1069–1092. https://doi.org/10.1016/j.marpetgeo.2009.10.015

Lopez-Mir, B., Anton Muñoz, J., & García Senz, J. (2014). Restoration of basins driven by extension and salt tectonics: Example from the Cotiella Basin in the central Pyrenees. Journal of Structural Geology, 69, 147–162. https://doi.org/10.1016/j.jsg.2014.09.022

López-Mir, B., Muñoz, J. A., & García-Senz, J. (2015). Extensional salt tectonics in the partially inverted Cotiella post-rift basin (south-central Pyrenees): Structure and evolution. International Journal of Earth Sciences, 104(2), 419–434. https://doi.org/10.1007/s00531-014-1091-9

Macchiaveli, C., Vergés, J., Schettino, A., Fernández, M., Turco, E., Casciello, E., … Tunini, L. (2017). A new Southern North Atlantic isochron map: Insights into the drift of the Iberian plate since the Late Cretaceous. Journal of Geophysical Research: Solid Earth, 122(12), 9603–9626. https://doi.org/10.1002/2017JB014769

Martín, M., & Canéro, J. (1977). Mapa Geológico de España 1:50.000, SE de España. Revista de la Sociedad Geológica de España (pp. 60–63). Heidelberg, Germany: Springer.

Martín-Martín, J. D., Vergés, J., Saura, E., Moragas, M., Messager, G., Baqués, V., … Hunt, D. W. (2017). Diapiric growth within an Early Jurassic rift basin: The Tazoult salt wall (central High Atlas, Morocco). Tectonics, 36(1), 2–32. https://doi.org/10.1002/2016TC004300

Martín-Rojas, I., Somma, R., Delgado, F., Estévez, A., Iannace, A., Perrone, V., & Zamparelli, V. (2009). Triassic continental rifing of Pangea: Direct evidence from the Alpujarride carbonates, Betic Cordillera, SE Spain. Journal of the Geological Society, 166(3), 447–458. https://doi.org/10.1144/0016-76492008-091

McClay, K. R. (Ed.) (1992). Thrust tectonics. London, UK/New York, NY: Chapman & Hall.

McClay, K. R., Muñoz, J. A., & García-Senz, J. (2004). Extensional salt tectonics in a contractual orogen: A newly identified tectonic event in the Spanish Pyrenees. Geology, 32(9), 737–740. https://doi.org/10.1130/G20565.1

McClay, K. R., & Price, N. J. (Ed.) (1981). Thrust and Nappe Tectonics. Geological Society of London by Blackwell Scientific (vol. 9).

Meléndez, N., Liesa, C. L., Soria, A. R., & Meléndez, A. (2009). Lacustrine system evolution during early rifting: El Castellar Formation (Galve sub-basin, Central Iberian Chain). Sedimentary Geology, 222(1–2), 64–77. https://doi.org/10.1016/j.sedgeo.2009.05.019

Moragas, M., Vergés, J., Naips, T., Saura, E., Martín-Martín, J. D., Messager, G., & Hunt, D. W. (2017). The impact of syn- and post-extension prograding sedimentation on the development of salt-related rift basins and their inversion: Clues from analogue modelling. Marine and Petroleum Geology, 88, 985–1003. https://doi.org/10.1016/j.marpetgeo.2017.10.001

Moragas, M., Vergés, J., Saura, E., Martín-Martín, J.-D., Messager, G., Merino-Tomé, Ó., … Hunt, D. W. (2018). Jurassic rifting to post-rift subsidence analysis in the Central High Atlas and its relation to salt diapirism. Basin Research, 30, 336–362. https://doi.org/10.1111/bre.12223

Moreno-Bedmar, J. A., Company, M., Bover-Arnal, T., Salas, R., Delany, G., Martínez, R., & Grauges, A. (2009). Biostratigraphic characterization by means of ammonoids of the lower Aptian Oceanic Anoxic Event (OAE 1a) in the eastern Iberian Chain (Maestrat Basin, eastern Spain). Cretaceous Research, 30(4), 864–872. https://doi.org/10.1016/j.cretres.2009.02.004

Moreno-Bedmar, J. A., Company, M., Bover-Arnal, T., Salas, R., Delany, G., Maurrasse, F.-M.-R., … Martínez, R. (2010). Lower Aptian ammonite biostratigraphy in the Maestrat Basin (Eastern Iberian Chain, Eastern Spain). A Tethyan transgressive record enhanced by synrift subsidence. Geologica Acta, 8(3), 281–299.

Moseley, F., Cuttell, J., Lange, E., Stevens, D., & Warbrick, J. (1981). Alpine tectonics and diapiric structures in the Pre-Betic zone of southeast Spain. Journal of Structural Geology, 3(3), 237–251. https://doi.org/10.1016/0191-8141(81)90020-1

Moulin, M., Aslanian, D., & Unternehr, P. (2010). A new starting point for the South and Equatorial Atlantic Ocean. Earth-Science Reviews, 98, 1–37. https://doi.org/10.1016/j.earscirev.2009.08.001

Naips, T., & Brun, J.-P. (1993). Salt flow and diapirism related to extension at crustal scale. Tectonophysics, 228(3–4), 349–362. https://doi.org/10.1016/0040-1951(93)90348-N

Navarrete, R., Liesa, C. L., Castanera, D., Soria, A. R., Rodríguez-López, J. P., & Canudo, J. I. (2014). A thick Tethyan multi-bed tsunami deposit preserving a dinosaur megatracksite within a coastal lagoon (Barremian, eastern Spain). Sedimentary Geology, 313, 105–127. https://doi.org/10.1016/j.sedgeo.2014.09.007

Navarrete, R., Rodríguez-López, J. P., Liesa, C. L., Soria, A. R., de Veloso, F. M. L. (2013). Changing physiography of rift basins as a control on the evolution of mixed siliciclastic-carbonate back-barrier systems (Barremian Iberian Basin, Spain). Sedimentary Geology, 289, 40–61. https://doi.org/10.1016/j.sedgeo.2013.02.003
