Abstract: Mapping and structural analysis of the south of the Serres de Llevant in Mallorca, shows that great part of the contacts between different lithological formations are Low-Angle Normal Faults (LANFs). These faults have strongly thinned the previous thrust stack producing omissions in the stratigraphic sequence. Extensional structures are observed at all scales and are especially evident in the Cretaceous and Upper Jurassic pelagic formations that have a rather penetrative S0-C’ fabric. Extension shows two orthogonal directions with NE-SW and NW-SE-directed transport. Extensional denudation of the Serres de Llevant occurred during the Middle Miocene, after the end of WNW-directed thrusting that lasted up to the Langhian, and before the deposition of flat-lying Tortonian marine sediments. This Middle Miocene extensional phase in the Balearic promontory suggests that the formation of the Algero-Balearic basin probably occurred at this time, later than usually considered. This process contributed to the westward displacement of the Betic internal zones since the Langhian, leaving the Mallorca foreland thrust belt stranded from its corresponding hinterland.

Keywords: Mallorca, extension, Serravallian, Western Mediterranean.
Introduction

The Mallorca island is the main onshore domain of the Balearic Promontory, which extends from NE to SW between the Valencia Trough to the NW and the Algero-Balearic basin to the SE (Fig. 1). Tectonically, it forms part of the Betics Foreland Thrust Belt (BFTB) (Vera, 2004). The tectonic evolution of Mallorca has been mostly described in terms of the BFTB evolution, emphasizing the importance of NW-directed nappe tectonics in the building of the island’s structure, coeval to the development of sedimentary basins around it (Sábat et al., 2011). Thrusting initiated in the Late Oligocene (~26 Ma) to the SE of the island and propagated in a piggyback sequence towards the NW, with some out of sequence thrusting, until the Langhian (~14 Ma) (e.g., Sábat et al., 1988; Gelabert et al., 1992; Sábat et al., 2011). This age period coincides with the formation of the Liguro-Provenzal basin (Cherchi and Montadert, 1982; Burrus, 1984; Gelabert et al., 2002; Ferrandini et al., 2003) (Fig. 1). The age and direction of extension in the Algero-Balearic basin, however, is more discussed with proposals coincident with the age of thrusting in Mallorca, with NW-SE-directed extension between 26-21 Ma (Schettino and Turco, 2006; Etheve et al., 2016), and others that suggest E-W to NE-SW opening during the Middle-Late Miocene (Mauffret et al., 2004; Booth-Rea et al., 2007; Driussi et al., 2015).

Formation of the Algero-Balearic basin has also been interpreted to have occurred by two orthogonal extensional phases, with N-S opening during the Early Miocene and E-W further extension during the Middle and Late Miocene (Aïdi et al., 2018). This paradox of the coincidence of shortening tectonics in Mallorca coeval to extension in the surrounding basins was manifested by Sábat et al. (2011), who wrote that the tectonic evolution of Mallorca is not properly explained by the existing tectonic models for the Western Mediterranean. Other works have proposed that the Balearic Promontory is located to the east of the Betics, separated from them by a NW-SE-oriented transform fault, forming part of the hinterland of the Tell orogen in Argelia (Vergés and Fernández, 2012). Thus, although Mallorca occupies a central position in the Western Mediterranean no work has satisfactorily explained its tectonic evolution in this framework. Mostly due to the above paradox, where extension in the Algero-Balearic basin was coeval to thrusting in the island, to the scarcity of kinematic data, and to the lack of a compelling back-stop to the SE.

The structure of Mallorca has been interpreted as a thrust and fold belt with NW vergence, affected by later minor NW-SE-directed extension. These normal faults would have determined the geometry of Late Miocene basins in Mallorca (Sábat et al., 2011). Paleostress determination using normal fault populations, however, shows a radial extension in the island (Céspedes et al., 2001).

Extension does not alter the initial superposition order produced by previous thrusting and can occur along low-angle fault surfaces (e.g., Reston et al., 2007), thus in a region where thrusting occurred beforehand, the regime of the observed faults has to be determined with care. In regions having undergone nappe tectonics like the Internal Betics, or the Appenines, normal faults can be characterized by producing omissions in the stratigraphic sequence or in the metamorphic zoning resulting after the thrusting event.
(e.g., Lonergan and Platt, 1995; Martínez-Martínez and Azañón, 1997), by cutting down into the structural pile in the direction of transport, or by their particular kinematics, fault rocks and cross-cutting relationships, different from the previous thrusts (e.g., Booth-Rea et al., 2004, 2005). Recent preliminary work has shown the existence of Low-Angle Normal Faults (LANFs) with NE-SW-directed extension in the Tramontana and Llevant Serres (Booth-Rea et al., 2016). Here we deepen into mapping and revising the regime and kinematics of the main tectonic contacts in the Serres de Llevant, differentiating between thrust and normal fault surfaces that cut into the previous thrust structure downwards. With these methods we intend to determine the tectonic evolution of the Mallorcan part of the BFTB, and in particular, the role of extensional tectonics during the Middle Miocene in the isolation of the Balearic Promontory from its corresponding internal zones. Finally, we propose a new tectonic model for the Miocene evolution of Mallorca in the frame of the Western Mediterranean.

**Geological setting**

Notwithstanding the central position of the Balearic Promontory in the Western Mediterranean, few works have analyzed the tectonic evolution and kinematics of this region recently. The first notes about the structure of the Serres de Llevant, the eastern ranges of Mallorca island (Fig. 1), describe the presence of thrust sheets with NW vergence of Oligocene age in the region of Artà and Miocene in Felanitx (Darder, 1925), similar to those described previously in the Sierra de Tramuntana, in the western Mallorca island (Fallot, 1922). The first detailed cartography and stratigraphy of the region was initiated in the NE of Mallorca, around Artà (Bourrouilh, 1983). This work that recognized two shortening events with SSW- and NW-directed thrusting between the Burdigalian and the Tortonian was the base for future work in the rest of the Serres de Llevant. Also important was the recognition of N120-140°E strike slip faults. These faults are the main structures to the south of the Serres de Llevant, where Sabat et al. (1988) interpreted them as lateral ramps of the NW-directed thrust system. These authors propose that all the structures in the Serres de Llevant are related to only one N310-directed shortening phase developed between the Late Oligocene and Middle Miocene. Slickensides associated to shear planes cutting the pressure-solution cleavage indicate complex kinematics during the thrusting stage with movement both parallel and perpendicular to the main thrusting direction (Casas and Sàbat, 1987). Sàbat et al. (1988) differentiated two regions in the Serres de Llevant, the northern one where the main structures have NE-SW trend, with minor transfer faults, and a southern one where the main faults are NW-SE lateral ramps, together with oblique faults. Up to seven thrust sheets were mapped, with the highest ones lying towards the SW of the Serres de Llevant, which imbricate towards the SW (Sàbat et al., 1988).

The nappe structure in Mallorca was later cut by Middle to Late Miocene NE-SW trending listric normal faults described in Sierra de Tramuntana; especially along its SE border where they bound the Palma and Inca basins (Sabat et al., 2011). Furthermore, an older set of LANFs, with SW-NE extensional direction, orthogonal to the younger NE-SW-trending normal faults occur both in Sierra de Tramuntana and Serres de Llevant (Booth-Rea et al., 2016). This NE-SW-directed extension is compartmented by ENE-WSW transfer faults, both with dextral and sinistral kinematics. Low-angle normal faulting occurred after the thrusting event in the Langhian and before the deposition of flat-lying Tortonian sediments, thus during the Serravallian (Booth-Rea et al., 2016).

**Lithostratigraphy**

The stratigraphy of Mallorca is well established by previous authors and compiled for example by Sabat et al. (2011) (Fig. 2). Here we describe the stratigraphy of the southern region of the Serres de Llevant. The stratigraphic sequence starts with a thick unit of dolostone of Late Triassic-Lias age that forms the base, in most cases, of the differentiated thrust sheets (Álvaro et al., 1989). We have mapped a thick package of dolomites at the base of the thrust stack and a second thinner unit located in the uppermost thrust sheet. These rocks are strongly deformed by brittle faults, forming fault breccias in many places. The contact with other rocks sequences is normally mechanical and locally an erosive unconformity. Regionally, these shallow carbonates are capped by a thin layer of sandstones and quartz microconglomerates that mark the rifting and consequent deepening of the Jurassic platform. However, these transitional layers have not been found in the studied region where the top of the dolomitic sequence is normally a fault. The Jurassic (Dogger-Malm) pelagic sequence starts with marly limestones and turbiditic limestones with large oolitic-limestone and dolostone olistoliths characteristic of reworked talus facies (Kettle, 2016). This sequence is followed by well stratified limestones with silex.

The pelagic series continues into the Early Cretaceous. The Neocomian (Berriasian–Hauterivian) crops out in all the studied area. It is formed by white-grenish marls with a penetrative brittle extensional cleavage. In some outcrops they are covered by bluish lutites with pirite nodules of the Gault Formation. The thickness of the Cretaceous sequence is very variable as it is strongly thinned and deformed, although we have observed a maximum thickness around 200 m.

During the Late Cretaceous and Early Eocene there is a stratigraphic hiatus. The Middle Eocene is represented to the south of the Serres de Llevant and in the Cabrera archipelago by the S’Envestida grainstones (Ramos Guerrero, 1988). This upper Lutecian-Bartonian formation is characterized by bioclastic limestones with Nummulites and intercalations of paralic marls towards the top of the sequence. It occurs above the Cretaceous forming positive isolated reliefs. The Late Eocene is only represented by olistostromic blocks of the Calvari Formation (Ramos Guerrero, 1988) included in Burdigalian marls to the west of the studied region. It is formed by grainstones at the base and strongly bioturbated marls and siltstones at the top, with an atributed Early Priabonian age.

The synorogenic sedimentation initiated during the Late Oligocene (Fornos et al., 1991). It starts with the Sant Elm calcarenitic formation of early Chattian to late Aquitanian age (Rodriguez-Perea, 1984). At the scale of the island it shows a
Fig. 2.- Geological map and cross-sections of the south of the Serres de Llevant, in the Felanitx region. Notice location of photographs in Figure 3.
very irregular distribution, with a great variety of facies from shallow marine to continental. In the studied region it includes litoral calcarenites and calcirudites, together with continental detritics. This unit is unconformable over the older sediments described above. Foreland basin, molasse-type deposits, are represented by the Lower Miocene (Burdigalian-early Langhian) Banyalbufar turbiditic series in Mallorca (Rodríguez-Perea, 1984). Thick turbiditic marls deposited with abundant resedimented detrital material, including conglomerates with Mesozoic and Palaeozoic clasts, mostly grauwackes. This sedimentary cycle ends with a regressive sequence of Langhian shallow marine bioclastic limestones, which also contain detrital, molasse-type clastics including Palaeozoic grauwackes (González-Donoso et al., 1982; Pomar and Rodríguez-Perea, 1983).

Serravallian sediments like the Manacor siltts (Barón, 1977), the Pina Marls (Pomar et al., 1983) or the Son Verdera limestones (Pomar et al., 1983) do not occur in the studied region of Felanitx. So, the synorogenic Oligocene to Lower Miocene sediments are covered by flat-lying Tortonian to Quaternary sediments. Tortonian reefal and Messinian litoral carbonates occur along the coast (Pomar et al., 1983). These sediments pass landwards to alluvial detritic limestones.

Structure of the southern part of the Serres de Llevant

Two superposed nappes including folded rocks attest to the contractive tectonics that determined the present structure of the south of the Serres de Llevant, characterized by the repetition of lithological formations (Parés et al., 1986; Casas and Sábat, 1987; Sábat et al., 1988) (Fig. 2). Each nappe includes a Mesozoic-Tertiary sedimentary succession, comprised between Triassic dolostone and Lower Miocene calcirudite, where rocks with contrasting rheologies alternate. Slickenlines at the base of preserved thrust segments indicate WNW-directed transport, towards N290E, for example at the base of Dogger-Malm carbonates in the San Salvador massif (Fig. 2). This shortening direction is transverse to the orientation of fold axes that trend between N-S and NNE-SSW. We have identified two thrust planes in the San Salvador massif. The structurally-lower thrust shows a hanging-wall and footwall ramp geometry that superposes Dogger-Malm pelagic limestones over Sant Elm Early Miocene conglomerates. Meanwhile, at the top of the massif a second fault overthrusts Triassic-Lias dolostone over Miocene conglomerates.

However, thrust faults with WNW-directed transport are not the most common structures in the region. We show that most of the brittle deformation in the Southern Serres de Llevant has an extensional regime with SW-NE and NW-SE kinematics.

Extensional structures in the Serres de Llevant

Extensional structures in the Serres de Llevant occur at all scales (Figs. 2, 3 and 4). They are especially penetrative at outcrop scale, where the less competent pelagic sediments are characterized by having a brittle extensional crenulation cleavage marked by $S_p$-C structures (Fig. 3A, B). $S_p$ surfaces are represented by the primary lithological banding and a pressure-solution cleavage (Casas and Sábat, 1987), whilst C’ surfaces are low-angle (5-30') shear planes, frequently with slickenlines defined by calcite fibers. In the more competent layers S surfaces cut by the C’ shear planes are rather complex, represented by $S_p$, older brittle shear planes or an anastomosed stylolitic cleavage (Fig. 3B). The slickenlines on the shear surfaces show mostly two populations that evidence two orthogonal directions of extension, NW-SE and NE-SW (Fig. 4). This deformation, characteristic of the Cretaceous and Dogger marls and marly limestones, evidences how the faults in these materials become LANFs where other high-angle faults root. Meanwhile, in more competent lithologies like the Triassic-Early Lias Dolostone, Early Jurassic oolitic limestones and Eocene carbonates, the extensional deformation is represented by intense brecciation related to high-angle normal faults (Fig. 3C, D). These non-cohesive breccias are exploited in several quarries in the region. The normal faults affecting these more competent rocks show fault mirrors with iron oxide slickenlines (Fig. 3C). The same as in the above case we measured two orthogonal directions of extension, NE-SW and NW-SE (Fig. 4). Although, these slickenside data could indicate radial extension, we favour the two-orthogonal extensional systems because in general, cross-cutting relationships indicate that the SE-directed extension occurred later than the NE-SW system. The sense of fault displacement has been determined from the geometry of calcite slickenfibers, tails of rotated porphyroclasts, by offset layers and by using kinematic indicators on fault mirrors on the more competent rocks (e.g., Doblas et al., 1997).

Thus, the rheological sandwich produced by the Early Miocene thrusting has favoured an extensional style where high-angle faults in the more competent layers, like the Triassic dolostones, root in LANFs in the pelitic lithologies, mostly Cretaceous marls (cross-sections A-A’ and B-B’ in Fig. 2). Therefore, producing an extensional system with ramps and flats and with multiple detachment surfaces as described in other regions like the Internal Betics or in the Apennines (Martinez-Martinez and Azañón, 1997; Booth-Rea et al., 2004, 2005; Brogui, 2008). This process has determined that most of the present contacts between pelagic marls and marly limestones with other lithologies are LANFs. Moreover, out of sequence high-angle normal faults, producing both NE-SW and NW-SE-directed extension frequently cut the older LANFs (Fig. 3C). This makes extension in the Serres de Llevant clearly polyphasic, with low-angle normal faults that are cut and tilted by other more recent ones, with the same or different kinematics (cross-sections in Fig. 2.). In many outcrops this has resulted in an anastomosed geometry of the LANFs (Fig. 3D), and in the development of extensional horses at different scales, bounded entirely by normal faults (Fig. 3B). Overall, the extensional structures in the Serres de Llevant have resulted in extreme thinning of the previous nappe sheets, producing general omissions in the stratigraphic series and frequent brittle “boudin” type features. In some cases, in necking domains of the extensional system, lithological sequences that normally are several hundred meters in thickness are reduced to only a few meters (Fig. 3A).

At map scale, the omissions and thinning of the previous nappe stack produced by normal faulting have resulted in
Fig. 3. Examples of extensional structures in the Felanitx region. Photos located in Figure 2. A. Extensional neck where polyphase extension has strongly thinned the stratigraphic sequence. Notice the Lower Cretaceous sediments show multiple extensional shear surfaces with south-westwards hanging-wall transport sense, cut by a high-angle normal fault with NE transport (see fault mirror). B. Outcrop of strongly deformed Lower Cretaceous sediments with brittle shear zones cutting down towards the SW. These faults bound an extensional horse of a more competent limestone block. C. High-angle normal fault with NE-directed transport cutting low-angle brittle extensional fabrics. D. Example of brittle extensional deformation in the basal dolostone unit. Notice several sets of normal faults mostly with SW-directed transport, cut by high-angle normal faults with NE and SW transport. Notice also, small folds and thrust surface cut by the extensional structures.
many small outcrops of different materials that have scarce spatial continuity (Fig. 2). Furthermore, the more competent materials like Triassic dolostones or Eocene limestones appear as blocks isolated in the more plastic pelites. In general, the NE-SW-directed extensional system is older than the NW-SE-directed one. There are many places where LANFs with SW hangingwall transport are cut by later SE-transport faults. Apart from LANFs, in the region there also are a few strike-slip faults with NW-SE and NE-SW orientation. These faults offset the extensional faults. In some cases the offset is contrary to their kinematics. For example, the sinistral fault in Figure 2, located above the label of Figure 3B, shows dextral offsets of the normal faults it bounds. Another feature observed at the scale of the island is that strike-slip faults with the same orientation have opposite kinematics, for example, the NE-SW-oriented Sant Joan and Sencelles faults that are dextral and sinistral, respectively (Booth-Rea et al. 2016). Both these features, coeval faults with the same orientation but with contrary displacements and faults with offsets contrary to their kinematics, are characteristic of transfer faults in extension (e.g., Martínez-Martínez, 2006; Giaconia et al., 2014). NW-SE-oriented strike-slip faults seem to be the most recent structures cutting clearly the normal faults with NE-SW transport.

Syn-extensional sediments do not occur in the studied

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**Fig. 4.-** Fault measurement stations in the Felanitx region. Stereographic projections in the lower hemisphere. Notice wide range of kinematics of the extensional faults with the main direction of extension (black arrows) variable among SSW-NNE, SW-NE, WNW-ENE, NW-SE and WNW-ESE. This variability in the main direction of extension probably reflects mixing in different proportions faults of the two extensional systems.
area, thus, dificulting the determination of the age of extension. Some extensional faults in Mallorca have been interpreted to be Cretaceous (Gelabert, 1998). Although, the normal faults that we have mapped in this work clearly cut the Mesozoic and Tertiary rocks, reaching up to the Lower Miocene conglomerates that crop out in the Salvador Massif and the Early Burdigalian molassic series around Felanitx (cross-sections A-A’ and B-B’, Fig. 2). We have interpreted that these Early Burdigalian molassic sediments also contain large mappable olistoliths of Jurassic and Eocene sediments similar to equivalent sediments in the western Betic (Suades and Crespo-Blanc, 2013) (Fig. 2). Although, they could also represent material thrusted over the Lower Miocene sediments. Furthermore, the extensional faults cut the thrust surfaces that developed during the Early Miocene. Shallow-marine Langhian calcarudites and grainstones are overthrust in Tramuntana and locally affected by an anastomosed spaced stylolitic cleavage, related to tectonic shortening in Mallorca (Gelabert, 1998). Thus, if thrusting lasted until the Langhian, the extensional structures collapsing the nappe stack must be older. On the other side, Tortonian limestones are flat-laying, and seal most of the orogenic deformation. Extension then, must have occurred between the Langhian and the Tortonian, during the Middle Miocene.

Discussion

Mapping and structural analysis of the southern end of the Serres de Llevant shows that extensional faults have strongly contributed to the present structure of the region (Figs. 2, 3 and 4). We have grouped these faults in two orthogonal extensional systems producing NE-SW- and NW-SE-directed extension. Especially, the NE-SW-directed extension occurred by the polyphase activity of LANFs that developed through the more pelitic pelagic Cretaceous and Dogger-Malm sequences present in the Mallorca nappe stack.

The Late Oligocene to Early Miocene WNW-directed thrusting event in Mallorca established the rheological sandwich that later determined the geometry of the extension we observe in the Serres de Llevant. An extension that is characterized by the development of stacked LANFs that root in the less competent pelitic lithologies. This extension had been previously overlooked but explains the strange features described by previous authors in the Serres de Llevant like the complex kinematics measured on the composite cleavage structures related to the thrusting (Casas and Sàbat, 1987), the SW branching of the supposed thrust surfaces or to the distribution of nappes, with the upper ones always located to the SW of the underlying nappes (Sàbat et al., 1988). This feature could be related to the activity of SW-transport LANFs, where the structurally-higher rocks were transported farther away in the direction of displacement than the underlying ones. Extensional tectonics in Mallorca must have initiated after the Langhian, once thrusting related deformation ended, and was sealed by flat-lying Tortonian marine sediments present in Mallorca. Although, further work is necessary to characterize the geometry and structural relationships between normal faults and syn-rift sediments in Mallorca, in other areas of the island where Middle Miocene sediments crop out.

These new structural data in the Serres de Llevant support the existence of widespread extension in the island of Mallorca (Booth-Rea et al., 2016) that thinned the previous nappe stack during the Middle Miocene. This extension is probably related to the opening of the oceanic Algero-Balearic basin to the south of the Balearic Promontory. Therefore, thrusting during the Early Miocene in Mallorca would not have been coeval to the opening of the Algero-Balearic oceanic basin to the south. This crustal thinning occurred later and strongly modified the orogenic structure in the region. Possibly contributing to the SW displacement of the Betic hinterland domain together with the aid of large strike-slip transfer faults representing Subduction Edge Propagator boundaries (STEP, Govers and Wortel, 2005) in the Betic and Tell-Rif (e.g., Medaouri et al., 2014; Mancilla et al., 2015). Middle to Late Miocene extension in and around the Algero-Balearic basin has now been documented in all its margins, to the west (Maurfret, 2004; Booth-Rea et al., 2007), in the Northeastern Rif margin (Booth-Rea et al., 2012), to the SE along the Tunisian margin (Booth-Rea et al., 2018a), and here in the Mallorca margin. The Late Oligocene to Early Miocene extension postulated for the Algero-Balearic basin (e.g., Schettino and Turco, 2006) affected the Betic hinterland, producing strong thinning of the Internal Zone units (e.g., Booth-Rea et al., 2004; Garrido et al., 2011) in a Proto-Alboran basin that was located to the south of Mallorca at the time. This Oligocene extension has been described in Ibiza (Ethève et al., 2016). However, the locus of this thinning underwent Early Miocene tectonic inversion (Hidas et al., 2013) and important displacements towards the WSW in a forearc setting, following the retreating Alboran slab, coeval to the opening of the Algero-Balearic basin and the accretion of the Alboran volcanic arc (Maurfret, 2004; Booth-Rea et al., 2007, 2018b; Gómez de la Peña et al., 2018), and presently forms the basement of the West Alboran basin (Booth-Rea et al., 2007; Mancilla et al., 2015; Gómez-Peña et al., 2018).

Conclusions

The south of the Serres de Llevant shows conspicuous extensional deformation that has reworked and cut the Early Miocene nappe stack. This extension shows two main directions of displacement, with an older SW-NE-transport system and a more recent NW-SE-directed one. Extension occurred during the Middle Miocene, after the thrust stacking period. This previously undistinguished extensional phase probably was related to the opening of the Algero-Balearic basin, supporting models for Middle-to-Late Miocene extension instead of the generally accepted Late Oligocene to Early Miocene age. The opening of the Algero-Balearic basin during the Middle to Late Miocene, thus, strongly modified the Betic orogen, separating its hinterland from the Mallorca BFTB segment, which is presently stranded between the Valencia and the Algero-Balearic basins.
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