Two Cenozoic extensional phases in Mallorca and their implications in the geodynamic evolution of the western Mediterranean

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November 22, 2022

Abstract

We study the structure of the Llevant ranges in Mallorca with special emphasis in the Cenozoic extensional evolution of the island, which we integrate in a new geodynamic model for the Westernmost Mediterranean. Mallorca underwent two rifting phases in the Oligocene and Serravallian, before and after the development of its Foreland Thrust Belt (FTB). The first extensional phase produced Oligocene semigrabens (?29-23 Ma) that were inverted during the Early-Middle Miocene (23-14 Ma) WNW-directed FTB development. The second rifting phase produced the extensional collapse of the Mallorca FTB during the Serravallian (?14-11 Ma). This later rifting was polyphasic, with NE-SW and NW-SE directed transport, resulting in an overall sequential, radial extension. The Oligocene extension affected great part of the Western Mediterranean, opening the Liguro-Provenzal and proto-Algerian basins after the collapse of the Palaeogene AlKaPeCa orogen, and Mallorca, its former hinterland. Continued plate convergence nucleated a new subduction system in the Early Miocene that initiated along the Ibiza transform, producing the Mallorca WNW-directed FTB and the subduction of the South-East Iberian passive margin. A process that individualized the Betic-Rif slab and initiated its westwards retreat. Serravallian extension occurred at the northern edge of the subduction system coeval to the Algero-Balearic basin opening. Extension initiated towards the SW direction of slab tearing and later rotated to a NW-SE direction, probably related to flexural and isostatic rebound. These processes drove the Alboran domain archipelago southwestwards until the Late Miocene, contributing to the present isolation of the Mallorca FTB from its Betic hinterland.

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Key Points:

- Two Cenozoic extensional phases thinned Mallorca before and after its Early Miocene shortening phase, in the Oligocene and Serravallian
- The Serravallian extension was radial with low-angle faults that cut through the previous thrust pile
- The Mallorca thrust belt formed part of the Betics in the Early Miocene and later was isolated from its hinterland by the Algero-Balearic basin formation

Abstract

We study the structure of the Llevant ranges in Mallorca with special emphasis in the Cenozoic extensional evolution of the island, which we integrate in a new geodynamic model for the Westernmost Mediterranean. Mallorca underwent two rifting phases in the Oligocene and Serravallian, before and after the development of its Foreland Thrust Belt (FTB). The first extensional phase produced Oligocene semigrabens (≈29-23 Ma) that were inverted during the Early-Middle Miocene (23-14 Ma) WNW-directed FTB development. The second rifting phase produced the extensional collapse of the Mallorca FTB during the Serravallian (≈14-11 Ma). This later rifting was polyphasic, with NE-SW and NW-SE directed transport, resulting in an overall sequential, radial extension. The Oligocene extension affected great part of the Western Mediterranean, opening the Liguro-Provenzal and proto-Algerian basins after the collapse of the Palaeogene AlKaPeCa orogen, and Mallorca, its former hinterland. Continued plate convergence nucleated a new subduction system in the Early Miocene that initiated along the Ibiza transform, producing the Mallorca WNW-directed FTB and the subduction of the South-East Iberian passive margin. A process that individualized the Betic-Rif slab and initiated its westwards retreat. Serravallian extension occurred at the northern edge of the subduction system coeval to the Algero-Balearic basin opening. Extension initiated towards the SW direction of slab tearing and later rotated to a NW-SE direction, probably related to flexural and isostatic rebound. These processes drove the Alboran domain archipelago southwestwards until the Late Miocene, contributing to the present isolation of the Mallorca FTB from its Betic hinterland.

Plain Language Summary

We integrate the geological evolution of the Mallorca island in its larger setting of the Western Mediterranean. For this we study the geological structure of Mallorca, finding that it underwent two thinning phases that occurred before and after a period of crustal thickening and shortening in the region between 19 and 14 Ma. These thinning phases coincided with the development of the western Mediterranean basins. The later crustal thinning occurred at the northern edge of the Betic-Rif subduction system, in relation to retreat of a portion of lithospheric root that detached under Mallorca at around 14 Ma. This tectonic mechanism occurring at the southern (along the present western Algerian margin) and northern edges of the subduction system favoured the westward retreat of the subducting mantle body presently imaged by seismic tomography under the westernmost Mediterranean. The geology of the Mallorca island supports that it formed part of the Betic orogen and was later isolated from its Betic hinterland by the opening of the Algero-Balearic basin. The Betic hinterland drifted westwards hundreds of km away from Mallorca, as an archipelago, until its final docking between Northern Africa and Southeastern Iberia approximately 9 Ma ago.

1 Introduction

The Balearic Promontory (BP) is set at the core of the Western Mediterranean orogenic system, forming part of the Betic Foreland Thrust Belt (Betic FTB), developed by NW- to WNW-directed thrust tectonics during the Late Oligocene to Early Miocene (Alvaro, 1987; Gelabert et al., 1992; Sabat et al., 1988, 2011)(Figure 1). However, the BP is missing a corresponding thick-skinned internal domain and is surrounded by deep basins developed mostly during Tertiary back-arc rifting phases (e.g. Aïdi et al., 2018; Burrus, 1984; Cherchi and Montadert, 1982; Etheve et al., 2016; Ferrandini et al., 2003; Gelabert et al., 2002; Jolivet et al., 2006; Schettino and Turco, 2006; Figure 1). The relative timing between crustal thickening and extension in the region has been the subject of great debate with most work suggesting that extension during the Oligocene to Early Miocene (26-19 Ma; Etheve et al., 2016; Schettino and Turco, 2006) was actually prior to crustal shortening that lasted until the Langhian (≈14-16 Ma; e.g. Sabat et al., 2011). Whilst there is some consensus on the age of crustal shortening —with deformation in Mallorca migrating from SE to NW between the late Oligocene and the Langhian (e.g. Sabat et al., 2011)—the age and significance of crustal extension in Mallorca and adjacent marine basins are not so well constrained.

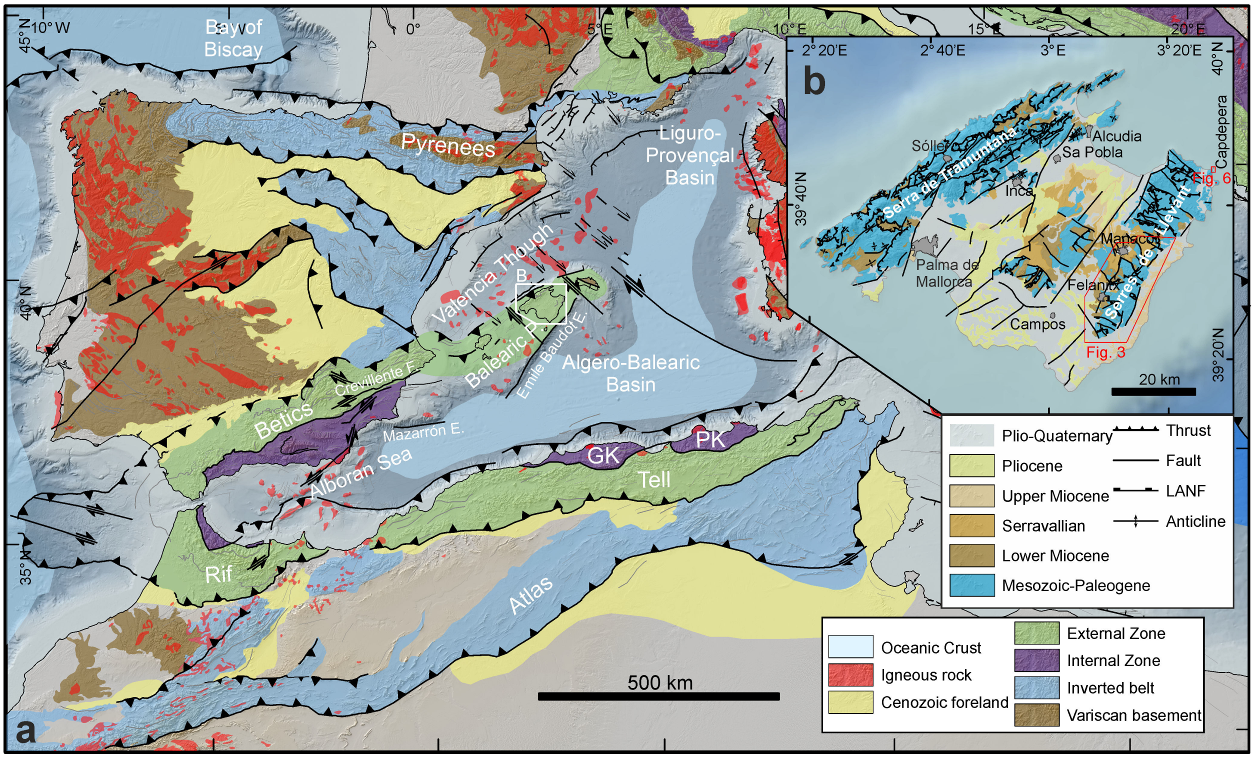


Figure 1. Tectonic map of the Western Mediterranean including main orogenic domains and basins (A). Inset, shows the Geology of the Mallorca Island and location of the study area (B).

Most work suggests that rifting in the region occurred between 30 and 16 Ma in the three basins surrounding the Balearic promontory: the Valencia Trough to the Northwest, the Liguro-Provencal Basin to the Northeast, and the Algero-Balearic basin to the South (Figure 1) (e.g. Arab et al., 2016; Etheve et al., 2016; Lepêtre et al., 2013; Maillard & Mauffret, 1999; Schettino & Turco, 2006; Speranza et al., 2002; Watts and Torne, 1992). Some authors proposed the rifting phase lasted longer, between 34 and 13 Ma, encompassing the development of the Mallorca FTB (Gelabert et al., 2002; Roca & Guimera, 1992; Roca 2001). Other work, however, has demonstrated the importance of Mesozoic rifting in the Valencia Trough, where a several km thick sequence of Jurassic sediments is found above a thin continental crust (Ayala et al., 2015; Etheve et al., 2018). This domain of Mesozoic rifting was further extended during the Cenozoic in its transition towards the Liguro-Provencal Basin, forming the differentiated Menorca basin in between (Pellen et al., 2016). Differential Tertiary extension between these domains was accommodated along NW-SE directed transfer fault zones like the North Balearic and Central fracture zones, among others, in a process accompanied by important Early to Middle Miocene magmatism (Maillard et al., 2020; Pellen et al., 2016, Figure 1). The role of Oligocene to Early Miocene extension in the formation of the present Algero-Balearic basin to the South has also been questioned, a region where several authors have highlighted the importance of oceanic crust development during the Middle to Late Miocene (Booth-Rea et al., 2007; 2018a; de la Peña et al., 2020a; 2020b; Jolivet et al., 2006; Mauffret et al., 2004). A process that followed the westward retreat of the Gibraltar arc subduction system (Lonergan & White, 1997) and concomitant slab detachment or STEP tearing along its Betic and Rif-Tell orogenic limbs, respectively (e.g. Duggen et al., 2003; García-Castellanos & Villaseñor, 2011; Hidas et al., 2016; 2019;Mancilla et al., 2015). This Middle to Late Miocene extension has also been described onshore along its continental margins, in Northern Tunisia, the BP and the South Eastern Betics (Booth-Rea et al., 2004; 2018b; Giaconia et al., 2014; Moragues et al., 2018). A two-phase opening model for the Algero-Balearic basin has also been proposed, with a first Oligocene-Early Miocene NW-SE phase followed by a Middle to Late Miocene E-W phase (Aïdi et al., 2018; Driussi et al., 2015a).

Cenozoic extension onshore Mallorca has not been extensively studied. Most work describes SW-NE trending high-angle normal faults that extended the southeastern margin of the Tramuntana ranges developing Middle to Late Neogene depocentres like the Inca, Palma and Sa Pobla basins (Benedicto et al., 1993; Gelabert, 1998; Ramos-Guerrero et al., 2000; Sabat et al., 2011)(Figure 1b). Also, a couple of NW-SE trending normal faults were differentiated in the Central Ranges of Mallorca (Anglada-Guajarro & Serra-Kiel, 1986; Sabat et al., 2011). Paleostress analysis from small-scale faults suggested the existence of radial extension during the late Neogene (Cespedes et al., 2001). Moreover, preliminary field work and structural analysis showed that many of the supposed thrust contacts between nappes in the Tramuntana and Levant ranges were actually reworked by two sets of orthogonal low- and high-angle normal faults producing NW-SE and NE-SW directed extension during the Middle Miocene (Booth-Rea et al., 2016; Moragues et al., 2018).

Here we study the Cenozoic extensional phases in Mallorca, analyzing the relationships between extensional faults and their related synrift deposits and identifying the main grabens with the help of the residual gravity map of the Island. We map the southern and central Llevant ranges, with a structural geology emphasis to determine the geometry and kinematics of brittle faults and their relations with the overlying Tertiary sedimentary sequence. We differentiate between extensional and shortening structures and analyze their relative timing. Furthermore, we determine the age of extensional deformation analyzing syn-sedimentary features in the alluvial sequences related to normal faulting, like progressive unconformities due to fault-bend related folding, clastic dikes developed by hydro-plastic deformation before the sediment consolidation and thickness and facies changes across faults. We describe two rifting phases in Mallorca that occurred, respectively, before and after the main shortening period that formed the Mallorca FTB in the Early Miocene. Finally, we integrate these data with previously published results in a new geodynamic model for the evolution of the Western Mediterranean during the Cenozoic.

2 Geodynamic and Geological Settings

2.1 Geodynamic Setting

Mallorca forms the largest island of the BP that represents an emerged archipelago over a relatively thin 22–26 km continental crust (e.g. Díaz & Gallart, 2009)(Figure 1). This crustal domain shows a thin lithospheric thickness, below 70 km (Jiménez Munt et al., 2003) and overlies an anomalously slow upper mantle with a strong NE-SW oriented Pn anisotropy, similar to the rest of the Betics (Díaz et al., 2013). Towards the Northwest it transitions to extremely thin continental crust of the Valencia Trough (Etheve et al., 2018; Maillard & Mauffret, 1999; Torné et al., 1992). To the Northeast, the BP is bounded by the Late Oligocene to Middle Miocene Liguro-provencal oceanic basin, across the dextral North-Balearic Fracture Zone (NBFZ) (e.g. Maillard et al., 2020). Oceanic crust is also found to the Southeast of the BP, forming the Algero-Balearic basin (Aïdi et al., 2018; Booth-Rea et al., 2007; 2018a; Grevemeyer et al., 2011; Leprêtre et al., 2013; Mauffret et al., 2004). The transition between the BP and Algero-Balearic basin domains occurs across both narrow transform domains like the Emile Baudot and Mazarron escarpments, and through wider extended continental crust domains, for example, to the South of Menorca (Driussi et al., 2015a). Both the Liguro-Provencal and Algero-Balearic basin are interpreted as back arc basins formed in the context of slab roll-back in relation to retreating Tethyan lithospheric mantle bodies, presently underlying the Calabrian, Gibraltar and Algero-Tunisian orogenic arcs (e.g. Booth-Rea et al., 2018b; El-Sharkawy et al., 2020; Faccenna et al., 2004; Fichtner & Villaseñor, 2015; Lonergan & White, 1997; Piromallo & Morelli, 2003; Wortel & Spakman, 2000). The present slab segmentation of the Western Mediterranean was probably determined by the location of transform faults inherited from the Mesozoic Tethys rifting stage (e.g. Angrand et al., 2020; Verges & Fernández, 2012).

Whilst the Liguro-Provencal basin is related to an Oligocene to Early Miocene volcanic arc cropping out in Corsica and Sardinia, the western Algero-Balearic basin formed behind the Alboran volcanic arc in the Eastern Alboran basin during the Middle to Late Miocene (Booth-Rea et al., 2007; 2018a; de la Peña et al., 2020b; Duggen et al., 2004; 2008). Slab retreat was facilitated by slab tearing or detachment at the edges of the western Mediterranean subduction arcs, along Subduction Transfer Edge Propagators (STEP) (Badji et al., 2015; Booth-Rea et al., 2018b; Gallais et al., 2013; Govers and Wortel, 2005; Hidas et al., 2019; Mancilla et al., 2015; van Hinsbergen et al., 2014). Mantle flow driven by the above slab tectonic mechanisms produces dynamic topography around the western Mediterranean with both areas of subdued topography above the subducting slabs and others undergoing uplift in backarc regions with mantle upwelling (Faccenna et al., 2014). This is the case of the BP that is located over a region with large positive dynamic topography (Faccenna & Becker et al., 2020).

2.2 Geological Setting

The Balearic Promontory rifted away from the East Iberian margin during the Jurassic when the Valencia Trough basin initially developed (Etheve et al., 2018). The Balearic region showed a similar evolution to the SE Iberian margin during the Mesozoic, with Germanic type facies during the Triassic that evolved towards shallow platform facies in the Early Jurassic, represented by shallow marine carbonates, including dolostone and limestones (Alvaro et al., 1989; Bourrouilh, 1983; Colom, 1973) (Figure 2). Further rifting is marked by the rupture of the platform and the deposition of lower Pleisbachian outer platform marls and marly limestones, followed by quartz-rich sandstones and microconglomerates (e.g. Alvaro et al., 1989; Sevillano et al., 2018). Since the Toarcian it formed a deep marine environment with typical turbiditic talus facies with resedimented olistholiths (Kettle, 2016). This pelagic environment continued with the Maiolica white nannofossil limestone during the Early Cretaceous and was later followed by the deposition of Barremian to Aptian grey-greenish marls with planktonic microfauna (Bourrouilh, 1983; Martin-Chivilet et al., 2019). Mesozoic rifting was segmented by NW-SE-oriented transform faults that determined the individualization of different blocks in the Tethys realm, for example, the Ebro block (Angrand et al., 2020).

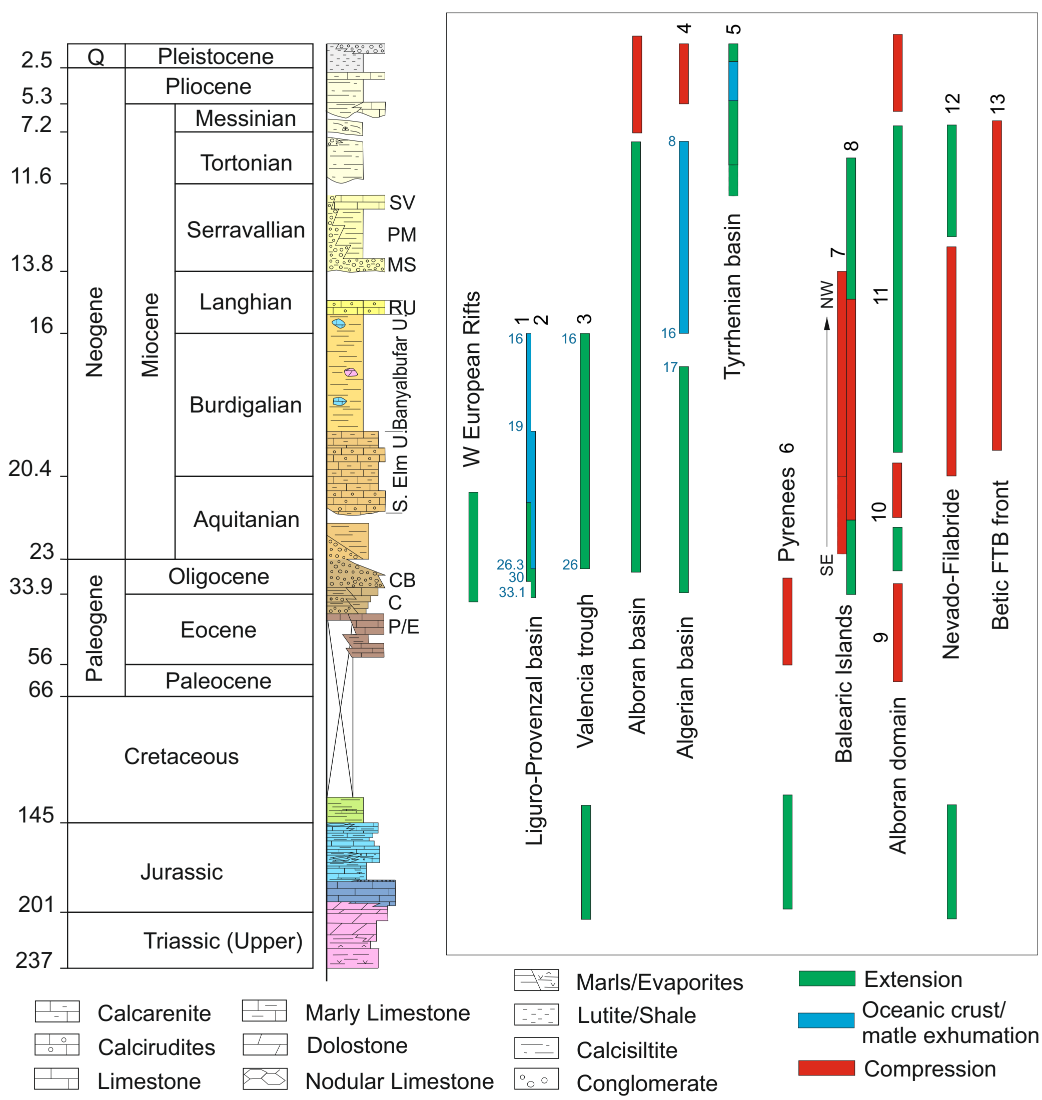


Figure 2. Stratigraphic sequence of the Mallorca Island (Mesozoic from Sabat et al., 2011; Palaeogene-Early Miocene (Colom; 1980; Martin-Closas & Ramos-Guerrero, 2005); Early Miocene to Tortonian (Ramos-Guerrero et al., 1989; 2000; Rodríguez-Perea, 1984); Tortonian to Quaternary, Ramos-Gerrero et al., 2000). Abbreviations of sedimentary unit names: C, Calvari Unit; CB, Cala Blanca Unit; MS, Manacor shales Unit; P/E, Peguera limestones

and S´Envestida grainstones; PM, Pina marls Unit; RU, Randa calcarenites Unit; SV, Sa verdera Unit. Tectonic events through time (blue numbers) of Western Mediterranean domains based on: 1, Faccenna et al. (2004), Burrus (1984); 2, Schettino & Turco (2006); 3, Vergés & Sabat (1999); 4, Aïdi et al. (2018); 5, Faccenna et al. (2004); 6, Vergés & Fernandez (2012); 7, Sabat et al. (2011); 8, present work; 9, Platt et al. (2005); 10, Hidas et al. (2013), Balanyá et al. (1997); 11, García-Dueñas et al. (1992), Lonergan & Platt (1995); 12, Platt et al. (2006); 13, Balanyá et al. (2007), Irribarren et al. (2007).

The Early Cretaceous deep basinal setting was interrupted by a hiatus from the Late Cretaceous to the Early Eocene. An event probably related to crustal thickening during the development of the Pyrenees (Verges et al., 2002), the Iberian Range (Guimerà et al., 2004), and the AlKaPeCa orogenic domain in the Western Mediterranean (Azañón et al., 1997; Balanyá et al., 1997; Boullin et al., 1986; Ramos-Guerrero et al., 1989; van Hinsbergen et al., 2014)(Figure 2). This continental thickening event has been dated as Eocene in HP/LT rocks of the Alpujarride complex in the Internal Betics (Platt et al., 2005), the Calabrian-Peloritani ranges (Heymes et al., 2010; Rossetti et al., 2002), the Kabylies (Bruguier et al., 2017) and Corsica (Martin et al., 2011; Vitale Brovarone & Herwetz, 2013). Following this hypothesis, the Balearic promontory formed part of the hinterland of the AlKaPeCa orogenic domain that was located along its southern margin, before the later opening of the Liguro-Provencal, Thyrrenian and Algerian basins (e.g. Booth-Rea et al., 2005; 2007; Boullin et al., 1986 ; van Hinsbergen et al., 2014). Most authors propose that this orogenic domain had southward tectonic vergence, developed in relation to northwestwards subduction of the Tethys lithosphere (e.g. Booth-Rea et al., 2005; Chertova et al., 2014; Jolivet et al., 2008; van Hinsbergen et al., 2014; Wortel & Spakman, 2000). This vergence is observed at the top of the AlKaPeCa orogenic domain, in the Malaguide thrust stack in the Betics, after undoing paleomagnetic rotations (Lonergan, 1993).

The Late Cretaceous to Early Eocene hiatus was followed by Eocene continental paralic facies that evolve towards a shallow marine transgression in the Middle Eocene (late Lutetian-Bartonian, ≈45–37 Ma) represented by the Peguera limestones and S´Envestida grainstones, respectively (Martín-Closas & Ramos-Guerrero, 2005; Ramos-Guerrero et al., 1989)(Figure 2). Continental deposition continued with some sedimentary gaps during the Late Eocene to Early Miocene with the deposition of conglomeratic wedges, sandstones and lacustrine carbonates that transition to shallow marine facies towards the SE, between the Priabonian and the Aquitanian (≈37–20.4 Ma, Martín-Closas and Guerrero, 2005; Ramos-Guerrero et al., 1989). The top of this mostly continental sequence is represented by Aquitanian marine marls (Colom and Sacares, 1968; Colom, 1980) (Figure 2). Equivalent conglomeratic wedges, dated as latemost Priabonian to Early Rupelian have also been described filling up semigrabens in Menorca (≈35–28 Ma, Bourrouilh, 1983; Martín-Closas & Guerrero, 2005; Sabat et al., 2018).

Coeval Oligocene to Early Miocene extension in a back-arc setting, exhuming the subcontinental mantle to plagioclase facies conditions, affected the Alboran orogenic domain, which was probably located to the South of the Balearic promontory at the time (e.g. Balanyá et al., 1997; Booth-Rea et al., 2005; 2007; Garrido et al., 2011; Marchesi et al., 2012). Oligocene extensional depocenters are also described at the top of the Alboran domain, in the Malaguide complex (Geel & Roep, 1998). The Palaeogene Malaguide-Alpujarride thrust stack was extended by low-angle normal faults and detachments at this time (Booth-Rea et al., 2004; Lonergan & Platt, 1995), concomitant to late Oligocene to Early Miocene tholeiitic dikes in the Malaguide domain (Duggen et al., 2004; Torres-Roldán et al., 1986), and calc-alkaline high-MgO andesite cumulates (Marchesi et al., 2012), arc-tholeiite gabbros (Hidas et al., 2015) and chromitites

(González-Jiménez et al., 2017) in the Ronda peridotites. This extension was coeval to opening of the Liguro-Provencal basin to the NE (Cherchi & Montadert, 1982; Ferrandini et al., 2003; Schettino & Turco, 2006; Speranza et al., 2002)(Figure 2).

Marine sedimentation initiated again in the Early Burdigalian, first with unconformable shallow calciruditic and calcarenitic platform facies of the Sant Elm formation in the Burdigalian (≈20.4-19 Ma, Donoso et al., 1982; Fornos et al., 1991; Rodríguez-Perea, 1984) and later followed by deep marine flysch deposits in the Burdigalian to Langhian (19-14 Ma, Alvaro et al., 1984; Ramos-Guerrero et al., 1989; Rodríguez-Perea, 1984)(Figure 2). The turbiditic marls of the Banyalbufar formation deposited in an unstable foredeep context related to the development of the Mallorca FTB and later evolved in a piggy back type setting as the basin was incorporated into the Betic imbricated thrust stack up to the Langhian (≈16-14 Ma, Alvaro, 1987; Gelabert, 1998; Ramos-Guerrero et al., 1989; Sabat et al., 2011). The turbidites include abundant resedimented blocks and olistoliths of Mesozoic and Paleozoic rocks, provenant from the Mallorca FTB hinterland to the S (González-Donoso et al., 1982; Moragues et al., 2018; Pomar & Rodríguez-Perea, 1983). Thus, Mallorca passed from being the hinterland of the Alboran and Kabilian orogenic domains in the Palaeogene to being part of the foreland of the Betic orogen after the Oligocene to Early Miocene extensional collapse of the region and its subsequent contractive inversion. Shallow platform calcirudites and grainstones in the Randa massif, attributed to the late Burdigalian to Langhian, show locally a spaced stylolitic cleavage that attests to active shortening in the Levant ranges at the time (Gelabert, 1998; Sabat et al., 2011).

Postorogenic sedimentation initiated with continental deposits in the Serravallian (13.8-11.6 Ma), represented by alluvial and lacustrine environments where silts, gravels, limestones and marls deposited (Figure 2). Three members are differentiated, the Manacor silts and conglomerates, the Pina marls and the Son Verdera limestones (Pomar et al., 1983; Ramos-Guerrero et al., 2000). These sediments show large lateral thickness variations that are related to their deposition during the activity of SW-NE striking normal faults along the SE border of the Tramuntana ranges (Benedicto et al. 1993). Middle-Miocene extensional structures strongly thinned the Early Miocene nappe stack, in two orthogonal directions, especially in the Llevant ranges (Moragues et al., 2018). During the Middle Miocene the BP must have formed an archipelago with other nearby islands in the Western Mediterranean that shared similar insular fauna. For example, Serravallian continental sediments in the Central Betics have similar glirid fauna to the one found in Mallorca (Bover et al., 2008; Suarez et al., 1993).

Marine flat lying limestones seal most of the deformation in Mallorca although they seem locally affected by SW-NE trending normal faults along the southeastern foothills of the Tramuntana and Llevant ranges (Gelabert, 1998; Sabat et al., 2011). Tortonian reefal and Messinian littoral carbonates occur along the coast and pass landwards to continental detrital deposits (Pomar et al., 1983). Offshore Mallorca, SW-NE trending normal faults cut the late Miocene sedimentary sequence including the Messinian (Driussi et al., 2015b).

3 Methods

We mapped the southern and central part of the Llevant ranges in SE Mallorca with a special emphasis in analysing the effects of extensional overprinting upon the Early Miocene FTB structure of the island (Figure 3). This extension is evidenced in three geological cross sections of the Llevant ranges (Figure 4). We have contrasted previous maps and geological cross sections of the region, mostly published in the IGME 1:50.000 geological maps (Alvaro-López, 1983; Barnolas et al. 1983) and also by Casas and Sabat (1987), Freeman et al. (1989), Pares et al. (1986), and Sabat et al. (1988). We compare the main faults and basins we observed with the previously published residual gravimetric map for Mallorca (Ayala et al., 1994; IGME, 2003). The residual gravimetric map was obtained from 3843 gravimetric data (Ayala et al., 1994). A density of 2.6 g/cm3 was used for the Bouguer reduction (IGME, 2003). The regional anomaly was calculated using a 3-order polynomic adjustment. Finally, the residual anomaly we show was obtained by subtraction of the regional anomaly from the Bouguer anomaly (Ayala et al., 1994; IGME, 2003).

Fault orientation and kinematics were measured in 45 sites with a total of 638 fault measurements (Figure 5). In sites with enough fault-slip data, a stress inversion analysis was carried out to obtain the paleo-stress state using a Search Grid method (Galindo-Zaldívar & Gonzalez-Lodeiro, 1988) and a Gauss paleostress method (T-Tecto 3.0 software; Zalohar & Vrabec, 2007). The first method is based in Bott's equation (Boot, 1959) were the best-fitting tensor, with the minimum sum of angular misfits between the predicted theoretical striae and the real striae, is searched. The remaining non-fitting faults are used to search for other possible tensors. In case of a multi-phase determination, the number of the phase is related to the number of assigned faults in each phase without any chronological meaning. The stress state is given by the orientation of the main axis of the stress tensors (maximum (σ_1), intermediate (σ_2), and minimum (σ_3) stress) and their axial ratio (R, (σ_2- σ_3)/(σ_1- σ_3)). In the second method, the results agree with the Amonton's Law by searching for the global and highest local maxima of the sum of compatibility functions (angular misfit and shear-normal stress ratio) for all fault-slip data. The results obtained with both methods are consistent and test their reliability.

The geodynamic reconstruction was carried out by integrating field observations presented in this study into previously published Eocene-Middle Miocene geodynamic evolution models of the Western Mediterranean after Booth-Rea et al. (2007), Etheve et al. (2016), Lepretre et al. (2018), van Hinsbergen et al. (2020) and references therein. The framework in our model is constrained by the paleogeographic positions and motions of Africa, Iberia and Adria relative to the Eurasian plate, based on Handy et al. (2010) and Rosenbaum et al. (2002). The Atlantic and Tethys ocean floor structure is reconstructed after Sallarès et al. (2011), and the Cenozoic seafloor evolution is after Poort et al. (2020). Ages of volcanism are compiled from Lustrino et al. (2011), Marti et al. (1992) and Maury et al. (2000) , and the position of coastlines is reconsidered after Jolivet et al. (2006) including stratigraphic data and continental vertebrate distribution from Azzaroli (1990), Bover et al. (2008), Boukhalfa et al. (2020), Costamagna and Schäfer (2013), de la Peña et al. (2020b), Martín-Closas and Ramos-Guerrero (2005), Mennecart et al. (2017) and Suarez et al. (1993).

4 Results, structure of the Llevant ranges

We show a new geological and structural map for the southern and central parts of the Llevant ranges that reinterprets many of the supposed thrust surfaces as low-angle normal faults (Fig. 3).

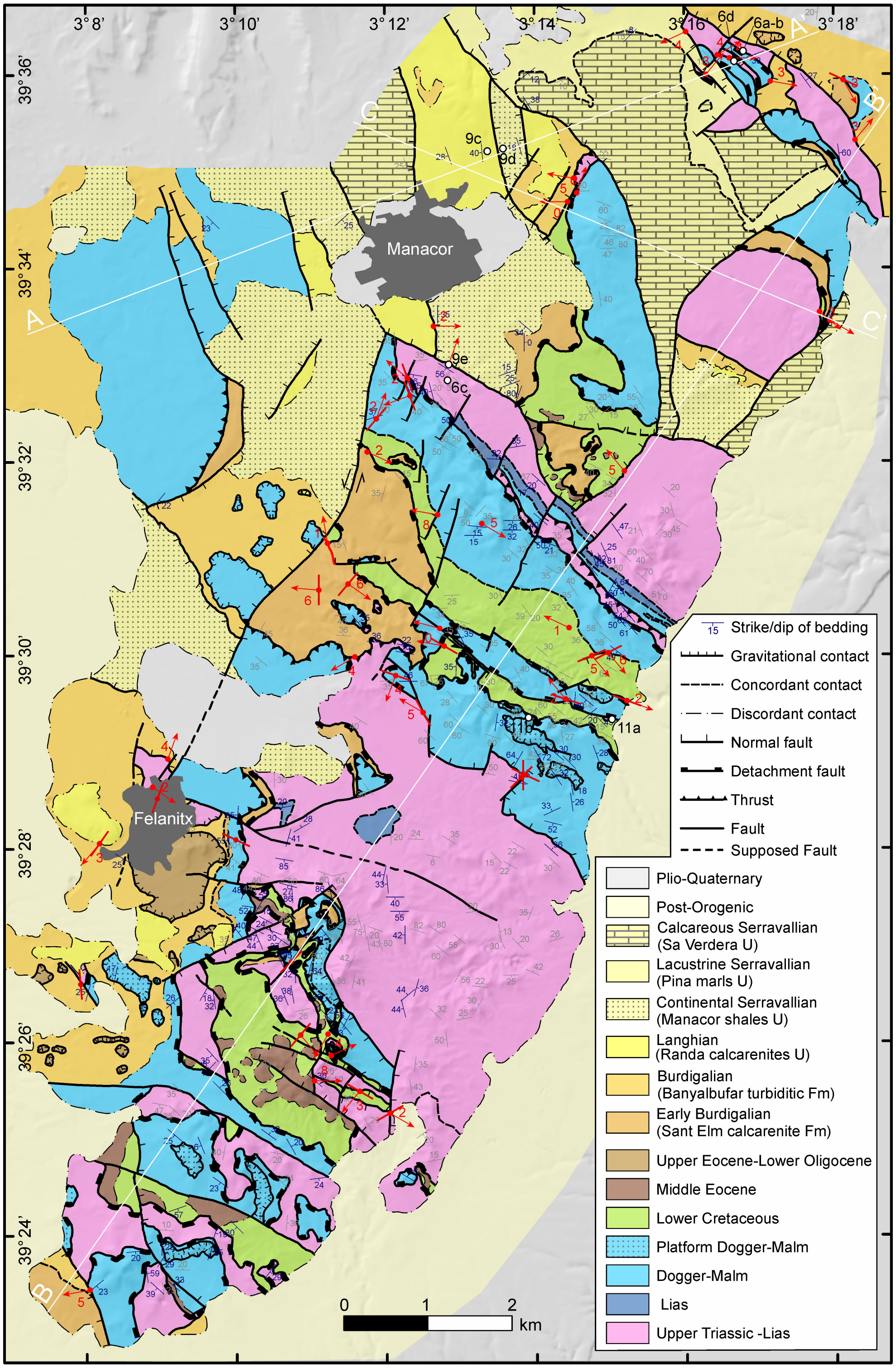


Figure 3. Geological map of the Serres de Llevant. Red lines and arrows, fault azimuths and kinematic vectors. Red numbers, dip angles in tens of degrees. Bedding, our data in black, IGME data in grey. White dots, Location of figures 6, 9, 11.White lines, location of cross-sections in Figure 4.

We observe that the contractive structures related to the Mallorca FTB development and the nappen they bound are pervasively overprinted by extensional brittle shear planes, especially in the most pelitic lithologies like the Cretaceous and late Jurassic pelagic marls (Fig. 6a, b, c). Slicken lines along these planes mark variable directions of transport, although mostly NE-SW and NW-SE directed (Figs. 3, 4 and 5). Meanwhile, more competent lithologies like Triassic dolostones are strongly faulted and brecciated (Fig. 6c, d). The geometrical and kinematic analysis of these structures and of the main brittle fault contacts between lithological units in the Serres de Llevant suggest that the Mallorca FTB was strongly thinned and extended in two orthogonal directions after the Early Miocene thrusting phase, however, preserving the previously established nappe superposition (Moragues et al., 2018 and in a wider region in Fig. 5). Low-angle normal faults with flat and ramp geometry developed thanks to the heterogeneous rheology of the crustal stack formed by the Mallorca FTB, where weak pelagic marls alternate with stronger dolostone and limestone lithologies (Fig. 6d). These faults are characterized by producing stratigraphic omissions along their contacts towards the direction of transport. In many cases, the different rock bodies in the Llevant ranges are bounded entirely by LANFs, forming extensional horses at different scales.

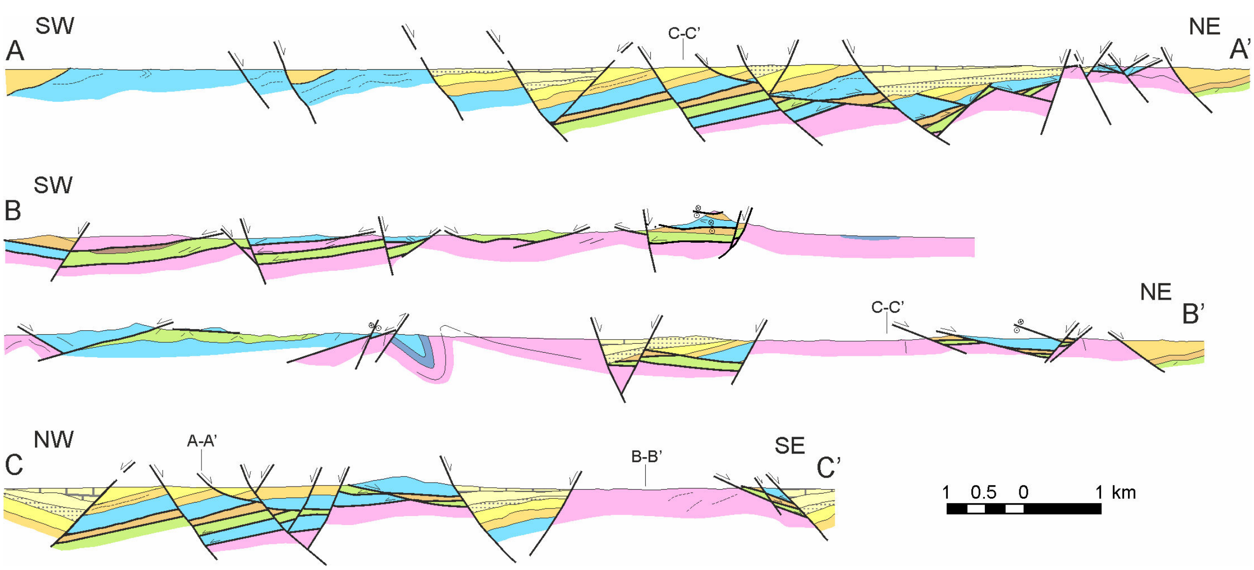


Figure 4. Cross sections through the Serres de Llevant. Legend and location in **Figure 3**.

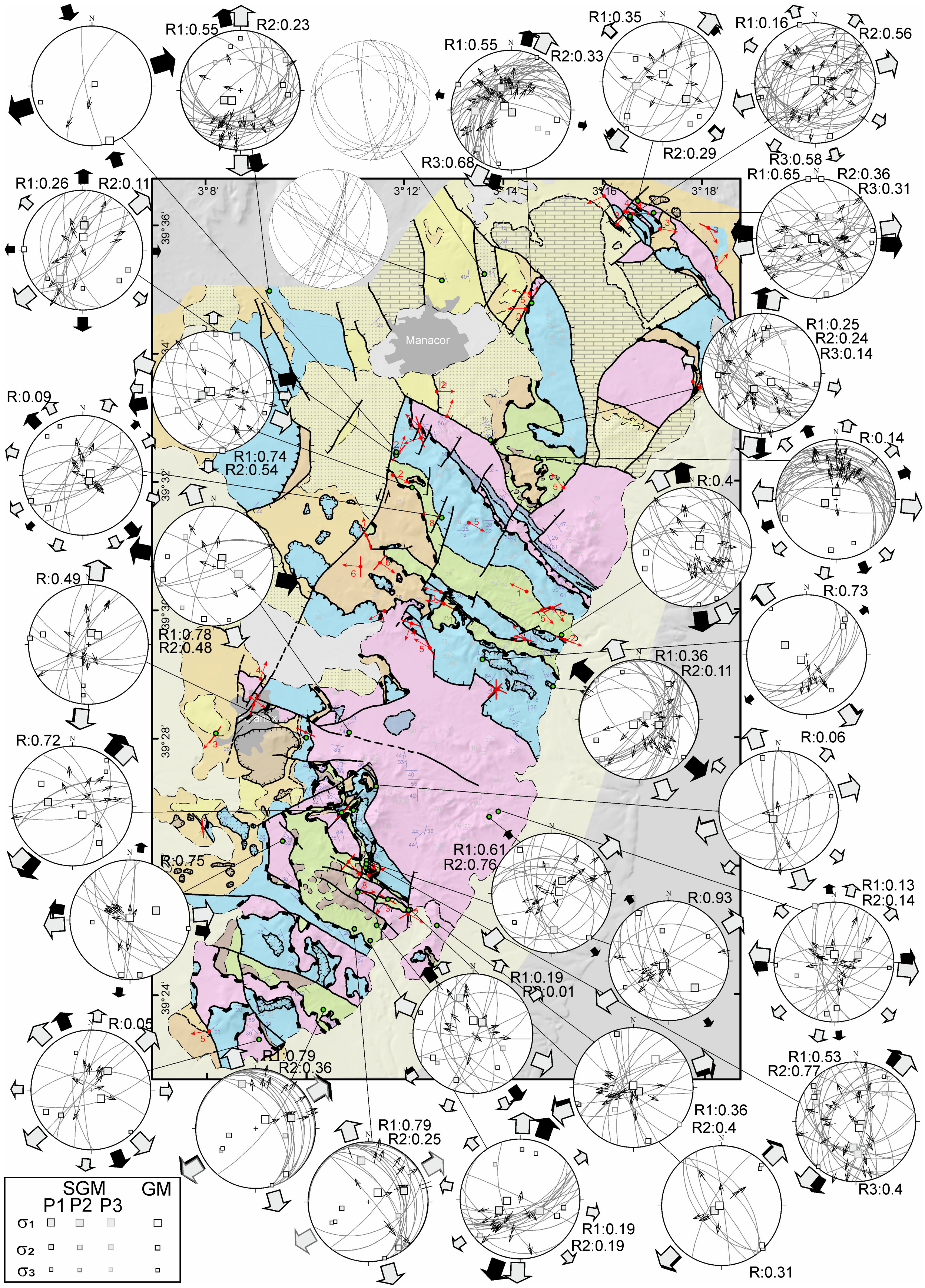

Manacor
3°8'
3°12'
3°14'
3°16'
3°18'
39°36'
39°34'
39°32'
39°30'
39°28'
39°24'
R1:0.55 R2:0.23
R1:0.55 R2:0.33 R3:0.68
R1:0.35 R2:0.29
R1:0.16 R2:0.56 R3:0.58
R1:0.26 R2:0.11
R1:0.65 R2:0.36 R3:0.31
R1:0.25 R2:0.24 R3:0.14
R:0.09
R1:0.74 R2:0.54
R:0.14
R:0.4
R:0.49
R1:0.78 R2:0.48
R:0.73
R1:0.36 R2:0.11
R:0.72
R:0.06
R:0.75
R1:0.61 R2:0.76
R:0.93
R1:0.13 R2:0.14
R1:0.19
R:0.05
R1:0.79 R2:0.36
R1:0.53 R2:0.77 R3:0.4
R1:0.36 R2:0.4
R1:0.79 R2:0.25
R1:0.19 R2:0.19
R:0.31
SGM GM
P1 P2 P3
σ1
σ2
σ3

Figure 5. Fault measurement stations with paleostress results obtained through the Search Grid (SGM; Galindo-Zaldívar and Gonzalez-Lodeiro, 1988) and Gauss paleostress methods (GM; Zalohar and Vrabec, 2007). Stereoplots of equal area, lower hemisphere projections show faults with arrows indicating slip vectors and stress tensor results, main axes (square) an axial ratios (R, $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$) for different stress phases (P1-P3). Also, the main horizontal compression and tension orientations are shown with black (GM) and grey (SGM) arrows. A table with paleostress analysis and location of stations is available as supplementary material.

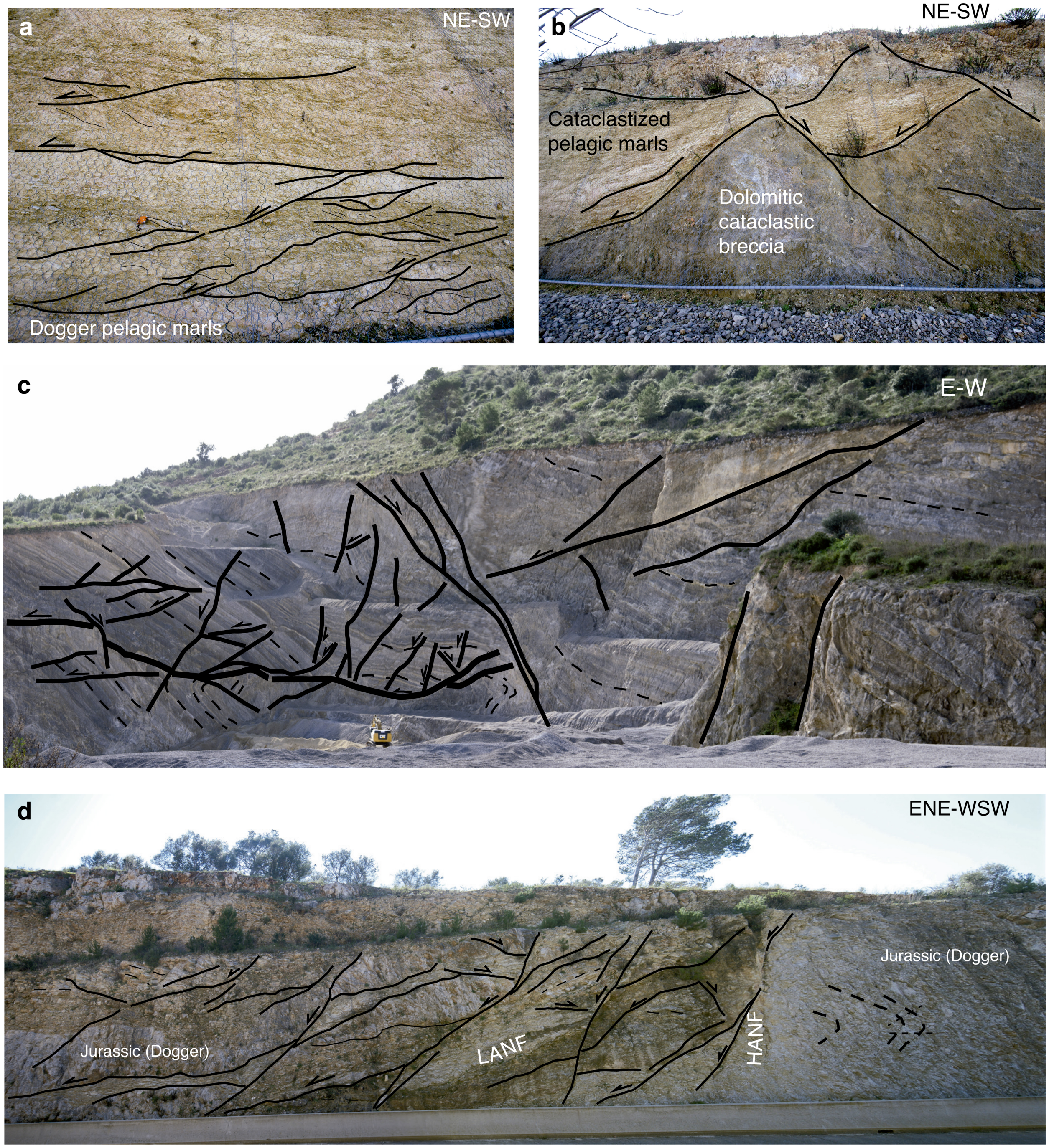


Figure 6. Brittle extensional shear zone with NE-directed transport developed in Jurassic marls **(a)**. Extensional shear zone between Jurassic marls and Triassic dolostone cut by later SW-directed normal faults **(b)**. Low-angle normal fault system cutting through folded Middle Jurassic limestones and marls, later cut by high-angle normal

faults with ENE-directed transport **(c)**. Extensional structures cutting through Triassic dolostones in a quarry nearby Manacor. Photo locations in Figure 3.

4.1 Oligocene rifting phase

Stratigraphic studies in Mallorca suggest that Oligocene to Aquitanian (≈29-23 Ma) continental deposits of the Cala Blanca Formation formed syntectonically to extensional faulting (Martín-Closas & Ramos-Guerrero, 2005; Ramos-Guerrero et al., 1989; 2000). However, Tertiary extensional structures formed before nappe tectonics in Mallorca have not been identified up to date. Here we describe a well-preserved outcrop that demonstrates the syn-extensional nature of these deposits.

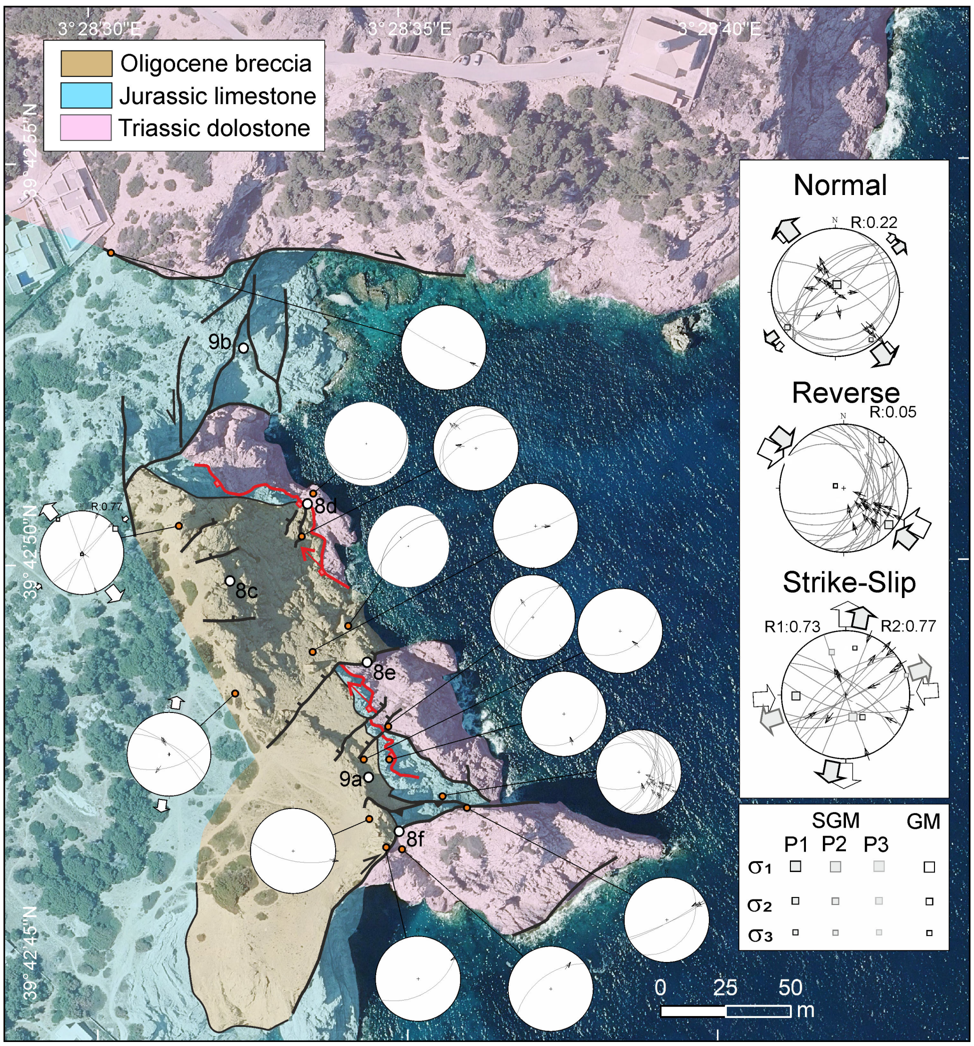


Figure 7. Structural map of the Capdepera Oligocene semigraben. Stereoplots of equal area, lower hemisphere projections show faults with arrows indicating slip vectors. Streoplot of paleostress results sorted by fault kinematics, axis (square) an axial ratio of each phase (R, $(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$) of stress tensors. Also, main horizontal compression and tension orientation are shown with black (GM) and grey (SGM) arrows.

The Capdepera semigraben is preserved at the North-East of Mallorca (Figure 1b, 7). The semigraben structure is filled by a continental carbonate breccia body with a wedge geometry that shows an internal fan-shape progressive unconformity, where the breccias dip between 55 and 15º towards the SE (N150ºE)(Figs. 7, 8 a, b).

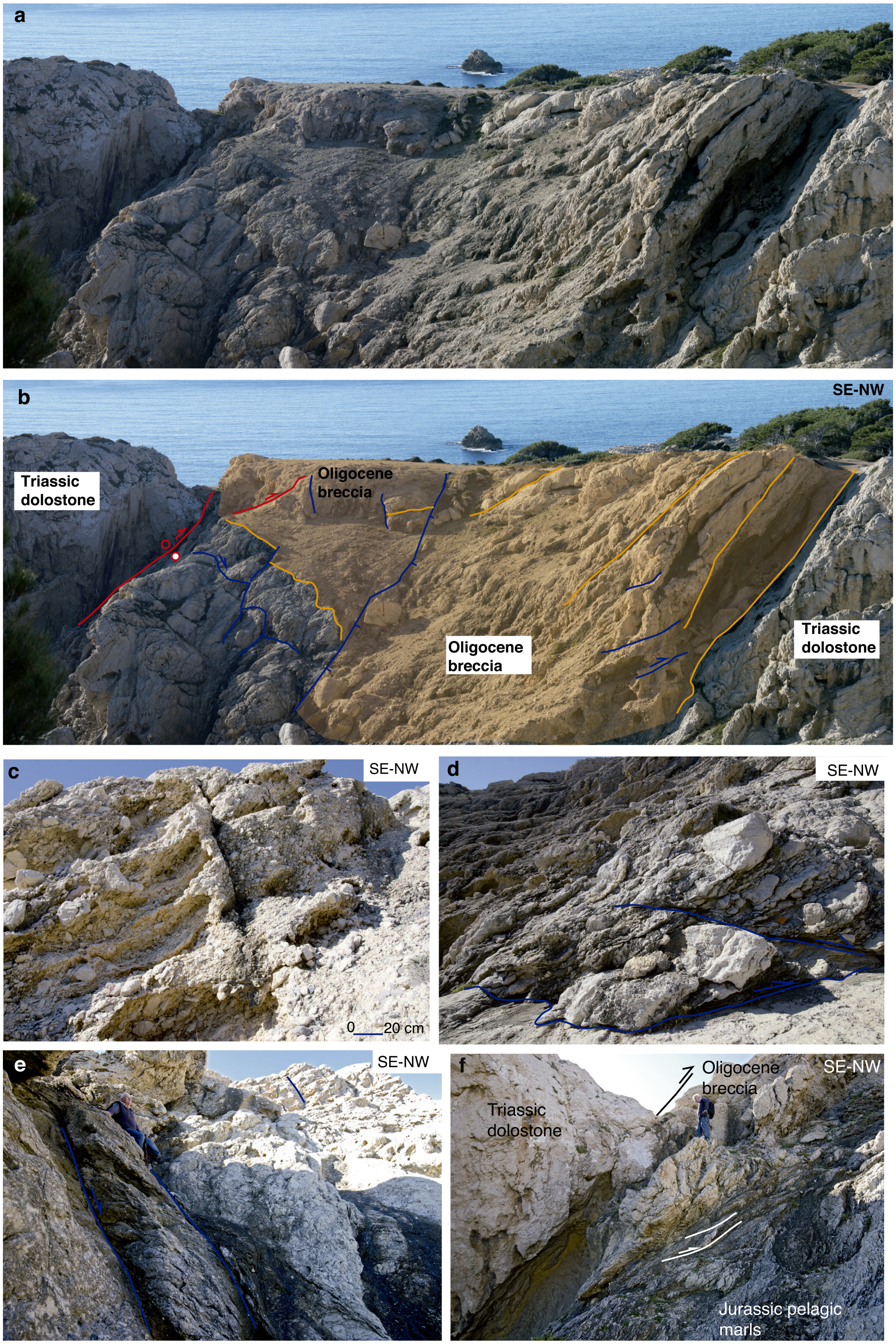


Figure 8. Panoramic view of the Capdepera Oligocene semigraben. Notice progressive unconformity developed in the Oligocene breccia wedge **(a)**. Interpretation of the structure of the Capdepera semigraben **(b)**. Small-scale normal fault cutting through the Capdepera Oligocene breccia, marked by the development of a clastic dike **(c)**. Detachment at the base of the Capdepera graben, between Oligocene breccia in the hanging-wall and Triassic dolostone in the footwall. Notice small riedel faults rooting into the detachment. High-angle normal fault that cuts through the Capdepera detachment, permeated by a black tar matrix **(d)**. Main high-angle fault bounding the Capdepera semigraben, inverted as a reverse and later dextral strike-slip fault. Notice strongly sheared Jurassic pelagic marls with abundant shear criteria and calcite veins.

The breccia is formed by angular fragments of mostly Jurassic limestones and Triassic dolostone (Bourrouilh, 1983). The breccia is affected by high-angle normal faults with meter-scale spacing. In some cases, these faults are defined by clastic dikes, formed by hydroplastic behavior during faulting (Figure 8c) and in many cases the breccia is cemented by a tar matrix. At the base of the wedge, the breccia is bounded from underlying Jurassic limestones by a low-angle normal fault with NW-directed transport, namely, the Capdepera LANF (Figure 8d). This LANF presently dips approximately 10º towards the SE, having been tilted by later high-angle listric faults (Figs. 7, 8e). The transport sense is defined by several structural criteria like the offset of the sedimentary bedding, rotation of the older bedding layers, orientation of riedel faults and the asymmetry of porphyroclast tails in the fault rock. Some of the normal faults cutting the breccia detach along this low-angle fault surface (Figure 8d). The Capdepera LANF is cut and displaced by other high-angle normal faults that cut through the breccia wedge, across which, the breccia shows changes in facies and thickness, with finer grained clastics and thicker deposits over the hanging-wall (Figure 8, 9e). These faults are also permeated by black hydrocarbons. All the above described extensional structures show NW-directed tectonic transport (Figs. 7, 8b, c, d, e).

The southern boundary of the breccia wedge is a subvertical fault that separates Triassic dolostones to the South, from Jurassic limestones and the overlying Oligocene breccia to the North (8f). This fault shows complex kinematics with three different sets of striae (Figure 7). The older set shows down-dip normal displacement marked by striations and grooves. Meanwhile, the footwall of the fault is affected by pervasive steeply- SE-dipping faults with NW-directed reverse kinematics marked by stepped calcite fibers. Finally, the fault surface shows late horizontal slicken sides indicating dextral strike-slip kinematics. In the proximity of the main bounding fault, the breccia is affected by a subvertical, SE-dipping spaced and anastomosed stylolithic cleavage (Figure 9a) and is also cut by low-angle SE-dipping meter-scale reverse faults. This small outcrop is preserved between, and cut by three strike-slip faults, a sinistral NW-SE striking one and two younger dextral NE-SW ones that also offset the sinistral fault (Figure 7, 9b).

Figure 9. Oligocene Capdepera breccia affected by spaced stylolithic cleavage related to the Early Miocene Mallorca FTB development (a). Strike-slip fault cutting the Capdepera semigraben. Notice sinistral fault with cataclastic fault gouge and vertical-axis folds, cut by later dextral SW-NE oriented fault (b). Late Burdigalian to Langhian calcirudites cut and tilted by the activity of Serravallian normal faults with NE-directed transport (c). Serravallian syn-rift sediments in the same road cut as c, also tilted and cut by normal faults (d). NE-directed Normal fault between Triassic dolostone and Serravallian conglomerates and silts at the southern border of the Manacor depocenter (e).

4.2 Middle Miocene rifting

The Early Miocene nappe stack structure in the Serres de Llevant is affected by a pervasive extensional fabric, marked by brittle shear faults at cm-scale in the most incompetent materials like Cretaceous or Late Jurassic marls (Figure 6a, b, c). Furthermore, many of the supposed thrust contacts between nappes are defined by fault rocks with slickenlines marking transport strongly oblique or orthogonal to their NW theoretical hanging-wall transport sense (Figs. 3, 5). A careful analysis of these low-angle brittle fault surfaces shows that they cut down into the structural pile in the direction of transport, indicating their extensional nature (Moragues et al., 2018)(Figs. 5, 6d). Also, several contacts previously interpreted as stratigraphical are reworked by LANFs (Figs. 3, 4). Since, this preliminary work, we have made further observations and mapped a larger area of the Serres de Llevant to include some nearby Middle Miocene sedimentary depocenters in the area of Manacor (Figure 3). This work shows that the general structure of the area is defined by several horsts and grabens, the later, filled by Early Miocene to Serravallian sediments (see geological map and cross sections, Figure 3 and 4).

At the scale of the Mallorca Island, the larger grabens are evident in the regional gravity anomaly map, producing negative anomalies that coincide with Serravallian and Early Miocene sedimentary outcrops in the Inca, Sa Pobla, Marineta, Manacor, Campos and Palma basins (Figure 10). The larger grabens show either NW-SE or NE-SW elongation and are offset laterally by NE-SW oriented lineaments that coincide in most cases with NE-SW dextral and sinistral strike-slip faults like the Orient, Sant Joan, Sencelles or Felanitx-Manacor faults (Figure 10). In other cases, these lineaments may correspond to NE-SW oriented normal faults along the SE margin of the Serres de LLevant (Sabat et al., 2011), which partially may affect the Tortonian sediments, although, these mostly seal all extensional structures (Figure 3).

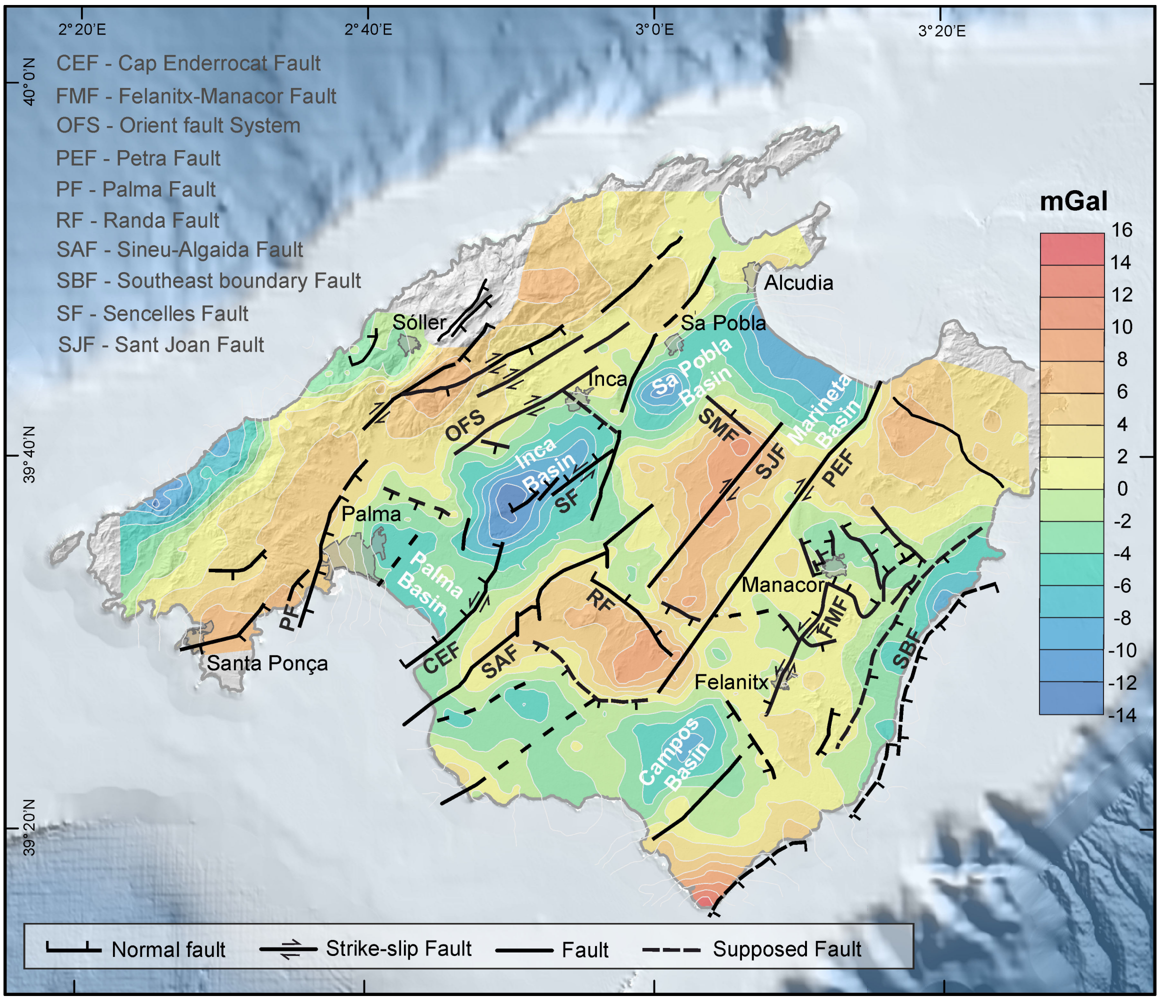


Figure 10. Residual gravity anomaly map of Mallorca (modified from Ayala et al., 1994; IGME, 2003) with main faults and Middle Miocene basins coincident with negative gravity anomalies.

The grabens that coincided with topographic lows in the region show both NW-SE and SW-NE orientation, bounded by normal faults with these orientations. In a general pattern, the normal faults bounding the grabens produce radial extension (Figs. 3 and 5). Many outcrops of the Langhian grainstones appear tilted and cut by decameter spaced normal faults, mostly with NW-

SE orientation (Figure 9c). This is especially clear to the West of Manacor, where the normal faults also cut Serravallian continental sediments, defining km-scale grabens (Figure 9d, e).

The Serravallian alluvial and lacustrine sequence around Manacor is frequently flat-lying, although locally it is also strongly tilted, reaching dips of 40º. In some outcrops, we observed a progressive unconformity within the Serravallian sequence, suggesting progressive tilting during normal fault activity. The Serravallian sediments are also locally faulted within the series but less frequently and more spaced than in the underlying Langhian calcirudites (Figure 9d, e). Tortonian limestones seal most of the normal faults along the southeastern foothills of the Serres de Llevant following a NE-SW strike, parallel to the most recent high-angle normal faults. This lineament also coincides with an elongated negative gravity anomaly parallel to the coast (Figure 10), which probably marks an important sedimentary depocenter determined by these faults that were active up to the Late Miocene, as observed offshore (Driussi et al., 2015b).

Extension was polyphasic, with the main faults bounding the grabens cutting older low-angle extensional structures that are partly sealed by Serravallian syn-tectonic sediments. Sequential extension accompanied by fault rotation has made older LANFs appear as if they were thrusts, with upwards hanging-wall displacement (for example, the Capdepera LANF, Figure 8d). Although, when their geometry is analyzed they cut down into the structural pile, producing omission in the direction of transport (Figure 4, B-B´). The main extensional system in the Manacor basin shows NE directed extension, observed both in the LANFs and the later high-angle normal faults. Meanwhile, further south, we observe mostly SW-directed hanging-wall transport, which leaves a horst-type structure in between, where the deepest thrust sheets in the region crop out, to the South of Manacor (Figures. 3, 4 B-B´, 5).

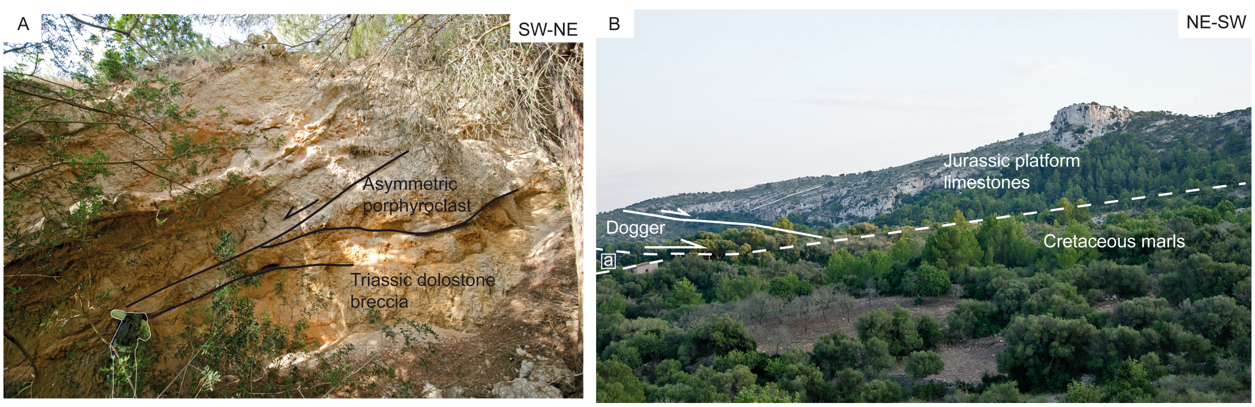


Figure 11. Outcrop of dolomitic cataclastic breccia affected by SW-directed LANFs. This small outcrop is located between Middle Jurassic limestones at the top and Cretaceous marls below, in a position like A, in Figure 11b **(a)**. Panoramic view of a low-angle normal fault cutting through Jurassic limestones that detaches over Cretaceous marls of an underlying, extended, thrust sheet. A represents the approximate structural position of the cataclastic breccias shown in a **(b)**.

The main horsts in the region are cored by the remains of at least four nappes of the Early Miocene thrust stack (Figure 3). Each nappe is represented from top to bottom by an incomplete sequence of materials from Triassic dolostones to Early Miocene calcarenites of the Sant Elm formation. Meanwhile, the topmost nappe includes Burdigalian turbidites of the Banyalbufar formation and Late Burdigalian to Langhian platform grainstones and calcirudites. The Early Miocene sediments of the topmost nappe are also locally overthrusted by Mesozoic sediments

(Figs. 3, 4). The deepest nappe crops out to the S-SE of Manacor and it is characterized by not being too affected by the extensional fabrics, except near the contacts with the Manacor sedimentary depocenter. This nappe shows several folds with NW-SE oriented axes, with the anticline at the core of the structure cut by a retro-NE-vergent reverse fault (Figure 4B-B´). This nappe that includes a continuous stratigraphic section from Triassic dolostones to Cretaceous marls is overlain by a LANF with SW-directed transport. Small Triassic dolomitic extensional horses occur over the LANF surface (Figure 11a). These are strongly comminuted and cut by low-angle faults with SW-directed transport (Figs. 4B-B´, 11a)). The hanging wall of the above LANF that forms the largest Triassic outcrops to the W of Felanitx, shows a ramp geometry with Triassic dolostones and overlying Jurassic limestones tilted over the Cretaceous marls of the underlying nappe (Figure 11b). Listric normal faults cutting through the Jurassic root in the LANF (Figs. 3, 4B-B´, 11b).

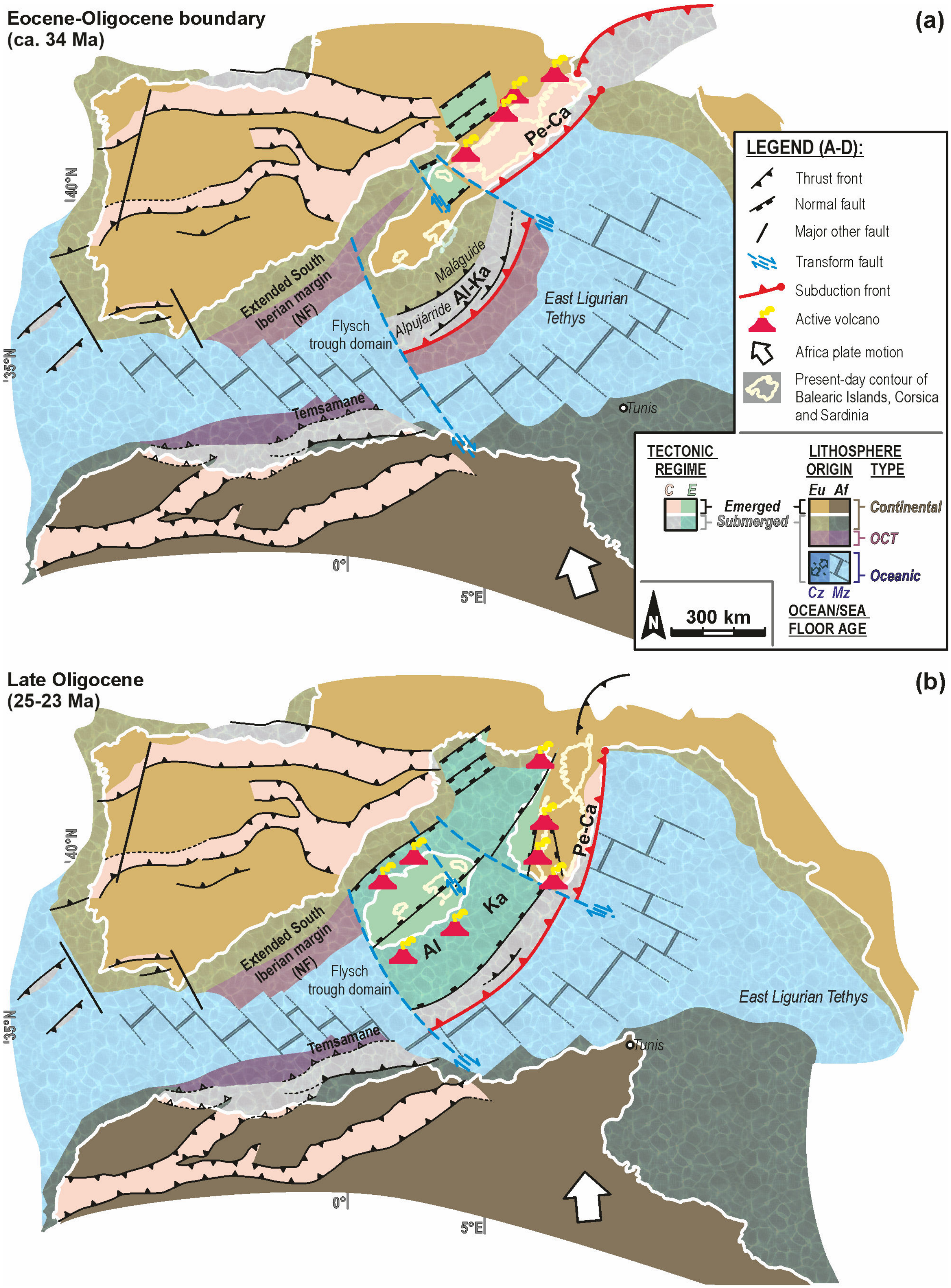
5 Discussion

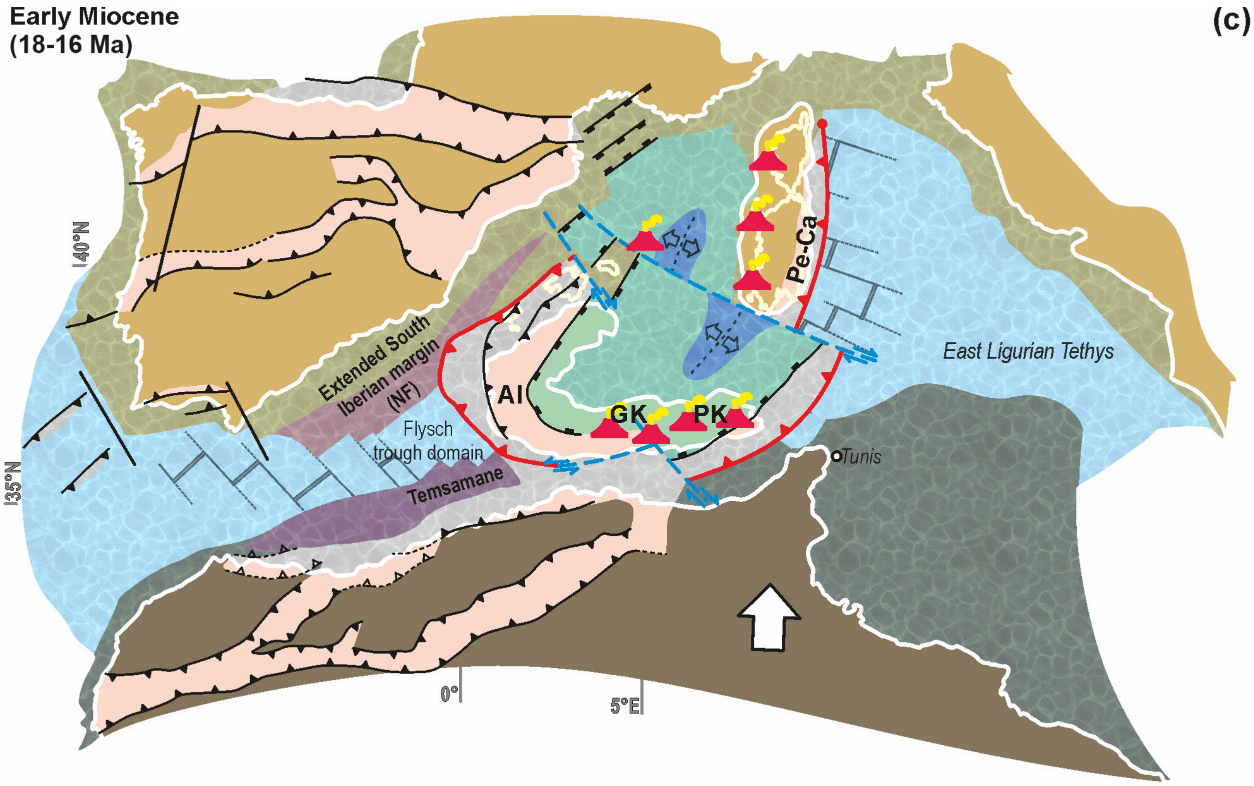
Most authors have interpreted that the structure of the Llevant ranges is mostly determined by the Early Miocene WNW-NW directed thrusting that formed the Mallorca FTB, where all tectonic contacts are interpreted as thrusts or lateral ramps of the thrust system. The shortening related to this period resulted in the imbrication of up to seven nappes formed by Triassic to Early Miocene sediments (Casas and Sabat, 1987; Parés et al., 1986; Sabat et al., 1988). Related to this shortening, the rocks in the Llevant and Tramuntana ranges show locally the development of brittle shear-planes with calcite fiber slicken lines, marking reverse WNW-directed displacement, and also a spaced anastomosed stylolitic cleavage, especially evident in the proximity of folds with mostly NNE-SSW oriented axes (Casas and Sabat, 1987; Gelabert et al, 1992), or reverse faults (Figs. 7, 8f, 9a). However, this work shows that Mallorca underwent two Tertiary extensional phases before and after the development of its fold and thrust belt structure during the Early Miocene. The first phase of extension occurred in the Oligocene (29—23 Ma) during the deposition of the Cala Blanca alluvial conglomerates and a second one during the Middle Miocene (14—11 Ma). This later extension preserved the lithological repetitions established during the Mallorca FTB development, but very rarely are the original thrust surfaces preserved, having been cut or reworked by the later extensional fault system (Figure 3 and cross-sections in Figure 4). Here we integrate these newly observed extensional phases with the previously established Early Miocene FTB development in Mallorca and we include them in a new geodynamic evolution for the Western Mediterranean for the period comprised between the Eocene and the Middle Miocene (Figure 12).

5.1 Oligocene extensional detachments and grabens

The Cala Blanca breccias in the Capdepera outcrop have not been dated directly, however, the fact that these breccias are affected by a spaced stylolitic cleavage and cut by meter-scale reverse faults related to the well dated Early Miocene thrusting makes them necessarily older than the development of the Mallorca FTB. The extensional system observed in Capdepera indicates a process of sequential extension with the development of a low-angle normal fault with NW-directed hanging wall transport that is cut by later high-angle normal faults detaching at a deeper crustal level (Figs. 7, 8). This extensional geometry is typical of highly extended terrains (Booth-Rea et al., 2004; Martínez-Martínez et al., 2002; Serck et al., 2020). Other outcrops along the coast in Mallorca also offer Northward-directed low-angle normal faults affecting the Mesozoic sequence, which are cut by later thrusts. This northwards extension in Mallorca is probably younger than normal faulting observed in Menorca (~35-28 Ma) that produced Oligocene half-grabens and low-angle detachments (Sabat et al., 2018), and Ibiza (Etheve et al., 2016), and overlaps the opening of the Liguro-Provencal basin (Cherchi & Montadert, 1982; Ferrandini et al., 2003; Rehault et al., 1984; Speranza et al., 2002; Schettino & Turco, 2006). Extension at this time has also been described at different lithospheric depths in the Alboran domain now outcropping in the Internal Betics, for example in the Ronda subcontinental peridotite sequence (Garrido et al., 2011) or at shallower crustal depths, with low-angle normal faults and detachments denudating the Paleogene Alpujarride-Malaguide thrust stack in the northeastern Betics (Booth-Rea et al., 2004; 2005). This extension affected the AlKaPeCa orogenic domain formed during the Late Cretaceous to Palaeogene, of which, the Balearic promontory represented its hinterland (Figure 12a). Late Oligocene extension, around 25 Ma, is also described in the Kabylies (Saadallah and Caby, 1996). Furthermore, Eocene to Aquitanian (40—23 Ma) depleted gabbros are described in the Kabylies, having formed either backarc or forearc oceanic crust of a proto-Algerian basin (Abbassene et al., 2016; Chazot et al., 2017; Fernandez et al., 2020). This Oligocene extension in a back-arc type setting is described in the whole Mediterranean realm and attributed to a decrease in absolute northward motion of Africa triggered by the Africa/Arabia-Eurasia collision that slowed down Africa (Jolivet & Faccenna, 2000).

Thus, our work supports a generalized extensional suprasubduction setting for the late Oligocene in the Western Mediterranean (Figure 12b). A feature that would explain contradictory hypotheses for the development, for example, of the Valencia through, where both Mesozoic and Tertiary extensional phases have been proposed (Etheve et al., 2018; Roca & Guimera, 1992). However, this basin in particular would occupy a foredeep context during the development of the Early Miocene to Langhian Mallorca FTB.


Eocene-Oligocene boundary
(ca. 34 Ma)
(a)
Pe-Ca
Extended South Iberian margin (NF)
Maláguide
Al-Ka
Alpujárride
Flysch trough domain
East Ligurian Tethys
Temsamane
Tunis
40°N
35°N
0°
5°E
LEGEND (A-D):
Thrust front
Normal fault
Major other fault
Transform fault
Subduction front
Active volcano
Africa plate motion
Present-day contour of Balearic Islands, Corsica and Sardinia
TECTONIC REGIME
C E
Emerged
Submerged
LITHOSPHERE ORIGIN TYPE
Eu Af
Continental
OCT
Oceanic
Cz Mz
OCEAN/SEA FLOOR AGE
N
300 km
Late Oligocene
(25-23 Ma)
(b)
Pe-Ca
Al
Ka
Extended South Iberian margin (NF)
Flysch trough domain
East Ligurian Tethys
Temsamane
Tunis
40°N
35°N
0°
5°E


Early Miocene
(18-16 Ma)
(c)
40°N
35°N
0°
5°E
Extended South Iberian margin (NF)
Flysch trough domain
Temsamane
Al
GK
PK
Pe-Ca
East Ligurian Tethys
Tunis

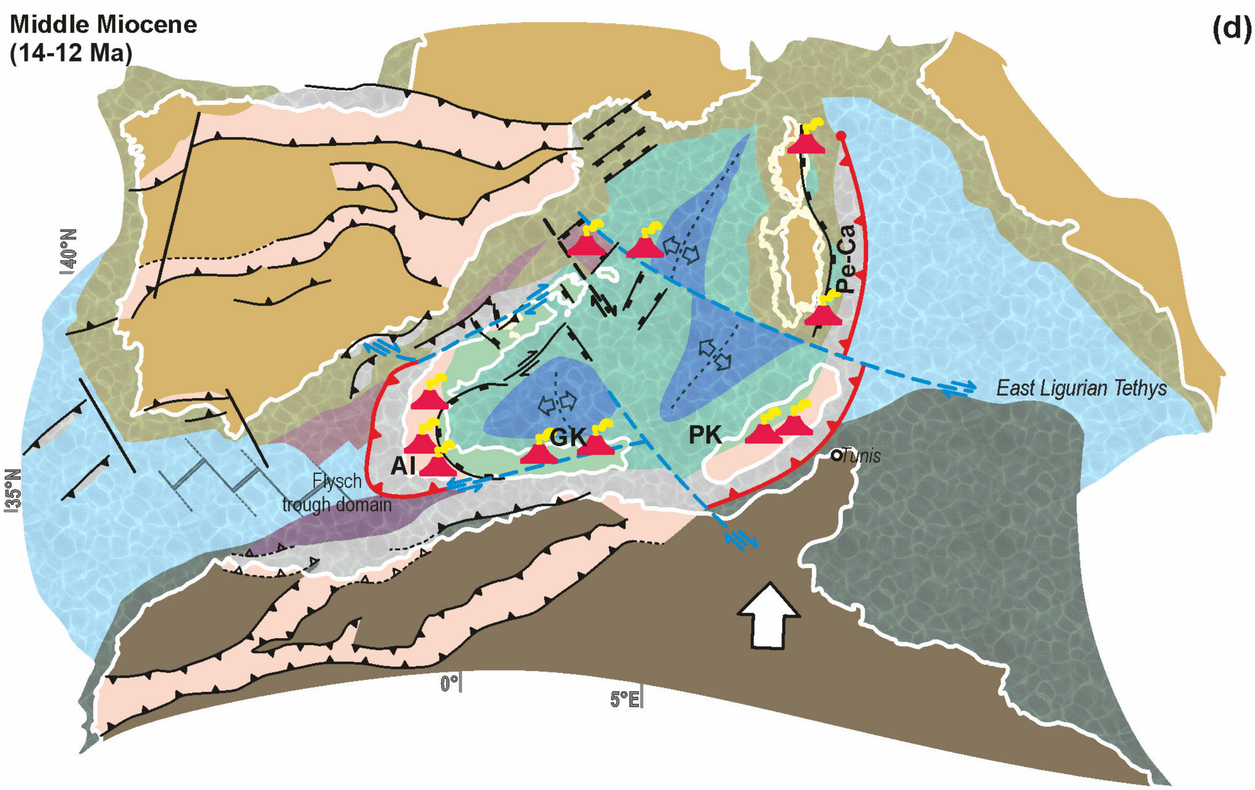

Middle Miocene
(14-12 Ma)
(d)
40°N
35°N
0°
5°E
Flysch trough domain
Al
GK
PK
Pe-Ca
East Ligurian Tethys
Tunis

Figure 12. Geodynamic reconstruction of the Western Mediterranean for late Eocene (a, 34 Ma), late Oligocene (b, 25-23 Ma), early Miocene (c, 18-16 Ma) and middle Miocene (d, 14-12 Ma) time frames. Abbreviations in the map: Al – Alborán domain; Ka – Kabylia; Pe – Peloritan domain; Ca – Calabria; NF – Nevado-Filábrides; GK – Grande Kabylie and PK – Petite Kabylie. Abbreviations in the legend: OCT – ocean-continent transition; C/E – compressive/extensional active tectonics; Eu/Af – European/African origin of the lithosphere; Cz/Mz – Cenozoic/Mesozoic age of the seafloor and ocean floor, respectively. The Africa plate motion and the paleo-position of the city of Tunis are shown after Handy et al. (2010) in each stage. See Methods chapter for further details on the reconstruction.

5.2 Early Miocene FTB development

Shortening and tectonic inversion followed in the Early Miocene, for example, the main high-angle normal faults bounding the Capdepera graben were inverted as attested by a second family of slicken-sides indicating reverse kinematics, a related spaced cleavage and small-scale reverse faults. The Mallorca FTB is interpreted to have formed between the Late Oligocene and the Langhian (e.g. Gelabert, 1998; Sabat et al., 2011), however, we find that most nappes in the Llevant ranges include the Sant Elm formation at the top, dated as Burdigalian (Rodríguez-Perea, 1984). Early Miocene rhyolites of the Puig de l´Ofre, dated by K-Ar at 19 Ma, and Langhian sediments are imbricated in the thrust stack at the Tramuntana ranges (Marti et al., 1992; Mitjavila et al., 1990). Thus, the main FTB building phase was probably shorter in time, between the Burdigalian and the Langhian (19 to 14 Ma)(Figure 12 c). This timing and its WNW- to NW-directed kinematics coincide with the main deformation phase in the External Betics and the Flysch through accretionary wedge that include Burdigalian sediments in the nappe stack (e.g. de Capoa, 2007; Guerrera et al., 2005; Luján et al., 2006), although, FTB development in the Betics and the Gulf of Cadiz continued at least until the Late Miocene (Iribarren et al., 2007; Jiménez-Bonilla et al., 2016; Martín-Martín et al., 2018), accompanied by important strike-slip faulting (e.g. de Galdeano and Vera, 1992; Geel and Roep, 1998; Jimenez-Bonilla et al., 2020; Martín-Martín et al., 2018; Pérez-Valera et al., 2013). The Mallorca FTB development was coeval to the ESE-directed continental subduction of the South Iberian passive margin that underwent HP/LT metamorphism during the Early to Middle Miocene to the South-West of Mallorca (e.g. Booth-Rea et al., 2015; Kirchner et al., 2016; López Sánchez-Vizcaino et al., 2001; Platt et al., 2006)(Figure 12c). Furthermore, at an early stage of this renewed contractive reorganization, the Alpujarride complex underwent its final northward-directed thrusting phase that involved the previously thinned Alpujarride section (Azañón et al., 1997; Balanyá et al., 1997; 1998; Booth-Rea et al., 2005; Simancas, 2018). A process that was followed shortly, between the Early and Middle Miocene, by the final exhumation of the Alboran domain, formed by the Malaguide and Alpujarride complexes at the top of the orogenic wedge (e.g. Booth-Rea et al., 2004; García-Dueñas et al., 1992; Lonergan & Johnson, 1998; Lonergan & Platt, 1995; Platt et al., 2003; 2005)(Figure 12c). Extension coeval to FTB development at the front of the orogenic wedge has been a paradigmatic feature of the Betics that lasted in time at least until the Late Miocene and has been related to westwards roll-back of the Tethys lithosphere (Faccenna et al., 2004; Lonergan & White, 1997), which presently forms a 700 km long slab underlying the Betics and Rif (e.g. Bezada et al., 2013; Wortel and Spakman, 2000).

This Early Miocene to Langhian shortening phase also affected the Oligocene proto-Algerian basin that was inverted and incorporated into the newly developed orogenic wedge, its vestiges now present as amphibolites in the Kabylies or as extremely thinned sub-continental mantle emplaced in the crust as the Ronda peridotite of the Western Betics (Booth-Rea et al., 2005;

Fernandez et al., 2020; Garrido et al., 2011; Hidas et al., 2013; Marchesi et al., 2012) and the Collo peridotites in the Kabylies (Boullin & Kornprobst, 1974; Laouar et al., 2017; Leblanc & Temagoult, 1989). Part of the proto-Algerian basin is presently represented by the Western Alboran basin that drifted westwards hundreds of km in a forearc position behind the retreating Betic-Rif slab (Booth-Rea et al., 2007, Figure 12c).

The Early Miocene contractive reorganization of the region and the initial individualization of the Betic-Rif Tethys slab we propose was triggered by the collapse of a former transform that separated the AlKaPeCa orogenic domain from the rest of the western Tethys during the Palaeogene (Figure 12a, b). This transform fault and the North Balearic one, were probably inherited from the Mesozoic rifting stage and must have determined the present slab segmentation pattern of the Western Mediterranean. A similar transform was proposed by Cohen (1980) and Verges and Fernández (2012) in their model of flipped vergence between the Betic-Rif and Algerian Tell orogens. However, we give this structure a different role during the Western Mediterranean evolution. During the Palaeogene it transferred shortening form the AlKaPeCa orogenic domain towards the Atlas to the SW, permitting the preservation of an undeformed Tethys domain and the Nevado-Filabride Ocean Continent Transitional (OCT) Iberian domain to the W (Figure 12a). Meanwhile, later it bounded the domain of Oligocene orogenic collapse and development of the proto-Algerian basin (Figure 12b). Finally, during the Early Miocene, around 20 Ma, it probably played a key role after collapsing (e.g. Zhou et al., 2018) and initiating a new westward migrating subduction system under the load of the developing Alboran thrust stack (Figure 12c). This 3-D configuration is necessary to explain the puzzling structure of the Betics, where you have Oligocene back-arc lithosphere—represented by the Ronda subcontinental peridotite and its overlying crustal sequence intruded by suprasubduction dikes (Hidas et al., 2015; Marchesi et al., 2012) —directly overlying the Flysch Trough sedimentary cover, off scraped from the Tethys oceanic lithosphere (e.g. Lujan et al., 2006). Thus, this domain passed from being in a back-arc position related to NW-directed subduction in the Palaeogene, to be in a forearc position relative to a newly formed Eastward-directed subduction during the Early to Late Miocene (Figure 12d). Moreover, our proposal reconciles other data concerning the provenance of the Alboran domain, including Paleozoic rocks form the Malaguide and Alpujarride complexes, for which their age patterns of detrital zircon populations coincide with those from the Variscan European margin. This is especially clear for the Malaguide complex that is equivalent to the Paleozoic rocks presently outcropping in Menorca, the Northeastern Iberian massif and the South of France (Jabaloy et al., 2021).

5.3 Middle Miocene extension and isolation of the Mallorca FTB

This work shows that the Mallorca Island also underwent important extensional tectonics during the Middle Miocene coeval to the later oceanic opening of the Algero-Balearic basin (Figure 12d). This extension was polyphasic, first with the activity of multiple low-angle normal faults thinning the previous nappe stack at different structural levels and later followed by horst and graben development controlled by high-angle bounding normal faults. The grabens are mostly filled by Serravallian (14-11 Ma) alluvial sediments that show syn-rift internal progressive unconformities. Meanwhile, the pre-rift Late Burdigalian to Langhian Randa calcarenites are cut and strongly tilted by the extensional system, especially at the margins of the Manacor basin (Figure 9c).

The kinematics of extension where determined using slicken-sides, riedel faults, offset layers and rotated porphyroclast tails and show variable directions of transport with two main orthogonal sets indicating SW-NE and NW-SE extension (Figure 5). Although, this variability could reflect radial extension (Cespedes et al., 2001) we find that in general, the NE-SW-directed extensional system is older and more penetrative than the NW-SE-directed system.

Recognizing the presence of middle Miocene LANFs in the Serres the Llevant changes strongly the previously established structure of the region, which was interpreted entirely as contractive (e.g. Sabat et al., 1988). We have identified LANFs cutting contacts that were interpreted as inverted stratigraphic, for example between Jurassic limestones overlying Cretaceous marls. However, we find that the interpreted stratigraphic contact forming the reversed limb of a large NE-vergent recumbent syncline is actually a westward transport LANF that locally has small extensional horses formed by Triassic dolostones in between, and thus, the syncline is inexistent (Figs. 11a, b). We find the deepest nappe in the region we mapped is located to the SW of Manacor, although, presently it forms a horst structure hosting a series of NW-SE oriented folds in its core, bounded towards the East by a high-angle normal fault that cuts through Serravallian sediments in its hanging-wall (cross section B-B´, Figure 4).

The Serravallian grabens are segmented and offset laterally by SW-NE oriented strike-slip faults that we interpret as transfer faults developed during rifting (Figure 10). These faults show both dextral and sinistral kinematics and also bound the main Middle Miocene sedimentary depocenters in the island, like the Inca, Sa Pobla, Manacor, Felanitx and Santa Margalida basins (Figure 10). Dextral-oblique kinematics are observed in the Orient and Sant Joan faults (Booth-Rea et al., 2016), whilst sinistral kinematics are found in the Sencelles and Felanitx faults (Figure 10, Mas et al., 2014). These faults are also parallel to the Emile Baudot scarpment that roughly separates the Mallorca continental crust from the Algero-Balearic basin oceanic domain, and has been interpreted as a transform fault (Acosta et al., 2001; Etheve et al., 2016). In previous studies, the transfer faults described are mostly NW-SE directed, for example the North Balearic, Central, Catalan and Ibiza fault zones that accommodate the NW-SE opening of the Ligurian and Minorca basins (Maillard et al., 2020; Pellen et al., 2016). Strike-slip faults with this orientation also occur in the Mallorca island, some of which had been interpreted as transfer faults related to the Early Miocene FTB development (Gelabert, 1998; Sabat et al., 1988). We also find NW-SE trending faults with both sinistral and dextral strike-slip kinematics in the Llevant ranges. These faults are in general shorter than the NE-SW trending ones, which cut through most of the island. In other cases, we observe these faults with two sets of striae, indicating both normal and strike-slip displacements. The fact that you find parallel strike-slip faults with opposite kinematics in the same region is a characteristic of extensional transfer faults (e.g. Giaconia et al., 2014; Martínez-Martínez, 2006) and as such we interpret them, related to the NW-SE directed extensional system. Although, others, may be related to the older FTB development, for example, the thick sinistral fault zone cutting the Capdepera semigraben, which is itself cut by later dextral NE-SW trending faults (Figs. 7, 9b).

5.4. Middle Miocene extension in the Balearic promontory and the geodynamics of the Western Mediterranean

Serravallian extension in Mallorca coincided with a period of deep paleogeographic changes in Mallorca that evolved from a mostly marine realm to continental. A process that changed the sediment provenance in Mallorca. During the Burdigalian and Langhian, the turbidity systems in Mallorca, which were feed from the South (Rodríguez-Perea, 1984), include clasts of “exotic” Paleozoic grauwackes similar to the Carboniferous sequence cropping out in Menorca and to the Malaguide complex at the top of the Betic internal zones (Bourrouihl, 1983; Cohen, 1980; Hollister, 1942), for which a common origin has been recently proposed (Jabaloy et al., 2021). This implies the existence of a Paleozoic emerged hinterland of the Mallorca FTB located to the South during the Early Miocene, compatible with the Alboran domain (Figure 12c). During the Serravallian, no exotic clasts are found and the sediment provenance is from the local horsts that formed during extension, mainly coincident with the present ranges. Thus, extension actually coincided with a topographic build up in Mallorca, which could be related to flexural rebound after unloading it by extensional collapse of its orogenic hinterland and excision of its lithospheric mantle root, maybe driven by tectonic mechanism like slab detachment or edge-delamination. This later tectonic mechanism has been proposed by several authors to have occurred under the Betics during the Late Miocene until the Pliocene or Present, driving concomitant topographic uplift and thinning of the South Iberian lithosphere (Capella et al., 2020; Chertova et al., 2014; Duggen et al., 2003; García-Castellanos & Villaseñor, 2011; Mancilla et al., 2015; Negredo-Moreno et al., 2020; Sun & Bezada, 2020). Slab detachment may have initiated in the Serravallian further to the NE, under part of the Balearic promontory and later propagated towards the SW. This hypothesis is supported by similar deformational behaviors followed by topographic rebound in the Eastern Betics and Mallorca, including the close association between extension and strike-slip transfer-fault development as proposed for the southern margin of Mallorca (Acosta et al., 2001; Driussi et al., 2015a) and the Eastern Betics (Giaconia et al., 2014; Mancilla et al., 2015; Pérez-Valera et al., 2013). In both regions extensional tectonics propagated into the external FTB with two orthogonal directions of extension, both parallel and transverse to the orogen trend resulting in an overall radial extension (Booth-Rea et al., 2004; Rodríguez-Fernández et al., 2011). Furthermore, extension and related strike-slip deformation was accompanied in both regions by Neogene clockwise paleomagnetic rotation in the order of 35-40º (e.g. Freeman et al., 1989; Lonergan & White, 1997; Mattei et al., 2006). In the Eastern Betics the subducted South-Iberian domain (Nevado-Filabride complex) was exhumed by SW-directed brittle-ductile extensional detachments in great part during the Middle to Late Miocene (Martínez-Martínez & Azañón, 1997; Martínez-Martínez et al., 2002), followed by important thinning after, in the Late Tortonian, producing SE-directed extension along the Almenara detachment (Booth-Rea et al., 2012). In general, this extension has been related to the opening of the western part of the Algerian basin between the Middle and Late Miocene in a back-arc setting (Booth-Rea et al., 2007; 2018b; Mauffret et al., 2004).

The different ages of back-arc rifting in the Western Mediterranean basins correlate with contrasting heat flow values in the region, with a clear increase from East to West in the Algero-Balearic basin, suggesting a Middle Miocene or younger age for opening to the West, and an older Oligocene to Early Miocene age for the Ligurian and central areas of the Algero-Balearic basins (Poort et al., 2020). Although, heat flow values increase also towards the Southeastern end of the Algerian basin, south of Sardinia. Meanwhile, the Valencia Trough shows relatively low heat flow, compatible with an older Mesozoic or Cenozoic rifting phase. Whilst the Mallorca domain extended in the Middle Miocene, the Betics extension propagated from the Internal Zones towards the Betic FTB in the Late Miocene, producing sedimentary depocentres that seal the contact between the two domains like the Fortuna, Lorca, Guadix-Baza and Granada basins (Booth-Rea et al., 2004; de la Peña et al., 2020b; Rodríguez-Fernández et al., 2011). Meanwhile, the Easternmost Algerian basin followed a parallel evolution to its westernmost segment, but with an opposite eastward's direction of extension (Figure 12d). This extension propagated into Northern Tunisia in the Late Miocene producing the collapse of the Tunisian Tell (Booth-Rea et al., 2018b).

Presently, the Balearic promontory is bounded to the south by the oceanic Algero-Balearic basin along the steep Emile Baudot and Mazarron scarpments, interpreted as transform boundaries (Acosta et al., 2001; Driussi et al., 2015a; Etheve et al., 2016). These faults, together with other parallel dextral ones cropping out onshore, like the Crevillente, Alpujarras, Torcal or the Orient fault in Mallorca probably contributed to the west-south westward stretching and displacement of the Alboran domain during the Middle to Late Miocene (e.g. Giaconia et al., 2014; Mancilla et al., 2015; Pérez-Valera et al., 2013). During the Serravallian the Balearic promontory and the Betic internal zones shared very similar insular vertebrate glirid fauna (Bover et al., 2008; Suarez et al., 1993). From where we can determine that either the Alboran domain formed a large archipelago together with the Balearic Promontory at the time, or it traveled southwestwards a long distance since the Middle Miocene separating from Mallorca, following the roll-back of the Alboran slab (e.g. Booth-Rea et al., 2007; Chertova et al., 2014; Driussi et al., 2015a; Faccenna et al., 2004; Lonergan & White, 1997)(Figure 12d). Considering that a Paleozoic hinterland existed to the south of Mallorca during the Early Miocene, the second option or a combination of the two seems more realistic. Towards the SW, the Betic hinterland, represented by the Alboran domain, was separated at the time from Iberia by a deep foredeep basin in the external Betics (de Galdeano and Vera, 1992; Geel et al., 1992; Martín-Martín et al., 2018). The Valencia Trough was the NE continuation of the External Betic Serravallian foredeep, although the thrust front there had resumed its activity after the Langhian (Etheve et al., 2016; Leprêtre et al., 2018). This domain and the Great and Petit Kabilies domains were also separated from the African emerged land to the South by an Early to Middle Miocene foredeep along Northern Algeria and Tunisia (Guerrera et al., 2005; Jolivet et al. 2006; Roure et al., 2012, Figure 12d). Thus, we propose the Alboran domain archipelago was driven southwestwards in a forearc, and its corresponding volcanic arc, setting until the Late Miocene, producing the present isolation of the Mallorca FTB from its corresponding Betic hinterland. This model implies very large displacements, in the order of 600 km between Mallorca and its corresponding Paleozoic hinterland since the Early Miocene, comparable to the length of the subducted Tethyan lithospheric mantle slab presently underlying the Betics (e.g. Bezada et al., 2013; Faccenna et al., 2004). This hypothesis contrasts with models suggesting very minor displacements, below 200, or even 100 km, for the Betic hinterland, respect to Iberia (e.g. Frasca et al., 2015, Pedrera et al., 2020; Verges & Fernández, 2012). However, we believe it is the only one that explains the great diversity of available geological and geophysical data presented above, including sediment provenance, detrital zircon population ages, subducted slab bodies, tectonic evolution, Western Mediterranean basins development, fossil faunal dispersal and the extensional collapse of the Mallorca and Betic FTB´s.

Finally, this work offers clues to the distribution of emerged forearc and volcanic arc land masses in the Western Mediterranean, isolated by marine gateways from Africa and Iberia between the Early Miocene and the Tortonian, when terrestrial vertebrates from Iberia mainland are found in sediments overlying the Alboran domain (Martín-Suarez et al., 2012). A process that contributed to the present biodiversity hotspot of the Southwestern Mediterranean (Hewit, 2011), in addition to the Messinian land bridge, which connected the Eastern Rif and SE Iberia (Booth-Rea et al., 2018a).

6 Conclusions

Structural analysis of the Llevant ranges in Mallorca show that two Cenozoic rifting phases predate and postdate the main Early Miocene shortening and FTB development in Mallorca. The earlier extensional phase produced NW-directed extensional detachments and semigrabens filled by Oligocene breccias, coeval to the opening of the Liguro-Provencal basin and extensional collapse of AlKaPeCa (Figure 12b). Oligocene extension in Mallorca is not precisely dated and may have continued up to the Aquitanian, although, dated sediments of this age are scarce in the island. This extension produced the first alpine structures observed in Mallorca after its hinterland position respect to the AlKaPeCa orogenic domain during the Paleocene-Eocene (Figure 12a).

The Mallorca promontory underwent Burdigalian to Langhian WNW-directed shortening and the development of its FTB structure coeval to the subduction of the Southeast Iberian passive margin and the birth of the Betic-Rif eastward dipping subduction system (Figure 12c). The second rifting phase produced the extensional collapse of the Mallorca FTB during the Middle Miocene, coinciding with the opening of central parts of the Algero-Balearic back-arc basin and the westwards drift of the Alboran domain and the proto-Algerian basin, presently represented by the western Alboran basin (Figure 12c).

The Serravallian extension was radial, initiating mostly with NE-SW directed extension and later evolving towards NW-SE directed transport. This rifting was accommodated along LANFs that cut through the previous FTB thrust pile, which were later cut by high-angle normal faults bounding the main Middle-Miocene sedimentary depocenters. The basins in Mallorca are strongly segmented by SW-NE oriented strike-slip faults, both sinistral and dextral, like the Orient, Sencelles, Sant Joan and Felanitx that acted as transfer faults of the Serravallian extensional system, which are parallel to the present transform continent-ocean transition along the Emile-Baudot scarpment.

Middle Miocene extension coincided with topographic build up in Mallorca, manifested by continentalization of the region and a change in the sediment provenance that became sourced from nearby horst highs. We relate this topographic development and coeval extension to flexural and isostatic rebound after initial detachment or tearing of the Betic-Rif mantle slab to the South of the BP.

The Mallorca FTB developed coeval and with the same kinematics as the Betic FTB, however, shortening in the Betics continued through the Middle and Late Miocene, coeval to the extensional collapse of Mallorca and the opening of the western domain of the Algero-Balearic basin, following the retreating Betic-Rif slab (Figure 12c).

Our data, thus supports that the Mallorca FTB formed part of the Betic orogen during the Early Miocene and later became stranded and isolated from its hinterland domain by the development of the Central and Western segments of the Algero-Balearic basin in the Middle to Late Miocene. A process that entailed important W to SW-directed displacements of the Betic hinterland in a forearc domain, as an archipelago, through the Western Mediterranean until its docking to SE Iberia in the Tortonian.

Acknowledgments and Data

This work was financed by the Spanish Science and Innovation Ministry ProjectPID2019-107138RB-I00/SRA (State Research Agency /10.13039/501100011033) and the "Junta de Andalucía" Project P18-RT-36332 and research groups RMN-131 and RMN-148. The fault station data are available in supplementary material.

References

Abbassene, F., Chazot, G., Bellon, H., Bruguier, O., Ouabadi, A., Maury, R.C., et al. (2016). A 17Ma onset for the post-collisional K-rich calc-alkaline magmatism in the Maghrebides: Evidence from Bougaroun (northeastern Algeria) and geodynamic implications. *Tectonophysics, 674*, 114-134, https://doi.org/10.1016/j.tecto.2016.02.013

Acosta, J., Muñoz, A., Herranz, P., Palomo, C., Ballesteros, M., Vaquero, M. & Uchupi, E. (2001). Geodynamics of the Emile Baudot Escarpment and the Balearic Promontory, western Mediterranean. *Marine and Petroleum Geology*, *18*, 349-369, https://doi.org/10.1016/S0264-8172(01)00003-4

Aïdi, C., Beslier, M.-O., Yelles-Chaouche, A.K., Klingelhoefer, F., Bracene, R., Galve, A., et al. (2018). Deep structure of the continental margin and basin off Greater Kabylia, Algeria – New insights from wide-angle seismic data modeling and multichannel seismic interpretation. *Tectonophysics*, 728-729, 1-22, https://doi.org/10.1016/j.tecto.2018.01.007

Alvaro-López, M., del Olmo, P., Ramírez del Pozo, J., Sabat, F. & Barnolas, A. (1983). *MAGNA, Hoja 700 Manacor. Mapa Geológico de España 1:50.000.* Instituto Geológico y Minero de España, Madrid.

Alvaro, M., Barnolas, A., del Olmo, P., Ramírez del Pozo, J. & Simo, A. (1984). El Neógeno de Mallorca: caracterización sedimentológica y bioestratigráfica. *Boletín Geológico y Minero XCV-I,* 3-25.

Alvaro, M. (1987). La tectónica de cabalgamientos de la Sierra Norte de Mallorca, Islas Baleares. *Boletín Geológico y Minero*, *98(5),* 34-41.

Alvaro, A., Barnolas, A., Cabra, P., Comas Rengifo, M. J., Fernández López, S. R., Goy, A., et al. (1989). El Jurásico de Mallorca (Islas Baleares). *Cuadernos de Geología Ibérica*, *13,* 67-120.

Anglada-Guajardo, E. & Serra-Kiel, J. (1986). El Paleógeno y tránsito al Neógeno en el área del Macizo de Randa, Mallorca. *Boletín Geológico y Minero*, *97(5),* 40-49.

Angrand, P., Mouthereau, F., Masini, E. & Asti, R. (2020). A reconstruction of Iberia accounting for Western Tethys–North Atlantic kinematics since the late-Permian–Triassic. *Solid Earth*, *11(4)*, 1313-1332, https://doi.org/10.5194/se-11-1313-2020

Arab, M., Rabineau, M., Deverchere, J., Bracene, R., Belhai, D., Roure, F., Marok, A., Bouyahiaoui, B., Grajeon, D., Andriessen, P. & Sage, F. (2016). Tectonostratigraphic evolution of the eastern Algerian margin and basin from seismic data and onshore-offshore correlation. *Marine and Petroleum Geology*, *77*, 1355-1375, https://doi.org/10.1016/j.marpetgeo.2016.08.021

Ayala, C., Torne, M. & Roca, R. (2015). A review of the current knowledge of the crustal and lithospheric structure of the Valencia Trough Basin. *Boletín Geológico y Minero*, *126(2-3),* 533-552.

Ayala, C., Pous, J., Sàbat, F., Casas, A., Rivero, Ll. & Gelabert, B. (1994). Modelización gravimétrica de la isla de Mallorca. *Revista de la Sociedad Geológica de España, 7 (3-4),* 215-227.

Azañón, J.M., Crespo-Blanc, A. & García-Dueñas, V. (1997). Continental collision, crustal thinning and nappe forming during the pre-Miocene evolution of the Alpujarride Complex (Alboran Domain, Betics). *Journal of Structural Geology*, *19,* 1055-1071, https://doi.org/10.1016/S0191-8141(97)00031-X

Azzaroli, A. (1990). Palaeogeography of terrestrial vertebrates in the perityrrhenian area. *Palaeogeography, palaeoclimatology, palaeoecology, 77*(1), 83-90.

Badji, R., Charvis, P., Bracene, R., Galve, A., Badsi, M., Ribodetti, A., Benaissa Z., Klingelhoefer, F., Medaouri, M. & Beslier, M. O. (2015). Geophysical evidence for a transform margin offshore Western Algeria: a witness of a subduction-transform edge propagator? *Geophysical Journal International, 200(2),* 1029-1045, https://doi.org/10.1093/gji/ggu454

Balanyá, J.C., García-Dueñas, V., Azañón, J.M. & Sánchez-Gómez, M. (1997). Alternating contractional and extensional events in the Alpujarride nappes of the Alboran Domain (Betics, Gibraltar Arc). *Tectonics*, *16*, 226-238, https://doi.org/10.1029/96TC03871

Balanyá, J.C., Garcia-Duenas, V., Azanon, J.M., Sanchez-Gomez, M. (1998). Comment on "Alternating contractional and extensional events in the Alpujarride nappes of the Alboran Domain (Betics, Gibraltar arc)" - Reply. *Tectonics* 17, 977-981.

Balanyá, J.C., Crespo-Blanc, A., Azpiroz, M.D., Exposito, I. & Luján, M. (2007). Structural trend line pattern and strain partitioning around the Gibraltar Arc accretionary wedge: Insights as to the mode of orogenic arc building. Tectonics 26, https://doi.org/10.1029/2005TC001932

Barnolas, A., Pares, J.M., Sabat, F., Álvaro, M., Ramírez del Pozo, J., Alvarado, M., et al. (1983). *MAGNA 725 Felanitx, Mapa Geológico de España 1:50.000. IGME, Madrid.*

Benedicto, A., Ramos-Guerrero, E., Casas, A., Sabat, F. & Baron, A. (1993). Evolución tectonosedimentaria de la cubeta neógena de Inca (Mallorca). *Revista de la Sociedad Geológica de España*, *6,* 167-17.

Bezada, M. J., Humphreys, E. D., Toomey, D. R., Harnafi, M., Dávila, J. M. & Gallart, J. (2013). Evidence for slab rollback in westernmost Mediterranean from improved upper mantle imaging. *Earth Planetary Science Letters*, *368*, 51-60, http://dx.doi.org/10.1016/j.epsl.2013.02.024

Booth-Rea, G., Azanon, J.M. & Garcia-Duenas, V. (2004). Extensional tectonics in the northeastern Betics (SE Spain): case study of extension in a multilayered upper crust with contrasting rheologies. *Journal of Structural Geolgy, 26*, 2039-2058, https://doi.org/10.1016/j.jsg.2004.04.005

Booth-Rea, G., Azanón, J.M., Martínez-Martínez, J.M., Vidal, O. & García-Dueñas, V. (2005). Contrasting structural and P-T evolution of tectonic units in the southeastern Betics: Key for understanding the exhumation of the Alboran Domain HP/LT crustal rocks (western Mediterranean). *Tectonics*, *24*, 1-23, https://doi.org/10.1029/2004TC001640

Booth-Rea, G., Ranero, C., Martínez-Martínez, J.M. & Grevemeyer, I. (2007). Crustal types and Tertiary tectonic evolution of the Alborán sea, western Mediterranean. *Geochemistry, Geophysics, Geosistems, 8*, Q10004, doi: 10010.11029/12007GC001661

Booth-Rea, G., Azañón, J.M., Roldán, F.J., Moragues, L., Pérez-Peña, V. & Mateos, R.M. (2016). WSW-ENE extension in Mallorca, key for integrating the Balearic Promontory in the Miocene evolution of the western Mediterranean. *GeoTemas 16, 81-84.*

Booth-Rea, G., Ranero, C.R. & Grevemeyer, I. (2018a). The Alboran volcanic-arc modulated the Messinian faunal exchange and salinity crisis. *Scientific Reports 8*, http://dx.doi.org/10.1038/s41598-018-31307-7

Booth-Rea, G., Gaidi, S., Melki, F., Marzougui, W., Azañón, J.M., Zargouni, F., Galvé, J. P. & Pérez-Peña, J. V. (2018b). Late Miocene Extensional Collapse of Northern Tunisia. *Tectonics 37*, 1626-1647, https://doi.org/10.1029/2017TC004846

Bott, M.H.P. (1959). The mechanics of oblique slip faulting. *Geological Magazine*, *96*, 109-117, https://doi.org/10.1017/S0016756800059987

Boukhalfa, K., Soussi, M., Ozcan, E., Banerjee, S., & Tounekti, A. (2020). The Oligo-Miocene siliciclastic foreland basin deposits of northern Tunisia: Stratigraphy, sedimentology and paleogeography. *Journal of African Earth Sciences, 170*, 103932.

Bouillin, J. P. & Kornprobst, J. (1974). Associations ultrabasiques de Petite Kabylie; peridotites de type alpin et complexe stratifie; comparaison avec les zones internes betico-rifaines. *Bulletin de la Société Géologique de France, 7*(2), 183-194.

Boullin, J.P., Duran-Delga, M. & Olivier, P. (1986). Betic Rifian and Tyrrhenian Arc: Distinctive features, genesis and development stages, in: Wezel, F. (Ed.), The Origin of Arcs. *Elsevier, New York,* pp. 281-304, https://doi.org/10.1016/B978-0-444-42688-8.50017-5

Bourrouilh, R. (1983). Estratigrafía, sedimentología y tectónica de la isla de Menorca y del Noreste de Mallorca (Baleares). La terminación nororiental de las Cordilleras Béticas en el Mediterráneo occidental. *Memorias del Instituto Geológico y Minero de España, 99*, 672 p.

Bover, P., Quintana, J. & Alcover, J. A. (2008). Three islands, three worlds: paleogeography and evolution of the vertebrate fauna from the Balearic Islands. *Quaternary International*, *182(1),* 135-144, https://doi.org/10.1016/j.quaint.2007.06.039

Bruguier, O., Bosch, D., Caby, R., Vitale-Brovarone, A., Fernandez, L., Hammor, D. et al. (2017). Age of UHP metamorphism in the Western Mediterranean: insight from rutile and minute zircon inclusions in a diamond-bearing garnet megacryst (Edough Massif, NE Algeria). *Earth and Planetary Science Letters*, *474*, 215-225, https://doi.org/10.1016/j.epsl.2017.06.043

Burrus, J. (1984). Contribution to a geodynamic synthesis of the Provencal Basin (north-western Mediterranean). *Marine Geology, 55*(3-4), 247-269.

Capella, W., Spakman, W., van Hinsbergen, D. J., Chertova, M. V. & Krijgsman, W. (2020). Mantle resistance against Gibraltar slab dragging as a key cause of the Messinian Salinity Crisis. *Terra Nova*, *32(2),* 141-150, https://doi.org/10.1111/ter.12442

Casas, J. M. & Sabat, F. (1987). An example of three-dimensional analysis of thrust-related tectonites. *Journal of Structural Geology*, *9(5-6):* 647-657, https://doi.org/10.1016/0191-8141(87)90149-0

Céspedes, A., Giménez, J. & Sàbat, F. (2001). Caracterización del campo de esfuerzos neógenos en Mallorca mediante el análisis de poblaciones de fallas. *Geogaceta 30*, 199-202.

Chazot, G., Abbassene, F., Maury, R. C., Déverchère, J., Bellon, H., Ouabadi, A. & Bosch, D. (2017). An overview on the origin of post-collisional Miocene magmatism in the Kabylies (northern Algeria): evidence for crustal stacking, delamination and slab detachment. *Journal of African Earth Sciences, 125*, 27-41. https://doi.org/10.1016/j.jafrearsci.2016.10.005

Cherchi, A. & Montadert, L. (1982). Oligo-Miocene rift of Sardinia and the early history of the western Mediterranean basin. *Nature*, *298(5876)*, 736-739, https://doi.org/10.1038/298736a0

Chertova, M.V., Spakman, W., Geenen, T., van den Berg, A.P. & van Hinsbergen, D.J.J. (2014). Underpinning tectonic reconstructions of the western Mediterranean region with dynamic slab evolution from 3-D numerical modeling. *Journal of Geophysical Research-Solid Earth*, *119*, 5876-5902, https://doi.org/10.1002/2014JB011150

Cohen, C. R. (1980). Plate tectonic model for the Oligo-Miocene evolution of the western Mediterranean. *Tectonophysics*, *68*(3-4), 283-311.

Colom, G. (1973) Esbozo de las principales lito-facies de los depósitos jurásico-cretáceos de las Baleares y su evolución preorogénica. *Memorias de la Real Academia de Ciencias 25 (2),* 116 p.

Colom, G. (1980). Sobre la posible extensión del Aquitaniense marino a lo largo de las sierras de Levante de Mallorca. *Bolletí de la Societat d'Història Natural de les Balears, 24,* 7-14.

Colom, G. & Sacares, J. (1968). Hallazgo del Aquitaniense marino en Mallorca. *Acta geológica hispánica, 3(5),* 135-137.

Costamagna, L. G. & Schäfer, A. (2013). The Cixerri Fm (Middle Eocene-Early Oligocene): analysis of a "Pyrenean" continental molassic system in southern Sardinia. *Journal of Mediterranean Earth Sciences Special Issue, 2013*, 41-44.

de Capoa, P., Di Staso, A., Perrone, V. & Zaghloul, M. N. (2007). The age of the foredeep sedimentation in the Betic–Rifian Mauretanian units: a major constraint for the reconstruction of the tectonic evolution of the Gibraltar Arc. *Comptes Rendus Geoscience, 339(2),* 161-170, https://doi.org/10.1016/j.crte.2007.01.003

de Galdeano, C. S. & Vera, J. A. (1992). Stratigraphic record and palaeogeographical context of the Neogene basins in the Betic Cordillera, Spain. *Basin Research, 4(1),* 21-36 https://doi-org/10.111/j.1365-217.1992

de la Peña, L., Grevemeyer, I., Kopp, H., Díaz, J., Gallart, J., Booth-Rea, G., Gràcia, E. & Ranero, C. R. (2020a). The lithospheric structure of the Gibraltar Arc System from Wide Angle Seismic data. *Journal of Geophysical Research: Solid Earth,* e2020JB019854, https://doi.org/10.1029/2020JB019854

de la Peña, L. G., Ranero, C. R., Gràcia, E. & Booth-Rea, G. (2020b). The evolution of the westernmost Mediterranean basins. Earth-Science Reviews, 103445, https://doi.org/10.1016/j.earscirev.2020.103445

Diaz, J. & Gallart, J. (2009). Crustal structure beneath the Iberian Peninsula and surrounding waters: a new compilation of deep seismic sounding results. *Physics of the Earths and Planetary Interiors, 173,* 181-190, https://doi.org/10.1016/j.pepi.2008.11.008

Diaz, J., Gil, A., & Gallart, J. (2013). Uppermost mantle seismic velocity and anisotropy in the Euro-Mediterranean region from Pn and Sn tomography. *Geophysical Journal International*, 192(1), 310-325. https://doi.org/10.1093/gji/ggs016

Donoso, J. G., Linares, D., Pascual, I. & Serrano, F. (1982). Datos sobre la edad de las secciones del Mioceno Inferior de Port d'es Canonge y Randa (Mallorca). *Bolletí de la Societat d'Història Natural de les Balears, 26,* 229-232.

Driussi, O., Briais, A. & Maillard, A. (2015a). Evidence for transform motion along the South Balearic margin and implications for the kinematics of opening of the Algerian basin. *Bulletin de la Société Géologique de France, 186(4-5),* 353-370, https://doi.org/10.2113/gssgfbull.186.4-5.353

Driussi, O., Maillard, A., Ochoa, D., Lofi, J., Chanier, F., Gaullier, V., Briais, A., Sage, F., Sierro, F. & Garcia, M. (2015b). Messinian Salinity Crisis deposits widespread over the Balearic Promontory: Insights from new high-resolution seismic data. *Marine and Petroleum Geology, 66,* 41-54, https://doi.org/10.1016/j.marpetgeo.2014.09.008

Duggen, S., Hoernle, K., van den Bogaard, P., Rupke, L. & Morgan, J.P. (2003). Deep roots of the Messinian salinity crisis. *Nature 422*, 602-606, https://doi.org/10.1038/nature01553

Duggen, S., Hoernle, K., van den Bogaard, P. & Harris, C. (2004). Magmatic evolution of the Alboran region: The role of subduction in forming the western Mediterranean and causing the Messinian Salinity Crisis. *Earth Planet Science Letters 218*, 91-108, https://doi.org/10.1016/S0012-821X(03)00632-0

Duggen, S., Hoernle, K., Klügel, A., Geldmacher, J., Thirlwall, M., Hauff, F., ... & Oates, N. (2008). Geochemical zonation of the Miocene Alborán Basin volcanism (westernmost Mediterranean): geodynamic implications. *Contributions to Mineralogy and Petrology*, *156*(5), 577

El-Sharkawy, A., Meier, T., Lebedev, S., Behrmann, J. H., Hamada, M., Cristiano, L., Weidle, C. & Köhn, D. (2020). The Slab Puzzle of the Alpine-Mediterranean Region: Insights from a New, High-Resolution, Shear Wave Velocity Model of the Upper Mantle. *Geochemistry, Geophysics, Geosystems, 21(8)*, https://doi.org/10.1029/2020GC008993

Etheve, N., de Lamotte, D. F., Mohn, G., Martos, R., Roca, E. & Blanpied, C. (2016). Extensional vs contractional Cenozoic deformation in Ibiza (Balearic Promontory, Spain): Integration in the West Mediterranean back-arc setting. *Tectonophysics, 682*, 35-55, https://doi.org/10.1016/j.tecto.2016.05.037

Etheve, N., Mohn, G., Frizon de Lamotte, D., Roca, E., Tugend, J. & Gómez-Romeu, J. (2018). Extreme Mesozoic crustal thinning in the eastern Iberia margin: the example of the Columbrets Basin (Valencia Trough). *Tectonics*, *37*(2), 636-662, https://doi.org/10.1002/2017TC004613

Faccenna, C., Piromallo, C., Crespo-Blanc, A., Jolivet, L. & Rossetti, F. (2004). Lateral slab deformation and the origin of the western Mediterranean arcs. *Tectonics 23*, https://doi.org/10.1029/2002TC001488

Faccenna, C., Becker, T. W., Auer, L., Billi, A., Boschi, L., Brun, J. P. & Piromallo, C. (2014). Mantle dynamics in the Mediterranean. *Reviews of Geophysics, 52(3),* 283-332, https://doi.org/10.1002/2013RG000444

Faccenna, C. & Becker, T. W. (2020). Topographic expressions of mantle dynamics in the Mediterranean. *Earth-Science Reviews, 209,* 103327, https://doi.org/10.1016/j.earscirev.2020.103327

Fernandez, L., Bosch, D., Bruguier, O., Hammor, D., Caby, R., Arnaud, N., Monié, P., Abdallah, N., Verdoux, P., Ouabadi, A. & Laouar, R. (2020). Vestiges of a fore-arc oceanic crust in the Western Mediterranean: Geochemical constraints from North-East Algeria. Lithos, 105649, https://doi.org/10.1016/j.lithos.2020.105649

Ferrandini, J., Gattacceca, J., Ferrandini, M., Deino, A. & Janin, M. C. (2003). Chronostratigraphy and paleomagnetism of Oligo-Miocene deposits of Corsica (France): geodynamic implications for the liguro-provencal basin spreading. *Bulletin de la Société géologique de France, 174(4)*, 357-371, https://doi.org/10.2113/174.4.357

Fichtner, A. & Villaseñor, A. (2015). Crust and upper mantle of the western Mediterranean – Constraints from full-waveform inversion. *Earth Planet Science Letters 428*, 52-62, https://doi.org/10.3997/2214-4609.201412905

Fornos J.J., Marzo, M., Pomar, L., Ramos-Guerrero, E. & Rodríguez-Perea, A. (1991). Evolución tectosedimentaria y anàlisis estratigráfico del Terciario de la isla de Mallorca. En: F. Colombo (Ed): *I Congreso del Grupo Español del Terciario, Vic. Libro Guía Excursión nº 2. Dept. G.D.G.P., Universitat de Barcelona,* 145 p.

Frasca, G., Gueydan, F. & Brun, J. P. (2015). Structural record of Lower Miocene westward motion of the Alboran Domain in the Western Betics, Spain. *Tectonophysics*, *657*, 1-20.

Freeman, R., Sabat, F., Lowrie, W. & Fontboté, J. M. (1989). Paleomagnetic results from Mallorca (Balearic Islands, Spain). *Tectonics, 8(3)*, 591-608, https://doi.org/10.1029/TC008i003p00591

Galindo-Zaldívar, J. & González-Lodeiro, F. (1988). Faulting phase differentiation by means of computer search on a grid pattern. *Annales Tectonicae 2(2),* 90-97.

Gallais, F., Graindorge, D., Gutscher, M. A. & Klaeschen, D. (2013). Propagation of a lithospheric tear fault (STEP) through the western boundary of the Calabrian accretionary wedge offshore eastern

Sicily (Southern Italy). *Tectonophysics*, *602*, 141-152, https://doi.org/10.1016/j.tecto.2012.12.026

Garcia-Castellanos, D. & Villaseñor, A. (2011). Messinian salinity crisis regulated by competing tectonics and erosion at the Gibraltar arc. *Nature, 480(7377)*, 359-363, https://doi.org/10.1038/nature10651

García-Dueñas, V., Balanyá, J.C. & Martínez-Martínez, J.M. (1992). Miocene extensional detachments in the outcropping basement of the Northern Alboran Basin (Betics) and their tectonic implications. *Geo-Marine Letters 12*, 88-95, https://doi.org/10.1007/BF02084917

Garrido, C.J., Gueydan, F., Booth-Rea, G., Precigout, J., Hidas, K., Padron-Navarta, J.A. & Marchesi, C. (2011). Garnet lherzolite and garnet-spinel mylonite in the Ronda peridotite: Vestiges of Oligocene backarc mantle lithospheric extension in the western Mediterranean. *Geology 39*, 927-930, https://doi.org/10.1130/G31760.1

Geel, T. & Roep, T.B. (1998). Oligocene to middle Miocene basin development in the Eastern Betic Cordilleras, SE Spain (Velez Rubio Corridor-Espuna): reflections of West Mediterranean plate-tectonic reorganizations. *Basin Research 10*, 325-343, https://doi.org/10.1046/j.1365-2117.1998.00068.x

Geel, T., Roep, T. B., Ten Kate, W. & Smit, J. (1992). Early-Middle Miocene stratigraphic turning points in the Alicante region (SE Spain): reflections of Western Mediterranean plate-tectonic reorganizations. Sedimentary Geology, 75(3-4), 223-239, https://doi.org/10.1016/0037-0738(92)90094-8

Gelabert, B., Sabat, F., y Rodríguez-Perea, A. (1992). A structural outline of the Serra de Tramuntana of Mallorca (Balearic Islands). *Tectonophysics, 203(1-4)*, 167-183, https://doi.org/10.1016/0040-1951(92)90222-R

Gelabert, B., Sàbat, F. & Rodríguez-Perea, A. (2002). A new proposal for the late Cenozoic geodynamic evolution of the western Mediterranean. *Terra Nova*, *14*(2), 93-100, https://doi.org/10.1046/j.1365-3121.2002.00392.x

Gelabert, B. (1998). La estructura geológica de la mitad occidental de la Isla de Mallorca. *Colección Memorias, V. 104. Instituto Geológico y Minero de España, Madrid, 129 p.*

Giaconia, F., Booth-Rea, G., Martínez-Martínez, J.M., Azañõn, J.M., Storti, F. & Artoni, A. (2014). Heterogeneous extension and the role of transfer faults in the development of the southeastern Betic basins (SE Spain). Tectonics 33, 2467-2489, https://doi.org/10.1002/2014TC003681

Gómez de la Peña, L., Grevemeyer, I., Kopp, H., Díaz, J., Gallart, J., Booth-Rea, G. & Ranero, C. R. (2020). The lithospheric structure of the Gibraltar Arc System from Wide Angle Seismic data. *Journal of Geophysical Research: Solid Earth,* e2020JB019854, https://doi.org/10.1029/2020JB019854

González-Donoso, J.M., Linares, D., Pascual, I. & Serrano, F. (1982). Datos sobre la edad de las secciones del Mioceno inferior de Es port des Canonge y de Randa (Mallorca). *Bolletí de la Societat d'Història Natural de Balears, 26*: 229-232.

González-Jiménez, J. M., Marchesi, C., Griffin, W. L., Gervilla, F., Belousova, E. A., Garrido, C. J., Romero, R., Talavera, C., Leisen, M., O´Reilly, S. Y., Barra, F. & Martin, L. (2017). Zircon recycling and crystallization during formation of chromite-and Ni-arsenide ores in the subcontinental lithospheric mantle (Serranía de Ronda, Spain). Ore Geology Reviews, 90, 193-209.

Govers, R. & Wortel, M. J. R. (2005). Lithosphere tearing at STEP faults: Response to edges of subduction zones. *Earth and Planetary Science Letters, 236*(1-2), 505-523.

Grevemeyer, I., Ranero, C. R., Leuchters, W., Booth-Rea, G. & Gallart, J. (2011). Seismic constraints on the nature of crust in the Algerian-Balearic Basin-implications for lithospheric construction at back-arc spreading centres. *American Geophysical Union, Fall Meeting, 2011*, T53D-04

Guerrera, F., Martín-Martín, M., Perrone, V. & Tramontana, M. (2005). Tectono-sedimentary evolution of the southern branch of the Western Tethys (Maghrebian Flysch Basin and Lucanian Ocean): consequences for Western Mediterranean geodynamics. *Terra Nova, 17(4)*, 358-367, https://doi.org/10.1111/j.1365-3121.2005.00621.x

Guimerà, J., Mas, R. & Alonso, Á. (2004). Intraplate deformation in the NW Iberian Chain: Mesozoic extension and Tertiary contractional inversion. *Journal of the Geological Society, 161(2)*, 291-303, https://doi.org/10.1144/0016-764903-055

Handy, M. R., Schmid, S. M., Bousquet, R., Kissling, E. & Bernoulli, D. (2010). Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps. *Earth-Science Reviews*, *102*(3-4), 121-158.

Heymes, T., Monié, P., Arnaud, N., Pêcher, A., Bouillin, J.P. & Compagnoni, R. (2010). Alpine tectonics in the Calabrian–Peloritan belt (southern Italy): New 40Ar/39Ar data in the Aspromonte Massif area*. Lithos, 114*, 451-472, https://doi.org/10.1016/j.lithos.2009.10.011

Hidas, K., Booth-Rea, G., Garrido, C.J., Martínez-Martínez, J.M., Padrón-Navarta, J.A., Konc, Z., et al. (2013). Backarc basin inversion and subcontinental mantle emplacement in the crust: Kilometre-scale folding and shearing at the base of the proto-alborán lithospheric mantle (Betic Cordillera, southern Spain). *Journal of the Geological Society 170,* 47-55, https://doi.org/10.1144/jgs2011-151

Hidas, K., Varas-Reus, M. I., Garrido, C. J., Marchesi, C., Acosta-Vigil, A., Padron-Navarta, J. A., Targuisti, K. & Konc, Z. (2015). Hyperextension of continental to oceanic-like lithosphere: The record of late gabbros in the shallow subcontinental lithospheric mantle of the westernmost Mediterranean. *Tectonophysics, 650*, 65-79.

Hidas, K., Konc, Z., Garrido, C. J., Tommasi, A., Vauchez, A., Padrón-Navarta, J. A., Marchesi, C., Booth-Rea, G., Acosta-Vigil, A., Szabó, C., Varas-Reus, M. I. & Gervilla, F. (2016). Flow in the western Mediterranean shallow mantle: Insights from xenoliths in Pliocene alkali basalts from SE Iberia (eastern Betics, Spain). *Tectonics, 35(11)*, 2657-2676, https://doi.org/10.1002/2016TC004165

Hidas, K., Garrido, C., Booth-Rea, G., Marchesi, C., Bodinier, J. L., Dautria, J. M., Louni-Hacini, A. & Azzouni-Sekkal, A. (2019). Lithosphere tearing along STEP faults and synkinematic formation of lherzolite and wehrlite in the shallow subcontinental mantle. *Solid Earth 10,* 1099-1121, https://doi.org/10.5194/se-2019-32

Hollister, J. (1942). La posición de las Baleares en las orogenias varisca y alpina. *Publicación Extraordinaria. Geología de España, I,* 71-102.

Iribarren, L., Vergés, J., Camurri, F., Fullea, J., & Fernandez, M. (2007). The structure of the Atlantic–Mediterranean transition zone from the Alboran Sea to the Horseshoe Abyssal Plain (Iberia–Africa plate boundary). *Marine Geology*, 243(1-4), 97-119. https://doi.org/10.1016/j.margeo.2007.05.011

IGME. (2003). Investigación Geotérmica en La Isla De Mallorca, unpublished report, 167 p.

Iribarren, L., Vergés, J., Camurri, F., Fullea, J. & Fernàndez, M. (2007). The structure of the Atlantic-Mediterranean transition zone from the Alboran Sea to the Horseshoe Abyssal Plain (Iberia-Africa plate boundary). Marine Geology 243, 97-119, https://doi.org/10.1016/j.margeo.2007.05.011

Jabaloy-Sánchez, A., Talavera, C., Rodríguez-Peces, M. J., Vázquez-Vílchez, M. & Evans, N. J. (2021). U-Pb geochronology of detrital and igneous zircon grains from the Águilas Arc in the Internal Betics (SE Spain): Implications for Carboniferous-Permian paleogeography of Pangea. *Gondwana Research, 90*, 135-158.

Jimenez-Bonilla, A., Torvela, T., Balanyá, J. C., Expósito, I. & Díaz-Azpiroz, M. (2016). Changes in dip and frictional properties of the basal detachment controlling orogenic wedge propagation and frontal collapse: The external central Betics case. *Tectonics, 35(12)*, 3028-3049, https://doi.org/10.1002/2016TC00419.

Jiménez-Bonilla, A., Crespo-Blanc, A., Balanyá, J. C., Expósito, I. & Díaz-Azpiroz, M. (2020). Analogue models of fold-and-thrust wedges in progressive arcs. Comparison with the Gibraltar Arc external wedge. *Frontiers in Earth Science, 8,* 72, https://doi.org/10.3389/feart.2020.00072

Jiménez-Munt, I., Sabadini, R., Gardi, A. & Bianco, G. (2003). Active deformation in the Mediterranean from Gibraltar to Anatolia inferred from numerical modeling and geodetic and seismological data. *Journal of Geophysical Research: Solid Earth, 108(B1)*, ETG-2, https://doi.org/10.1029/2001JB001544

Jolivet, L. & Faccenna, C. (2000). Mediterranean extension and the Africa-Eurasia collision. *Tectonics, 19*(6), 1095-1106.

Jolivet, L., Augier, R., Robin, C., Suc, J. P. & Rouchy, J. M. (2006). Lithospheric-scale geodynamic context of the Messinian salinity crisis. *Sedimentary Geology*, 188, 9-33.

Jolivet, L., Augier, R., Faccenna, C., Negro, F., Rimmele, G., Agard, P., Robin, C., Rossetti, F. & Crespo-Blanc, A. (2008). Subduction, convergence and the mode of backarc extension in the Mediterranean region. *Bulletin de la Société Géologique de France, 179*, 525-550, https://doi.org/10.2113/gssgfbull.179.6.525

Kettle, S. (2016). Sedimentology of a Middle Jurassic base-of-slope environment, Cutri Formation, Mallorca. *Journal of Iberian Geology, 42(1*), 95-112, https://doi.org/10.5209/Frev_JIGE.2016.v42.n1.50710

Kirchner, K. L., Behr, W. M., Loewy, S. & Stockli, D. F. (2016). Early Miocene subduction in the western Mediterranean: Constraints from Rb-Sr multimineral isochron geochronology. *Geochemistry, Geophysics, Geosystems, 17*(5), 1842-1860.

Laouar, R., Satouh, A., Salmi-Laouar, S., Abdallah, N., Cottin, J. Y., Bruguier, O., Bosch, D., Ouabadi, A., Boyce, A.J. & Fallick, A. E. (2017). Petrological, geochemical and isotopic characteristics of the Collo ultramafic rocks (NE Algeria). *Journal of African Earth Sciences, 125*, 59-72.

Leblanc, M. & Temagoult, A. (1989). Chromite pods in a lherzolite massif (Collo, Algeria): Evidence of oceanic-type mantle rocks along the West Mediterranean Alpine Belt. *Lithos, 23*(3), 153-162.

Leprêtre, A., Klingelhoefer, F., Graindorge, D., Schnurle, P., Beslier, M.O., Yelles, K., Déverchère, J. & Bracene, R. (2013). Multiphased tectonic evolution of the Central Algerian margin from combined wide-angle and reflection seismic data off Tipaza, Algeria. *Journal of Geophysical Research: Solid Earth 118*, 3899-3916, https://doi.org/10.1002/jgrb.50318

Leprêtre, R., de Lamotte, D. F., Combier, V., Gimeno-Vives, O., Mohn, G. & Eschard, R. (2018). The Tell-Rif orogenic system (Morocco, Algeria, Tunisia) and the structural heritage of the southern Tethys margin. *Bulletin de la Société Géologique de France,* 189(2), 10, https://doi.org/10.1051/bsgf/2018009

Lonergan, L. (1993). Timing and Kinematics of Deformation in the Malaguide Complex, Internal Zone of the Betic Cordillera, Southeast Spain. *Tectonics 12*, 460-476, https://doi.org/10.1029/92TC02507

Lonergan, L. & Johnson, C. (1998). Reconstructing orogenic exhumation histories using synorogenic detrital zircons and apatites: an example from the Betic Cordillera, SE Spain. Basin Res 10, 353-364.

Lonergan, L. & Platt, J. (1995). The Malaguide-Alpujarride boundary: a major extensional contact in the Internal Zone of the eastern Betic Cordillera, SE Spain. *Journal of Structural Geology 17*, 1665-1671, https://doi.org/10.1016/0191-8141(95)00070-T

Lonergan, L., White, N. (1997). Origin of the Betic-Rif mountain belt. Tectonics 16, 504-522. https://doi.org/10.1029/96TC03937

López Sánchez-Vizcaíno, V., Rubatto, D., Gómez-Pugnaire, M.T., Trommsdorff, V. & Müntener, O. (2001). Middle Miocene high-pressure metamorphism and fast exhumation of the Nevado-Filábride complex, SE Spain. Terra Nova 13, 327-332, https://doi.org/10.1046/j.1365-3121.2001.00354.x

Lujan, M., Crespo-Blanc, A. & Balanya, J.C. (2006). The Flysch Trough thrust imbricate (Betic Cordillera): A key element of the Gibraltar Arc orogenic wedge. *Tectonics 25(6),* https://doi.org/10.1029/2005TC001910

Lustrino, M., Duggen, S. & Rosenberg, C. L. (2011). The Central-Western Mediterranean: Anomalous igneous activity in an anomalous collisional tectonic setting. *Earth-Science Reviews, 104*(1-3), 1-40.

Maillard, A. & Mauffret, A. (1999). Crustal structure and riftogenesis of the Valencia Trough (north-western Mediterranean Sea). *Basin Research, 11(4)*, 357-379, doi:10.1046/j.1365-2117.1999.00105.x

Maillard, A., Jolivet, L., Lofi, J., Thinon, I., Couëffé, R., Canva, A. & Dofal, A. (2020). Transfer zones and associated volcanic province in the eastern Valencia Basin: Evidence for a hot rifted margin? *Marine and Petroleum Geology 119*, 104419, https://doi.org/10.1016/j.marpetgeo.2020.104419

Mancilla, F.L., Booth-Rea, G., Stich, D., Pérez-Peña, J.V., Morales, J., Azañón, J.M., et al. (2015). Slab rupture and delamination under the Betics and Rif constrained from receiver functions. Tectonophysics 663, 225-237, https://doi.org/10.1016/j.tecto.2015.06.028

Marchesi, C., Garrido, C.J., Bosch, D., Bodinier, J.L., Hidas, K., Padron-Navarta, J.A. & Gervilla, F. (2012). A Late Oligocene Suprasubduction Setting in the Westernmost Mediterranean Revealed by Intrusive Pyroxenite Dikes in the Ronda Peridotite (Southern Spain). *Journal of Geology 120*, 237-247, https://doi.org/10.1086/663875

Marti, J., Mitjavila, J., Roca, E. & Aparicio, A. (1992). Cenozoic Magmatism of the Valencia Trough (Western Mediterranean) - Relationship between Structural Evolution and Volcanism. *Tectonophysics 203*, 145-165, https://doi.org/10.1016/0040-1951(92)90221-Q

Martin, L. A., Rubatto, D., Brovarone, A. V. & Hermann, J. (2011). Late Eocene lawsonite-eclogite facies metasomatism of a granulite sliver associated to ophiolites in Alpine Corsica. *Lithos, 125(1-2),* 620-640, https://doi.org/10.1016/j.lithos.2011.03.015

Martín-Chivelet, J., López-Gómez, J., Aguado, R., Arias, C., Arribas, J., Arribas, M.E., et al. (2019). The Late Jurassic–Early Cretaceous Rifting, in: Quesada, C., Oliveira, J.T. (Eds.), *The Geology of Iberia: A Geodynamic Approach: Volume 3: The Alpine Cycle. Springer International Publishing,* 169-249.

Martín-Closas, C. & Ramos-Guerrero, E. (2005). Paleogene Charophytes of the Balearic Islands (Spain). *Geologica Acta, 3(1),* 39-58, https://doi.org/10.1344/105.000001413

Martín-Martín, M., Guerrera, F., Rodríguez-Estrella, T., Serrano, F., Alcalá, F. J., Raffaelli, G. & Tramontana, M. (2018). Miocene tectono-sedimentary evolution of the eastern external Betic

Cordillera (Spain). *Geodinamica Acta, 30(1),* 265-286, https://doi.org/10.1080/09853111.2018.1493879

Martín-Suárez, E., García-Alix, A., Minwer-Barakat, R., Agustí, J. & Freudenthal, M. (2012). Filling the gap: first evidence of early Tortonian continental deposits in southern Iberia. *Journal of Vertebrate Paleontology*, *32*(6), 1421-1428.

Martínez-Martínez, J. M. (2006). Lateral interaction between metamorphic core complexes and less-extended, tilt-block domains: the Alpujarras strike-slip transfer fault zone (Betics, SE Spain). *Journal of Structural Geology*, 28(4), 602-620.

Martínez-Martínez, J. M. & Azañón, J. M. (1997). Mode of extensional tectonics in the southeastern Betics (SE Spain): Implications for the tectonic evolution of the peri-Alborán orogenic system. *Tectonics*, 16(2), 205-225, https://doi.org/10.1029/97TC00157

Martínez-Martínez, J.M., Soto, J.I. & Balanyá, J.C. (2002). Orthogonal folding of extensional detachments: structure and origin of the Sierra Nevada elongated dome (Betics, SE Spain). Tectonics, 21, https://doi.org/10.1029/2001TC001283.

Mas, G., B. Gelabert, and J. J. Fornós. (2014) Evidencias de desplazamiento direccional de la falla de Sencelles (Mallorca, Islas Baleares). *Segunda reunión Ibérica sobre fallas activas y paleosismología*, 47.

Mattei, M., Cifelli, F., Rojas, I. M., Blanc, A. C., Comas, M., Faccenna, C. & Porreca, M. (2006). Neogene tectonic evolution of the Gibraltar Arc: New paleomagnetic constrains from the Betic chain. *Earth and Planetary Science Letters*, *250*(3-4), 522-540.

Mauffret, A., F. de Lamotte, D., Lallemant, S., Gorini, C. & Maillard, A. (2004). E-W opening of the Algerian Basin (Western Mediterranean), *Terra Nova*, *16*(5), 257-264, https://doi.org/10.1080/09853111.2018.1493879

Maury, R. C., Fourcade, S., Coulon, C., Bellon, H., Coutelle, A., Ouabadi, A., Semroud, B., Megartsi, M., Cotten, J., Belanteur, O., Louni-Hacini, A., Piqué, A., Capdevilla, R., Hernandez, J. & Réhault, J. P. (2000). Post-collisional Neogene magmatism of the Mediterranean Maghreb margin: a consequence of slab breakoff. *Comptes Rendus de l'Académie des Sciences-Series IIA-Earth and Planetary Science, 331*(3), 159-173.

Mennecart, B., Zoboli, D., Costeur, L., & Pillola, G. L. (2017). Reassessment of the latest Oligocene ruminant from Sardara, the last non-insular mammal from Sardinia (Italy). *Neues Jahrbuch für Geologie und Paläontologie-Abhandlungen, 286*, 97-104.

Mitjavila, J., Ramos-Guerrero, E. & Martí, J. (1990). Les roches pyroclastiques du Puig de l'Ofre (Serra de Tramuntana, Majorque): position géologique et datation K-Ar. *Comptes rendus de l'Académie des Sciences. Série 2, Mécanique, Physique, Chimie, Sciences de l'univers, Sciences de la Terre, 311(6),* 687-692.

Moragues, L., Booth-Rea, G., Ruano, P., Azañón, J. M., Gaidi, S. & Pérez-Peña, J. V. (2018). Middle Miocene extensional tectonics in Southeast Mallorca Island (Western Mediterranean). *Revista de la Sociedad Geológica de España, 31, 2.*

Negredo Moreno, A. M., Mancilla, F. D. L., Clemente, C., Morales, J. & Fullea, J. (2020). Geodynamic modeling of edge-delamination driven by subduction-transform edge propagator faults: the Westernmost Mediterranean Margin (Central Betic Orogen) Case Study. *Frontiers in Earth Science, 8,* https://doi.org/10.3389/feart.2020.533392

Parés, J. M., Sàbat, F. & Santanach, P. (1986). La structure des Serres de Llevant de Majorque (Baléares, Espagne): données de la région au Sud de Felanitx. *Comptes rendus de l'Académie des sciences. Série 2, Mécanique, Physique, Chimie, Sciences de l'univers, Sciences de la Terre, 303(6),*475-480.

Pedrera, A., Ruiz-Constán, A., García-Senz, J., Azor, A., Marín-Lechado, C., Ayala, C., Díaz de Neira, J. A. & Rodríguez-Fernández, L. R. (2020). Evolution of the South-Iberian paleomargin: From hyperextension to continental subduction. *Journal of Structural Geology, 138*, 104122.

Pellen, R., Aslanian, D., Rabineau, M., Leroux, E., Gorini, C., Silenziario, C., et al. (2016). The Minorca Basin: a buffer zone between the Valencia and Liguro-Provençal Basins (NW Mediterranean Sea). *Terra Nova, 28(4),* 245-256, https://doi.org/10.1111/ter.12215

Peréz-Valera, L.A., Rosenbaum, G., Sánchez-Gómez, M., Azor, A., Fernández-Soler, J.M., Peréz-Valera, F. & Vasconcelos, P.M. (2013). Age distribution of lamproites along the Socovos Fault (southern Spain) and lithospheric scale tearing. Lithos 180, 252-263, https://doi.org/10.1016/j.lithos.2013.08.016

Piromallo, C. & Morelli, A. (2003). P wave tomography of the mantle under the Alpine-Mediterranean area. *Journal of Geophysical Research 108*, 2056, https://doi.org/10.1029/2002JB001757

Platt, J.P., Allerton, S., Kirker, A., Mandeville, C., Mayfield, A., Platzman, E.S. & Rimi, A. (2003). The ultimate arc: Differential displacement, oroclinal bending, and vertical axis rotation in the External Betic-Rif arc. *Tectonics 22*, https://doi.org/10.1029/2001TC001321

Platt, J.P., Kelley, S.P., Carter, A. & Orozco, M. (2005). Timing of tectonic events in the Alpujárride Complex, Betic Cordillera, southern Spain. *Journal of the Geological Society*, *162*, 1-12, https://doi.org/10.1144/0016-764903-039

Platt, J.P., Anczkiewicz, R., Soto, J.I., Kelley, S.P. & Thirlwall, M. (2006). Early Miocene continental subduction and rapid exhumation in the western Mediterranean. *Geology 34,* 981-984, https://doi.org/10.1130/G22801A.1

Pomar, L. & Rodríguez-Perea, A. (1983). El Neógeno inferior de Mallorca: Randa. El Terciario de las Baleares (Mallorca-Menorca). (L. Pomar, A. Obrador, J.J. Fornos y A. Rodríguez-Perea, Ed). Guía de las excursiones del X Congreso Nacionial de Sedimentología. Menorca 1983. *Institut d'Estudis Baleàrics, Universitat de Palma de Mallorca*, 115-137.

Pomar, L., Esteban, M., Calvet, F. & Barón, A. (1983). La Unidad Arrecifal del Mioceno superior de Mallorca. En: L. Pomar, A. Obrador, J.J. Fornos y A. Rodríguez-Perea (Eds). El Terciario de las Baleares (Mallorca-Menorca. Guía de las excursiones del X Congreso Nacional de Sedimentología. Menorca 1983. *Institut d'Estudis Baleàrics*, *Universitat de Palma de Mallorca*, 21-44.

Poort, J., Lucazeau, F., Le Gal, V., Dal Cin, M., Leroux, E., Bouzid, A. & Ferrante, G. M. (2020). Heat flow in the Western Mediterranean: Thermal anomalies on the margins, the seafloor and the transfer zones. *Marine Geology, 419*, 106064, https://doi.org/10.1016/j.margeo.2019.106064

Ramos-Guerrero, E., Rodriguez-Perea, A., Sabat, F. & Serra-Kiel, J. (1989). Cenozoic tectosedimentary evolution of Mallorca island. *Geodinamica Acta, 3(1)*, 53-72, https://doi.org/10.1080/09853111.1989.11105174

Ramos-Guerrero, E., Berrio, I., Fornós, J. J. & Moragues, L. (2000). Chapter 40: The Middle Miocene Son Verdera Lacustrine-Palustrine System (Santa Margalida Basin, Mallorca), in Gierlowski-Kordesch E.H. and Kelts, K.R., eds, Lake basins trough space and time. AAPG Studies in Geology 46, 441-448, https://doi.org/10.1306/St46706C40

Rehault, J.P., Boillot, G., Mauffret, A. (1984). The western Mediterranean basin geological evolution. *Marine Geology 55*, 447-477, https://doi.org/10.1016/0025-3227(84)90081-1

Roca, E. (2001), The Northwest Mediterranean Basin (Valencia Trough, Gulf of Lions and Liguro-Provencal basins): structure and geodynamic evolution, *Mémoires du Muséum National d'Historie Naturelle*,*186*, 671-706

Roca, E. & Guimera, J. (1992), The Neogene Structure of the Eastern Iberian Margin - Structural Constraints on the Crustal Evolution of the Valencia Trough (Western Mediterranean), *Tectonophysics*, *203*(*1-4*), 203-218, https://doi.org/10.1016/0040-1951(92)90224-T

Rodríguez-Fernández, J., Azor, A. & Azañón, J.M. (2011). The Betic Intramontane Basins (SE Spain): Stratigraphy, Subsidence, and Tectonic History. In C. Busby & A. Azor (Eds.), *Tectonics of Sedimentary Basins: Recent advances*. John Wiley & Sons, Ltd, pp. 461-479, https://doi.org/10.1002/9781444347166.ch23

Rodríguez–Perea, A. (1984). El Mioceno de la Serra Nord de Mallorca. Estratigrafía, sedimentología e implicaciones estructurales. Doctoral Thesis, Universitat de les Illes Balears.

Rosenbaum, G., Lister, G. S. & Duboz, C. (2002). Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene. *Journal of the Virtual Explorer, 8*(January).

Rossetti, F., Faccenna, C., Goffe, B., Funiciello, R. & Monie, P. (2002). Tectono-metamorphic evolution of the ophiolite-bearing HP/LT Gimigliano-Monte Reventino Unit (Gimigliano, Sila Piccola); insights for the tectonic evolution of the Calabrian Arc. *Bollettino della Società geologica italiana, 121(1),* 51-67.

Roure, F., Casero, P. & Addoum, B. (2012). Alpine inversion of the North African margin and delamination of its continental lithosphere. *Tectonics, 31*(3).

Saadallah, A. & Caby, R. (1996). Alpine extensional detachment tectonics in the Grande Kabylie metamorphic core complex of the Maghrebides (northern Algeria). *Tectonophysics, 267(1-4)*, 257-273, https://doi.org/10.1016/S0040-1951(96)00101-1

Sàbat, F., Muñoz, J.A. & Santanach, P. (1988). Transversal and Oblique Structures at the Serres-De-Llevant Thrust Belt (Mallorca Island). *Geologische Rundschau, 77(2)*, 529-538.

Sàbat, F., Gelabert, B., Rodríguez-Perea, A. & Giménez, J. (2011). Geological structure and evolution of Majorca: Implications for the origin of the Western Mediterranean. *Tectonophysics, 510(1-2)*, 217-238, https://doi.org/10.1016/j.tecto.2011.07.00

Sàbat, F., Gelabert, B. & Rodríguez-Perea, A. (2018). Minorca, an exotic Balearic island (western Mediterranean). Geologica Acta, 16(4), 411-426, https://doi.org/10.1344/GeologicaActa2018.16.4.5

Sallarès, V., Gailler, A., Gutscher, M. A., Graindorge, D., Bartolomé, R., Gracia, E., Díaz, J., Dañobeitia, J.J. & Zitellini, N. (2011). Seismic evidence for the presence of Jurassic oceanic crust in the central Gulf of Cadiz (SW Iberian margin). *Earth and Planetary Science Letters, 311*(1-2), 112-123.

Schettino, A., and E. Turco (2006), Plate kinematics of the Western Mediterranean region during the Oligocene and Early Miocene, *Geophysical Journal International*, *166*, 1398-1423, https://doi.org/10.1111/j.1365-246X.2006.02997.x

Serck, C. S., Braathen, A., Olaussen, S., Osmundsen, P. T., Midtkandal, I., Yperen, A. E. V. & Indrevær, K. (2020). Supradetachment to rift basin transition recorded in continental to marine deposition; Paleogene Bandar Jissah Basin, NE Oman. *Basin Research 33*, 544-569, https://doi.org/10.1111/bre.12484

Sevillano, A., Rosales, I., Bádenas, B., Barnolas, A. & López-García, J.M. (2018). Spatial and temporal facies evolution of a Lower Jurassic carbonate platform, NW Tethyan margin (Mallorca, Spain). *Facies 65,* 3, https://doi.org/10.1007/s10347-018-0545-0

Simancas, J. F. (2018). A reappraisal of the Alpine structure of the Alpujárride Complex in the Betic Cordillera: Interplay of shortening and extension in the westernmost Mediterranean. *Journal of Structural Geology, 115*, 231-242, https://doi.org/10.1016/j.jsg.2018.08.001

Speranza, F., Villa, I. M., Sagnotti, L., Florindo, F., Cosentino, D., Cipollari, P. & Mattei, M. (2002). Age of the Corsica–Sardinia rotation and Liguro–Provençal Basin spreading: new paleomagnetic and Ar/Ar evidence. *Tectonophysics*, *347(4)*, 231-251

Suarez, E. M., Freudenthal, M. & Agusti, J. (1993). Micromammals from the Middle Miocene of the Granada basin (Spain). *Geobios, 26(3),* 377-387, https://doi.org/10.1016/S0016-6995(93)80028-P

Sun, M. & Bezada, M. (2020). Seismogenic Necking During Slab Detachment: Evidence From Relocation of Intermediate-Depth Seismicity in the Alboran Slab. *Journal of Geophysical Research: Solid Earth*, 125(2), e2019JB017896, https://doi.org/10.1029/2019JB017896

Torné, M., Pascal, G., Buhl, P., Watts, A. B. & Mauffret, A. (1992). Crustal and velocity structure of the Valencia trough (western Mediterranean), Part I. A combined refraction/wide-angle reflection and near-vertical reflection study. *Tectonophysics, 203(1-4),* 1-20, https://doi.org/10.1016/0040-1951(92)90212-O

Torres-Roldán, R.L., Poli, G. & Peccerillo, A. (1986). An Early Miocene arc-tholeiitic magmatic dike event from the Alboran Sea-Evidence for precollisional subduction and back-arc crustal extension in the westernmost Mediterranean. *Geologische Rundschau* 75, 219-234.

Van Hinsbergen, D.J.J., Vissers, R.L.M. & Spakman, W. (2014). Origin and consequences of western Mediterranean subduction, rollback, and slab segmentation. *Tectonics 33 (4),* 393-419, https://doi.org/10.1002/2013TC003349

Van Hinsbergen, D. J., Torsvik, T. H., Schmid, S. M., Maţenco, L. C., Maffione, M., Vissers, R. L., Gürer, D. & Spakman, W. (2020). Orogenic architecture of the Mediterranean region and kinematic reconstruction of its tectonic evolution since the Triassic. *Gondwana Research, 81*, 79-229.

Vergés, J. & Sàbat, F. (1999). Constraints on the Neogene Mediterranean kinematic evolution along a 1000 km transect from Iberia to Africa. *Geological Society, London, Special Publications, 156*(1), 63-80.

Vergés, J. & Fernàndez, M. (2012). Tethys–Atlantic interaction along the Iberia–Africa plate boundary: The Betic–Rif orogenic system. *Tectonophysics*, *579,* 144-172, https://doi.org/10.1016/j.tecto.2012.08.032

Vergés, J., Fernàndez, M. & Martínez, A. (2002). The Pyrenean orogen: pre-, syn-, and post-collisional evolution. *Journal of the Virtual Explorer,* 8, 55-74, https://www/doi.org/10.3809/jvirtex.2002.00058

Vitale Brovarone, A. & Herwartz, D., 2013. Timing of HP metamorphism in the Schistes Lustrés of Alpine Corsica: New Lu–Hf garnet and lawsonite ages. *Lithos 172-173*, 175-191, https://doi.org/10.1016/j.lithos.2013.03.009

Watts, A. B. & Torné, M. (1992). Subsidence history, crustal structure, and thermal evolution of the Valencia Trough: A young extensional basin in the western Mediterranean. *Journal of Geophysical Research: Solid Earth, 97(B13),* 20021-20041, https://doi.org/10.1029/92JB00583

Wortel, M.J.R. & Spakman, W. (2000). Subdcution and Slab Detachment in the Mediterranean-Carpathian Region. *Science 290,* 1910-1917, https://doi.org/10.1126/science.290.5498.1910

Žalohar, J. & Vrabec, M. 2007. Paleostress analysis of heterogeneous fault-slip data: the Gauss method. *Journal of structural Geology, 29(11),* 1798-1810, https://doi.org/10.1016/j.jsg.2007.06.009

Zhou, X., Li, Z. H., Gerya, T. V., Stern, R. J., Xu, Z. & Zhang, J. (2018). Subduction initiation dynamics along a transform fault control trench curvature and ophiolite ages. Geology, 46(7), 607-610, https://doi.org/10.1130/G40154.1