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Plio-Quaternary strike-slip tectonics in the Central Mallorca Depression, Balearic Promontory: Land–sea correlation

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Abstract :

The Balearic Promontory (Spain) is of key importance to understand the tectonic kinematics of the westernmost Mediterranean, because its continued marine sedimentation has recorded the contrasting effects expected from competing geodynamic models proposed for the region. Near the center of this promontory, between the islands of Mallorca and Ibiza, the Miocene to Pleistocene stratigraphy of the Central Mallorca Depression presents an ideal record of the tectonic deformation that has received only limited attention. We use a widespread dataset of 2D seismic reflection profiles to identify, interpret and map the main prominent reflectors and extrapolate the thickness of the pre-Messinian and Pliocene-Quaternary sedimentary units. We then quantify the timing and style of deformation related to the various fault systems. Our results reveal for the first time a series of aligned small depressions bounded by extensional and strike-slip faults and filled with Plio-Quaternary sediment, perfectly aligned with the sub-basins of the onshore Mallorca Graben. A subsidence analysis confirms this correlation. We identify non-cylindrical deformation within the Plio-Quaternary unit that is remarkably similar to that observed onshore, suggesting continuous fault zones from the Central Mallorca Depression to Mallorca Island. We interpret an intra-PQ unconformity as the marker of a transition from extensional to strike-slip tectonic regime. The strike-slip stage is represented by both transpressional and transtensional structures, interpreted as restraining/releasing bends respectively and step overs along the faults. We show that these offshore faults in the Central Mallorca Depression overlap well with seismic epicenters and suggest major active strike-slip corridors that have an onshore continuity both until eastern Mallorca and in the southwestern Ibiza margin. The role of previous tectonic inherited structures (rifting, Betic thrusts, post-orogenic collapse) on the deformation reported here is discussed and we propose a tentative sketch that integrates our results in a Miocene to Present-day evolution at regional scale.

Highlights

► Post-Messinian deformation affects the Central Mallorca Depression. ► Strike-slip fault systems correlate onland-offshore Mallorca and Ibiza Islands. ► The systems localize extensional / compressional structures into long corridors. ► Small depocenters of PQ units align onland-offshore. ► Recent tectonics and important structural inheritance control local subsidence.

Keywords : Central Mallorca Depression, Balearic Promontory, strike-slip corridors, structural inheritance, earthquakes

1. Introduction

In its present-day setting, the Western Mediterranean Basin is undergoing a diffuse compressional deformation due to the continuous convergence between the African and Eurasian plates (Serpelloni et al., 2007; Stich et al. 2003). The deformation is localized, mainly in the thrust belts of North Africa and the active northern African margin near Algiers, and partly in the external Betic Cordillera (Serpelloni et al., 2007; De Galdeano & Alfaro, 2004). Located between two extensional basins: the Valencia Basin to the north and the Algerian Basin to the south (Fig. 1), the Balearic Promontory (BP) is considered the NE extension of the external Betic Cordillera (Fig. 1).

The BP area recorded several tectonic phases since its formation and is tectonically active in the present (Fontboté et al., 1990; Gelabert et al., 1992; Sàbat et al., 1997; 2011; Acosta et al., 2001a; 2003; Sanchez-Alzola et al., 2014), as evidenced by numerous earthquakes taking place both onshore and offshore (Fig. 1). This activity is not equally partitioned along the BP, as its southwestern part (Spanish margin offshore Alicante) has a relatively higher seismic activity than the rest of the BP, and it evidences clear active compressional deformation (Fig. 1; Alfaro et al., 2012; Maillard and Mauffret, 2013; Acosta et al., 2013; Sanchez-Alzola et al., 2014). The central and northern parts of the BP are less seismically active, but some earthquakes have been recorded (Silva et al., 2001; Sanchez-Alzola et al., 2014). Mallorca accommodates most of this tectonic activity onland, except for 2 seismic events on Menorca Island (Fig. 1). The highest magnitude recent seismic event recorded on Mallorca is the 1851 Palma earthquake (VIII, MSK intensity), known to have been generated along the active Sencelles fault (Fig. 2D; Silva et al., 2000, 2001).

Several studies have been carried out to understand the structure and Cenozoic evolution of Mallorca and Ibiza Islands on the BP, in the framework of the Western Mediterranean dynamics (Sàbat et al., 1995, 1997; Verges and Sàbat, 1999; Acosta et al., 2001a; Gelabert et al., 2002, 2004; Sàbat et al., 2011; Driussi et al., 2015b; Etheve et al., 2016; Booth-Rea et al., 2017; Moragues et al., 2021). However, few studies focused on post-Messinian tectonics and/or concentrated on local faults activities (Silva et al., 2001; Giménez and Gelabert, 2002; Giménez, 2003; Mas et al., 2014). Only recently Capó and Garcia, (2019) studied in detail the Pliocene-Quaternary (PQ) sedimentary cover and evolution of the Mallorca Island.
So far, little attention was given to the offshore part of the BP, especially to the depression lying between Mallorca and Ibiza islands, known as the Central Mallorca Depression (CMD), that has accommodated a relatively important number of seismic events (Fig. 1 and Fig. 2D). Since the detailed structural and morphometric works of Acosta et al. (Acosta et al., 2001a; 2001b; Acosta, 2003; Acosta et al., 2004a; 2004b), works focusing mainly on the Messinian Salinity Crisis (MSC) (Maillard et al., 2014; Driussi et al., 2015a; Raad et al., 2021) and/or mass transfer deposits (Betzler et al., 2011; Lüdmann et al., 2012) were carried out in the offshore part of the BP.

In this study, we focus on the Central Mallorca Depression area offshore, and on the Mallorca Graben onshore (Fig. 1). The aim of our study is to: 1- show the deformation style along the faults systems since the late Miocene up to present day and interpret their chronology; 2- compare and correlate the offshore structures to the onshore faults systems and PQ sedimentary units and trace their continuation along the whole study area; 3- integrate the offshore post-Messinian tectonic and seismic activity to the observations onland Mallorca and interpret the style of the deformation; 4- understand the role of the various tectonic inheritances and provide an integrated offshore/onshore sketch of the late Miocene to Quaternary tectonic evolution of the area. The final purpose is to propose a tectonic evolution of the BP during the Pliocene to Quaternary period, coherent with the western Mediterranean kinematics.

Thanks to previous works associated with new data, we evidence a post-Messinian deformation linked to important structural heritages. We show a complex and continuous active fault systems deforming the recent Plio-Quaternary (PQ) strata of the CMD.

2. Geological and morphological setting

2.1. Physiography of the study area

The study area is located in the central part of the BP, between the islands of Mallorca and Ibiza-Formentera (Fig. 1). It includes the SW shelf and slope of Mallorca, the Central Mallorca Depression (CMD, sensu Acosta et al., 2004a) and the E and SE slope of Ibiza. To the north, the CMD is partly connected to the deep Valencia Basin (water depth up to 1500 m) through the Mallorca Channel (Fig. 1). To the south, it is limited by the steep Emile Baudot Escarpment (EBE), dipping abruptly towards the Algerian abyssal plain where water depth exceeds 2800 m. The seafloor morphology of the study area has been widely investigated (Acosta et al., 2003; Acosta et al., 2004a, b; Camerlenghi et al., 2009). The water depths in the CMD range from 700 to 1 050 m. The Mont Ausias Marc and Mont dels Oliva are flat carbonate seamounts that are thought to be isolated parts of the Ibiza-Formentera shelf (Acosta et al., 2004a). The western Mallorca margin displays two prominent ridges: the Andraitx Salient in the prolongation of the Mallorcan Tramuntana Ranges (Fig. 1) which is partly closing the CMD to the North; the second ridge is along strike with the Llevant Ranges and the Cabrera Island (Fig. 1), and is aligned with the EBE including the Emile Baudot Volcanic Mounts (EBVM) which is composed of several cone-shaped volcanic mounts of Pleistocene age (Acosta et al, 2001a; Acosta et al., 2004b).

2.2. Regional geological setting and Late Oligocene to Miocene tectonics

The BP is bounded to the North by the Valencia Basin, an aborted rift linked to the opening of the Liguro-Provençal oceanic Basin, which underwent extensional tectonics from Late Oligocene / middle Miocene times (Clavell & Berastegui, 1991; Maillard et al., 1992; Roca, 1992; 2001). The EBE bounds the BP to the south and is known to represent the transcurrent oceanic-continental crust transition with the Algerian Basin that opened during Miocene times (Acosta et al., 2001a; Mauffret et al., 2004; Camerlenghi et al., 2009; Driussi et al., 2015b). In the regional extensional context (ongoing rifting processes in the Valencia and Algerian basins) the BP formed as a result of the compressional deformation associated with the Betic ranges in SE Spain (Ramos Guerrero et al., 1989; De Galdeano, 1990; Roca et al., 2001). The Betic thrusts are well expressed onshore both on Ibiza and on Mallorca with the Tramuntana, Central and Llevant Ranges (Fig. 1) that belong to the External zones of the Betic mountain Ranges (Bourrouilh, 1970; Fourcade et al., 1982; Casas and Sàbat, 1987; Sàbat et al., 1988; Gelabert et al., 1992, 2004; Sàbat et al., 2011; Etheve et al., 2016). Compression involved Mesozoic and Cenozoic units, along thrusts trending ESE-WNW with variable displacement between NW and SW-directed hanging-wall transport and fold vergence (Fig. 1; Canas and Pujades, 1992; Durand-Delga, 1980; Fourcade et al., 1982; Roca, 1992; Gelabert et al., 1992, 2004; Sabàt et al., 2011). Paleomagnetic studies showed that during the compressional event Mallorca experienced clockwise rotation (Parès et al., 1992; Freeman et al., 1989). Offshore, thrusts are also clearly observed in the lower slope North of Ibiza (Maillard et al., 1992; Roca and Guimera, 1992; Ethève et al., 2016). Further North-East, the prolongation and attenuation of this thrust system is still under debate (Roca and Guimera, 1992; Gelabert et al., 1992; Maillard et al., 1992; Mauffret et al., 1992; Roca, 2001). The compression has been proposed to have initiated to the south during the Late Oligocene and propagated toward the north during the Burdigalian to Langhian times (Bourrouilh, 1970; Sàbat et al., 1988; Rodriguez-Perea, 1984, Gelabert et al., 1992) but could have occurred in a shorter period restricted to 19 to 14Ma bracketed by extension (Moragues et al., 2021). Rifting of the Valencia Basin that occurred during late Oligocene to lower Miocene also affected the BP. Tilt blocks from this phase are mostly observed in the SW part of the BP. The tilt blocks were then reworked while compression propagated northwestward.

Following the betic compressional phase, the BP underwent another extensional event from Serravallian to Tortonian ages, interpreted as post-orogenic extension by collapse (Roca, 1992; Benedicto et al., 1993; Céspedes et al., 2001; Booth-Rea et al., 2016; Moragues et al., 2018; 2021). This generated the configuration of basins and ranges onland Mallorca (e.g., the Mallorca Graben), and partly the offshore depressions such as the CMD and the Formentera Basin (Fig. 1; Sàbat et al., 1997). The upslope domains of Ibiza and Mallorca margins towards the Valencia Basin are also structured by recent normal faults postdating the rifting phase and crosscutting the betic thrusts (Maillard et al., 1992; Driussi et al., 2015b; Etheve et al., 2016; 2018), probably linked to the same Late Miocene extensional event. The Late Miocene direction of extension was proposed to be perpendicular to the WSW-ENE faults that limit the Mallorca Graben, so globally NW-SE directed (Sabàt et al., 2011). The sub-basins (respectively the Palma, Inca, and Santa Pobla sub-basins; Fig. 1) located inside the Mallorca Graben have been interpreted as transtensional structures linked to this phase (Giménez and Gelabert, 2002; Giménez et al., 2003). Local transtensional events occurred at the same time on Ibiza (Durand-Delga, 1980; Fourcade et al., 1982) and Menorca (Bourrouilh, 1973). These transtensional events are in accordance with recent works that showed kinematic evidence for WSW-ENE probable transfer faults showing both dextral and sinistral displacements, related to NE-SW directed extension (Booth-Rea et al., 2016; Moragues et al., 2018; 2021) during the Serravallian after the main subsidence of the sub-basins (Benedicto et al., 1993).

2.3. Onland Neogene stratigraphic and tectonic records

A complete Neogene record of the evolution of the BP is found onshore Mallorca where two groups of sediments have been distinguished (Pomar et al., 1983; Fornós et al., 1991; Alonso-Zarza, 2003; Sàbat et al., 2011). The lower group comprises pre- and syn-orogenic sediments (lower and middle Miocene; Fig. 1) that onlap the Paleogene and Mesozoic rocks. The entire record of this group is folded and thrusted. The upper group is post-orogenic and Middle Miocene (Serravallian) to Plio-Pleistocene in age (Fig. 1). It rests uncomfortably on the deformed lower group and/or on the Mesozoic and Paleogene rocks, having undergone tilting and flexure associated with normal and strike-slip faulting during the late Miocene to Middle Pleistocene extensional phase (Fig. 3; Pomar et al. 1983; Fornós et al., 1991; Mas et al., 2014; Canò and Garcia, 2019; Moragues et al., 2021).The first post-orogenic sediments consist in continental deposits in the Serravallian that represent lacustrine and alluvial environments (Manacor and San Verder formations, Fig. 3), showing extensional and transtensional structures in two orthogonal directions that thin the Early Miocene orogenic nappes (Benedicto et al., 1993; Ramos Guerrero et al., 2000; Moragues et al., 2018). The extensional/transtensional regime seems to have ceased by the end of the Miocene (Sàbat et al., 2011). Post-Serravallian deposits are up to 1000 m thick and have been divided into five major sedimentary sequences (Pomar et al. 1983, 1991; Fornós and Pomar., 1983; Mas and Fornós, 2013; Mas, 2015; Fig. 3): (i) Lower Tortonian littoral and fan-delta deposits ; (ii) upper Tortonian-Lower Messinian reefal carbonates (Reef Complex); (iii) Late-Messinian Santanyi limestones (TCC sensu Esteban, 1979) including their distal equivalent Gypsum in the Palma bay; (iv) Pliocene-Quaternary marine to eolian/continental deposits (Son Mir Calcisiltites-San Jordi Calcarenites). Some of those sequences record gentle folds that suggest that compression or transpression could have taken place during the Pleistocene. Some post-orogenic extensional structures (e.g. Sencelles Fault; Fig. 3A) that developed as normal faults during the Miocene were subsequently reworked as left-lateral strike-slip faults during the Pliocene (Mas et al., 2014). Some authors suggested a change to N-S compression and E-W extension during Pliocene times as supported by some associated compressional deformation during Quaternary times along the Sencelles Fault (Silva et al., 1998; 2001; Giménez and Gelabert, 2002; Giménez, 2003; Mas et al., 2014).

2.4. Present-day tectonics

Active tectonic deformation has long been reported locally over the whole offshore BP (Mauffret et al., 1987; Acosta et al., 2003), in accordance with the convergent regional context of the Algero-Balearic domain (De Galdeano and Alfaro, 2004; Serpelonni et al., 2007). The BP appears to accommodate only a small portion of this convergence as it is characterized by a weak tectonic and seismic activity. Recent post-Messinian deformation (local uplift; normal and strike-slip faulting) is nevertheless well expressed in the western domain of the Promontory, in the Ibiza Channel and on the Alicante shelf, where seismic markers belonging to the Late Miocene's Messinian Salinity Crisis are deformed up to the seafloor (Alfaro et al., 2002; 2012; Maillard and Mauffret, 2013; Driussi et al., 2015b). Between Ibiza and Mallorca gentle folds on the seabed were also interpreted as the result of compressional deformation (Sàbat et al., 1997). Right lateral NE-SW strike-slip structures are locally evidenced by deformation on the sea-floor, visible particularly both on Mont Ausias Marc and Mont dels Oliva in the CMD (Acosta et al., 2003; 2004a). Acosta et al. (2004a) showed systems of near-vertical normal and/or strike-slip faults affecting Pliocene and Quaternary units, together with numerous pockmarks widespread over the area. On the margins of the BP, the abundance of both volcanic and mass failure structures also suggests active tectonic processes (Acosta et al., 2001b; Acosta, 2003; Acosta et al., 2004a; 2004b; Lastras and al., 2004).

Regarding the present-day tectonics, most of the recorded seismicity is located in the central part of Mallorca Island and offshore in the Mallorca channel (Figs. 1 and 3D). It is characterized by low to moderate magnitude earthquakes (between 2.6 and 4.3 of magnitude; Fig. 3D; Silva et al., 2001) spatially associated with pre-existing Neogene NE–SW faults (Serpelloni et al., 2007; Sanchez-Alzola et al., 2014). On Mallorca Island, geological evidence suggests that the current tectonic regime is characterized by a coeval N-S compression and E-W extension, which varies laterally (Silva et al., 2001; Giménez, 2003). Unfortunately, no focal mechanisms in the islands are available. Based on analysis of strain rates, Sanchez-Alzola et al., (2014) proposed a gradual variation of the regime across the Promontory, with a NW–SE shortening in Menorca and eastern Mallorca, E–W extension in central Mallorca and WNW–ESE extension in Formentera and Ibiza. The present stress regime is consistent with the left-lateral movement on the NE–SW faults bounding the Mallorca Graben (Inca and Campos basins, Fig. 3; Giménez, 2003; Morey and Mas, 2009; Sàbat et al., 2011; Sanchez-Alzola et al., 2014).

3. Methodology

3.1. Offshore seismic data

This work relies on the interpretation of a series of 2D seismic profiles available offshore and covering the whole study area (Fig. 2A). The datasets consist of both high-resolution (SIMBAD cruise: Maillard and Gaullier, 2013 and CARBMED cruise; Hübscher et al., 2010) and low-resolution profiles (Valsis cruise (Mauffret et al., 1992); SH cruise; MA and FOR profiles provided by the Instituto Geologico y Minero de Espana (IGME); MAP and MED old oil industry profiles recently re-processed with a standard processing flow until pre-stack time migration and provided by Spectrum and Western Geco Companies).

The seismic lines were interpreted according to the conventional concept of seismic stratigraphy (Mitchum and Vail, 1977) and based on previous works over the area (Maillard et al., 2014; Driussi et al., 2015a, b; Raad et al., 2021). High- and low-resolution lines were interpreted jointly and the main structures were mapped. Seismic horizons were interpreted and picked using the software Petrel® by Schlumberger®. The interpreted horizons of the bathymetry, Base PQ and the acoustic basement are now made available online with open access as part of a wider dataset in the Western Mediterranean by Bellucci et al. (2021). We constructed maps using the convergent interpolation algorithm provided by Petrel, which is a control point orientated algorithm that converges upon the solution iteratively increasing resolution with each iteration reaching a maximum chosen resolution of 2x2km. In order to quality check the resulting maps, we compared the seismic derived bathymetry map (Fig. 2A) with the high-resolution bathymetry shown on figure 1. The Base PQ and Top Basement surfaces (Fig. 2B and C respectively) were compared with the maps published by Leroux et al. (2019).

3.2 Backstripping

In order to quantify the amount of post-Messinian flexural-isostatic subsidence resulting from sediment load and compaction, we perform pseudo-3D backstripping on a regional scale following the methodology of Heida et al. (2021). The results are shown along the SW-NE section across the CMD shown in Figure 4. This approach allows for the comparison between local Airy isostasy and load subsidence associated with a stronger crust, in order to discuss the potential effect of the considerable post-Messinian sediment thickness variations across the CMD, the onshore Balearic Islands and the surrounding Valencia and Algerian basins. The regional scale distribution of the sediment load and depths of horizons used were taken from Heida et al. (2021), then resampled into grids with a resolution of 2.155 by 2.225 km. Time-to-depth conversion of the Miocene-Pliocene boundary follows the exponential time-depth function from Urgeles et al. (2011) derived from well data in the Ebro margin and takes the form:

Depth (m) = 1135.13*TWTT(sec)*1.3643

Densities of the PQ sedimentary load and of the asthenosphere were set at 2100 and 3250 kg/m3 respectively. The values adopted for the effective elastic thickness were between 5 (close to local isostasy) and 15 km, in agreement with the young tectonothermal age of the region (e.g., Gaspar-Escribano et al., 2004) and with results from spectral analysis of potential fields and topography (Tesauro et al., 2009; Kaban et al., 2018). For details about the backstripping methodology and other parameters adopted, see Heida et al. (2021) and references therein. Vertical motions caused by the Messinian Salinity Crisis (MSC) events were not tested here but are addressed in the large-scale study performed in Heida et al., (2021).

4. Results and interpretations

4.1. Offshore seismic stratigraphy and main units

Figure 5 shows the typical seismic stratigraphy in the CMD, that we deducted from the interpretation of high- and low-resolution seismic profiles. Five seismic horizons, bounding four seismic units, were outlined over the study area based on major unconformities and clear changes in seismic facies. The units are described here after from bottom to top:

- **Acoustic basement**: in general, it is characterized by internal chaotic facies with few reflections on both high and low-resolution seismic profiles (Figs. 5 and 6). It can locally present formless internal patterns and can be layered in its upper part (Figs. 6, 7 and 12A). Its top always corresponds with a prominent high-amplitude reflection, sometimes associated with diffracting hyperbolas, attesting to an important lithological contrast with the overlying unit. The top acoustic basement reflection displays an irregular morphology on all seismic lines and reveals a highly tectonized sequence (Figs. 2C and 7). There is no constraint on the age and lithology of the sediments constituting the basement offshore. Based on the geological context and on the basement rocks outcropping onshore in Mallorca and Ibiza (Fig. 1), the acoustic basement in the CMD is most probably made of Mesozoic and Neogene sediments belonging to the pre- and syn-orogenic group (Fig. 3C and F; Sàbat et al., 2011). This is supported by the presence of some folded-like bedded reflections within the chaotic complex and truncations at its top, suggesting the top acoustic basement boundary to be the post-Betic unconformity (Fig. 7). Locally, a volcanic origin could also be invoked as part of the acoustic basement (Acosta et al., 2003, 2004b), especially on the EBVM.

Figure 8 shows the present-day depth map in s twtt of the Top Acoustic Basement, highlighting the orogenic structures.

- **Pre-Messinian Salinity Crisis unit (pre-MSC)**: lies unconformably on the acoustic basement (onlaps, Fig. 5A and B). Its upper boundary looks conformable with the MSC unit except locally where it shows toplap terminations (Fig. 6). This unit is characterized by low internal reflectivity (sometimes reflection-free on low resolution seismic; Fig. 5) with frequent low amplitude intercalated beddings in some places. Except in the deep CMD, the pre-MSC unit is anisopaquous with several clear "fan-shaped" geometries (Figs. 6 and 7), which suggests deposition in a post-orogenic/syn-extension context, thus probably corresponding the lower part of the second sedimentary group found onshore Mallorca (see section 2.3).

- **Messinian Salinity Crisis unit (MSC)**: it is generally characterized by a very high reflectivity and horizontal beddings making it clearly distinguishable from the underlying and overlying sedimentary units (Fig. 2). On high resolution seismic profiles, this unit can be divided into several sub-units that were described in detail by Maillard et al., (2014) and Raad et al., (2021). In the deepest part of the CMD, the MSC unit includes a salt layer (Fig. 9). The MSC salt layer is characterized by the classic reflection free facies described elsewhere in the Mediterranean (e.g., Lofi et al., 2011; Fig. 9) and by ductile deformation (salt tectonics, Figs. 9 and 12B). Salt tectonics is however reduced in the CMD because of the small thickness and limited extension of the layer, and because of the closure of the depression, probably preventing the salt from further gliding and/or spreading.

Figure 10 shows the present-day depth map of the Top MSC Surface (base Pliocene). To the north, the top MSC lies at a relatively shallow depth (500 – 900 m deep below sea level) on a high that we call the Mallorca Channel Horst Zone (MCHZ). In the CMD, the top MSC deepens down to 1300 – 1500 m bsl and shallows laterally towards the slopes of the islands. The top MSC surface mimics the present-day bathymetry (Fig. 2A and B).

- Pliocene-Quaternary unit (PQ). It is bounded below by either the MSC unit, the pre-MSC unit or the substratum (acoustic basement), and above by the sea floor. On the basin scale, the PQ can be divided into 2 sub-units, PQ1 and PQ2, separated by an angular unconformity (intra PQ-unconformity, Fig. 5). The lower sub-unit PQ1 is characterized by a bedded facies with low reflectivity which is characteristic of the lower Pliocene unit observed elsewhere in the western Mediterranean (transparent Pliocene sensu Lofi et al., 2011). In the CMD, PQ1 drapes the underlying topography represented by the MSC unit (Figs. 6 and7). PQ1 is bounded above by the intra-PQ unconformity and onlapped by PQ2. Except in its lower part, PQ2 consists of high reflective continuous beddings on high resolution seismic profiles (Fig. 5). The internal reflections of PQ2 locally show onlap terminations on the intra-PQ unconformity (Figs. 6 and 7). In the CMD, the stacking pattern of these reflections shows a progressive filling of the depocenter (Fig. 9). The topmost part of PQ2 has been sampled on the southern shelf of Mallorca where it is composed of carbonate rich pelagic sediments (Betzler et al., 2011)**.** The lower part of the PQ sequence has been recovered only on the far western part of the BP in two industrial boreholes (Muchamiel and Calpe boreholes on the Alicante shelf; Ochoa et al., 2015; Ochoa et al., 2018), where it consists of soft silty clays and limestones (Ochoa et al., 2015; their post-evaporitic unit).

4.2. Offshore deformation:

4.2.1- Post-Messinian deformation.

Several features diagnostic of post-Messinian deformation are observed over the study area. Figure 10 presents the distribution of these structures, superimposed on the present-day depth map of the Top MSC (base Pliocene). The post-Messinian deformations appear mainly along the borders of the CMD.

- Normal faults and associated depocenters: these faults are evidenced by offset of the reflectors or by the syn-sedimentary deformation of the PQ unit and/or the MSC unit. We label the normal faults F1 to F4 from NE to SW, respectively (Fig. 10). In the MCHZ, a set of normal faults, some of which already described by Acosta et al. (2004), are trending N070°E and are mostly dipping southwards (Figs. 7 and 10). They belong to a system of two major faults, F1 and F2, that forms a NE-SW structural boundary between the MCHZ topographic high and the CMD low. F1 is the only fault over the study area that can be traced nearly continuously from NE to SE (Fig. 10). Its footwall includes the MCHZ along strike with the indentation of the Mallorca shelf (Andraitx Salient). Deeper to the south lies F2 with scarps facing North or South alternatively. Both F1 and F2 root in the basement and can be traced down to 2 sec twtt on deep-penetrating seismic profiles (F2 in Fig. 6, profile Map 70) and are clearly related to crustal tectonics. If these faults were already active before PQ (see paragraph 4.2.2.), the activity of F1 and F2, as well as other associated faults within that area, persisted during and after the MSC. This is also supported by the following observations:

- Some of these faults are locally reaching the seabed (Figs. 6 and 7).
- Some faults clearly offset the MSC unit by few to 350 m (Figs. 6A and 7) with local thickening of the MSC unit toward the faults (F2 fault, Fig. 12 A and B), suggesting that extension along the faults was active during the MSC.
- F1 and F2 are associated with a series of PQ depocenters, labeled D1 to D6, well visible in the PQ unit thickness map (Fig. 13).

Figure 7 illustrates depocenter D1 related to a graben structure bounded to the NNW by F1 and containing a ~350m thick PQ-unit (Fig. 13). Further NE, depocenter D2 displays a ~500m-thick PQ unit and is bordered by the fault F2 which hanging wall shows a clear tilting of the MSC unit (Fig. 6). Within the PQ unit, almost only PQ1 is affected by the deformation. PQ1 is thickened in grabens (D1, Fig. 7) or half-grabens, presenting syn-sedimentary fan-shaped geometries (PQ1 in D2, related to F2,

Fig. 6), which suggests that post-Messinian extension persisted during the deposition of PQ1, up to the intra-PQ unconformity (Fig. 5). PQ depocenters D1 and D2 are along strike with a third depocenter, D3, located eastward (Fig. 13). D1, D2 and D3 align with 3 additional depocenters D4, D5, and D6 (Fig. 4A) that will be discussed later. They all together form a N070° elongated corridor aligning along the F1 and F2 fault systems and filled with PQ unit up to ~600m thick (Fig. 13). We call this corridor the Mallorca Channel Depression Zone (MCDZ). Offshore it runs along a 100 km long and 20 km wide line going from the SW Mallorca margin to the Ibiza NE margin, parallel to the Andraitx Salient and the MCHZ (Fig. 13).

- Flexure: D4 belongs both to the MCDZ previously described and to the northern part of the CMD (Fig. 13). The PQ unit in D4 is up to ~600m thick, thus forming the thickest of the PQ depocenters. D4 appears not only related to the post-Messinian activity of the normal fault F2 but also to a post-MSC flexure involving the MSC unit and the PQ1 unit, both folded isopachously as shown in figure 9. Onlaps of PQ2 onto the intra-PQ unconformity show that the folding occurred at the end or just after the emplacement of PQ1. D4 draws a syncline fold trending NNW/SSE which axis is highlighted by the deformation of the base of the MSC salt. Elsewhere over the study area, the MSC salt is not deformed, except by salt-related gravity-gliding responsible for small halokinetic faults locally observed on the borders of the CMD (Fig. 9) and with a surficial expression in the bathymetry (Fig. 1). These faults were active since the salt deposition but are not related to crustal tectonics.

- Folds and strike-slip faults: some complex faults systems and associated deformation have been observed from the seismic profiles. On seismic profile Ba 16 (Fig. 6A), the fault F2 has a normal offset and dips 75° to 80° southward. On the same seismic profile, fault systems F3 and F4 appear much steeper, almost vertical (Fig. 14C). They are located on fold hinges (fold axis Fig. 13) and could resemble reverse faults. Both F3 and F4 affect the MSC, PQ1 and PQ2 units with little offsets. They occasionally reach the sea floor (Fig. 6). The MSC and PQ1 units are conformable along the fold associated with F3 suggesting a mainly post PQ1 activity of this individual structure. The next structure toward the south (F4-Fold A) exhibits little thinning of the MSC and PQ1 units at the apex of the fold (Fig. 6) suggesting some slow development of this structure during that time span.

Furthermore, we outline the existence of a number of folds from both the bathymetric data (Fig. 1) and the top MSC map (Fig. 10). They form undulations that run parallel to each other and trend SW-NE (folds A and B-B’ in Fig.10).

On the SW Mallorca margin, the formation of fold B has been active from PQ1 times up to recent times as demonstrated by onlapping geometries (onlaps of PQ1 on top of the MSC unit and of PQ2 onto the intra PQ unconformity, Fig. 12B) and by the deformation of the seafloor, (folds B-B’, Fig. 12A and B). Fold B was already known from previous studies based on the interpretation of high-resolution sparker data (Acosta et al., 2001a) and multichannel seismic profiles (Sàbat et al., 1995). Other antiform structures are evidenced locally in various locations within the study area (Fig.10). A seismic profile running across the Mont Dels Oliva structure clearly images fold C, deforming the MSC unit and crosscut by vertical faults (fold C, Fig. 12C). Here, PQ unit reaches 400m in thickness in the lows on each side of the fold, forming the depocenters D5 and D5' located NW of Mont Dels Oliva (Fig. 13). Only the PQ1 unit seems deformed by the tectonics associated with the creation of fold C which thus occurred before the deposition of PQ2 deposition. Further south however, fold D, on the SE side of Mont Dels Oliva, is emplaced recently, as attested by the isopachous deformation of the entire PQ unit, and of the presence of associated undulation on the sea floor (fold D, Fig. 12D). Folds are mostly observed along the NW-SE trending seismic profiles. The determination of their trends is constrained by the morphology of the Top MSC map and by the bathymetry but remains uncertain due to their low lateral continuity and to the low-density of seismic coverage in this sector (Fig. 2A). Vertical faults crosscut fold C and the PQ depocenters D5 and D5'. This complex and highly deformed area represents the SW prolongation of the MCDZ, which terminates with depocenter D6 located further West on the lower Ibiza slope (Fig. 13).

On the southern Mallorca margin, vertical faults affecting all the units up to the seafloor express active strike-slip motion (SLA and SL-B Fig. 10 and zooms Fig. 12). For example, the complex deformation zone presented on figure 12, (SL-A and -A', Fig. 12A and B) is a 5-8 km large depression affected by sub-vertical faults deep seated in the acoustic basement and pre-MSC unit, but that also reach the seafloor and involve the MSC and PQ units with normal offset on the borders of the structure (right part of SL-A'). The F2 fault, with normal offset, does not show a typical normal fault dip nor filling geometry, but seems to have been verticalized (Fig. 6).

4.2.2. Chronology of the deformation.

4.2.2.1 - Remobilization of former structures

The post-Messinian deformation is influenced by the Oligo-Miocene tectonic history of the area. Most of the faults offsetting the MSC and PQ units are linked to former structures that influence the latter deformation style.

- **Betic thrusts**: We locate new compressional betic structures on the MCHZ and Andraitx Salient areas (Fig. 8) that correlate well with deep-seated thrusts identified on the ESCI deep seismic profile (Figs. 3D and 6; Gallart et al., 1995; Sàbat et al., 1997). North of the MCHZ, towards the Valencia Basin, thrusts are oriented along strike of the downslope domain of Ibiza (NNW of Figs. 7 and 8). Betic thrusts are also observed elsewhere over the study area, for instance near Formentera, where the post-orogenic discontinuity is well imaged thanks to the erosion on top of folds in the acoustic basement (Fig. 12D). The thrusts remain poorly observed in the CMD where the thick sequence of sediments possibly prevents their identification. If present, they must have been overprinted by the post-orogenic extension and subsequently by the post-Messinian deformation. This is evidenced by comparing the faults plotted above the acoustic basement and base Pliocene depth maps (Figs. 8 and 10), which illustrate that the post-Messinian faults and former structures observed deeper in the acoustic basement are superimposed. On the lower slope of the SW Mallorca margin, the sedimentary units are folded from the basement up to the sea floor (fold B and B', Fig. 12A and B) where a prominent high seems related to the presence of deep crustal structures. Here, deep reflections dipping SE may be related to Betics deformation, similarly to the thrusts recorded between the BP and the Valencia margin (between fold B and SL-A, Fig. 12B). The nearly vertical fault limiting the high to the NW together with the folded MSC and PQ units are indications of a recent (up to Present-day?) remobilization of the structure, probably with a strike-slip motion. The transcurrent zone SL-A -A' also records pre-MSC deformation observed in the acoustic basement, most probably linked to former Betic reverse faults that have been reactivated with a dominant strike-slip motion.

The Betic thrusts on the BP acted during or just after the regional Oligo-Miocene rifting structuration in the surrounding basins. The horsts resulting from this extension (see paragraph 2.2) and still largely observed on the BP where post-orogenic extension (almost) did not overprint these former structures (e.g., Ibiza Channel, Formentera margin), are poorly preserved in the study area. However, we cannot disproof that the Betic thrusts observed here are reactivated normal faults linked to the rifting.

- **Normal faults linked to the post orogenic extension**: The pre-MSC deposits are anisopachous with several depocenters (Fig. 11B) in which some syn-sedimentary fan-shaped growth strata can be observed in association with the previously mentioned fault systems F1 and F2 (Fig. 6). These syn-tectonic features in the pre-MSC unit prove that these faults acquired most of their normal offsets prior to MSC times, most probably linked to the post-orogenic extensional phase. At depth, F1 and F2 root in SE-dipping deep reflectors in the acoustic basement that we correlate with thrusts (Figs. 7 and 12B). On the deep penetration seismic profiles, folds observed in the acoustic basement at the southern border of the MCHZ abut on the vertical faults (Betic thrusts and folds, NW-most fold on F2 in Fig. 12B; fold on SE of Mont Dels Oliva on Fig. 12C). These geometries suggest that the compressional structures (thrusts) have been subsequently inversed during the extension phase affecting the pre-MSC unit (D, Fig. 3). F1 and F2 that are at the origin of the MCDZ were thus structurally controlled by the former thrusts (F2, Fig. 12B; Fig. 3D), as also proposed by Sàbat et al. (1997), Gallart et al. (1995), and Sàbat et al. (2011). The pre-MSC unit filling grabens or half-grabens (Figs. 6 and 11) also confirm that the CMD already existed before the Messinian times, as proposed by some authors (Roca, 1992; Céspedes et al., 2001; Acosta et al., 2004a; Sàbat et al., 2011). The thickest pre-MSC depocenters (up to 900 m-thick) are located on the southern border of the CMD, as shown by the pre-MSC unit thickness map (Fig. 11B). However, we did not identify any major faults controlling the pre-MSC depocenter in this area.

4.2.2.2 - PQ deformations

During the Pliocene, the main depocenters shifted northward as shown by the pre-MSC versus PQ units thickness map (Fig. 11A). They developed along the MCDZ, bordered by the set of faults F1 and F2 that are characterized by a dominant listric geometry. Some of those steeply dipping faults were previously described and interpreted as triggered by surficial gravitational movements (Acosta et al., 2004). Our results show that they are deep-seated faults that were active during the deposition of the PQ1 unit as evidenced by the syn-sedimentary geometry of its internal reflectors. The unconformity at the top of the PQ1 unit must then correspond to the end of this major extensional episode, although the tectonic activity and subsidence should have carried on with a weaker amplitude until recent times (i.e., PQ2 unit). Accordingly, the existence of PQ depocenters (depressions D1, D2 and D3), present in the NE-SW the MCDZ are related mainly to an extension phase that was active during the PQ1 deposition and later attenuated during the deposition of PQ2.

We also observe very recent strike-slip deformation (Fig. 10), along similar direction to the main NE-SW trending normal faults that affect the MSC unit. The fact that the normal faults are particularly vertical (Fig. 6), suggests that some of the major normal faults have been reactivated as strike-slip faults during the deposition of the PQ2 unit. This phase of deformation could still be active today as revealed by some earthquakes epicenters that are localized along the active part of the faults (red faults in Fig.15). Transcurrent tectonic regime is also coherent with the alternations of non-cylindrical highs (related to folds) and lows (related to the depocenters, grey and yellow areas, Fig. 15). This is supported by the alignment of the PQ depocenters and the folds, both having no lateral extension and forming in small and narrow mini-basins along the NE-SW elongated MCDZ corridor.

We thus observe evidence for two distinct post-MSC tectonic deformation episodes (Fig. 17B and C): the first one corresponding to an extension, probably NW-SE trending, coeval with the continuation of the development of grabens and with the deposition of PQ1, and the second one associated with strike-slip tectonics along pre-existing normal fault zones, contemporaneously with the deposition of PQ2 unit, and probably still active at present-day.

4.2.3. Role of PQ charge in the vertical movements

The results of the pseudo-3D backstripping performed along strike the mini-basins (Fig. 4; see section 3) allow evaluating the contribution of the post-Messinian sediment load, and associated subsidence, on the formation of the PQ depocenters D1 to D6. The reconstructed paleo topography of the top MSC across these depocenters, before deposition of the PQ unit, is shown in figure 4. The results using effective elastic thickness TE=5 km (close to local isostasy, Fig. 4D) show that the topographic lows were already existing at the end of the MSC, as they remain visible on the backstripped section. The PQ sedimentary cover creates a mean subsidence of approximately 80m, with maximum values in the D4 depocenter reaching 110m (plot 2 in Fig. 4B). The PQ sediment load is maximal in D4, which therefore is the most sensitive area to variations of parameters in the backstripping analysis like TE. In D4, the sediment load can significantly amplify the MSC resulting topography. Here a pre-existing low has been enhanced by the syn-PQ2 flexure (Fig. 9). Results show that for the depocenters D1, D2 and D5, the PQ load only is not enough to significantly deform the top MSC surface. The PQ load may have contributed more significantly to the formation of the depressions D3 and D6, as a result of a thick PQ related to post-Messinian shelf progradation (A, Fig. 4).

Any slight increase in TE value implies a much smaller contribution of PQ sedimentary load-induced subsidence and therefore a more pronounced pre-existing topography in the reconstructed end-MSC surface. With TE=15 (regional isostasy, Fig. 4E), deflection is thus very small and only reflects the regional large-scale flexure of the CMD. The PQ load is responsible for only 50m of subsidence (Fig. 4B). In both models presented above (Te=5 and TE=15), the restored top MSC surface is relatively similar, both in term of pre-PQ depth and of overall morphology. This is in favour of the development of a mostly rigid deformation resulting from a more efficient regional effect of the surrounding deep basins (Heida et al., 2021). In addition, the morphology of the restored top MSC surface is not very different from the present-day buried one, suggesting that the topographic lows were already present before the PQ load. Because the PQ isostatic load cannot account for the creation of the local depressions, a significant amount of subsidence has to be driven by tectonic deformation, also brought out through our observations.

4.3. Land-sea correlation and interpretation

4.3.1. Structural continuity and comparison

Figure 15 shows that the main structures in the Mallorca Channel are along strike with the major structures observed on the Mallorca Island. As attested by the observation of the Betic thrusts in this area, the MCHZ and the Andraitx Salient are the offshore continuation of the Tramuntana Ranges (see paragraph 4.2.2; Fig. 8 and Fig. 3D). In the same way, the Central Ranges may extend offshore via the SW-NE trending topographic/structural high observed on the SW Mallorca margin and extending downslope to the CMD (folds B-B' area where thrusts are observed, Fig. 8). Between both Ranges, the MCDZ is along strike with the Mallorca Graben. The faults bordering the MCDZ also align with onland structures. The F1 set of faults is at large scale along strike with the Alfabia and Alaro faults (Orient faults system) that limit the Inca and Santa Pobla sub-basins, respectively (Fig. 15). Figure 3 highlights the analogies between the onshore and offshore records. It displays at the same scale two transverse sections across the Inca and Palma depressions onshore (Capó and Garcia et al.,

2019) and across the mini-basin related to D2 offshore. These basins are all bordered by faults separating the pre-orogenic basement from the basin fills. The NW fault limiting the Inca sub-basin has been proposed to root on deep Betic thrusts (Sàbat et al., 2011; Fig. 3A) and so do the faults F1-F2 bounding the mini-basin related to D2 offshore (see paragraph 4.2.2).

The Palma sub-basin is separated to the North from the Tramuntana Ranges by the N15°-N20° trending Palma fault. We do not observe any prolongation of the Palma fault offshore as proposed by Sanchez-Alzola et al. (2014) (Fig.15). This structure (former thrust?) may be expressed in the structural high that disconnects the Palma Bay from the mini-basin related to D3 (Fig. 4A). Further south, the F3 fault is along strike with the faults limiting the Mallorca Graben from the Central Ranges (CEP fault, Fig.10).

The onshore and offshore sections (Fig. 3) display comparable thicknesses of post-orogenic sediments. Both onland and offshore faults constrain anisopachous pre-MSC units that evidence the post-orogenic extension (Sàbat et al., 2011; Moragues et al., 2021). They remain active during the Plio-Quaternary times as evidenced by the isopach map of the PQ sediments. Indeed figure 13 illustrates a clear alignment of the post-MSC depocenters extending from the Mallorca Graben onshore to the MCDZ offshore. This alignment includes from east to west, the Alcudia Bay, Santa Pobla Basin, Inca Basin, Palma Bay and the mini basins related to D1 to D6. All of these basins show the same order of dimensions (~6x10 km; Fig. 3). Their alignment forms a 150km long and continuous NE-SW trending offshore/onshore trough restricted in a narrow (10km) corridor, the MCDZ-Mallorca corridor, or the Northern corridor (Fig.15).

Along strike sections show that the depocenters are separated from each other by highs which are unfortunately not clearly imaged due to the quality of the seismic data close to the Palma Bay (Fig. 4A and C). For example, the Palma sub-basin onland seems disconnected from the offshore Palma Bay, which prevents confidently correlating the continuity of the sedimentary units from the CMD to the Palma Bay (Maillard et al., 2014; Raad et al., 2021).

Onland Mallorca, the Sencelles Fault constitutes one of the main post-orogenic extensional structures (Fig. 16). Its deep structure shows that it roots on the Alfabia fault (Sàbat et al., 2011; Fig. 3A). Being initially a normal fault, it reversed during the Pliocene as left-lateral strike-slip fault. Compressive structures affected Neogene and Quaternary materials in the Palma and Inca sub-basins (Giménez, 2003), such as the Son Seguí-Santa Eugènia topographic high (Fig. 14A). The Late Messinian limestones associated with this antiform structure are, located in an anomalous position more than 300 m high (Fig. 14B), in a fold that affected the Messinian and Pliocene units. Located along the NW extremity of the Sencelles fault, this fold is associated with the transpressive strike-slip motion along the fault (Fig. 16). Inversely, at the other extremity of the fault, the same deposits are buried in the Llubí area (Fig.16; Mas et al., 2014) and the resulting depression is interpreted as a negative flower structure due to a step-over along the Sencelles fault. These structures are interpreted as a push up structure and associated pull apart-like depression respectively along the Sencelles fault (Fig. 14). Some major detachments resulting from the positive and negative strike-slip structures have been produced (Fig. 14; Mas and Fornós, 2020), possibly exploiting the clayey plastic sediments belonging to the final MSC stage also known as 'Lago Mare' (Andreetto et al., 2021), but possibly occurring later as slickenlines which are observed in Pliocene calcarenites (Mas, 2015). Offshore, we observe very similar structures on the high-resolution seismic profiles (Fig. 6). Local non cylindrical folds are indeed of the same order of magnitude as the Son Segui-Santa-Eugènia antiform in both width and height (200-300m) (Fig. 14). Changes in footwalls along the offshore faults are also in accordance with strike-slip movements. Other small folds were observed onshore in the Levant and Central Ranges associated with some vertical faults interpreted as positive flower structures (Punta Roja vertical fault, Giménez, 2003).

4.3.2. Structural interpretation

We interpret the Son Seguí-Santa Eugènia antiform as the result of recent transcurrent tectonics. This is consistent with the interpretation at larger scale of the tectonics in the entire Mallorca Graben as a strike-slip zone during Pliocene and Quaternary times associated with the sinistral movement of the main NE–SW faults of the island (Giménez and Gelabert, 2002; Giménez, 2003). In accordance with these former works and with our observations, and as the MCDZ is the offshore prolongation of the Mallorca Graben, we interpret the entire MCDZ-Mallorca corridor (Northern corridor) as a transcurrent trough. Therefore, the complex structures forming the MCDZ-Mallorca corridor are interpreted as alternations of transpressional (push up) and transtensional (pull apart) –type like structures respectively, in a large wrench zone allowing the coeval existence of compressional and extensional strains localized along restraining bends and step overs (Figs. 15 and 17d; Harding, 1985; Cunningham & Mann, 2007). Location of compressional versus extensional areas are reported in figure 15. The folds that consist of narrow antiforms all cut by vertical faults, resemble positive flower structures that could correspond to restraining bends. This is the case on folds B –B' where low magnitude earthquakes confirm their activity (Fig. 10). Remobilization of F2 structure and SL-A-A' display narrow synform limited by mostly normal separations, that are in that way interpreted as negative flower structures linked to divergent part of a wrench faults area (Huang and Liu, 2017). The D4 flexural depocenter that corresponds to the post-MSC synclinal fold can be linked to local transpression, induced by strike-slip relative movement along the F2 and F3 faults that limit the depocenter to the North (Fig. 15). Unfortunately, we do not have focal mechanisms of the seism located on the extremity of the F2 fault (Fig. 15). The MCDZ ends on the SE Ibiza margin, where we observe the curvature of the structure expressed in the area of fold C-C' and the associated offset of the D5, D5' and D6 mini-basins, with faults trending N20° and N15° respectively, associated with surficial deformation in the bathymetry (Acosta et al., 2004). This complex area is likely to be interpreted as the termination of a wrench zone (horsetail like structure?) (Fig. 15).

Beside the main transcurrent MCDZ-Mallorca (or Northern) corridor, some other corridors can be traced from onshore to offshore in the entire study area. On the down slope domain of the SW Mallorca margin, folds B and B' not only display structural highs along strike with the Central Ranges of Mallorca, but also reveal, as suspected by Acosta et al., (2001a), post-Messinian deformation comparable to the recent folds parallel trending (Llucmajor anticline, Fig. 10; Sanchez-Alzola et al., 2014; Sàbat et al., 2011). The SL-A -A' apparent negative flower structure appears in a depression facing the Campos Basin. These structures are difficult to follow southwestward in the deep CMD domain where the PQ unit is barely deformed, but could be continuous with the Mont dels Oliva and Mont Ausias Marc faults on the other side of the CMD. These 2 mounts indeed show signs of recent faulting (Fig. 12C). Mont Ausias seamount shows a NE–SW oriented fault which dissects its flat top with a relief of more than 25 m. This complex fault network has been related with NE–SW transcurrent faulting (Acosta et al., 2003; 2004) with right lateral displacement, not in accordance with the left-lateral movements recorded onland. The deep domain of the CMD is however "split" by a structural high (Fig. 10) whose nature is unknown but that resembles the B-B' fold. This elongated high could connect the strike slip zone (including faults SL-A-A' and fold B-B') to Mont Ausias fault system in a long transcurrent zone crossing the CMD, that we call the Southern corridor (Fig. 15).

4.3.3. Identification of the units and dating of deformation

- Pre-MSC unit and post orogenic extension phase*:* As explained in paragraph 4.2.2., the main N070° faults in the study area were active during the post-orogenic extension (middle Miocene times), perpendicular (NW-SE) to the thrusts proposed by Sàbat et al., (2011). They could also be associated with or followed by a NE-SW extension by processes of radial collapse (Moragues et al., 2021) responsible for dextral strike-slips on the N070° faults. The thickness of the post-orogenic sediments (Fuster, 1973) reaches 300-400m in the Palma and Inca sub-basins and includes Plio-Pleistocene sediments with a mean thickness of 100m (Capó and Garcia, 2019), attesting that the subsidence started before the Pliocene. Offshore, depocenters D2 and D3 accumulated around 400m of pre-MSC deposits (Fig. 11B) showing that those depressions likewise are pre-Pliocene. They thus display a clear analogy with the Mallorca Graben's depocenters, not only in terms of geometry and width but also in thickness. Based on this analogy, we propose a middle to late Miocene (Serravallian to Messinian pre-MSC) age for the pre-MSC unit offshore, which's fan-shaped geometry is in accordance with extension or possible transtension phase (cf section 5.3; Fig. 17A). Note that the main depocenter for the pre-MSC units remains in the south of the CMD and are divided into 2 sub-basins (Fig. 11). One of them is located in the offshore continuation of the Campos basin and could possibly be related to the same type of structuration. The south of the CMD (Southern corridor) was mainly formed during the pre-MSC times, while its northern part underwent tectonic subsidence mostly after the MSC.

-MSC drawdown: An important base level fall during the MSC affected the morphology of the area by erosion, as observed on all Mediterranean margins (the MES; Margin Erosion Surface; Lofi et al., 2011; Roveri et al., 2014; Maillard et al., 2014; Mas and Fornós, 2020; Raad et al., 2021). Offshore, this erosion was responsible for the creation of the Palma onshore/offshore valley dug in former grabens that were initiated during the post-orogenic extension (Maillard et al., 2014). Erosion is also observed locally on the slopes of the CMD and on the Mallorca Channel (Raad et al., 2021). In the meantime, MSC-related deposits accumulated in pre-existing depressions both onshore (gypsum sampled by drillings in the Palma sub-basin; see Mas and Fornós, 2020 and references therein) and offshore in the CMD and on its slopes (Figs. 9 and 10; Maillard et al., 2014; Driussi et al., 2015a; Raad et al., 2021). The MSC event thus affected the study area and generated well identified surfaces and units that are used as a temporal marker (5.97-5.33 Ma). Fan-shaped MSC deposits show that extension persisted during their deposition in the Late Messinian.

-PQ1 unit and Pliocene deformation: The results of Capó and Garcia, (2019), suggested 50 to 150m of subsidence for the onland Palma, Inca and Santa Pobla sub-basins during the Pliocene-Quaternary. Such amplitudes of subsidence rates are in accordance with the PQ load we calculated offshore in the MCDZ (around 50m of subsidence, Fig. 4B). Onshore, during the Pliocene, heterogeneous marine sedimentation occurred as attested by the Son Mir Formation in the Mallorca Graben (Capó and Garcia, 2019). In the Palma sub-basin, subsidence is maximal during this period (Fig. 3) and sediments fill up pre-existing topographic lows. At the scale of the Mallorca Graben, the subsidence rate deduced from accumulation rates decreases from the Lower Pliocene (Son Mir Formation) to the late Pliocene (San Jordi eolian Formation; Capó and Garcia, 2019).

Observations made in the PQ geometries offshore can help understanding the onshore records and vice versa. Based on thickness and geometry analogies, we interpret the PQ1 unit offshore as the equivalent of the Son Mir Formation onshore. The fan-shaped geometry of the PQ1 unit offshore is controlled by nearly vertical faults, while onshore, in the Inca sub-basin, the filling is clearly related to the Sencelles fault (Fig. 3) which played an important role for creating accommodation space during the Lower Pliocene (Sàbat et al., 2011; Capó and Garcia, 2019). The important activity of the N070° set of faults controlling the depocenters along the MCDZ corridor reveals a localization of the deformation with still NW-SE extensional component with possible progressive change to a strike-slip regime (transtentional) (Fig. 17B). Offshore, PQ1 lies directly above the MES or the MSC unit (Fig. 7). Similarly onshore, the Son Mir formation lies unconformably on an erosional surface cutting the top of the Late Messinian Santanyi limestones or of the reef unit (Fig. 3) which is interpreted as the MES

(Mas and Fornós, 2020). The relatively transparent seismic facies of the PQ1 unit suggests homogeneous fine-grained sedimentation, in accordance with the hemipelagic sediments described on the SW Mallorca margin (Acosta et al., 2004a; Lüdmann et al., 2012). It is also in agreement with marlstones facies encountered at the base of the Son Mir formation deposited during high stand see level, in accordance with post-MSC Zanclean refilling.

PQ2 and late-Pliocene/Quaternary deformation: using borehole data tied to seismic profiles on the BP, Lozano, (2016) proposed that the top of the transparent PQ unit corresponds to the top of the Zanclean dated at 3.6Ma. Thus, following Lozano, (2016) we tentatively interpret the change in seismic facies between PQ1 and PQ2 as corresponding to the change in lithology between the Son Mir (Zanclean) and the Sant Jordi (Piacenzian) formations. If so, the distal equivalent of the sandstones forming the Sant Jordi FM tie distally with the more reflective facies observed within PQ2. This facies should then include the Quaternary sediments in its upper part. The PQ2 is less fan-shaped and more isopachous which fits with the diminution of the tectonic subsidence through the Pliocene time onshore, as a result of the decrease in normal faulting activity and the change toward a strike-slip regime. However, there is no evidence onshore for any intra-PQ unconformity, as observed offshore, and the Pliocene succession onshore passes gradually vertically and marginward from deep silty deposits (Son Mir Calcisiltites) into calcarenites (Sant Jordi Calcarenites).

Onland, recent strike-slip movement is attested by late Pliocene/Quaternary tectonic fracturing and brecciation in the Inca sub-basin (Mas et al., 2014), in accordance with evidences for Quaternary seismic activity widespread on the island (Silva et al., 1998, 2001; Giménez and Gelabert, 2002; Giménez, 2003; Fornós et al., 2005). Offshore, normal or transtensive movements seem to decrease during PQ2 deposition, with F1 set of faults becoming non-active. F2 fault and several strike-slip faults southward in the CMD, affecting the sea floor, confirm a recent activity. Folds are particularly active and seem to confirm that transpression could be predominant (Fig. 17C), in accordance with reverse movement along the Sencelles fault (Silva et al., 1998; 2001; Giménez and Gelabert, 2002; Giménez, 2003; Mas et al., 2014).

Offshore seismicity (Fig. 1) is likely to be related to the transcurrent structures, confirming the present-day activity. Significant earthquakes (magnitude > 3) are located offshore on tectonic structures described in this study. One epicenter is located on an active segment of F2, precisely where a transversal fault offsets the MCDZ near the depocenter D4 (Fig. 15). Another epicenter is located on the fault bordering the Palma Bay to the SE. Some others are in the vicinity of the fold B and correlate with the Southern corridor. The epicenter located precisely on the active strike-slip fault south of the CMD (active SL, zoom 1, Fig. 12B) confirm its present-day activity. This corridor appears particularly active when compared with faults system F1 and F2 which could suggest that deformation propagates southwards.

5. Discussion

Hereafter, we integrate our study area into the BP and a larger regional scale sketch. How can the tectonic evolution of the CMD from late Miocene to recent fit with the regional tectonic evolution and kinematics? Is it compatible with what is recorded on the other large faults of the area?

5.1. Regional extension of the corridors

The western termination of the proposed Northern strike-slip corridor is localized offshore, at the SE Ibiza margin where faults are turning toward a N010°-020° direction in the D6 area (Fig. 10). It may possibly extend further westwards between Ibiza and Formentera Islands as the rough scarp of the Ibiza SW shelf is perfectly aligned with the F1 set of faults and connects westward with a small earthquake swarm along a normal fault (Fig. 15). Moreover, some important post-Messinian deformation is observed offshore the SW Ibiza margin. It corresponds to a number of active structures such as the Xabia and El Cid Sea Mounts without clear lateral continuity but which are also characterized by a similar N060°-N080° trend (Fig. 1; Acosta et al., 2001b; Maillard and Mauffret, 2013; Driussi et al., 2015b). Farther to the west, the Ibiza Channel between mainland Spain and Balearic Islands (Fig. 1) acts as a boundary east of which the main trend of the structural pattern changes slightly from N065-070°E to N080-085°E, becoming roughly parallel to the Mazarron escarpment. The Ibiza Channel could include a NW-SE directed transfer zone extending northward to the western boundary of the Valencia Basin (Nao Fracture Zone that offsets the Betic front, Fig. 1; Maillard, 1993; Nao FZ, Fig. 17). Within the Valencia Basin, some other NW-SE transfer zones have been proposed and linked to the Oligo-Miocene rifting episode and associated volcanism (Maillard and Mauffret, 1993; Acosta et al., 2004b; Pellen et al., 2016). One of them, the Ibiza Fracture Zone, was supposed to extend between Ibiza and Mallorca and has been proposed to account for differential rotations between both these Islands during the Betic orogeny (IFZ, Fig. 17; Parés et al., 1992; Acosta et al., 2001a). In our study area, this transfer zone could be expressed by the NE Ibiza rough escarpment and the NW-SE trending faults east of the Mont Ausias Marc (Fig. 10). It has been proposed to still be active and responsible for recorded seismic events (Acosta et al., 2001a; Sanchez Alzola et al., 2014). Our results show no evidence for any active NW-SE trending structures, and only some minor NW-SE structures were described from onland Mallorca (Sàbat et al., 2011; Mouragues et al., 2021).

On the other side of the study area, NE of Mallorca, the faults bordering the Santa Pobla sub-basin extend offshore in the Alcudia Bay. There, the activity of these faults and their offshore prolongation is outlined by seismic activity through the location of several earthquakes (Fig. 15). We do not have enough data coverage to specify how far the faulted corridor extends to the NE on the Mallorca shelf. Further NE, Menorca is separated from the rest of the Promontory by another major NW-SE trending transfer zone that distinguishes it from the other islands (Central Fracture Zone, Maillard, 1993; Pellen et al., 2016; Maillard et al., 2020; CFZ Fig. 17).

South of the study area, the Mont Ausias Marc faults were also interpreted as strike-slip structures by Acosta et al. (2003; 2004a), in accordance with our proposition for a Southern Corridor (Fig. 15). Moreover, a N060-070°E fault also limits the North of the Formentera Basin (Driussi et al., 2015b; Etheve et al., 2016; Fig.1): as poor post-orogenic extension is observed there (Maillard et al., work in progress), it could also accommodate some recent strike-slip deformation, and could therefore correspond to the western prolongation of the Southern corridor.

The strike-slip faults systems outlined from this study are continuous from the east of the Ibiza Channel toward the NE Mallorca shelf and thus reveal a homogeneously deformed Ibiza-Mallorca block during at least the late Miocene to Quaternary times.

5.2. Regional scheme, relations with Emile Baudot Escarpment (EBE)

We identify several large-scale parallel strike-slip corridors across the entire study area, from both onshore and offshore data (Fig. 15). Bordering the BP to the south, the EBE is running strictly parallel to these corridors. This major structural lineament must thus be taken into consideration when relocating our observations in a regional tectonics framework.

The EBE is often interpreted as a crustal-scale structure formed by the westward motion of the Alboran block, during the rollback of the slab from the Ligurian Tethys lithospheric slab (Cohen, 1980; Lonergan and White, 1997; Rosenbaum et al., 2002; Mauffret et al., 2004; Mattauer, 2007; Gutscher et al., 2002, 2012; Medaouri et al., 2014) presently located under the Gibraltar Arc, as visible in seismic tomographic data (Spakman & Wortel, 2004; Garcia-Castellanos and Villaseñor, 2011; Vergés & Fernàndez, 2012). Though the age and even the nature of the Algerian basin are poorly constrained, most authors propose an oceanic accretion phase dated from late Burdigalian or Langhian (19-15Ma) to Tortonian (8Ma), younging westward (Mauffret et al., 2004; Jolivet et al., 2009; Crespo-Blanc et al., 2016; Leprêtre et al., 2018; Romagny et al., 2020; Haidar et al., 2021). If that right-lateral origin for the EBE is adopted, then it would seem reasonable that the strike-slip corridors of the CMD also originated by the same dextral motion. While we will adopt such interpretation for the following discussion, it must be kept in mind that other regional tectonic models do not involve a large westward rollback at the BP (Vergés & Fernàndez, 2012; García Castellanos & Villaseñor, 2011). In fact, the first post-orogenic deposits on the BP are apparently linked to NW-SE extension rather than to strike-slip tectonics, at least in the central part of the Mallorca Graben (Benedicto et al., 1993; Sàbat et al., 2011). Indeed, the Mallorca Graben faults seem to record normal movement in accordance with the fan-shaped geometry of the pre-MSC units that we observe offshore associated to the structural development of the MCDZ. Booth-Rea et al., (2017) suggested that a WSW-ENE extension on the BP would be expressed by WSW-ENE strike-slip faults acting during late Langhian–Serravallian*,* as in particular, the dextral-oblique strike-slip system that limits the southern foothills of the Tramuntana ranges (Alfabia/Alaro fault zones). They have related these deformations to the opening of the Algerian Basin coevally with the transfer fault along the EBE. Etheve et al. (2016) proposed to explain the formation of the Formentera basin south of Ibiza by dextral transtensional movement associated to the same episode. Such a movement is coherent with NW-SE trending faults spread all over the BP, not predominant in the CMD but widely observed throughout the South Menorca Block, where they have been related to SW-NE extension (Driussi et al., 2015b; Fig. 17A). One should however notice that the NW-SE faults from the BP developed over short distances and that they show offsets of the MSC unit. Thus they could alternatively, and preferably, be related to extensional local step-over along the Plio-Quaternary strike-slip faults. Mouragues et al. (2021) recently proposed a collapse during Serravallian associated with low angle normal faults and accompanied by radial extension ranging from SW-NE to NW-SE directions. The NE-SW-directed faults were transfer faults during the first episode of extension, with most of them expressing right-lateral displacement but with a few others showing left-lateral displacements. Such complex displacement pattern is relatively common in transfer fault systems that are related to extension (*e.g*. Giaconia et al., 2014). Faults with very similar orientation have also been observed in the Betics on mainland Spain, and were interpreted in the same way (Martínez-Martínez et al. 2006; Giaconia et al., 2014; Fig. 17). These SW-NE trending long faults, as well as the EBE, are usually supporting the kinematic reconstitutions of the Algerian Basin, through a process of slab tearing during upper Miocene times, in accordance with the interpretation of the west Algerian margin as a STEP fault (Medaouri et al., 2014; Leprêtre et al., 2018; Haidar et al., 2021) and the EBE as a transform margin (Mauffret et al., 2004; Driussi et al., 2015b). These SW-NE faults in the Betic domain have been suspected to still be active under Plio-Quaternary transpression (e.g. Bousquet, 1979; Giaconia et al., 2013; 2014). Such faults with changing kinematics, with here an early behavior as dextral transtension and followed by later transpression (*e.g.*, Meijninger and Vissers, 2006; Ferrater et al., 2015; Martínez-Martínez et al., 2006), are likely similar to the faulted corridors in the Balearic Promontory. Considering a dextral motion along the main SW-NE faults in eastern mainland Spain and along EBE during the westward drift of the Alboran Block, the faulted corridors described from this study should also record an early dextral movement during Serravalian to Tortonian times (Fig. 17A). Our data do not show evidence of right-lateral movement in the pre-MSC unit that would anyway have been overprinted by the following tectonic phases but its fan-shaped geometry could account for transtension. It cannot either be excluded that the initiation of the faults could be older and therefore related to the Oligo-Miocene rifting episode in this region, and if so, they could have recorded also some extensional deformation during the early stages of the post-orogenic collapse (early Serravallian).

During Plio-Quaternary times, if a possible left-lateral reactivation of the corridors is compatible with general strain that changed to NS compression (Fig. 17), its relationship with the EBE is not straightforward, as no clear motion is recorded there. Only very small magnitude earthquakes (magnitude up to 1.9 Mw; Fig. 2D) are localized along the EBE, showing little active deformation. Numerous volcanic pinnacles on the EBVM could reveal some relatively recent activity as a Pleistocene age was attributed to a basalt sample recovered from the area (Acosta et al., 2004b). In our seismic data, we recognize some volcanic lava flows interbedded within the PQ unit close to the EBE, which also confirms some recent activity from these volcanoes (seismic profile Carbmed 141, Fig. 12F). Along the EBE scarp the presence of volcanic material is also suggested by widespread chaotic seismic facies and by magnetic anomalies (Fig. 1 and Driussi et al., 2015b), attesting for a period of intense volcanic spreading, which started before the Pliocene. Reflective layers indicative of lava-flows on the seismic profiles are also locally observed in the pre-MSC unit. They may be linked in age to volcanism that grew by local transtension along the EBE, which may have allowed magmatic intrusions along deep fractures (Camerlenghi et al., 2009). The recent magmatism probably initiated during the slab retreat through STEP process along the EBE that then became an active transform zone during the oceanic accretion of the Algerian basin. Volcanism could have continued after EBE became passive. Some transform margins, such as Guinea or Agulhas transform margins, also experienced volcanism during their passive margin stages (Benkhelil et al., 1995, Mercier De Lépinay et al., 2016). Volcanic seamounts can be lined up with transform margins, which could have acted as a lithospheric weakness zone (Deplus et al., 1998; Basile et al., 2013), and inversely, transform margins can be reactivated and can localize deformation (Attoh et al., 2005). Acosta et al. (2001a; 2004b) proposed a genetic link between the recent formation of the volcanic pinnacles with a process of decompression resulting from the extensional deformation. This normal faulting episode consequently led to the subsidence of the CMD. However, as shown by the distribution of the depocenters on the pre-MSC thickness map (Fig. 11B), the main subsidence episode already occurred before the Pliocene (Fig. 10; Capó and Garcia, 2019).). Instead, we prefer to invoke some degree of reactivation of the EBE as a left-lateral fault, triggered by the ongoing convergence between Nubia and Eurasia. However, the occurrence of recent volcanism in the nearby Valencia Basin (e.g., Columbretes Islands and offshore extension, CV., Fig. 1) may rather require a regional explanation. The alkaline nature of this recent magmatic episode of the Valencia Basin, late Miocene to Quaternary in age (Martí et al., 1992; Réhault et al., 2012), has been related there with recent widespread lithospheric extensional deformation at the European scale (Morocco to North Sea large shear zone, Lopez-Ruiz et al., 2002; Muñoz et al., 2005). This is not clear for the BP, as the lithospheric thickness is not thin (70 to 80km, Roca et al., 2004; Carballo et al., 2015) and regional heat flow is as low as in the Valencia Basin (Fernandez et al., 1998) and very variable at the western part of the EBE (Poort et al., 2020). Although the recorded high heat flow values are not spatially correlated with the known volcanic intrusions, they could be related to recent volcanism, as observed on the Columbretes Islands where heat flow values reach 120-150 mW/m2 (Poort et al., 2020).

The regional setting during the Pliocene is contractional as Africa is currently converging toward Eurasia at a rate of 5 mm/yr in this area (DeMets et al., 1990; Nocquet and Calais, 2003; Serpelloni et al., 2007). The deformation associated to this convergence is mainly localized in the thrust belts of North Africa and in the active Algerian margin, with the major faults showing compressional focal mechanisms (Meghraoui, 1988; Yielding et al., 1989; Déverchère et al., 2003, 2005; Domzig et al., 2006; Yelles et al., 2009). Contraction is well expressed on the BP only around the Ibiza Channel where recent folds reshape the Alicante shelf (e.g. Tabarca and Cogedor highs; Fig. 1 and Fig. 17C), as well as numerous recent mass-wasting events on the SW Ibiza margin (Alfaro et al., 2002; Acosta et al., 2003, 2004a, 2004b, 2013; Lastras et al., 2004; Camerlenghi et al., 2009; Maillard and Mauffret, 2013). The easiest way to explain left-lateral strike-slip motion during Quaternary along the NE-SW trending corridors of the CMD and of Mallorca is to relate them to the general NS to NNW-SSE contraction, as also proposed by Sàbat et al. (2011). It also explains the compressional deformation recorded on the nearly E-W trending structures of the Alicante shelf, parallel to the Mazarron Escarpment and the strike-slip motion along the Crevillente fault zone where the Llorca earthquake occurred in 2011 (Fig. 17C).

6. Conclusion

The results of our investigation on the central part of the Balearic Promontory show moderate but clear post-Messinian tectonics. Our data and analysis, together with onshore-offshore comparisons and correlations, leads us to propose a coherent interpretation for the structures observed offshore in the Pliocene to Quaternary sedimentary units.

In the Central Mallorca depression (CMD), we show that the main recent depocenters, Pliocene to Quaternary in age, display a succession of mini-basins that line up along a large NE-SW corridor, the MCDZ or Northern corridor, along strike with the onshore Mallorca Graben, also composed of three sub-basins of similar scale. The main fault system bordering the corridor has been correlated with onland faults bordering the Mallorca Graben, which we interpret as reactivated post-orogenic normal faults. Extensional tectonics persists after the Messinian. The combination of onland stratigraphic data and offshore seismic stratigraphy and geometry of the units allows us to date a change of the tectonic regime from extension to strike-slip by the end of the Zanclean stage. Moreover, it led us to specify the correlations between different seismic facies, PQ1 and PQ2, with contrasted lithologies observed onland respectively from the Son Mir (Zanclean) and the Sant Jordi (Late Pliocene) formations with an unconformity in between.

The activity of large strike-slip systems, mainly during the late Pliocene and the Quaternary, can explain the complex and non-cylindrical extensional and compressional structures observed. They consist of narrow open anticlines crossed by vertical faults that resemble positive flower structures in restraining bends, and of small-scale mini-basins corresponding to the depocenters of the Plio-Quaternary series. These mini-basins are therefore interpreted as releasing bends along the strike-slip fault system. We show that some local folds developed offshore along faults that prolongate into the Mallorca Graben. They are equivalent to the one uplifting the Messinian units of 300m onshore along the Sencelles fault in the Inca sub-basin, which confirm the existence of the long offshore/onshore Northern strike-slip corridor. Such recent folds, mini-basins, and associated faults are observed also in the south of the Central Mallorca Depression and can be linked to onshore features such as NE-SW trending folds and sinistral strike-slip faults around the Campos Basin. We thus propose a coherent land-sea tectonic state that includes active strike-slip tectonics responsible for the distribution of earthquake epicenters along the corridors.

At the scale of the Balearic Promontory, we show that the faulted corridors extend east of Mallorca Island to the Alcudia Bay and also westward to the Ibiza Channel, revealing a homogenously deformed Ibiza-Mallorca block, running parallel to the Emile Baudot Escarpment (EBE) that corresponds to the main morphological feature of the BP, with recent activity expressed by some Pliocene to Quaternary volcanism. Our study shows that, during the late Miocene, the main faults already existed, with syn-extension sedimentation as it can be observed in the post-orogenic grabens onland Mallorca. Thus, our reconstruction through time of successive basin geometries and tectonic pattern illustrates the importance of structural inheritance. Some of the initial Betic thrust systems (pre-Middle Miocene) have been firstly inverted as normal faults during post-orogenic extension in the middle to late Miocene, leading to the development of the Central Mallorca Depression offshore similarly to the Mallorca Graben onland. The faults could also record some mostly dextral strike-slip displacements during the late Miocene, in accordance with a westward escape of the Alboran Block accommodated by the EBE crustal-scale transform fault between the BP and the surrounding Algerian oceanic basin. Then, most of these deeply-rooted crustal faults have been again reactivated from Pliocene times to Present-day. They localize the PQ depocenters along the MCDZ during the Pliocene while the pre-MSC depocenters were preferentially located to the south of the Central Mallorca Depression. During the Quaternary, the current regional strain characterized by a nearly N-S compression driven by Africa-Eurasia convergence is responsible for reactivation of the faulted corridors of the Central Mallorca Depression with some mostly left-lateral transpressive tectonics.

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FIGURES

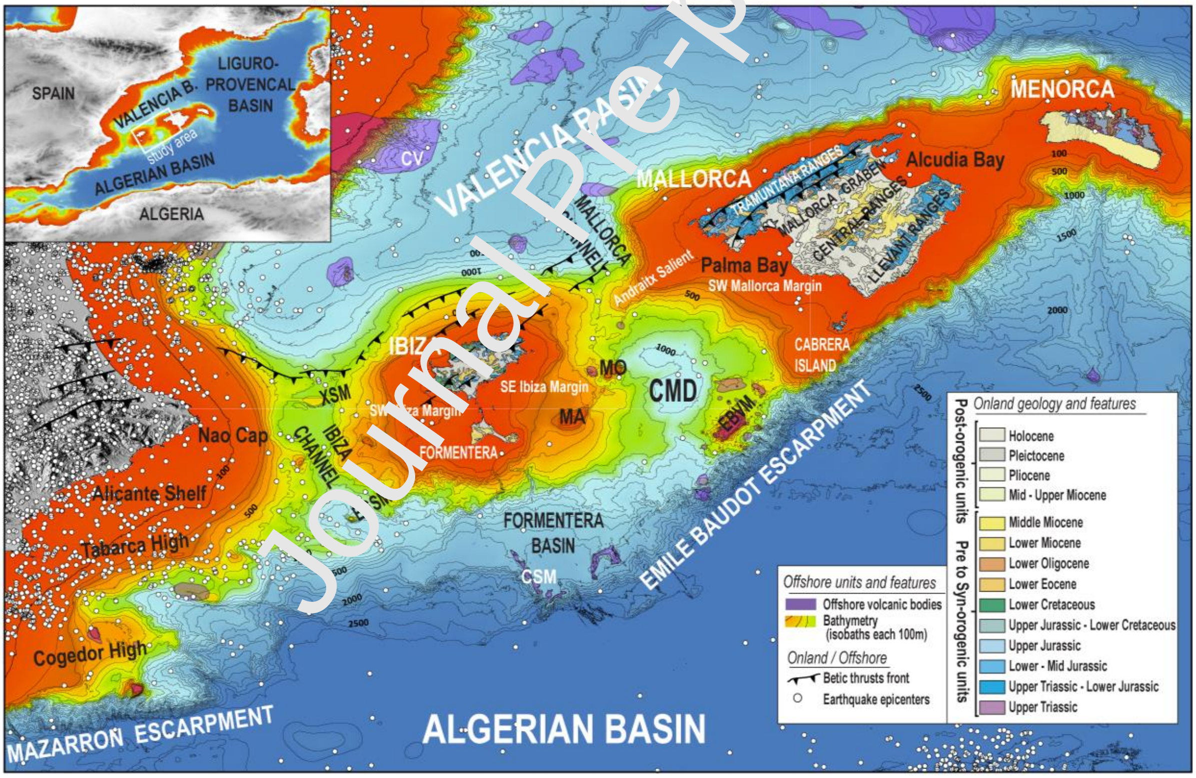

Figure 1. Map of the Balearic Promontory. The study area is located between Ibiza and Mallorca Islands. The bathymetric data for the offshore domain is downloaded from the European Marine Observation and Data network (EMODnet) database available online (www.emodnet-bathymetry.eu). The onland geology of Menorca, Mallorca and Ibiza islands is modified from the geological map of Spain 1:1000000; IGME. Epicenters of the recorded earthquakes are from International Seismological Centre (2020), On-line Bulletin (https://doi.org/10.31905/D808B830; Storchak et al., (2017); (2020)). Onshore digital elevation model has been produced using Copernicus

data and information funded by the European Union- EU-DEM layers (www.eea.europa.eu). CMD= Central Mallorca Depression; MA= Mont Ausias Marc; MO= Mont des Oliva; EBVM= Emile Baudot Volcanic Mounts. CSM= Chimene Sea Mount; CV= Columbretes Volcano; XSM= Xabia Sea Mount; ECSM= El Cid Sea Mount.

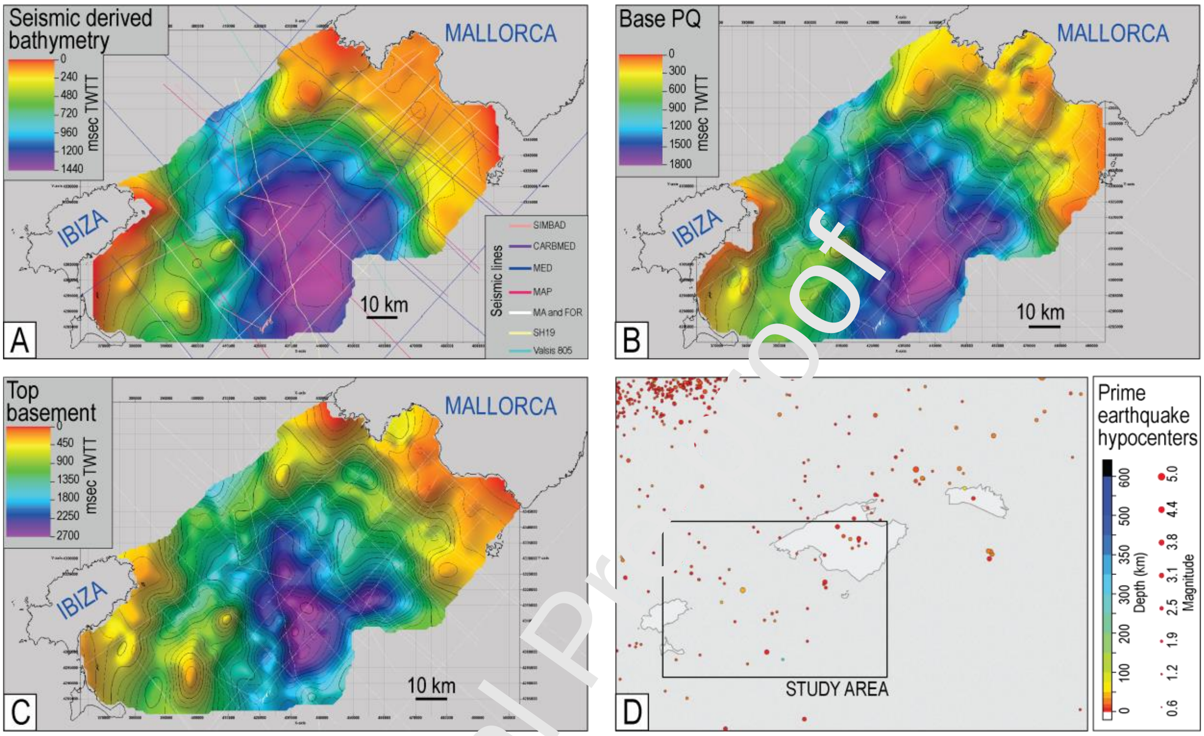

Figure 2. A: Location of the seismic dataset used in the study area superimposed on the seismic data-derived bathymetry map. B and C: Time structure maps showing the present-day depth of the Base PQ and the Top acoustic basement respectively. Thin white lines represent the position of the same seismic profiles shown in A. D: Map showing the position of all prime earthquake hypocenters registered in the BP area and its surrounding (courtesy of International Seismological Centre (2020), On-line Bulletin https://doi.org/10.31905/D808B830; Storchak et al., (2017); (2020)).

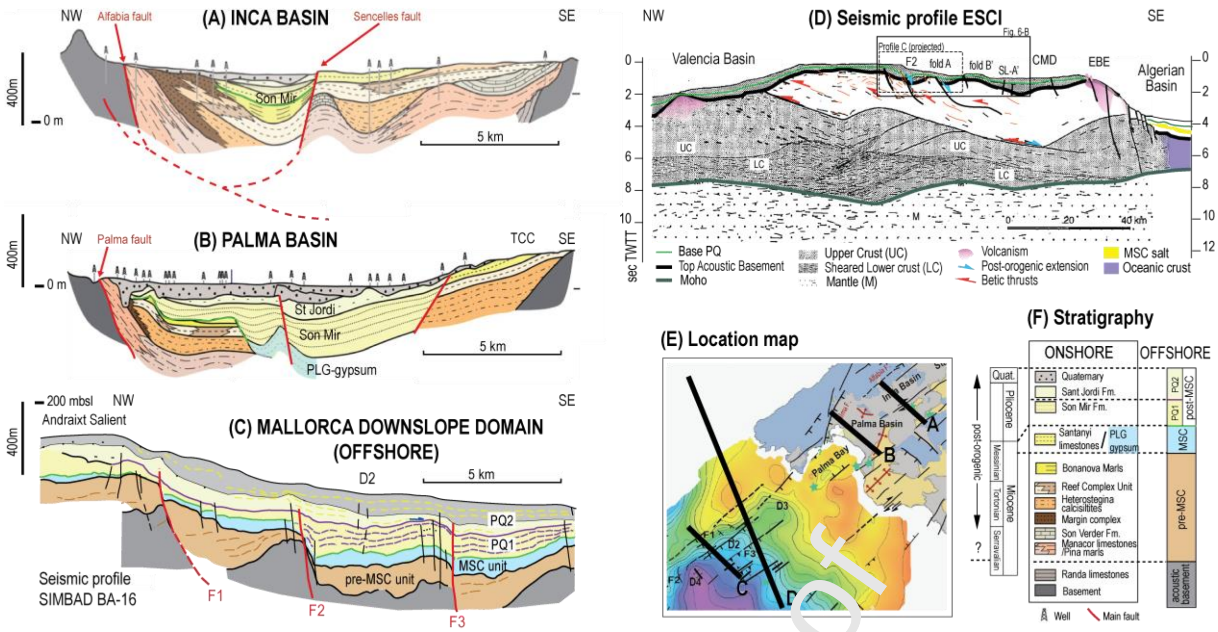

Figure 3. Onland-offshore comparison of the geological records (drawn at the same scale) across A-B: the Mallorca Graben (Inca and Palma sub-basins, modified from Capó and Garcia, 2019) and C: the offshore depocenter D2 (drawn from seismic profile Simbad BA-16, Fig. 6A) located on the downslope domain of Mallorca margin. Deep parts of the Alfabia and Sencelles faults come from figure 16 in Sàbat et al. (2011). Offshore faults can be compared to the faults bounding the Palma and Inca sub-basins. Intra basins faults delineate the same kind of folded structures (along F2, F3 and the Sencelles fault). Infilling units are of comparable thicknesses. D: Correlation of seismic profiles on the large-scale ESCI line (modified from Sàbat et al., 1997), showing deep-seated structures. E: Location of sections and profiles superimposed to the Base Pliocene isobaths map (see Figure 10). F: Onshore stratigraphy of the study area (modified from Capó and Garcia, 2019) and offshore equivalence.

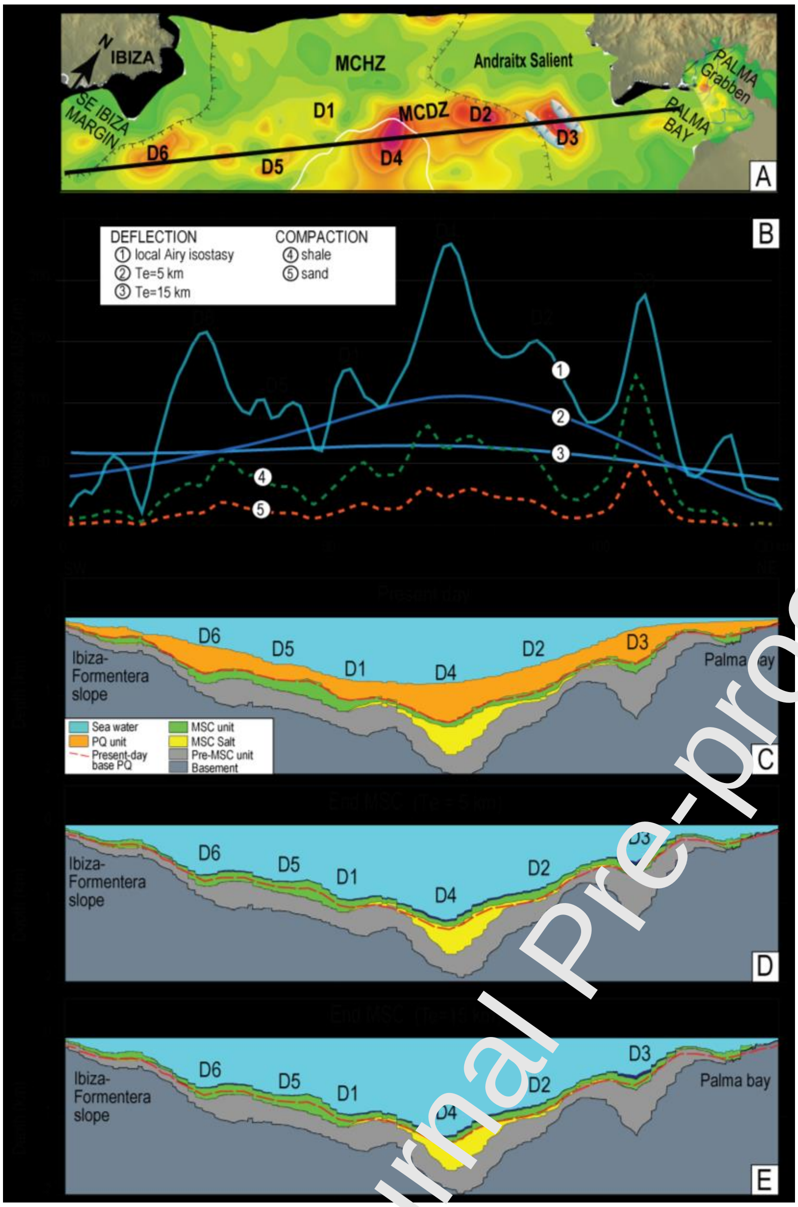

Figure 4. Results from the flexural-isostatic reconstruction of the original vertical position of the Plio-Quaternary sediment units along-strike the depocenters D1 to D6. A: Localization of the section on the map displaying the PQ thickness (Figure 11A). MCHZ= Mallorca channel Horst Zone; MCDZ= Mallorca channel Depression Zone. B: Sedimentation-induced subsidence contributions of post-MSC (Plio-Quaternary). Stronger TE value leads to a smaller, more uniform subsidence, the narrow shape of the basins means increasing TE values lead to decreasing subsidence values. Sediment compaction values are presented for compaction curves for sand and shale lithologies from Sclater and Christie (1980). C: Present-day configuration of sediments along profile with depths of key horizons. D: Reconstructed profile for near-local isostasy (TE 5 km) after removal of Plio-Quaternary sediments and decompaction of Pre-MSC sediments. E: same reconstructed profile for TE value of 15 km. See text for comment.

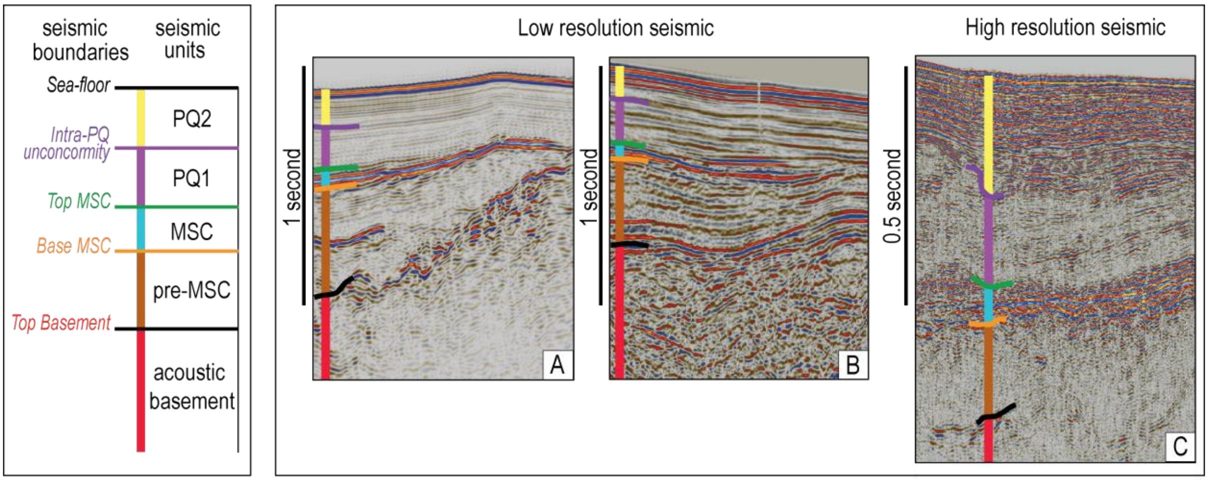

Figure 5. Presentation of the interpreted seismic units and their boundaries, on low resolution-deep penetration industrial (A (line MED26) and B (line MAP70)) and academic high-resolution seismic profiles (C (line SIMBAD)). Acoustic basement includes pre- and syn-orogenic units.

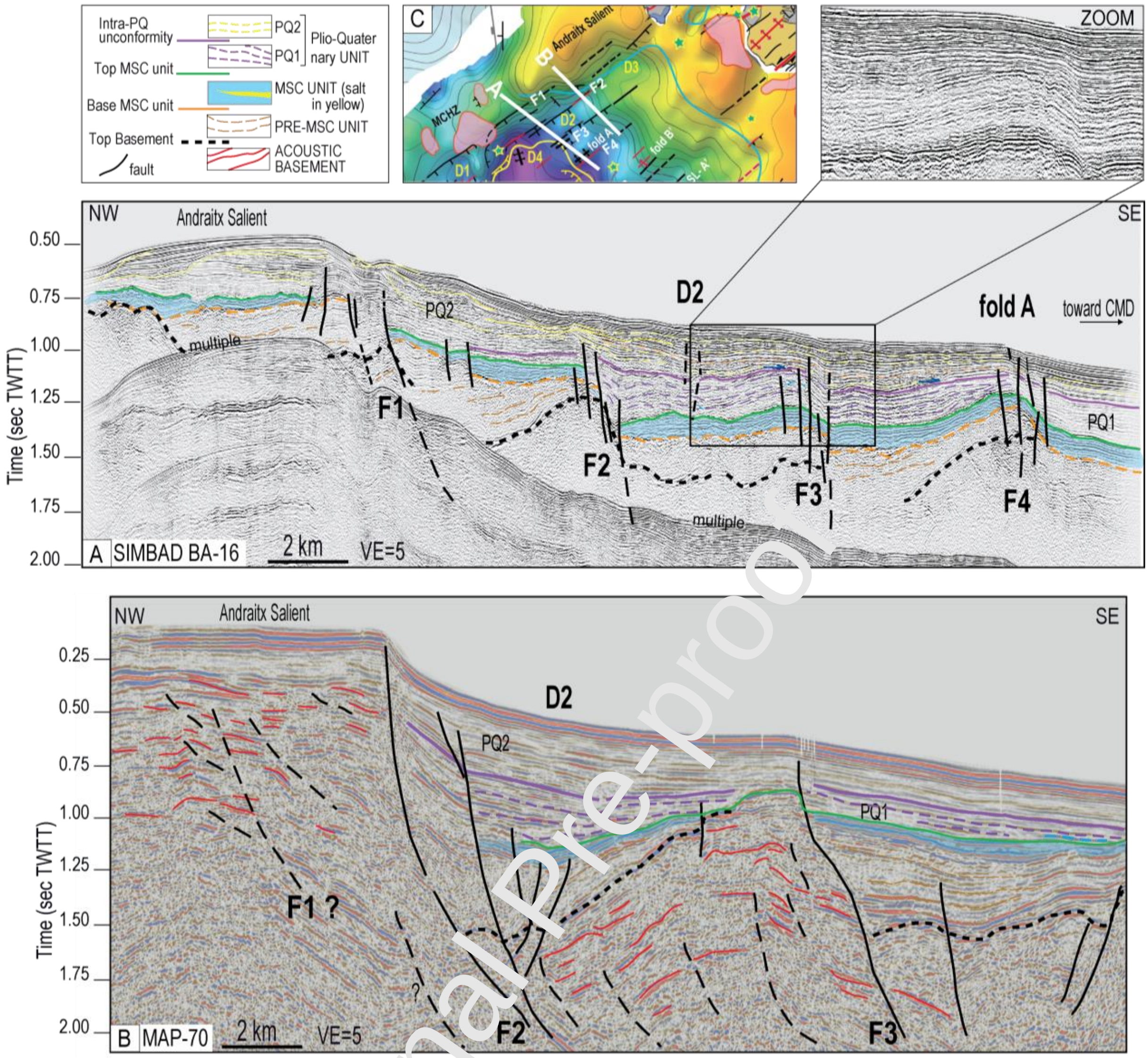

Figure 6. A: High-resolution academic seismic profile Simbad BA-16. B: MAP-70 industrial deep penetration seismic profile. Seismic sections crossing depocenter D2 and the complex associated deformation of the area. F1 and F2 faults structure a nice half graben underlain by fan-shaped pre-MSC unit and locally MSC and PQ unit (Map-70). The faults are however particularly vertical and F3 and F4 are associated to folds that reach the seafloor (line BA-16). Remnant of thrusts could be present NW of MAP-70 in the highly deformed acoustic basement. C: Base Pliocene isobaths map (see Figure 10) showing the location of the seismic profiles shown in A and B.

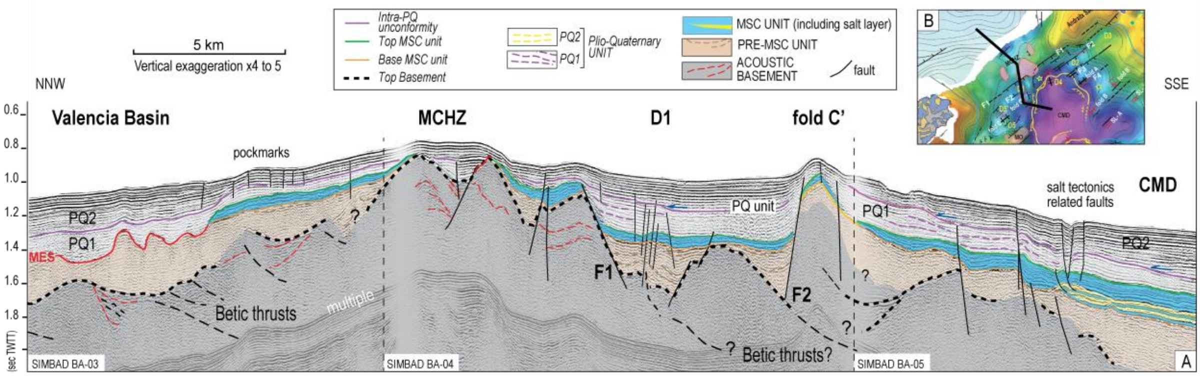

Figure 7. A: Seismic profile across the Mallorca Channel, illustrating the MCHZ (Mallorca Channel **Horst** Zone) adjoining the MCDZ (Mallorca Channel **Depression** Zone, here D1 depocenter/mini-basin). Faults clearly offset the MSC unit (in blue) and thicken the PQ unit. Betic orogenic thrusts are observed towards the Valencia Basin and normal faults like F1 could sole at depth into the thrusts, as observed on deep penetration seismic lines. B: Base Pliocene isobaths map (see Figure 10) showing the location of the seismic profile shown in A.

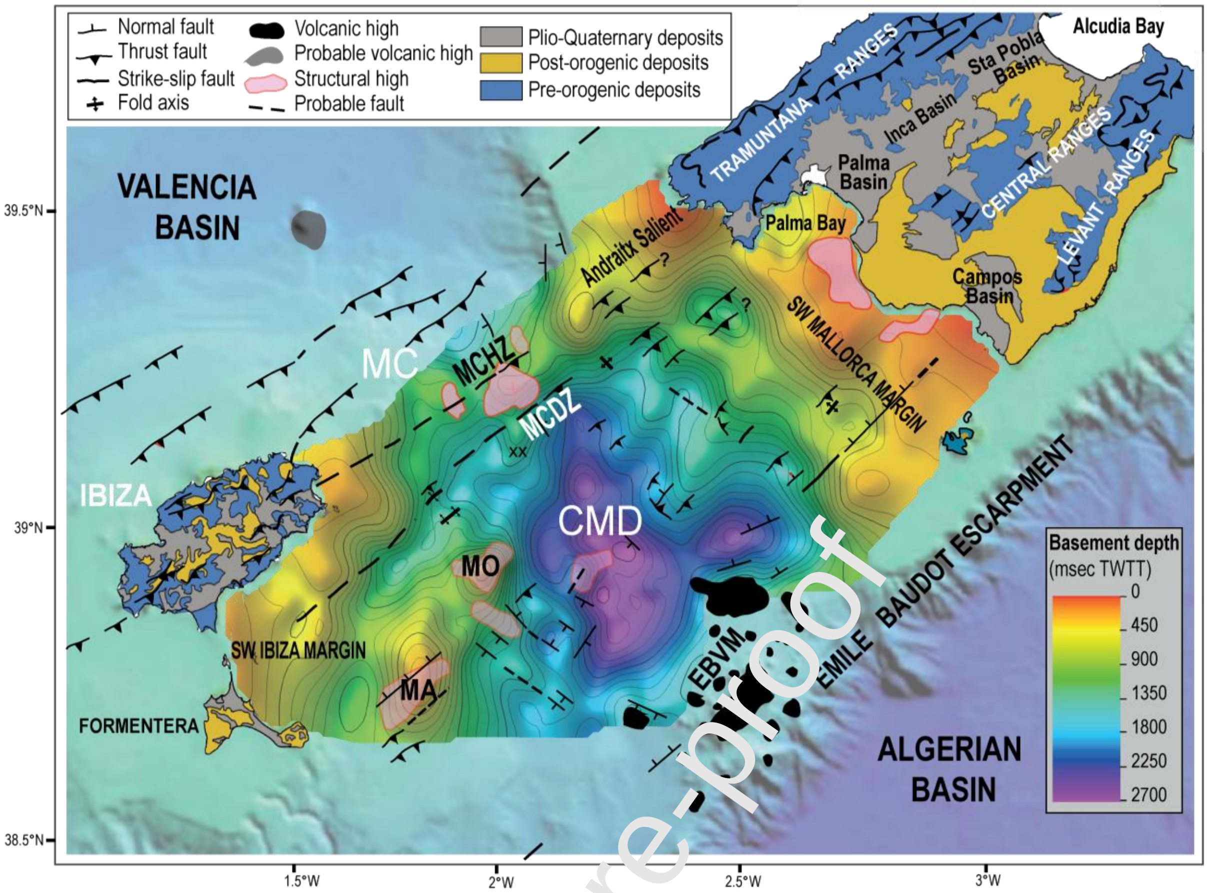

Figure 8. Map of the main orogenic structures superimposed on Top Basement depth map (msec TWTT) and onland geology. The thrusts are clearly observed and continuous from Ibiza Island into the Mallorca Channel (MC). They are more difficult to follow from the Tramuntana Ranges to the Andraitx Salient located offshore, but topography prolongates the ranges southwestward. Through the Central Mallorca Depression (CMD), orogenic structures are only observed locally. Onland geology mapping of south Mallorca and North Ibiza is modified from geological map of Spain 1:50000 (IGME). The offshore coloured map surrounding the structural map of our study area represent the present-day bathymetry (from Acosta et al., 2003).

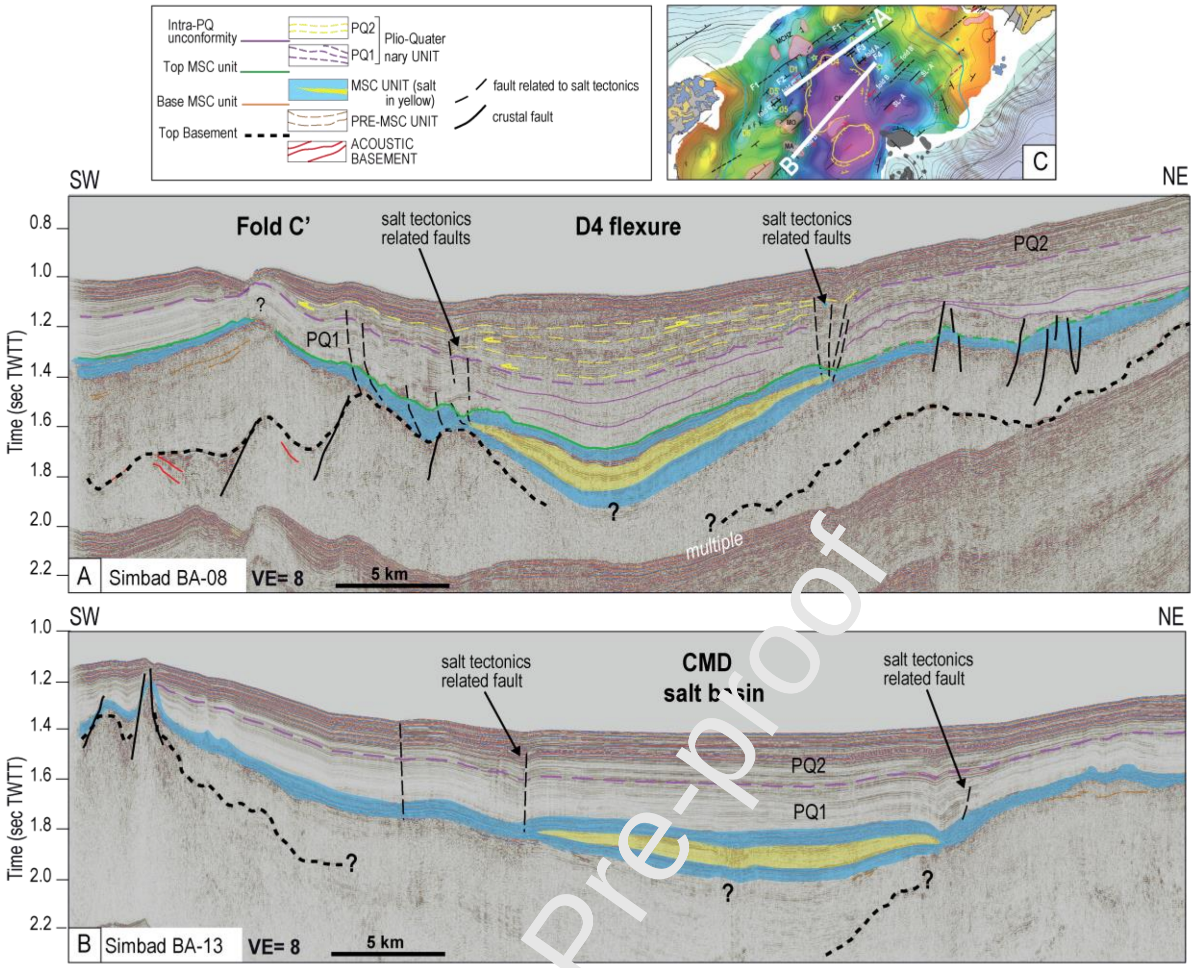

Figure 9. A and B: Seismic cross sections along the CMD where MSC salt (in yellow) deposited in between 2 MSC Bedded Units (BU, Raad et al., 2021; in blue). The salt is limited to the deep part of the CMD and usually appears as a flat unit, except due to moderate salt tectonics deformation located at the wedges. High-resolution seismic profile Simbad BA-08 (B) shows a post MSC/syn-PQ flexure (depocenter D4) that must result from crustal tectonics. C: Base Pliocene isobaths map (see Figure 10) showing the location of the seismic profiles shown in A and B.

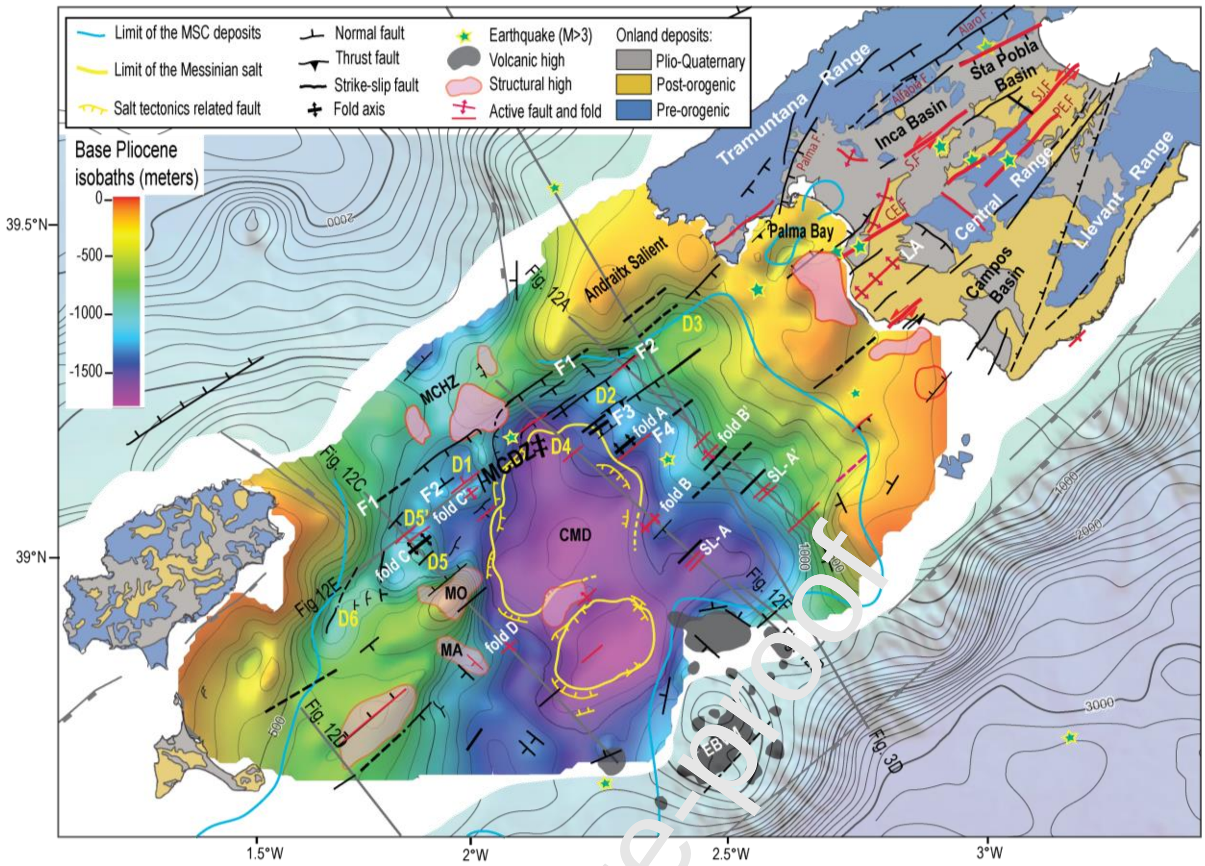

Figure 10. Structural map of the post-MSC deformation superimposed on the base Pliocene isobaths map (Top MSC unit). Onland faults and structures are modified from Silva et al., 2001; Sàbat et al., 2011; Sanchez-Alzola et al., 2014 and Mauragues et al., 2021. Location of earthquakes (from Sanchez-Alzola et al., 2014 and from International Seismological Centre, Bulletin 2020; see figures 1 and 2D for more info) show that they are related to the main faults that bound the Mallorca and Mallorca Channel Depression Zone (MCDZ). The offshore colored map surrounding the structural map of our study area represent the present-day bathymetry (from Acosta et al., 2003). LA = Llucmajor anticline. CE.F: Cap Enderrocap Fault; S.F.: Sencelles Fault; SJ.F: San Joan Fault; PE.F: Petra Fault.

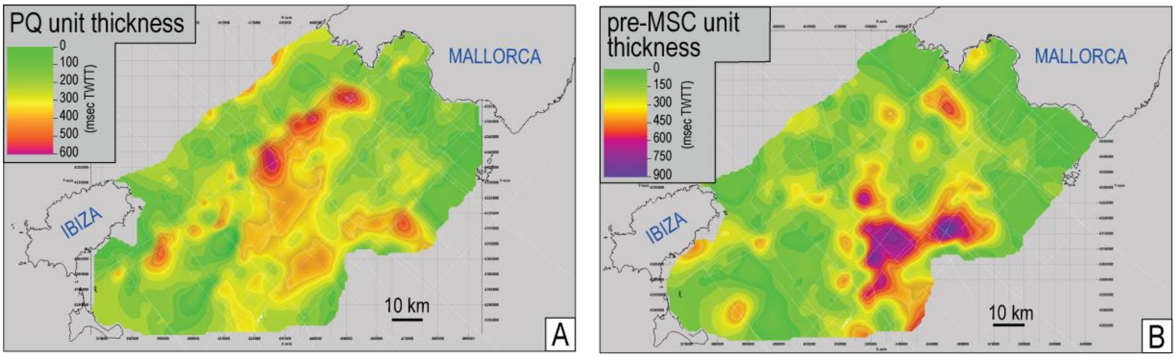

Figure 11. Thickness maps, in msec TWTT, of the A: PQ unit (Pliocene-Quaternary sediments) and B: pre-MSC unit (post-orogenic sediments, older than MSC unit). Thin white lines represent the position of the same seismic profiles shown in figure 2A. Note the evident change of depocenters from Miocene to Pliocene time.

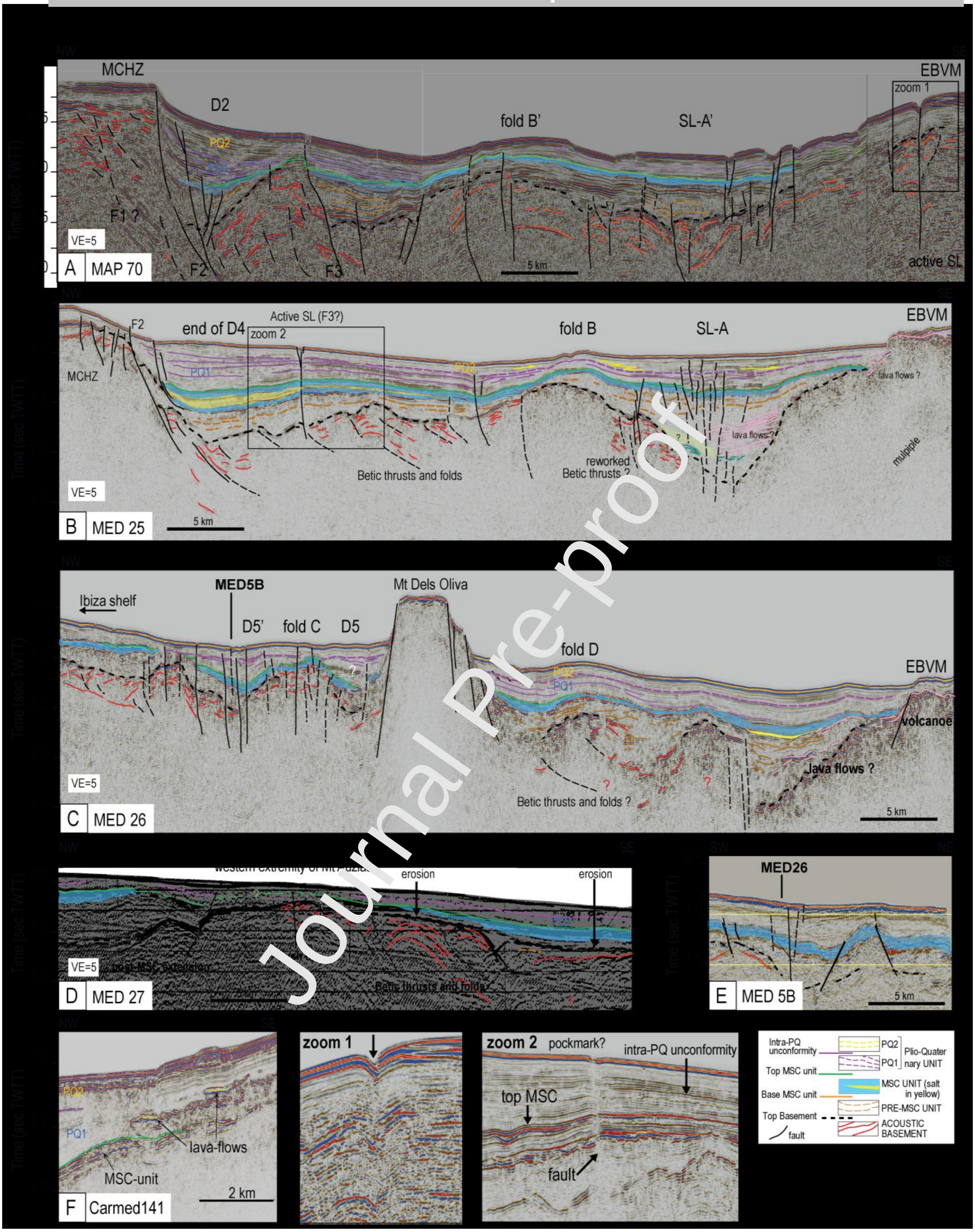

Figure 12. Deep penetrating seismic cross lines running from the Mallorca Channel Horst Zone (MCHZ) to the Emile Baudot Volcanic Mounts (EBVM) and illustrating the complex deformation of the study area that reworked Betic thrusts. See text for explanations. Notice the change in facies on the opposite sides of SL-A, could also indicate a strike-slip motion. See figure 10 for location.

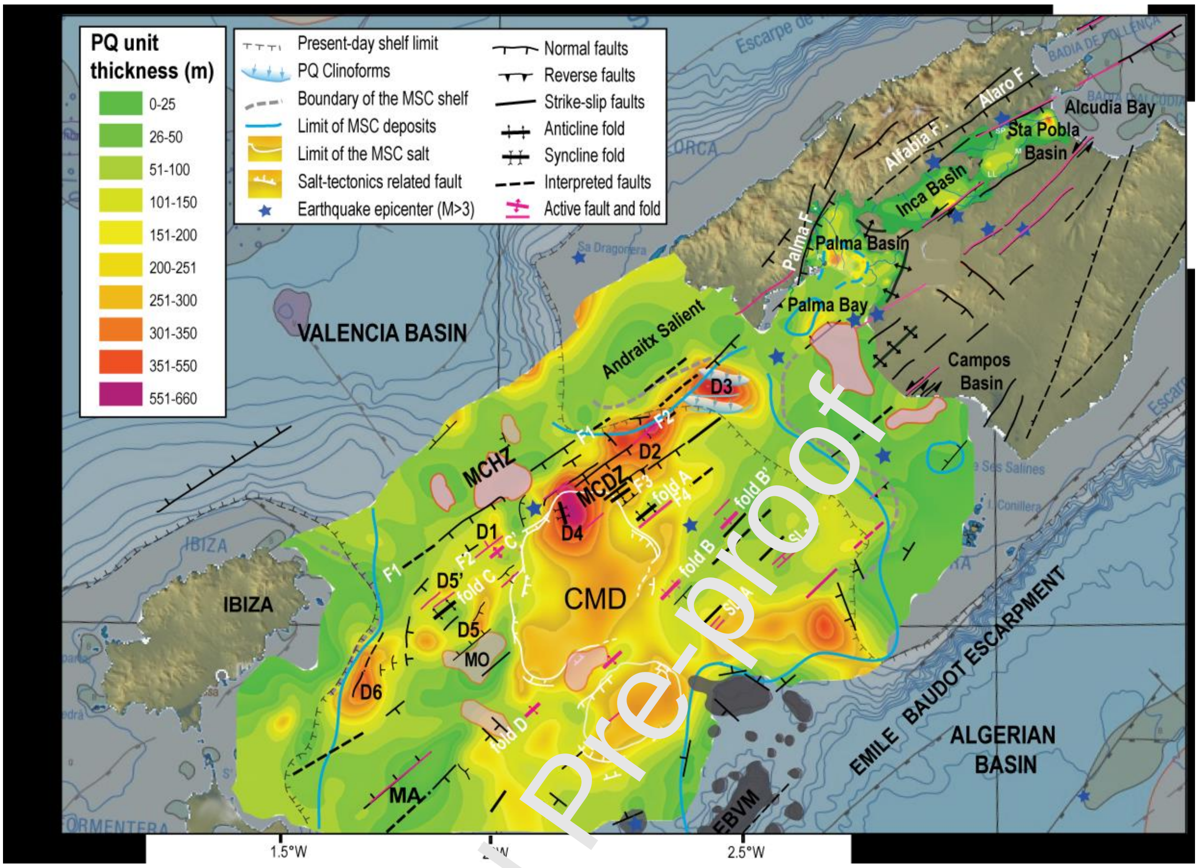

Figure 13. Onland-offshore thickness map of the Pliocene-Quaternary (PQ) unit, in meters. It illustrates the relationships between the main post-MSC faults and structures and the PQ depocenters (D1 to D6) in the Mallorca Channel Depression Zone (MCDZ). Land-sea correlation shows the continuity between those depocenters offshore, and the Mallorca Graben onland, with same order of thickness. PQ thickness on Mallorca Island is taken from Capó and Garcia, 2019. Some structures on the South Ibiza margin are modified from Acosta et al., (2004). Surrounding areas are from the geological map of Spain 1:1000000; IGME.

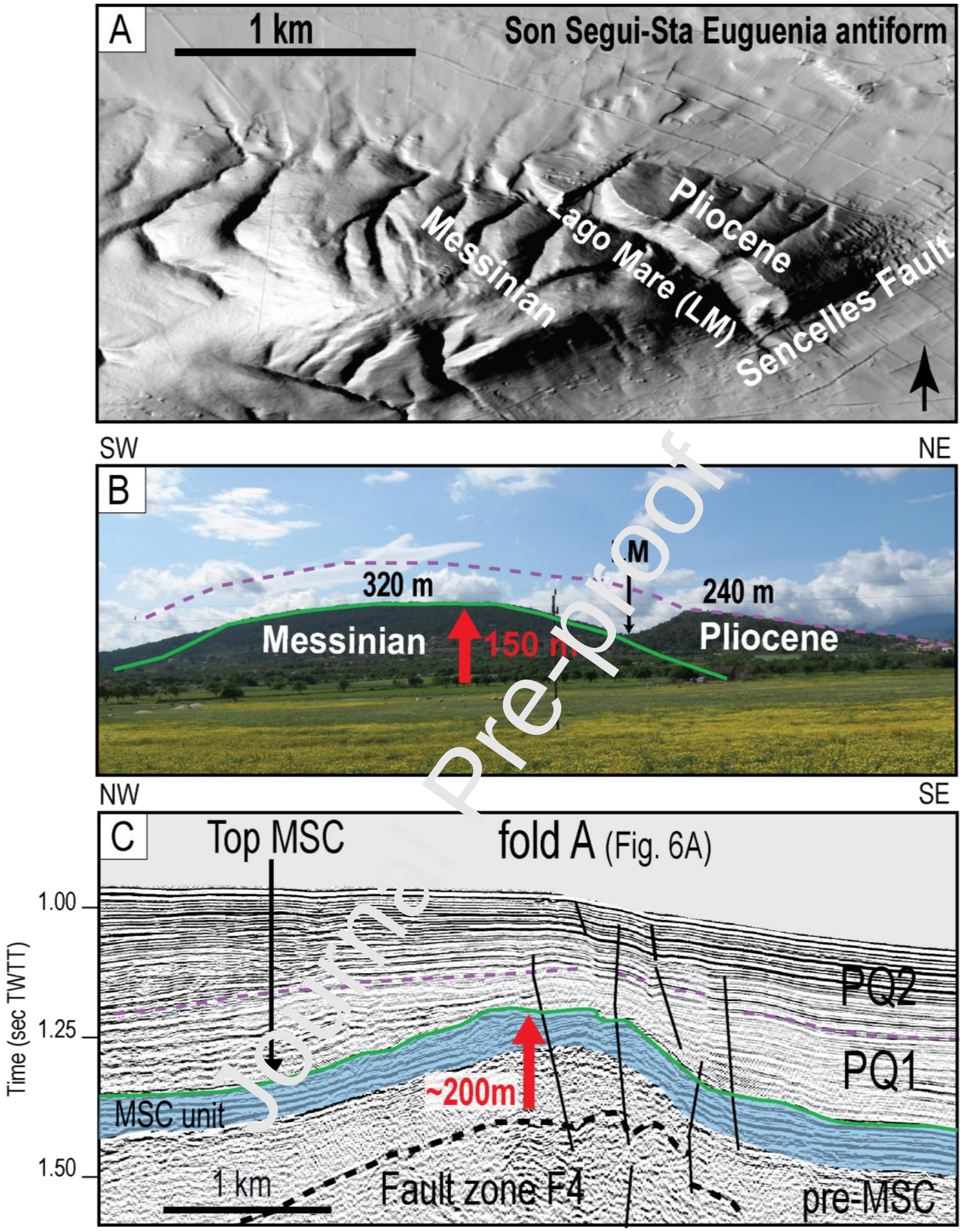

Figure 14. Comparison between onshore and offshore positive flower-type structures. A and B: Onshore Son Seguí-Sta Eugènia antiform structure: correspondence between (A) the antiform on a Digital elevation model (DEM; location on figure 16) and (B) the field relief due to the Messinian and Pliocene bending. (DEM data is downloaded from the Spanish Centre for Geographic Information (https://www.ign.es/web/ign/portal/qsm-cnig). C: Offshore, seismic image of fold A on F4 fault zone as visible on profile BA-16 (extract from figure 6A), at same scale than B (1/1). Both structures are 1-2 km long and 150-200m in height.

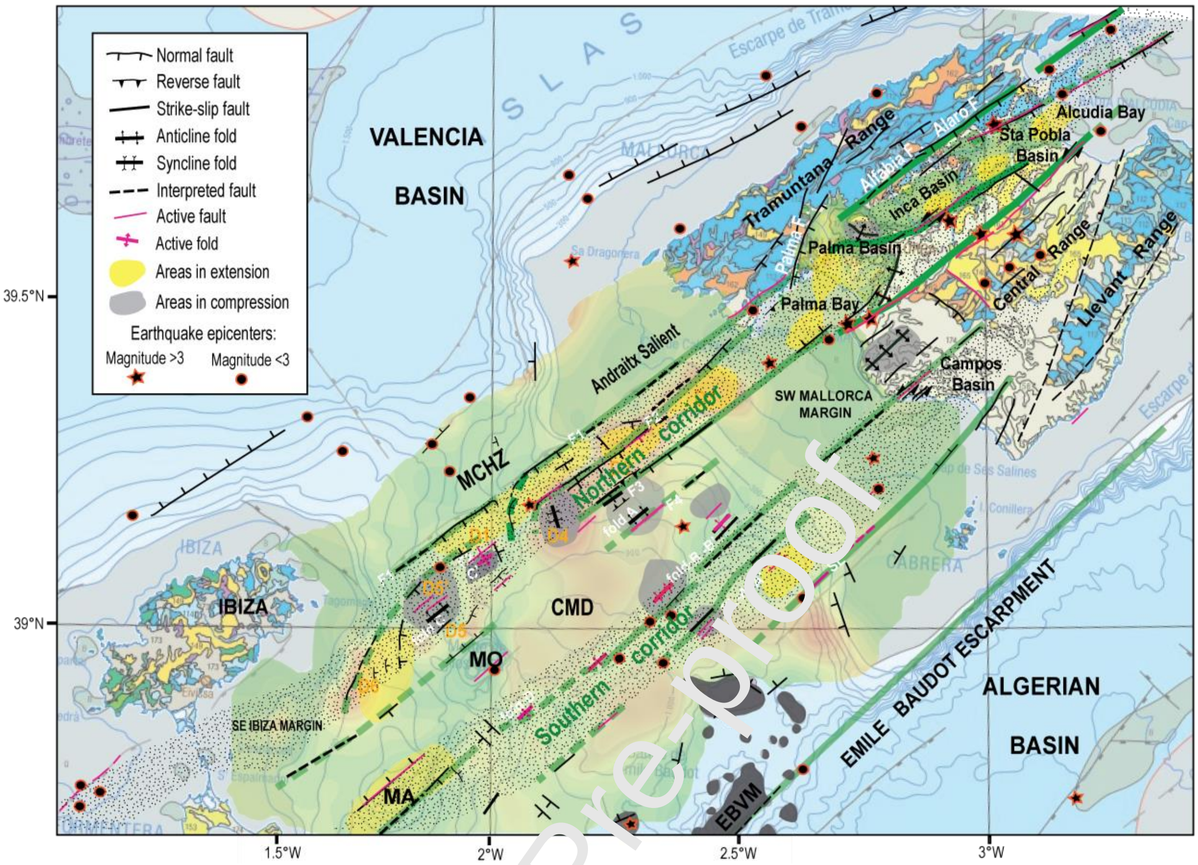

Figure 15. Interpretative map of the post-MSC tectonics distributed in long transcurrent onshore-offshore fault zones (in green) resulting in corridors (dotted area) where effects of locally extensional (PQ depocenters) or compressional (folds) environments combine. Surrounding areas showing bathymetry and onland geology are from the geological map of Spain 1:1000000 (legend in figure 1); IGME. Pliocene-Quaternary (PQ) unit thickness map is superimposed displaying the PQ depocenters.

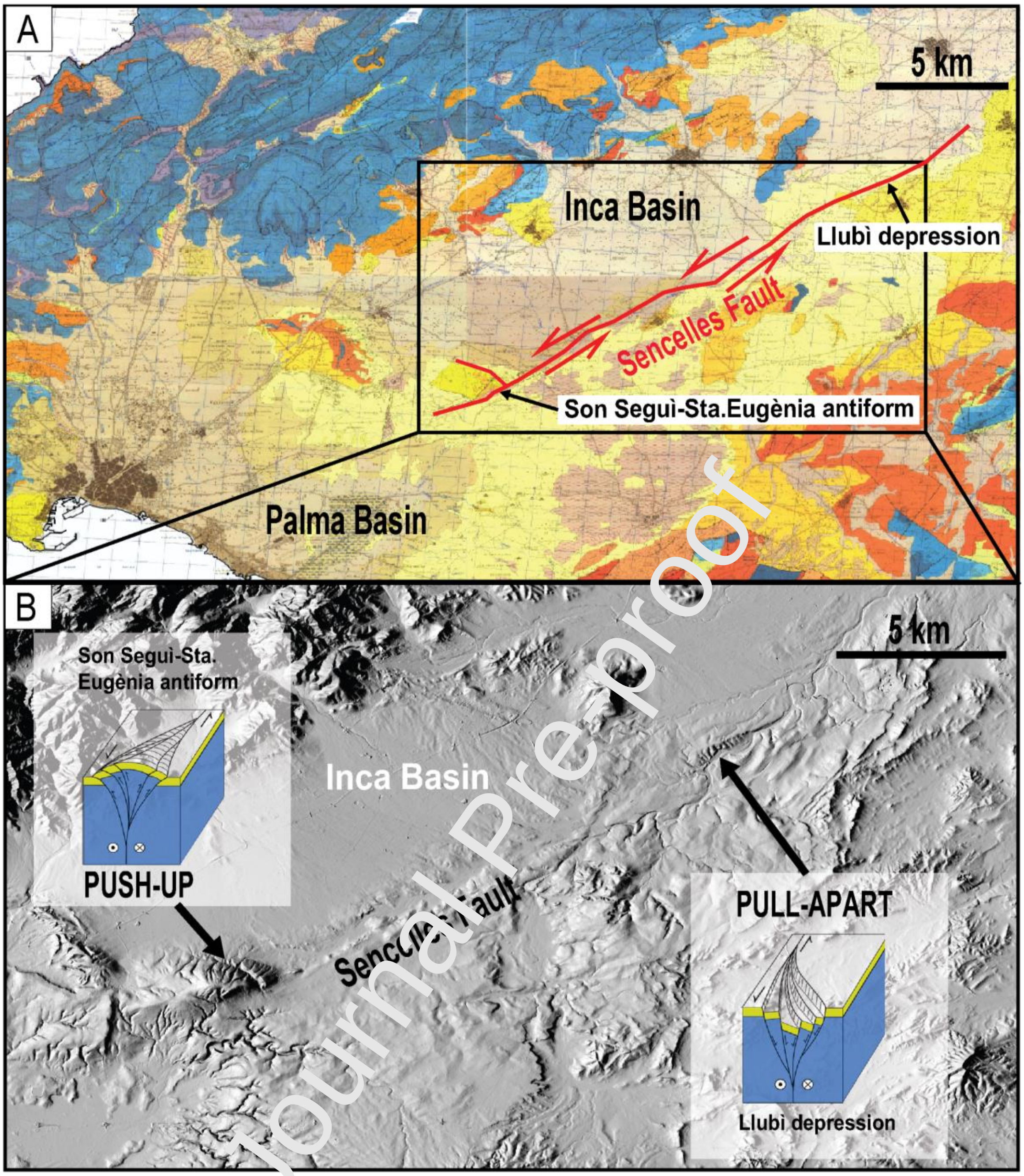

Figure 16. A: Geological location of the structures on the Inca sub-basin. B: Digital Elevation Model (DEM) of Inca sub-basin illustrating the Sencelles Fault area (DEM data is downloaded from the Spanish Centre for Geographic Information (https://www.ign.es/web/ign/portal/qsm-cnig). Son Seguí-Sta.Eugènia antiform and Llubí depression can be the expression of restraining (push-up positive structure) / releasing (pull-apart negative structure) bends respectively along the Sencelles Fault.

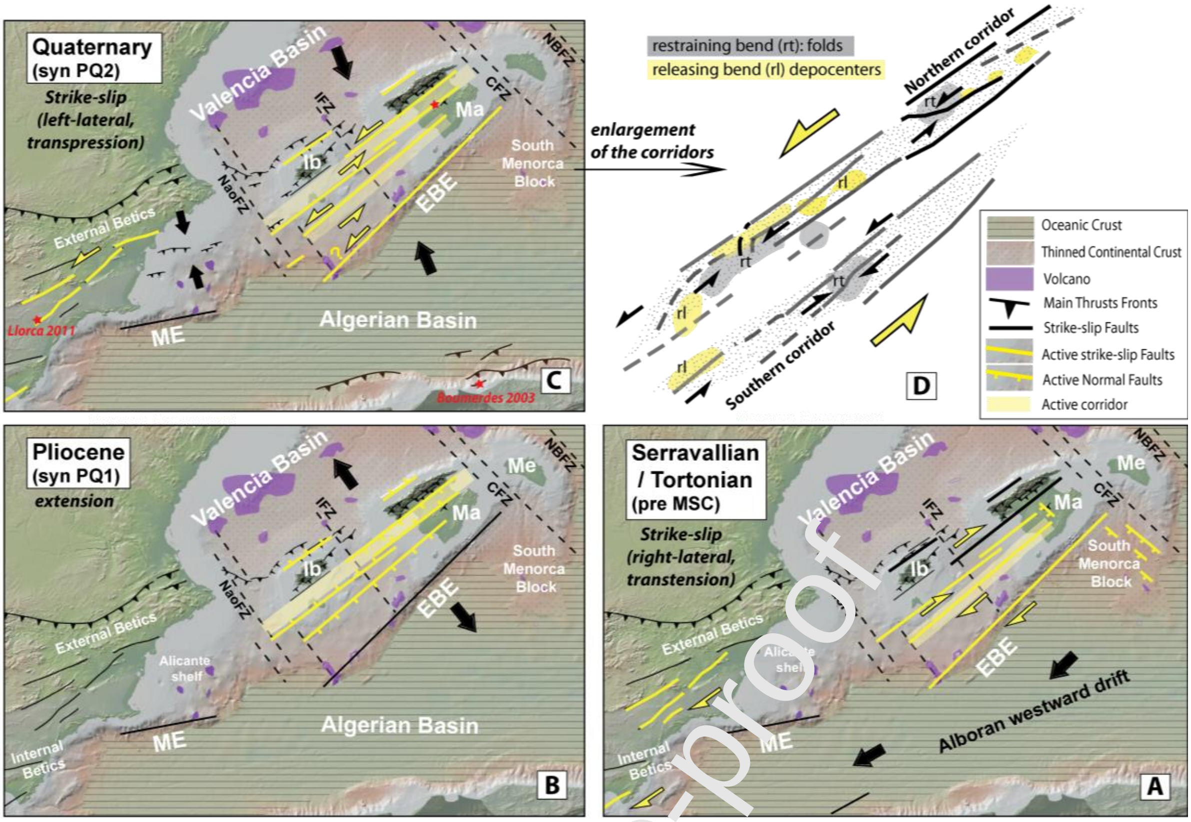

Figure 17. Schematic sketch of the evolution of the tectonic regimes proposed in the study area since the Late Miocene. The Ibiza-Mallorca corridors are included in a regional view that does not take into account the kinematics as the blocks are presented in their present-day configuration. In yellow are the active structures. A: During pre-MSC Middle Miocene times, tectonic regime is driven by the Alboran Block southwestward escape and the related accretion in the Algerian Basin; the main depocenter are localized in the Southern Corridor (see Figure 11). B: During the Pliocene, extension and/or transtension is responsible for the normal activity of the faults zones that reshape the Ibiza and Mallorca margins and localize the depocenters in the Northern Corridor. C: Quaternary to Present-day convergence accounts for left-lateral reactivation of the Ibiza-Mallorca corridors and the Southeastern Spain faults zones, and the compressional structures on the Alicante shelf. D: Enlargement of the strike-slip faulted Northern and Southern corridors showing tectonics and highlighting the extensional/compressional areas during the Quaternary stage.

Credit Author Statement

A. Maillard was primarily responsible for the idea of the paper, the structural interpretation and writing of the manuscript. F. Raad interpreted the seismic data, described the seismic stratigraphic record and mapped the onshore and offshore geology and surfaces. F. Chanier contributed in the kinematic and structural interpretation of the study area. H. Heida and D. Garcia-Castellanos oversaw the subsidence analysis procedure. J. Lofi contributed in seismic data interpretation and the making of the figures. G. Mas guided us to the field in Mallorca and provided precious contribution on the onland geology. All authors contributed to the writing and making edits on the manuscript and figures.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- Post-Messinian deformation affects the Central Mallorca Depression
- Strike-slip fault systems correlate onland-offshore Mallorca and Ibiza Islands
- The systems localize extensional / compressional structures into long corridors
- Small depocenters of PQ units align onland-offshore
- Recent tectonics and important structural inheritance control local subsidence