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Research paper

Messinian Salinity Crisis deposits widespread over the Balearic Promontory: Insights from new high-resolution seismic data

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ABSTRACT

The current interpretation of the Messinian Salinity Crisis (MSC) involves the deposition of peripheral or marginal evaporites in onshore basins as well as the erosion of the margin and the deposition of thick evaporites in deep basins. The so-called intermediate basins are formed in domains between the onland outcrops and the deep basins. The Balearic Promontory is a bathymetric high located between the deep Algerian and Liguro-Provençal basins and the onland Spanish basin. The SIMBAD project aims to investigate the spatial variability of the MSC-related deposits and to assess the extent of post-MSC reactivation over the Balearic Promontory. We present here the first results of the SIMBAD high-resolution seismic survey (January 2013) which imaged for the first time a thin MSC-related unit widely distributed in small sub-basins over the Balearic Promontory.

Borehole analyses have shown that this unit could be correlated with primary gypsum formations linked to the peripheral evaporites. Locally, in the Central Depression between Mallorca and Ibiza islands, a thicker MSC unit is observed whose lowermost transparent part could correspond to a salt layer. Geometrical relationships suggest that the MSC in the Central Depression could postdate the primary gypsum. The occurrence of a halite layer in the Central Depression, at depths of 1000 to 1500 m, favours the hypothesis that the evaporites precipitated passively in closed or partially closed perched sub-basins, possibly as a result of evaporative drawdown at different depths and possibly diachronously, at least with respect to the deep-basin evaporites.

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1. Introduction

The Messinian Salinity Crisis (MSC) has been the focus of much research since the drilling of evaporites and salt in the Mediterranean basins during the 1970s (Hsü et al., 1973a, 1973b; Ryan et al., 1973).

The widely accepted model for the two-stage development of the MSC (Clauzon et al., 1996; CIESM et al., 2008) proposes that, during stage 1 (5.97–5.60 Ma, Gautier et al., 1994; Krijgsman et al., 1999; Manzi et al., 2013), primary shallow-water evaporites (Primary Lower Gypsum, PLG) accumulated in semi-enclosed marginal (or peripheral) basins now cropping out onshore. During stage 2 (5.60–5.33 Ma, Gautier et al., 1994, Krijgsman et al., 1999; Manzi et al., 2013), a substantial fall in sea level of the Mediterranean accounts for the deposition of thick MSC halite units in the deep basin (1–2 km of halite), while the marginal areas and slopes were subject to intense and polygenic erosion (the MES, Margin Erosion Surface, Lofi et al., 2005, 2011a). However, debate is still continuing about the amplitude of the sea-level fall, as well as the timing and depositional environment of the salt (formation of brines by

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evaporation of shrinking basins: Ryan, 2008; Lofi et al., 2011b; resedimented evaporites and cumulates with moderate fall in base level: Roveri et al., 2008, 2014; salt precipitation after dessication in shallow water: Bache et al., 2009).

Until now, no stratigraphic or lithological calibration could be established between the depositional units of the deep offshore basins and the onland succession. Both kinds of deposits are geometrically and geographically disconnected and their correlation and timing are still subject to uncertainties and controversy (Rouchy and Caruso, 2006; CIESM et al., 2008; Ryan, 2009).

For these reasons, we focus on the Balearic Promontory, which provides a record of the MSC extending spatially from the onshore basins of the Eastern Spanish margin and Mallorca Island to the abyssal plains of the Algerian and Valencia basins. The recent acquisition of high-resolution seismic reflection data supplemented by a large data base resulting from industrial and academic research allows us to characterize for the first time a MSC-related seismic unit widely developed over the entire Promontory. The mapping of this unit reveals a set of stepped Messinian basins at various depths distributed nearly continuously between the onland outcrops and the deep basins. The preservation of such MSC unit at shallow depths provides us with targets to study the MSC event, since only a widely developed erosion surface (the Margin Erosion Surface, MES, Lofi et al., 2011a) is observed on the other passive margins of the NW Mediterranean which is the offshore outcome of the Messinian Erosional Surface observed onland. The MSC unit of the Balearic Promontory is correlated with well data and its significance is discussed with regard to other known MSC units.

2. Physiography and geological setting of the Balearic Promontory

The Balearic Promontory is a continental rise (500-km-long, 120 km-wide) which includes the Balearic Islands, surrounded by narrow platforms and steep slopes toward the surrounding basins (Fig. 1). It is bounded to the North by the Valencia continental Basin, an aborted rift subject to extensional tectonics from the Oligocene to the Serravalian/Tortonian (Maillard et al., 1992; Mauffret et al., 1992; Roca and Guimera, 1992). The southern border of the Balearic Promontory shows a steep slope (6.5–8°), which is composed of the Mazarron and Emile Baudot escarpments (Acosta et al., 2001a, 2002, 2013), separating the Promontory from the oceanic Algerian Basin where water depths exceed 2400 m (Figs. 1 and 2). The adjacent Algerian and Valencia basins are connected by two channels cutting through the Promontory, the Ibiza Channel and the Mallorca Channel, respectively. The Balearic domain is bounded to the east by the Menorca slope, descending abruptly towards the Liguro-Provençal oceanic Basin and prolonged to the south by a topographic high, the Menorca Rise (Fig. 1).

Located between two extensional basins, the Balearic Islands result from compressional deformation associated with the Betic thrusts (Sanz De Galdeano, 1990; Ramos Guerrero et al., 1989: Roca, 2001). The Betic thrusts are well expressed on the islands of Ibiza and Mallorca (Fourcade et al., 1982; Gelabert et al., 1992, 2004; Sabat et al., 2011) and can be traced offshore in the Valencia Basin and in the lower slope domain of the Islands (Maillard et al., 1992; Mauffret et al., 1992, Fig. 2). The compression initiated during the Late Oligocene to the south and propagated northwards

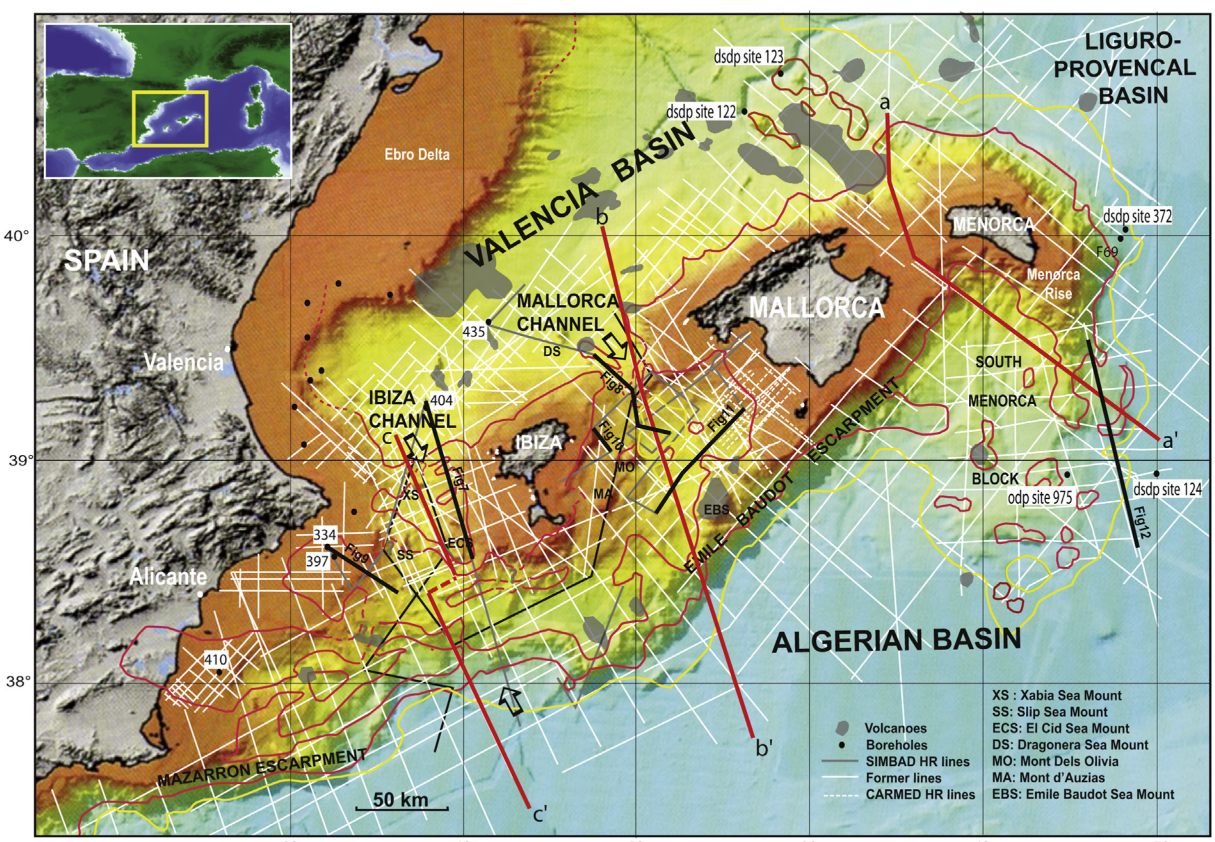

Figure 1. Bathymetric map after Brosolo and Mascle, 2008, showing location of the study area. The seismic profiles used in this study are shown as well as the location of lines aa', bb' and cc' (Fig. 3). The thick black lines show the location of the following figures. Red line represents the limit of the MSC deposits. Black arrows show the location of the channels. No MSC deposits exist on the shelves of the Balearic Islands. Yellow line represents the limit of the salt (MU). Seafloor volcanic mounts are shown as grey-shaded areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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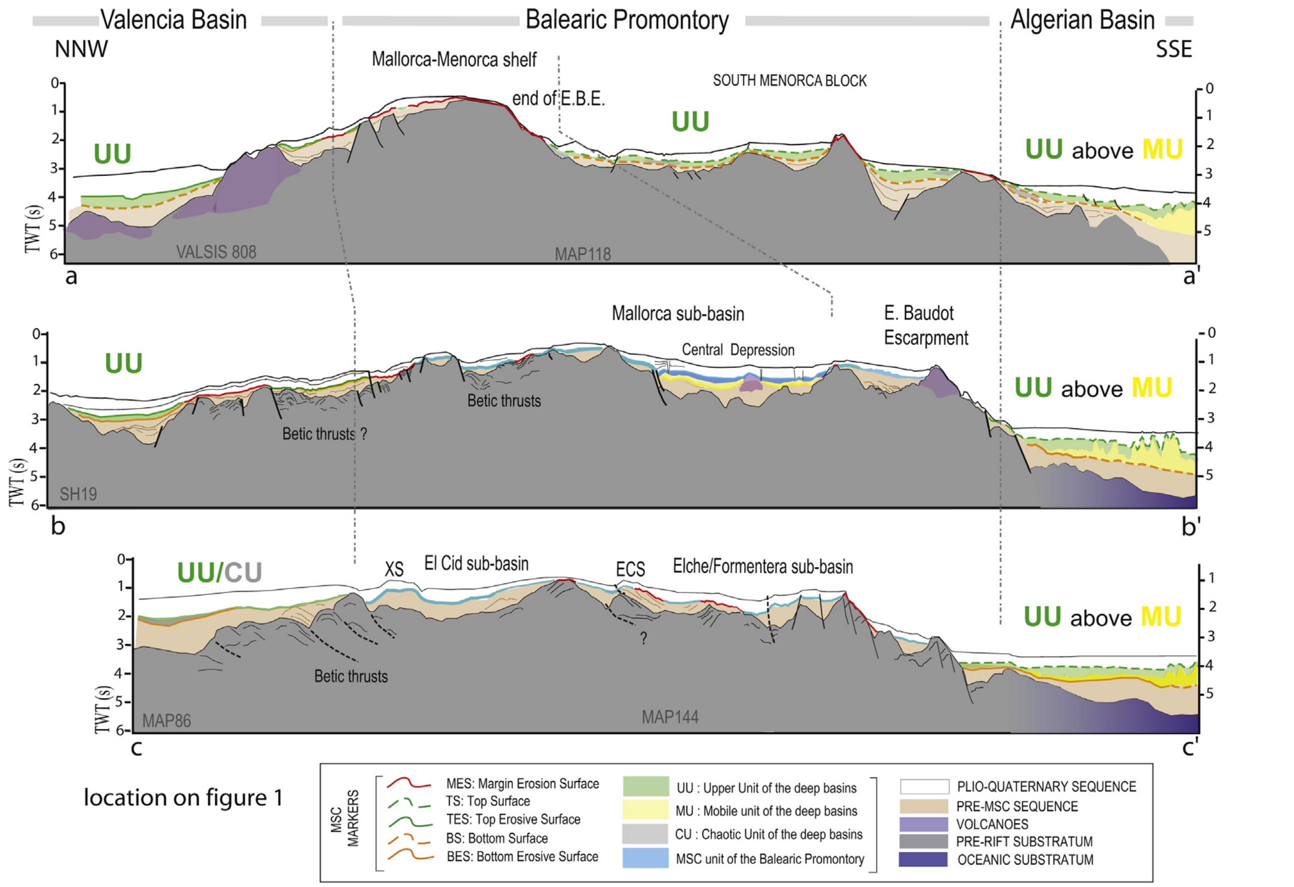

Figure 2. Synthetic line drawings of multichannel seismic profiles crossing the Balearic Promontory showing the general architecture of the area. aa': Section crossing the South Menorca Block, a marked continental indentation in the surrounding Algerian Basin, covered by the UU of the deep basin. The MSC unit is not present on the Menorca-Mallorca shelf. bb': Section crossing the Mallorca Channel, where the MSC unit exists in the Central Depression but also all around in the Mallorca sub-basin, disconnected from the deep basin by the steep Emile Baudot Escarpment. cc': Section crossing the Ibiza Channel, where the MSC unit extends nearly continuously from the Valencia Basin to the Algerian Basin. XS : Xabia Seamount; ECS : El Cid Seamount

during the Burdigalian (Bourrouilh, 1970; Sabat et al., 1988; Gelabert et al., 1992; Sabat et al., 2011), while extension affected the Valencia and Algerian adjacent basins. The Balearic Promontory then underwent extensional post-orogenic deformation from Late Serravalian to Recent times, resulting in ENE–WSW-trending normal faults expressed notably in the Palma graben on Mallorca (Roca and Guimera, 1992). The Miocene episodes of continuous deformation (compressional and extensional) are thus responsible for the complex structural setting of this area.

Although the borders of the Balearic Promontory are considered as passive margins, gentle active deformation has been reported over the whole offshore area around the Balearic Promontory (Mauffret et al., 1987; Sàbat et al., 1997; Maillard et Mauffret, 2013, Fig. 2). However, recent strike-slip and normal faults are commonly observed and may reactivate former structures (Fig. 2). On the margins of the Balearic Promontory and in the Ibiza Channel, the abundance of mass failure structures also supports active tectonic processes and/or volcanism (Acosta et al., 2002; Lastras et al., 2004; Acosta et al., 2013).

3. Setting of the Messinian Salinity Crisis

3.1. The MSC in its Western Mediterranean context

The Balearic Promontory is surrounded by several basins showing various MSC records.

Following the most recent nomenclature proposed by Lofi et al. (2011a), the MSC record of the Liguro-Provençal and Algerian basins consists of three units (see Fig. 3), which are considered as the deep basin trilogy (Ryan et al., 1973; Mauffret et al., 1973; Hsü et al., 1973a, 1973b, 1978). From top to bottom, the MSC record is made up of the Upper Unit (UU, corresponding to the former “Upper Evaporites”), the Mobile Unit (MU, corresponding to the former “thick salt layer”) and the Lower Unit - (LU, corresponding to the former “Lower Evaporites”). The MU is always overlain by UU (Lofi et al., 2011a, 2011b), whose uppermost part has been recovered by DSDP drillings at sites 124 and 372 located on the border of the deep Menorca margin (Figs. 1 and 3).

The Valencia Basin records solely the presence of the UU, taken as equivalent to units of the intermediate-depth basins (Lofi et al., 2011a, 2011b; Fig. 3), which is characterized by two to four strong parallel high-amplitude reflectors, and by the absence of the MU, except in its deepest part northeast of the volcanic ridge at DSDP Site 12, (Mauffret, 1976; Field and Gardner, 1991). This unit consists essentially of gypsum, anhydrite and dolomitic marl (DSDP Site 122, Leg 13, Hsü et al., 1973a, 1973b), and is correlated laterally with the UU of the deep Liguro-Provençal Basin (Maillard et al., 2006). In the Valencia basin, the UU is bracketed by erosion surfaces at the top and base (Escutia and Maldonado, 1992; Maillard et al., 2006, Fig. 3). The UU of the Valencia Basin pinches out at about 2.8 s TWT on the Catalan margin, where the Margin Erosion Surface (MES) is clearly observed (Garcia et al., 2011; Urgelès et al., 2011). On the Balearic side, however, the UU drapes the margin (Fig. 2).

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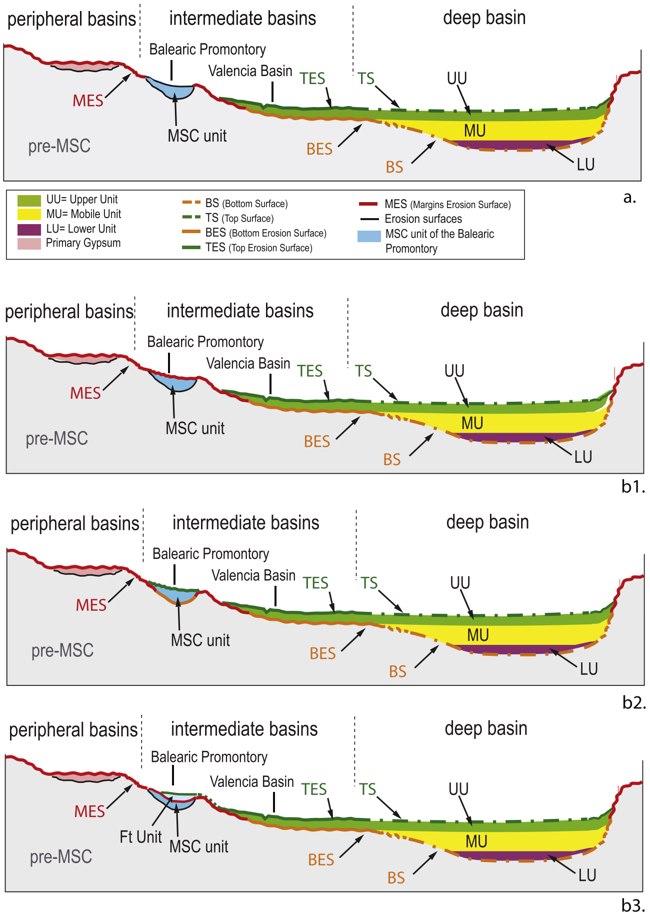

Figure 3. Schematic cross-sections of the Western Mediterranean basin illustrating the geometry of the MSC markers (units and erosional surfaces) from the peripheral basins to the deep basin. Intermediate basins are located at various depths between the peripheral basins and the deep basin, either connected or disconnected from the deep basin (in the case of the Valencia Basin or the Balearic sub-basins, respectively). The Balearic basin deposits are referred to here as the MSC unit because it remains unclear whether they are related to the peripheral evaporites or the deep basin evaporites (UU). a: conceptual model (modified after Lofi et al., 2011a). b: different interpretations of the erosion surfaces bracketing the MSC unit of the Balearic Promontory if: b1: the MSC unit corresponds to the PLG; b2: the MSC unit corresponds to the UU of the Valencia Basin; b3: the MSC unit corresponds both to the PLG and the deep evaporites.

3.2. *The MSC in the Balearic Domain*

On the Mallorca shelf, an unconformity truncating the Miocene units has been interpreted as the MES (Acosta et al., 2001a, 2001b, 2002, 2004a, 2004b, 2013; Lüdmann et al., 2011; Just et al., 2011). In the Central Depression offshore Mallorca (Fig. 2bb'), a partly stratified unit limited to the topographic lows has been interpreted as the Upper Evaporites unit, although the lateral geometrical continuity with the UU of the deep Valencia or Algerian basins has never been observed (Acosta et al., 2001a, 2001b, 2002, 2004a, 2004b).

Evaporites attributed to the MSC have been drilled onshore in the Bay of Palma depression (hydrological prospect boreholes; Rosell et al., 1998; Mas and Fornós, 2011, 2012). These MSC-related deposits are made of at least 13 layers of selenitic gypsum recording a progressive filling of the basin and a decrease of the water depth. According to Rosell et al. (1998), the Palma gypsum could correspond to the Primary Lower Gypsum (PLG) observed on Sicily and in the Apennines (Roveri et al., 2003, 2008).

4. Data and methodology

To study the MSC-related deposits, 26 high-resolution seismic profiles (~1800 km) were acquired on the Balearic Promontory during the "SIMBAD" cruise onboard the R/V "Téthys II" (INSU-CNRS/CIRMED) in January 2013, which was funded by the ACTION MARGES II programme (Fig. 1).

The seismic system deployed is composed by a mini-GI (SODERA) air gun and a 6-channel streamer (channel interval 25 m). The processing sequence aims to improve the signal-to-noise ratio, and includes the following steps: Common Mid-Point (CMP) gathering, gain recovery, normal moveout correction using variable velocity, CMP stacking (sixfold coverage), post-stack Kirchhoff migration and time-variable frequency filtering. Due to the seismic acquisition system used in the SIMBAD-experiment, the maximum offset does not exceed 250 m, so that no velocity model can be inferred from our dataset. Without velocity information, the main purpose of the migration is to focus most of the diffraction artifacts. Tests on the migration velocities indicate that the hyperbolae are optimally focused for RMS-velocities of 1500 m/s on the margin.

The high-resolution seismic lines (Fig. 1) are crossed with several already published seismic profiles (Roca and Guimera, 1992; Maillard et al., 1992; Maillard, 1993; Gallart et al., 1994; Mauffret et al., 1995; Sàbat et al., 1997; Acosta et al., 2001b; Just et al., 2011; Maillard and Mauffret, 2011; Maillard et al., Unpublished Data) to follow the MSC markers over all the study area. This seismic database includes academic seismic profiles obtained during several scientific cruises and oil-industry profiles from the SIGEOF database compiled by the Instituto Geologico y Minero de España (IGME, www.igme.es; Fig. 1). We also make use of digital high-resolution multi-channel seismic lines collected by the CARBMED project during the M69/1 cruise onboard the R/V "Meteor" in 2006 (Hübscher et al., 2010).

The acquired lines also cross two oil-industry wells on the Alicante shelf (Elche sub-basin) and two wells in the Valencia Basin (Fig. 1). All boreholes were drilled for oil- and gas-exploration purposes and have provided a complete well log dataset and continuous sampling of core cuttings.

The map of the base of the Pliocene–Quaternary unit (P–Q unit) presented in Figure 4 shows the present-day Top surface of the MSC unit (in isobaths) in cases where a MSC unit is present, and refer to the Miocene/Pliocene–Quaternary boundary (i.e. the MES) when no MSC unit is observed. Figure 5 shows the thickness of the MSC-related units, including the UU and MU in the Algerian, Liguro-Provençal and Valencia basins. The LU is not taken into account because this unit cannot be clearly identified over the mapped area. The velocity used for the conversion is derived from detailed curves giving a mean value of 2.29 km/s for the Pliocene–Quaternary and 3.4 km/s for the Miocene, based on wells (wells 331, 466, 473 and 553 from Lanaja, 1987) and ESP analysis (ESP 2, 3, 4, 5, 6 and 7 in the Valencia Basin, Pascal et al., 1992) and assuming a value of 1.5 km/s for the "acoustic velocity" in seawater (Maillard et al., 1992; Pascal et al., 1992).

5. Results

5.1. *Facies and distribution*

The presence of a MSC-related seismic unit on the Promontory is suspected from low-resolution seismic data. It appears on these profiles as a thin seismic facies made of one or two very high amplitude reflectors on the low-frequency seismic lines (Fig. 6). The existence of this MSC unit is now confirmed owing to the new high-resolution Simbad seismic survey. In fact, the

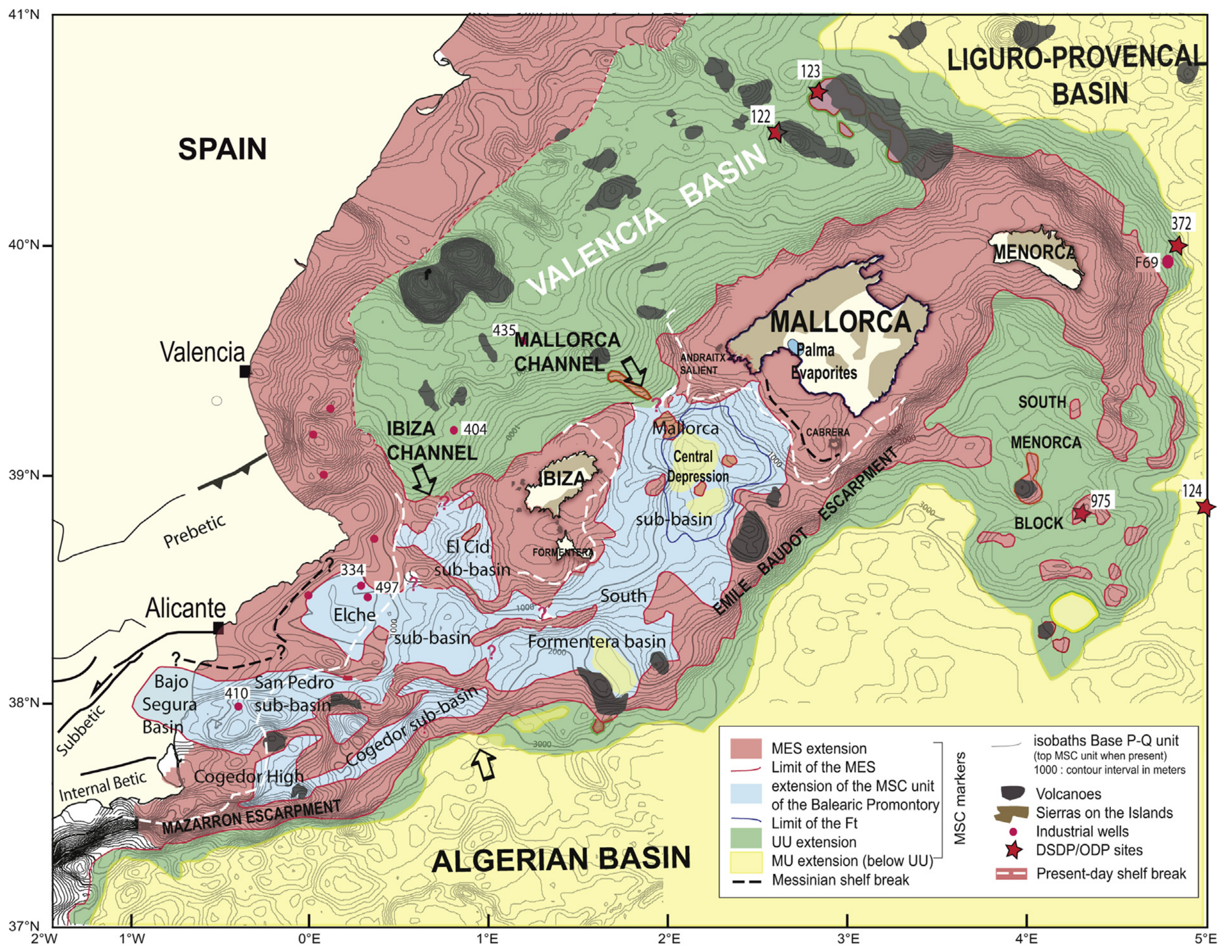

Figure 4. Map showing present-day extent of the MSC units in the study area. The MSC unit of the Balearic Promontory is shown in blue. The MSC units of the deep basin are displayed in green (UU) and yellow (MU). Extent of the Margin Erosion Surface (MES) is shown in red. The isobaths show the depth to the base of the Pliocene–Quaternary unit (P–Q unit), corresponding either to the top of the MSC units, or to the top of the pre-MSC units when no Messinian is present. The distribution of these isobaths represents the location of the MSC-related basins at different depths. Black arrows show the location of the channels. The different shelf-breaks have been defined from the seismic reflexion profiles used for this study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

prominent reflectors observed on the low-resolution seismic profiles actually correspond to a package on the high-resolution seismic data (Fig. 6) characterized by sub-parallel continuous reflectors (2–7) of medium amplitude (Fig. 7, Zoom 1). An internal facies made up of very thin reflectors (Ft: Facies thin) with lower amplitude (Fig. 7, Zoom 2) can often be picked out, usually at the top of the MSC unit, locally onlapping the underlying strong reflectors.

From the contrasting impedance of this unit compared with the over- and under-lying units (P–Q unit and pre-MSC unit, respectively; Fig. 6), the correlations with the boreholes and MSC-related units all over the NW Mediterranean, we can infer that it is MSC–related, and thus Late Messinian in age. The basal part of the P–Q unit displays a transparent facies (Pt: transparent Pliocene) that is correlated in the boreholes to the basal Pliocene.

The distribution of the MSC unit reveals a set of stepped Messinian basins distributed nearly continuously between the onland outcrops and the deep basins (Fig. 4, unit shown in blue), at depths currently lying between 600 and 2000 m. This unit occurs in small sub-basins, i.e.: the Mallorca sub-basin, the South Formentera sub-basin, the El Cid sub-basin between Ibiza Island and Cap Nao, as well as some small elongated sub-basins on the Alicante shelf (Fig. 4). The MSC unit is 0–100 m thick (0.05–0.1 s TWTT) in most parts of the study area and reaches up to 300 m in the Central Depression (>0.1 s TWTT). It is very thin and chaotic on the slope (30–50 m thick; 0.02–0.05 s TWTT; Figs. 4 and 5).

Outside the MSC sub-basins, the MES (Fig. 6) can be identified due to truncated reflectors in the underlying layered seismic facies which are correlated to pre-MSC units observed locally outside the structural highs and the shelves (Fig. 8, Zoom 1), or owing to a high contrast between under- and over-lying seismic facies.

5.2. Alicante shelf: ties between wells and seismic profiles

On the Elche sub-basin in the Alicante shelf, the MSC unit can be correlated with two wells (i.e. Calpe-1, borehole 334 and Alicante MU-1, borehole 497) that are intentionally tied to some new seismic profiles (Figs. 1 and 4). In this area, the unit displays 4 reflectors at 0.7 s TWTT, with very strong impedance reflections at the base and top (Fig. 9). Well completion reports indicate that our MSC unit corresponds to massive layers of white gypsum and anhydrite interbedded with thin grey calcareous clays of Miocene age (Fig. 9, Zooms 1 and 2). Although the original completion reports do not contain detailed chronostratigraphic data, our micropaleontological data indicate a Late Messinian age for the sequence (Ochoa et al., 2014).

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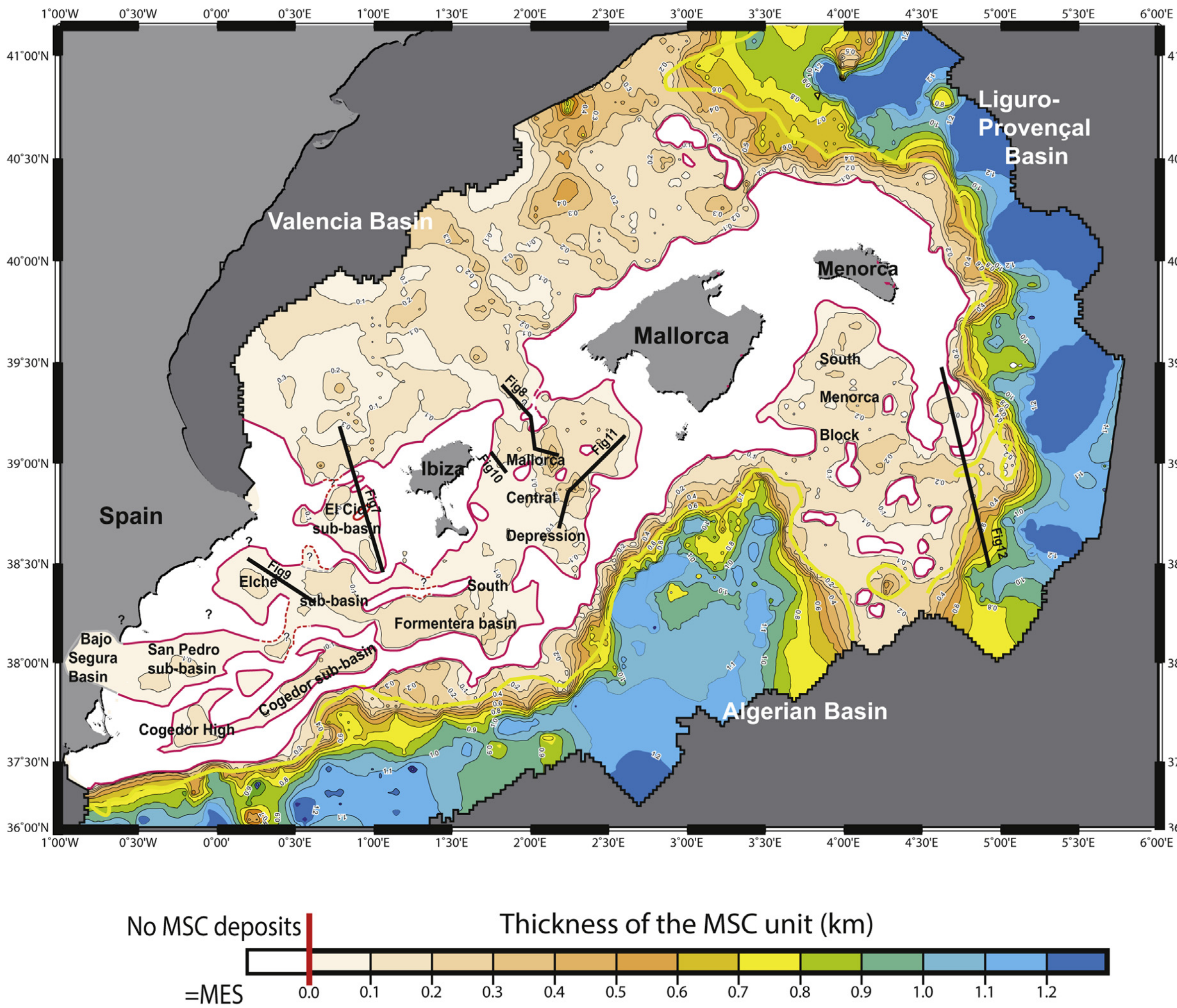

Figure 5. Thickness (in metres) of the MSC units in the study area. The average velocity used to calculate the thickness of the MSC unit is 3400 m/s (Maillard et al., 1992; Pascal et al., 1992; Torné et al., 1992). Red line represents the limit of the MSC unit. No MSC deposits exist on the shelves of the Balearic Islands. Yellow line represents the limit of the salt (MU). White areas: no MSC unit. Grey areas: not represented. Thick black lines show the location of the presented seismic profiles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The base of the MSC unit is the most reflective, but no erosion can be seen; the underlying reflectors seem concordant, even though multiples prevent clear observation. Laterally and down to the present-day shelf break, the MSC unit thickens and is clearly eroded on top) and covered by the transparent facies of the P–Q unit (Fig. 9, toplap on Zoom 3. Downslope, the MSC unit passes into a chaotic unit (Fig. 9, Grey Unit) which is most likely MSC-related as well. The multiples on the line prevent us from seeing the geometry of the reflectors of the Pliocene–Quaternary unit on the shelf, but they appear discordant on the MSC unit on the slope (Fig. 9, Zoom 1). Pliocene–Quaternary soft silty clays and limestones overlie the MSC unit, building the Present-day shelf and slope (Fig. 9, Zoom 2). Farther south-east, the MSC unit is present in a graben located 0.5 s TWTT downward. Indeed, the MSC unit is offset by post-MSC faults observed in many other sites throughout the Promontory.

The MSC unit can be traced on oil-industry seismic profiles, and extends across another sub-basin, the San Pedro sub-basin, which is also E–W elongated and separated from the Elche sub-basin by the Tabarca High. The San Pedro sub-basin continues onland into the Bajo Segura basin, where the same MSC unit can be followed from land to sea at a depth of 500 m in the 410 well (Soria et al., 2008; Alfaro et al., 2012). Onshore studies along the Bajo Segura Basin have dated this unit (i.e. San Miguel Fm.) as Messinian (Montenat et al., 1990; Soria et al., 2008) and have interpreted the gypsum beds as equivalent to the Yesares member of the Sorbas Basin (Soria et al., 2008). Thus, this sequence corresponds to the lithological expression of MSC stage 1 (CIESM et al., 2008). Hence, the well-to-seismic tie indicates that the MSC unit on the Alicante shelf corresponds to the Primary Lower Gypsum (PLG).

Another sub-basin (the Cogedor sub-basin) can be observed farther south, showing a narrow and SW–NE elongated outline.

5.3. Ibiza Channel

The left part of the Figure 7 shows the UU across the Valencia Basin and the location of a seismic-tied well (Ibiza Marino AN-1, borehole 404). At this point, UU is found at 2 s TWTT and shows high amplitude reflectors. Borehole data indicate that these reflectors correspond to 37 m of gray clays and marls intercalated with thin beds of anhydrite and gypsum (1645–1682 m well depth; Fig. 7, Zoom 1). Underlying these alternating clays and marls, the seismic profile shows a package formed of chaotic seismic facies, which corresponds to 108 m of gray marls with some gypsum laminae. This package is interpreted as the Complex Unit (CU), which has been linked to the clastic products of former Messinian drainage networks (Lofi et al., 2005) or as resedimented turbidites

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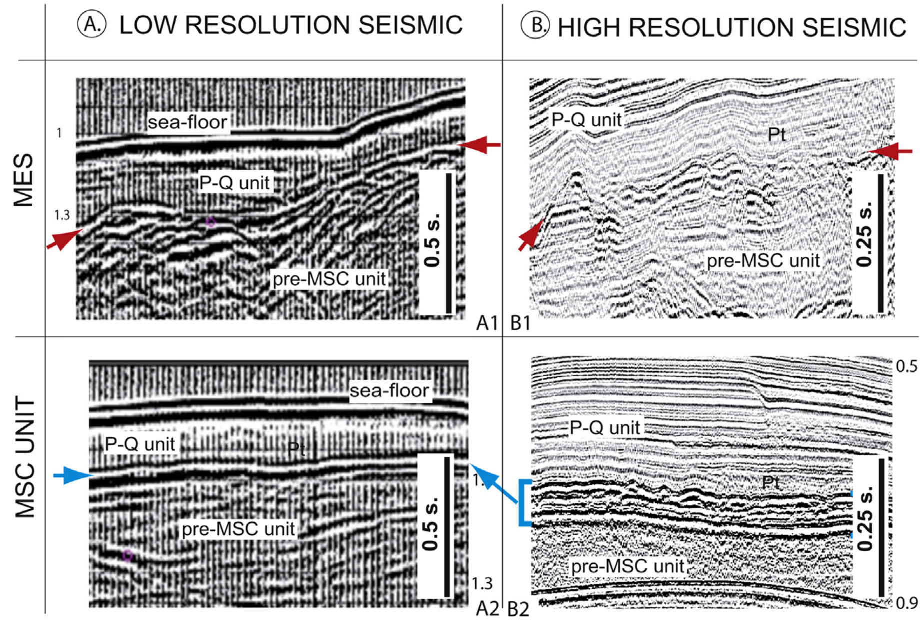

Figure 6. Sections showing the different seismic facies of the MSC unit and the MES in the study area, based on the available low-resolution (column A) and high-resolution (column B) seismic data. P–Q unit = Pliocene–Quaternary seismic unit. Pt = transparent seismic facies at the base of the P–Q unit. Red arrows show the MES. In blue: the MSC unit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Martínez del Olmo, 2011). The MSC unit of the Valencia Basin drapes the margin towards the Ibiza Channel. It could not be tied unequivocally to the MSC unit of the El Cid sub-basin because of highs related to the Betic thrusts (Fig. 7). However, throughout the Balearic Promontory, the MSC unit appears below the nearly transparent seismic facies (Pt) which is widely present in the NW Mediterranean at the base of the P–Q unit. In the study area, this transparent facies has been drilled in two oil-industry wells (at Ibiza Marino AN-1 (borehole 404 on Fig. 7) and Calpe-1 (borehole 334 on Fig. 2). Recent biostratigraphic analyses have been carried out on post-evaporitic sediments from both wells. Based on the First Occurrences (FO) of *Globorotalia margaritae* (5.08 Ma) and *G. punticulata* (4.52 Ma) in these wells, a Zanclean age is supported for the transparent reflectors (Ochoa et al. unpublished data). Since the Pt seismic facies is continuous throughout the Balearic Promontory from the Valencia Basin (correlated to DSDP drillholes 122 and 123 in the NE part of the basin) across to the Algerian domain (correlated also with the Pliocene in DSDP drillholes 124 and 975), it is most likely that the MSC unit, always located at the base of the Pt unit, records the same age as the UU.

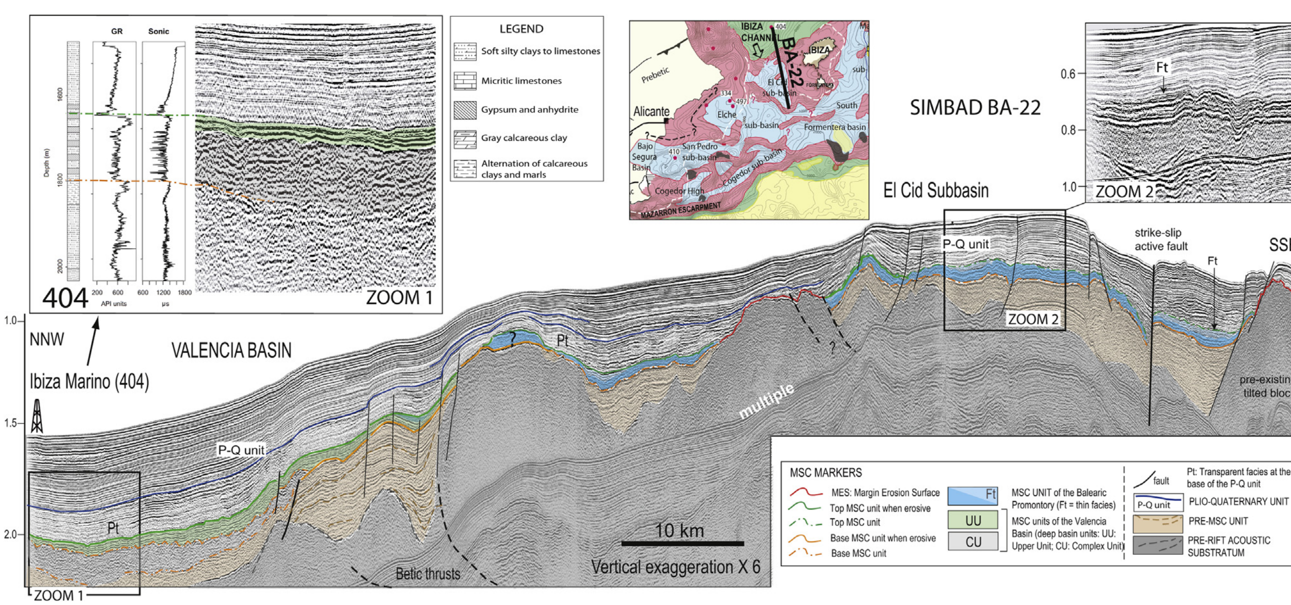

Figure 7. Simbad-BA22 seismic line in the Ibiza Channel, illustrating the transition between the Valencia Basin and the El Cid sub-basin. The MSC unit of the Valencia Basin (UU, in green), is tied to the Ibiza Marino 404 borehole (Zoom 1, see text for explanation). The MSC unit of the El Cid sub-basin on the Balearic Promontory is thin and isopachous, locally containing the thin facies (Ft; zoom 2). The substratum shows complex deformation, related to tilt blocks associated with rifting, Betic thrusts and present-day reactivation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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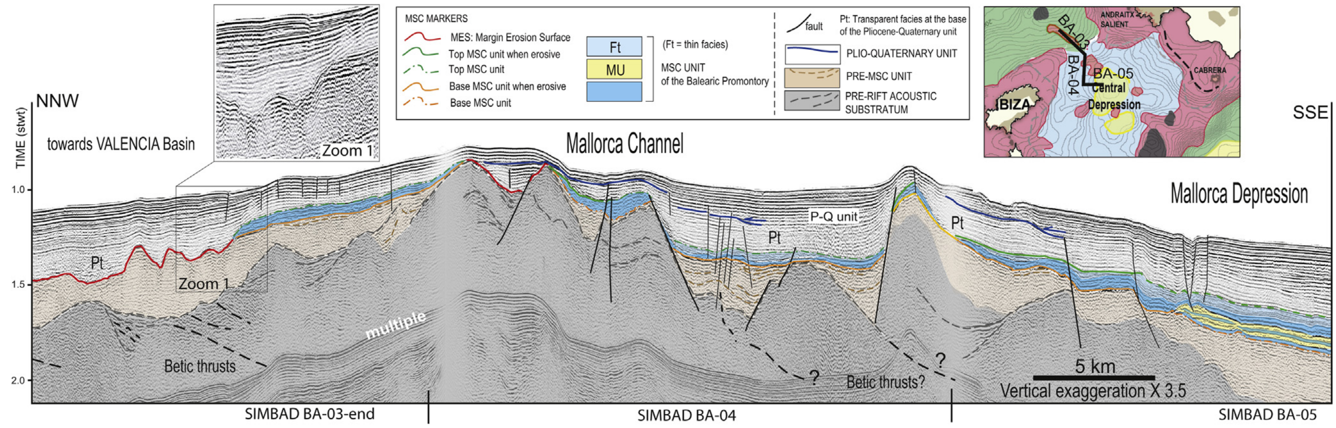

Figure 8. Simbad-BA03-04-05 seismic profiles in the Mallorca Channel, illustrating the transition between the Valencia Basin and the Central Depression. The MES is largely represented in the Valencia Basin, while the MSC unit (in blue) is widely present in the Mallorca Channel, thickening towards the Central Depression where the MU is intercalated. The MSC unit is offset in most cases by normal and strike-slip faults. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Figure 7 shows the continuity of the Pt unit towards the south of the Ibiza Channel, along with a rather well-layered seismic facies beneath with a thickness often reaching 0.1 s TWTT (100 m; Fig. 5) representing the thin isopachous MSC unit in the El Cid sub-basin. Facies Ft can often be observed on the top of four well-expressed high-amplitude reflectors. The base of the MSC unit is the most highly contrasted reflector, being rather flat, while the top is more deformed, corrugated and locally eroded. The underlying unit in this area shows a non-layered and mostly homogenous seismic facies (transparent to chaotic), which prevents us from seeing if the base of the MSC unit is an erosion surface. The El Cid sub-basin appears disconnected from the Elche sub-basin by a structural high.

The southern part of the Ibiza Channel shows an important MSC sub-basin, the South Formentera sub-basin, containing a thick MSC unit (>100 m, Fig. 5) that seems to prolong the Elche basin. Eastward, no high-resolution seismic data is available, but correlations with the numerous oil-industry seismic surveys are clear enough to support a connection between the MSC unit existing in the South Formentera sub-basin and in the Mallorca sub-basin. However, the South Formentera and Cogedor sub-basins are clearly disconnected from the MSC units (both UU and MU) of the deep Algerian basin by highs (Mazarròn escarpments, volcanoes and/or tilt blocks).

5.4. Mallorca Channel

The thick MSC unit of the Mallorca sub-basin connects with the South Formentera sub-basin. Everywhere except in the Central Depression, the MSC unit is present with the same seismic facies as in the Ibiza Channel, made up of 2–5 subparallel reflectors in places overlain by the Ft (Fig. 8, Line BA-04). Both the base and Top of the MSC unit are locally erosive. However, the unit below the MSC unit is often non-reflective and nearly transparent. The pre-MSC unit thickness does not vary in relation with the highs or lows (Fig. 8, Line BA-04): the faults affecting the MSC unit mostly express post-MSC tectonics. It is noteworthy that the highest parts of the Mallorca Channel contain an MSC unit, while the lower slope towards the Valencia Basin is eroded by the MES. On the borders of the sub-basin, the MSC unit is thin but drapes the Ibiza and Mallorca slopes up to 0.5 s TWTT. Upslope, the MSC unit passes into the MES, which is characterized by a single strong reflector (Fig. 10).

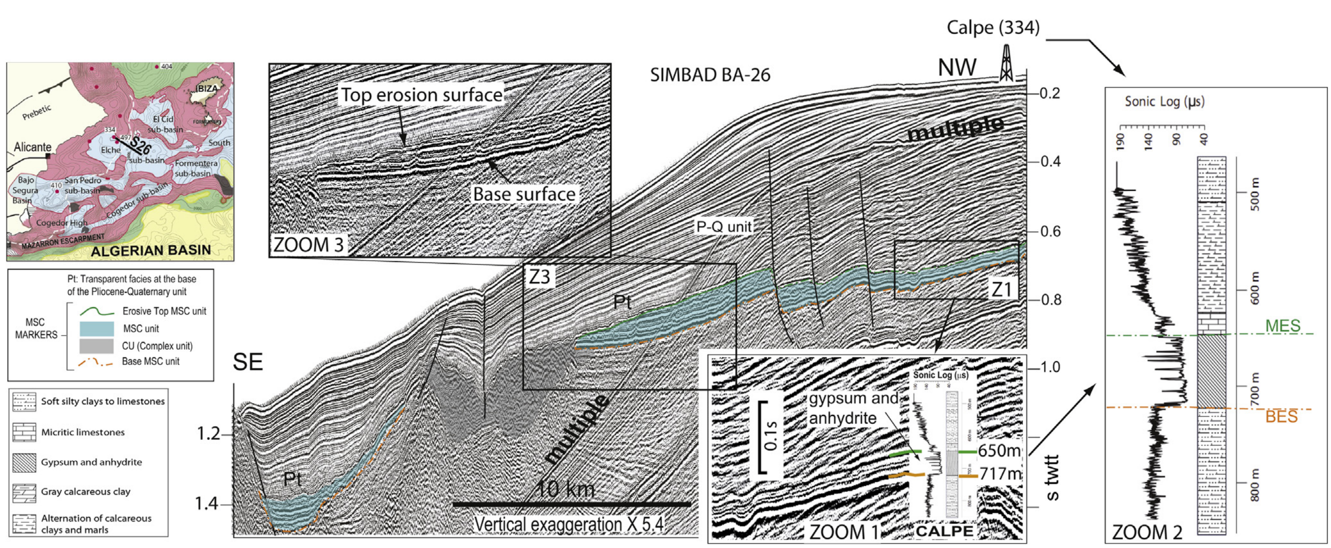

Figure 9. Simbad-BA26 seismic line in the Elche sub-basin, illustrating the MSC unit (in blue) on the Alicante shelf. The MSC unit is tied to the Calpe (334) borehole and occurs at a depth of 650–717 m (Zoom 1). It is made up of gypsum and anhydrite beds (Zoom 2). The MSC unit thickens basinwards and is offset by post-MSC faults. Zoom 3 shows clear erosion at the top of the MSC unit. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

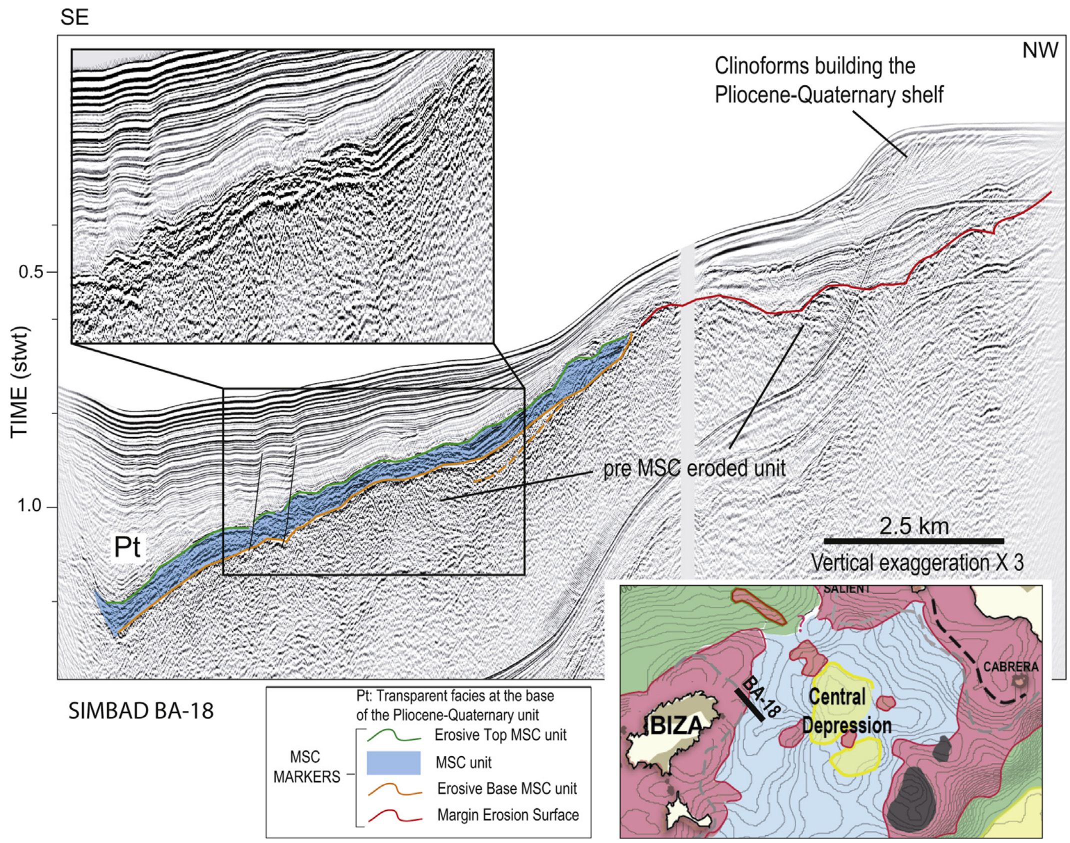

Figure 10. Seismic profile Simbad-BA18 in the Mallorca sub-basin illustrating the MSC unit present in the Ibiza slope domain. The MSC unit is present up to 0.6 s TWTT, associated with disturbed seismic facies linked to gliding on its base (Zoom 1). The base of the MSC unit is clearly erosive here. Upslope, the MSC unit thins upwards, onlapping onto the Ibiza margin and passing into the MES.

Towards the Central Depression, the MSC unit thickens (Fig. 8, Line BA-05) and its seismic facies changes. Indeed, a transparent seismic facies appears in the deep part of the depression (deeper than 1.5 s TWTT), intercalated at the base of the MSC unit (Fig. 8, Line BA-05 and Fig. 11, unit shown in yellow), which can reach a thickness of 0.1 s TWTT (i.e. 300–350 m). The base of the MSC unit is difficult to pick out precisely because there could be rigging artefacts (Fig. 11). The base of the MSC unit shows erosion toward the borders of the Central Depression, locally displaying some truncated reflectors in the pre-MSC unit (Figs. 10 and 11). On the borders of the depression, we find evidence of faults affecting the MSC and P–Q units and/or a downward bending of the P–Q unit. The observed deformation is located at the pinch-out of the transparent facies (Fig. 8 Line BA-04 and BA-05, Fig. 11, Zoom 1), but the faults are clearly rooted in the transparent facies and affect only the overlying sedimentary cover. We therefore assume that the transparent facies corresponds to a ductile layer which can be correlated with a salt unit (MU). This layer thus provides a *décollement* to account for the gravity gliding and/or spreading of the brittle overlying units (Gaullier and Vendeville, 2005; Rowan et al., 2012). Displacement and deformation are weak mainly because the depression is small and closed, preventing lateral salt flow (Fig. 5). The Ft facies is observed above the MU, being localized in the Central Depression (Fig. 4, limit of the Ft). No erosion is observed at the top of the facies here, which may be due to the flat morphology of the Central Depression and the correlative concordance of the seismic units. Towards the borders of the Central Depression, the Ft facies onlaps onto the MSC unit located on the slopes (Fig. 11, Zoom 2).

5.5. South Menorca Block

Except on local structural highs, the MSC unit covers the South-Minorca Block (UU, Figs. 2, aa' and 4). Since the thickness of this unit reaches more than 200 m (0.2–0.3 s TWTT; Fig. 5), it can be clearly seen on the low-resolution seismic database. It displays 2 to 6 high-amplitude reflectors contrasting with over/underlying seismic units and thickens progressively downslope. Figure 12 shows 3 structural blocks (probably horsts inherited from the rifting) that disconnect the MSC unit, but the geometry of the reflectors reveals a recent phase of crustal tectonic activity: the faults delimiting the blocks disrupt the MSC and the Plio-Quaternary units. Moreover, the Plio-Quaternary unit is bent parallel to the MSC unit and both can be locally eroded at the surface. In the southern part of the line, salt tectonics is linked to the presence of the MU in the deep basin (Fig. 12, on the right). Once removing both the effects of crustal post-MSC tectonics and salt gravity gliding, we can easily connect the MSC unit across each part of the structural highs, and establish that the MSC unit on the South Menorca Block is continuous with the UU of the deep basin.

Away from the South-Menorca Block, the UU extends to the east (NE Menorca margin) and to the west (E. Baudot and Mazzaron Escarpments), where the pinch-out of the MSC unit onto the margins is sharp and apparently controlled by faults (Sàbat et al., 1997; Camerlenghi et al., 2009; Maillard and Gorini, 2010; Fig. 2bb' and cc'). Where the margins are less steep or display steps, the MU pinches out progressively and only the UU covers the stepped horizontal ramp, as it is the case on the South Menorca Block, or

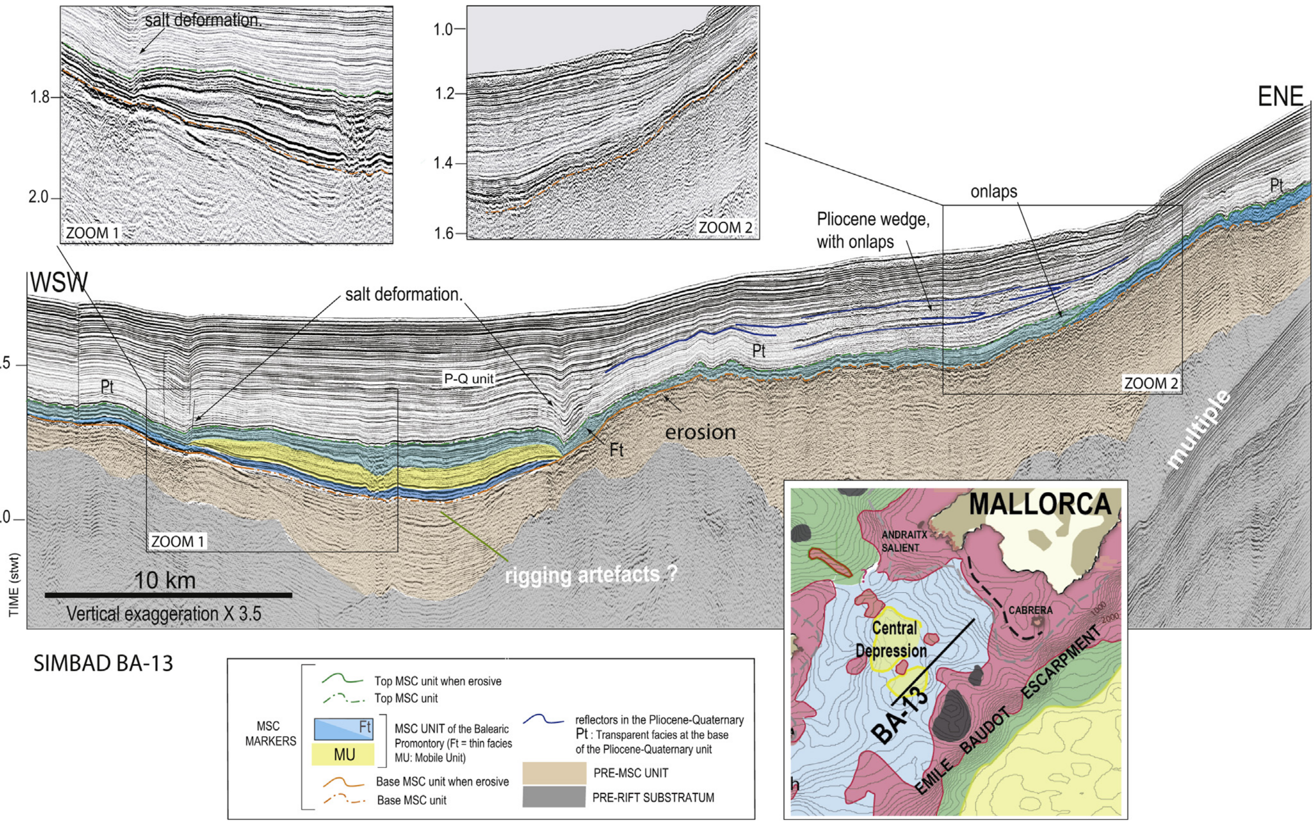

Figure 11. Seismic profile Simbad-BA13 in the Mallorca sub-basin illustrating the MSC unit extending from the Central Depression to the Mallorca slope. The MSC unit in the Central Depression contains the MU, which is responsible for salt deformation (Zoom 1), with the thin facies (Ft) on top, which extends onto the borders. In the Mallorca slope domain, the MSC unit thins upwards and the Ft onlaps onto the MSC unit present on the slope (Zoom 2).

across the entire Valencia Basin (Intermediate-depth basin between margins and deep basins, Fig. 3a; Lofi et al., 2011a).

6. Discussion

The study of MSC markers on the Balearic Promontory shows the occurrence of a thin but widespread MSC unit over the whole of this domain.

The thin and nearly isopachous MSC unit drapes the Balearic Promontory at all depths ranging from 500 to 2000 m present-day water depth, except on some local highs (Figs. 4 and 2). In our study, MSC deposits are recorded nearly continuously from the Alicante shelf to the Mallorca SW shelf, distributed in partially closed sub-basins. This unit is clearly disconnected from the Algerian basin by the Mazzaron and E. Baudot Escarpments, where the deep-basin MSC units (MU and UU, Fig. 2, bb', cc' and Fig. 4) onlap onto the margin, as observed around most of the NW Mediterranean margins. Indeed, the MU/UU usually onlaps at around 3 s TWTT onto the MES. Thus, the MES is usually observed on the slopes of the Liguro-Provencal and Algerian basins where such a thin MSC unit has never been observed (Lofi et al., 2011b). Peripheral MSC basins lie at the margins of the deep basin and

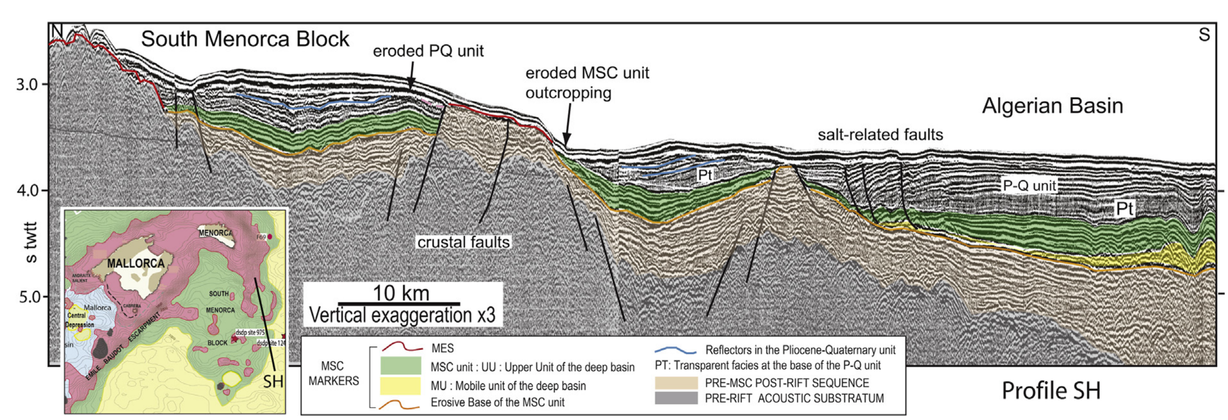

Figure 12. Industrial low-resolution seismic profile SH across the South Menorca Block illustrating the MSC unit (UU shown here in green), which is in continuity with deep-basin evaporites in the Algerian Basin composed of MU and UU. Faults illustrate an important phase of post-MSC deformation that may reactivate crustal blocks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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crop out at present onland, which is not the case for the sub-basins mapped on the Alicante shelf. Thus, the presence of a MSC unit at such shallow depths on the Promontory is unexpected. On the northern side, a connection with Valencia basin remains possible.

6.1. Correlation between the different sub-basins

Considering the homogeneous seismic facies and thickness of the MSC units (between 100 and 200 m) in all the small sub-basins, it is most likely that their environments and depths of deposition were all rather similar. However, the spatial/geometrical and stratigraphic relationships among the various MSC units observed are difficult to assess at the scale of the study area. Due to the structural complexity of the area, it is difficult to recognize lateral continuity/discontinuity among the MSC units, either because such a connection did not exist, or because post-MSC tectonics overprinted the records. The occurrence of post-MSC displacements along faults adds further complexity to deciphering the lateral continuity of the MSC units.

In the Ibiza Channel, the disconnection between the sub-basins is partly due to local structural highs that clearly existed before the crisis, mostly resulting from rifting but also from Betic thrusts. These highs evidently show post-MSC remobilization (Maillard and Mauffret, 2011; Alfaro et al., 2012; Acosta et al., 2013). Even if a disconnection existed, it is however difficult to imagine any large differences in paleodepth. Depth differences never exceed 0.2 s TWTT and, moreover, the MSC unit is not horizontal but instead deformed (Fig. 2cc'). We propose that the sub-basins of the Ibiza channel (El Cid, Elche and Formentera) could have formed only a single basin before post-MSC tectonics.

As we can correlate the MSC unit of the Elche and San Pedro sub-basins with the peripheral gypsum, all the MSC sub-basins found between Alicante and Ibiza are thus likely to represent the PLG (Fig. 3b1).

Towards the east, the Formentera sub-basin joins up with the Mallorca sub-basin (Fig. 4). The MSC unit extends here onto the Ibiza and Mallorca slopes and into the Mallorca Channel, so its interpretation as representing the PLG would also be compatible with the existence of gypsum in the Bay of Palma onshore. Indeed, according to Rosell et al. (1998), the number of cycles recorded in this unit is close to that observed in Italy and Sicily in the Lower Evaporites (Rosell et al., 1998) and these gypsum beds appear to be correlated with the peripheral evaporites (PLG-stage 1, CIESM et al., 2008).

In the Central Depression, however, a particular onlap geometry is observed: the thick MSC unit, including the MU overlain by Ft, seems to passively fill the depression and onlaps onto the thinner MSC unit of the borders (Fig. 11, Zoom 2; Maillard et al., submitted for publication). This geometrical relationship allows us to identify at least two generations of MSC deposits in the area, with progressively younger units forming in the depression. In that case, the MSC unit (or at least part of it) in the Central Depression could postdate the PLG.

Ft can also be distinguished in the Ibiza Channel, lying unconformable at the top of the MSC unit (Fig. 7, Zoom 2). However, it cannot be observed on the low-resolution seismic profiles, so its extension cannot be traced any further. The MSC unit seems not to be restricted to lows, perhaps because of post-depositional reactivation, more important here than in the Mallorca Channel area, which could lead to major vertical movements. It is also worth noting that the only place where Ft is completely missing is the Alicante shelf, where the MSC unit is tied to boreholes that have drilled the PLG. Ft could then be linked to the second generation of evaporites (deep evaporites).

6.2. Correlation with MSC units in the deep basins (Fig. 3b)

The geometrical relationship between the MSC units of the sub-basins and evaporites in the deep basins is the key to linking the scenario adopted for the formation of peripheral and deep evaporites during the MSC.

The MSC unit of the Balearic Promontory deepens progressively towards the Valencia Basin. The relationships with the MSC units in the Valencia Basin are crucial for constraining the timing of evaporite precipitation. However, the continuity cannot be established at present with any certainty due to the presence of structural sills disconnecting the basins. Moreover, there are insufficient high-resolution seismic lines to identify a possibly localized connection. Figure 7 nevertheless shows lateral relationship between the MSC unit in the Ibiza Channel and the MSC unit (UU) of the Valencia Basin: the depth and facies are very similar and both MSC units are eroded at their top and base. These observations favour a continuous MSC unit forming a drape extending from the Valencia Basin to the Balearic Promontory, contrary to the situation observed on the Liguro-Provençal and Algerian margins (Fig. 3b2). However, since the UU of the Valencia Basin is correlated with the UU of the adjacent Liguro-Provençal deep basin, and the Elche MSC unit to the PLG evaporites, this would imply a single phase of deposition for the evaporites.

Borehole analyses provide evidence that the MSC unit cored in the Ibiza Marino well located in the Valencia Basin can be distinguished from the PLG gypsum. Another possibility is to link the shallow MSC unit of the Balearic Promontory to the peripheral PLG evaporites, and the Central Depression succession (Ft and MU) to the deep-basin evaporites, as proposed in the two-step scenario (CIESM; Fig. 3b3).

Indeed, in the Central Depression, the occurrence of a thinly bedded seismic facies Ft above mobile salt exhibits a strong analogy with the deep-basin evaporites, which consists of UU overlying MU, or with the Sicilian succession consisting of Upper Evaporites above Halite (Decima and Wezel, 1973; Roveri et al., 2008; Manzi et al., 2009; Lofi et al., 2011a). Moreover, the possible layered reflections below the salt could be compared to the LU. The MU found in the Central Depression currently lies at depths of 1000 to 1500 m, which is much shallower than the depth of the MU in the deep basins (3500–4500 m). It is also thinner (100–200 m thick) and intercalated within bedded reflections. Such thin salt layers possibly also exist locally in the depression south of the Formentera sub-basin (Fig. 4 and Camerlenghi et al., 2013), and others have been recently observed in the UU of the west Sardinia deep margin (Geletti et al., 2014). No chronostratigraphic correlation can then be established between these salt layers and the MU of the deep-basin succession.

The two-step scenario involves intense erosion of the peripheral evaporites during the precipitation of deep evaporites. As regards to the Mallorca sub-basin, we note that no erosion is observed on top of the Ft unit in the Central Depression, whereas it is clearly observed in shallower environments at the borders of the depression. In the Elche sub-basin also, erosion clearly affects the top MSC unit (Fig. 9, Zoom 3). Figure 8 (Zoom 1) shows erosion on top of a perched MSC unit that connects with the MES at progressively greater depths towards the Valencia Basin. Even if the MES is polygenic, it seems difficult to understand how the MSC unit could be deposited while erosion was taking place in the deeper area at the same time. Geometrical relationships suggest linking the major erosion marker (the MES) to erosion on top of the MSC unit of the Mallorca Channel (Fig. 8, Line BA-03, Zoom 1). In the Valencia Basin, the MSC unit (UU) is also eroded on top, but this erosion surface (TES) is flat and incised by a drainage network (Escutia and Maldonado, 1992; Maillard et al., 2006), so we would more likely link the MES to the bottom erosion surface (Fig. 3, BES). As a consequence, the MSC unit of the Mallorca Channel would be older than the ones in the Valencia Basin.

In that case, the MSC unit of the Balearic Promontory would be coeval with the first-stage evaporites and could have been eroded during the major drawdown (second stage), while only the Central Depression succession (Ft and MU) would be deposited coevally with the deep basin evaporites (Fig. 3b3). We support that interpretation.

6.3. Local occurrence of halite in the Central Mallorca Depression

The occurrence of a halite layer in the Central Depression, at a depth of 1000–1500 m, challenges the concept that salt is generally restricted to the deep abyssal domain of the Northwest Mediterranean in passive tectonic settings (at around 4000–5000 m depth).

Post-MSC vertical movements in Mallorca could not account for such differences: subsidence of the Central Depression is weak, since the maximum thickness of the Plio-Quaternary unit is 500 m, and post-MSC tectonics consists mostly of normal and strike-slip faulting (Fig. 8; Acosta et al., 2004a, 2004b). Removing these effects would in any case enhance the offset between the deep domains and the Balearic Promontory.

For comparison, few areas containing MU have been identified in the shallow parts of the Northwest Mediterranean. The East Sardinia Basin located on the continental crust of the East Tyrrhenian margin is disconnected from the oceanic domain, and contains MU deposits at around 2.5–3.0 s TWTT – depth (Gaullier et al., 2014). Salt also exists on the continental shelf of Greece offshore from Thassos Island, at around 2 s TWTT – depth (Prinos Basin, Proedrou and Papaconstantinou, 2004), at depths comparable to those of the occurrences studied here. Proedrou and Papaconstantinou (2004) also describe erosion cutting the top of the Messinian unit in the Prinos Basin. A similar configuration is observed on the Tunisian margin downslope where 200 m of Messinian halite eroded at the top have been drilled (El Euch-El Koundi et al., 2009). Other halite deposits are known onland, such as in the Sicilian succession, as well as in Calabria (on the Ionian seaboard), but controversy persists as to whether they represent deep or marginal basins (Butler et al., 1995; Clauzon et al., 1996; Rouchy and Caruso, 2006; Roveri and Manzi, 2006, 2014). These examples show that evaporites occurring at intermediate depths between the deep and marginal basins could have formed in perched basins during the MSC. However, their active tectonic settings are very different from the passive margins of the Northwest Mediterranean, which prevents from restoring the exact paleo-topography.

The existence of salt in the Central Depression at shallow depths, belonging to an undeformed and possibly complete MSC succession, favours the hypothesis that the MU was deposited passively as the filling of a closed or partially closed perched basin.

6.4. Proposed local scenario for the MSC on the Balearic Promontory

In a passive tectonic setting such as developed in the Northwest Mediterranean, the horizontal onlap of MSC units onto the MES on the slopes (Fig. 3a) suggests the progressive infilling of the deep basin (Bache et al., 2009, 2012). The same configuration of MSC units in the Central depression is observed at shallower depth, supporting the idea of a parallel development of several more or less disconnected sub-basins with different base levels. The onlap of the deep-basin MSC units onto the MES at the margins can no longer be interpreted simply as a paleomorphological marker.

Outside the Central Depression, the MSC units are thin and bedded, and do not contain any record of MU. The different MSC sub-basins were perhaps not deep enough or sufficiently confined to allow precipitation of halite.

Such thin MSC units have been described locally on seismic profiles around the Northwest Mediterranean, all located at intermediate depths between deep and peripheral basins (Fig. 3; West Corsica basin, East Corsica basin, East Sardinia Margin, Lofi et al., 2011a; Gaullier et al., 2014). These profiles reveal a thin-bedded MSC record essentially composed of a single unit (BU or Bedded Unit), that can also be disconnected from the deep basins (East Corsica, Thinon et al., 2011).

The MSC units of the study area could fill a pre-existing perched and closed topography, possibly deposited as a result of evaporative drawdown at different depths as proposed by Rouchy and Caruso (2006) and Ryan (2008). Their precipitation could have occurred diachronously or at least diachronously with respect to the deep-basin evaporites. However, to test this hypothesis, we need to reconstruct the Messinian paleotopography, taking into account vertical movements that could be more important than previously thought.

7. Conclusion

The SIMBAD seismic survey allows us to observe that:

1. The MSC unit is widespread over the Balearic Promontory. It appears as a thin bedded unit 0–200 m thick in most parts of the study area. Boreholes analyses suggest that it is correlated on the Alicante shelf with the primary gypsum (PLG, Rossell et al., 1998; Roveri et al., 2003), and geometrical relationships suggest its continuity until the Mallorca area. The MSC unit is eroded at its top and passes laterally into the MES at depths shallower than 500 m.
2. The Central Depression between Mallorca and Ibiza islands displays a thicker MSC unit, whose lowermost transparent part, displaying flow features, corresponds to a salt layer. This MSC unit resembles the deep-basin MSC succession. Geometrical relationships suggest that the MSC in the Central Depression could postdate the primary gypsum.
3. The MSC unit is distributed over the Promontory in small perched sub-basins. The sub-basins are locally separated by highs which are controlled by the post-MSC tectonics. They are clearly disconnected from the Algerian Basin, but could have been all connected during the Messinian crisis. The upper part of the MSC unit of the Balearic Promontory (Ft and MU) could be correlated with the MSC unit of the Valencia Basin.

Deciphering the spatial/geometrical and stratigraphic relationships among the MSC units in all sub-basins is complex because of the occurrence of tectonic heritage and post-MSC deformation. Considering the homogeneous seismic facies and thickness of the MSC units in all the small sub-basins, it is most likely that their environments and depths of deposition were all rather similar. Most surprising is the relationship with the Valencia Basin, where the MSC units are geometrically nearly continuous with the ones observed on the Promontory, which could favour of a synchronous character of the onset of all the Mediterranean evaporites (Krijgsman et al., 1999). However, the lack of unequivocal ubiquist chronostratigraphic data prevents us from establishing a precise correlation between the different MSC-units. Based on the observation of at least two generations of MSC deposits in the Central Depression, we suggest that the evaporites of the Balearic Promontory were deposited passively in closed or partially closed perched sub-basins, possibly as a result of evaporative drawdown at different depths and possibly diachronously, at least with respect to the deep-basin evaporites.

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