Seismic imaging of Late Miocene (Messinian) evaporites from Western Mediterranean back-arc basins

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Abstract: An analysis of multichannel seismic reflection data was conducted focusing on the comparison between the Messinian Salinity Crisis (MSC) and Plio-Quaternary (PQ) evolution of the eastern Sardo-Provençal and northern Algero-Balearic basins and related margins in the West Mediterranean Sea. Both basins were completely opened during the MSC and their well-defined seismic stratigraphy is very similar in the deep parts. The primary difference between these two basins is due to their different pre-MSC extensional history, including the opening age and the stretching factors. These factors influenced the occurrence of post-MSC salt tectonics on these margins.

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The understanding of the Messinian Salinity Crisis (MSC) as a Mediterranean basin-wide event requires an improved knowledge of the stratigraphy in the deep basins and continental margins (e.g. Roveri et al. 2014). Due to the lack of lithological information from scientific and industrial wells, improvement of seismic imaging is currently the key element used to study the MSC stratigraphy in the deep basins, at least in academic seismic datasets (e.g. Lofi et al. 2011a).

In the Western Mediterranean, the geometry and distribution of the seismic markers of the MSC are not completely known due to uneven data distribution. In addition, seismic imaging is often hampered by deformation of the deep salt, high absorption and scattering of seismic energy by salt and other evaporitic formations, and high variability in seismic velocity across the salt sequence.

In this paper we focus on two recently acquired high resolution multi-channel seismic reflection datasets in the eastern Sardo-Provençal and northern Algero-Balearic basins (Figs 1 and 2). We have integrated the newer data with vintage seismic reflection profiles characterized by lower frequencies and higher penetration. Our aims are two-fold: (a) to test the possibility to improve the imaging of the sedimentary sequence and particularly of the seismic markers of the MSC affected by post-depositional deformation through accurate targeted seismic velocity analysis for pre-stack depth migration (PSDM); (b) to compare the structural and stratigraphic records of the two diachronous back-arc basins using the MSC sequence as a reference chronostratigraphic marker.

Geodynamic evolution and seismic stratigraphy

The Western Mediterranean region (Fig. 1) consists of several sedimentary basins evolved diachronously as back-arc response to the subduction of the Tethys Ocean lithosphere beneath the European plate to form the Apennines–Maghrebides Orogen during the Cenozoic (Cherchi & Montadert 1982; Gueguen et al. 1998; Carminati et al. 2012).

The first phase of the opening of the Western Mediterranean basins spans from the Early Oligocene (32 Ma, Carminati et al. 2012; 30 Ma, Cherchi & Montadert 1982; Rehault et al. 1984) to the Early Miocene (23 Ma, Cherchi & Montadert 1982; 21 Ma, Rehault et al. 1984; 22 Ma, Carminati et al. 2012), when continental back-arc rifting occurred with NE–SW strike in response to the northwestward subduction of the Tethys oceanic lithosphere below the European continental plate. This caused the clockwise rotation of the Balearic promontory and consequently the opening of the continental rift in the Valencia Trough.

In the Early Miocene (23–19 Ma, Cherchi & Montadert 1982; 22–15 Ma, Carminati et al. 2012; 21–18 Ma, Rehault et al. 1984; 21–16 Ma, Mauffret et al. 2004), the rifting progressively evolved eastwards to generate spreading of oceanic crust and led to the anticlockwise rotation of the Corso-Sardinian block that separated from the Balearic block through extensive right lateral motion along the North Balearic fracture zone (NBFZ). The formation of oceanic crust in the central Sardo-Provençal deep basin (Fig. 1) has been demonstrated through the identification of magnetic anomalies (Rehault et al. 1984), with magnetic and seismic reflection data (Fanucci & Morelli 2001) and with wide-angle and reflection seismic data (Afflhidho et al. 2015; Moulin et al. 2015). The Sardo-Provençal basin is therefore considered a back-arc basin confined between the conjugated passive margins of the Corso-Sardinian micro-plate to the east and of the Gulf of Lions and Provence to the NW (Rehault et al. 1984; Fanucci & Morelli 2001; Finetti et al. 2005).

The Oligo-Miocene continental and open marine rift to drift deposits of the Sardo-Provençal basin were covered by the MSC evaporites and successively by the Plio-Quaternary (PQ) deep marine sediments. The present Sardo-Provençal abyssal plain is deepest (locally more than 2900 m) at the toe of the west Sardinian continental slope. This bathymetric trend is due to the large sedimentary influx from the Rhône and Ebro rivers, which feed large deep-sea fans prograding towards the east and SE. Due to the minor fluvial sedimentary supply, the deep-sea fans originated from the Corso-Sardinian continent are very small and steeper compared to the Rhône and Ebro fans.

The following rifting episode in the area was the opening of the Algero-Balearic basin (Fig. 1), separated from the Sardo-Provençal basin by the NW–SE-trending Hamilcar magnetic anomaly (HMA) (Mauffret et al. 2004; Driussi et al. 2015). In this case there are alternative geodynamic interpretations. According to some, rifting and seafloor spreading was triggered by the westward migration of the Gibraltar Arc from the Langhian (16 Ma) to the Tortonian...
5.96 Ma (Krijgsman 2005; Domzig 2012). The northern margin of the Algero-Balearic basin (narrow shelf and steep slopes) is formed by a transform fault system (Emile Baudot Escarpment, EBE) (Acosta et al. 2001; Mauffret et al. 2004; Camerlenghi et al. 2009). Oceanic crust is present below the central parts of the deep basins (within the dashed line, according to Gueguen et al. 1998). The Hannibal ridge (HR) is considered the buried spreading centre of the oceanic Algero-Balearic basin (Mauffret et al. 2004). Black arrows indicate the direction of movement along the NBFZ and the EBE. The Hannicar magnetic anomaly (HMA) (Mauffret et al. 2004) separates the Sardo-Provençal and the Algero-Balearic basins. Bathymetric contours are every 500 m.

There is general agreement that the Sardo-Provençal and the Algero-Balearic basins were both completely opened in the Quaternary sedimentary fill about 800 m thick. Messinian evaporitic sequence less than 1 km thick and a Plio-Pleistocene succession of Menorca Island (Mauffret et al. 2004; Camerlenghi et al. 2009) separates the Sardo-Provençal and the Algero-Balearic basins. Bathymetric contours are every 500 m.

(8 Ma) in an ENE–WSW direction (e.g. Driussi et al. 2015). Evidence for this is the identification of the north–south-trending Hannibal Ridge (HR), and associated magnetic anomalies, a relict and buried spreading centre with associated volcanic centres south of Menorca Island (Mauffret et al. 2004). Such direction of the Algero-Balearic basin opening is supported by the interpretation of the northern margin of the basin, marked by the Emile Baudot Escarpment (EBE), as a right-lateral strike-slip fault system generated in response to the westward migration of the Gibraltar Arc (Mauffret et al. 1992, 2004; Acosta et al. 2001; Camerlenghi et al. 2009; Driussi et al. 2015). Similarly the southern margin of the Algero-Balearic basin is defined by the North African continental margin, a rifted margin with dominance of left-lateral strike-slip deformation. This margin has been recently reactivated by active compressional deformation offshore Algeria (Déverchère et al. 2005; Domzig et al. 2006; Mauffret 2007). An alternative geodynamic model suggests that the accretion of the Middle Miocene oceanic crust occurred in a NW–SE direction as consequence of the eastward migration of the Apennines–Maghrebides arcs (Rehault et al. 1984; Gueguen et al. 1998; Carminati et al. 2012). According to Gallart et al. (1995) and Sàbat et al. (1995), the deep Algero-Balearic oceanic basement is covered by about 1800 m of Miocene sediments that include a deformed Messinian evaporitic sequence less than 1 km thick and a Plio-Quaternary sedimentary fill about 800 m thick.

There is general agreement that the Sardo-Provençal and the Algero-Balearic basins were both completely opened in the Torontian (8 Ma) (Rehault et al. 1984; Gueguen et al. 1998; Mauffret et al. 2004; Carminati et al. 2012).

The MSC in the Mediterranean basin began shortly after, at 5.96 Ma (Krijgsman et al. 1999; CIESM 2008) and affected the whole Mediterranean region in the following 640 ka (Krijgsman et al. 1999; Roveri et al. 2014). This brief and dramatic event occurred in response to a tectonically driven reduced seawater exchange between Mediterranean and Atlantic waters (Clauzon et al. 1996; Krijgsman et al. 1999; CIESM 2008). Evaporites were deposited in the deeper basins, on the lower continental slopes and on several shallower marginal basins, whereas coeval erosion affected the intermediate and upper continental margins (Ryan et al. 1973; Butler et al. 1995; Clauzon et al. 1996; CIESM 2008; Roveri et al. 2014).

In the Western Mediterranean offshore, the seismic stratigraphic expression of the MSC is provided by a consistent succession of three seismo-stratigraphic units in the deep basins and lower slopes described for the first time in seismic profile MS-39 in the Sardo-Provençal basin (Finetti & Morelli 1973; Fig. 3). Seismic velocities obtained by Montadert et al. (1978) allowed the definition of three stratigraphic units (the ‘Messinian Trilogy’) that Rehault et al. (1984) subdivided into (from the bottom) the Lower Evaporites, Messinian Salt and Upper Evaporites. In this study we adopt the terminology proposed by Lofi et al. (2011a), who identified the Lower Unit (LU), Mobile Unit (MU) and Upper Unit (UU), respectively.

Additional Messinian surfaces are: the Bottom Surface/Bottom Erosion Surface (BS/BES) at the base of the MSC; the Intermediate Erosion Surface (IES) within the MSC; and the Top Surface/Top Erosion Surface (TS/TES) at the top of the MSC deposits. On the upper continental slope, where the Messinian succession is generally absent, the Margin Erosion Surface (MES) is a prominent reflector corresponding to a hiatus in the entire MSC strata.

Locally, evaporite deposition occurred also on the upper continental slopes and shelves (Lofi et al. 2011a; Geletti et al. 2014), as well as in the present onshore regions (Cornée et al. 2008), probably during the first phase of the MSC (Butler et al. 1995;
The seismic expression of these evaporites is defined as the Bedded Unit (BU), depicted by sub-parallel reflections and bounded by the TES and BES.

At the end of the MSC at 5.33 Ma, sea water refilled the Mediterranean basin and the Lower Pliocene (LP) pelagic sediments draped the margins extending to the entire Western Mediterranean basin (Rivas et al. 1973; Rehault et al. 1984) with a typical semi-transparent acoustic facies. The Upper Pliocene–Quaternary (UPQ) more reflective turbiditic layers correspond to coarse sediments deposited by European rivers (Rehault et al. 1984; Sage et al. 2005; Aslanian et al. 2012; Geletti et al. 2014).

Seismic datasets

The multichannel seismic reflection data used in this work were acquired in the framework of four research projects (Fig. 2): MS (Mediterranean Sea, Finetti & Morelli 1973), CROP (CROsta Profonda, Scrocca et al. 2003; Finetti 2005), WS10 (West Sardinia, Geletti et al. 2014) and SF12 (Eurofleets project Salt deformation and sub-salt Fluid circulation – SALTFLU). The MS and CROP regional projects covered extensive areas of the Mediterranean, while WS10 and SF12 were targeted to specific regions. The WS10 dataset consists of 15 multichannel seismic profiles in the eastern sector of the Sardo-Provençal basin and adjacent passive margin, the SF12 dataset consists of 10 multichannel seismic profiles in the northern sector of the Algero-Balearic basin and adjacent passive margin. Location and seismic acquisition parameters of each survey are reported in Figure 2 and in Table 1, respectively. During the WS10 and SF12 projects, sub-bottom profiles and multibeam bathymetry were also acquired.

The WS10 and SF12 profiles were acquired with the specific aim of investigating the Messinian and post-Messinian sedimentary
sequences. With this aim the acquisition parameters were chosen with a good compromise to obtain satisfactory resolution and sufficient penetration. The MS and CROP data were acquired with the purpose of investigating the deep crustal structure; thus they allowed us to define the basement and, locally, the lower crust and the Moho.

We calculated the theoretical vertical resolution for each dataset according to the $\lambda/4$ (where $\lambda$ is the seismic wavelength) Rayleigh criterion (Kallweit & Wood 1982) and considering the maximum source frequency listed in Table 1 and an average seismic velocity of 2000 m s$^{-1}$ for shallow, post-MSC sediments. SF12 and WS10 datasets are characterized by a vertical resolution of 2.5 m.

Table 1. Acquisition parameters of the available datasets in the Western Mediterranean Sea

<table>
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<th>Project name</th>
<th>WS10</th>
<th>CROP</th>
<th>SF12</th>
<th>MS</th>
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<td>OGS lines</td>
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<td>Sercel SN 358 DMX</td>
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<td>2</td>
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<td>Low 8 Hz, high 77 Hz</td>
<td>Out–out</td>
<td>Low 10 Hz, high 72 Hz</td>
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<td>30, 45</td>
<td>60</td>
<td>12, 24</td>
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<td>Air guns</td>
<td>GI-gun Sercel</td>
<td>Flexotir</td>
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<td>60</td>
<td>200</td>
<td>100</td>
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<tr>
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<td>$4 \times 8$ guns = 5000 cubic inch</td>
<td>$2 \times 4$ gunsx210 = 1680 cubic inch</td>
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<td>170, 150</td>
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Fig. 4. Velocity spectrum analysed on Semblance panel from Common Mid Point Gather (CMP, time domain) of profile MS-39 (CDP 6510, location in Fig. 3a). Interval velocity of Upper Unit (UU), Mobile Unit (MU) and Lower Unit are, respectively, about 3100 m s$^{-1}$, 5100 m s$^{-1}$ and 4200 m s$^{-1}$. The interval velocity of 5100 m s$^{-1}$ for MU is higher with respect to the mean value of about 4500 m s$^{-1}$ provided by Montadert et al. (1978) on the same line. PSDM with MU interval velocity of 5100 m s$^{-1}$ yields a complete flattening of the base of salt, compensating for the velocity pull-up effect of the section processed in time domain (see Fig. 3).
and 3 – 4 m, respectively. MS and CROP datasets provide a vertical resolution of 6 – 7 m and 8 m, respectively.

The available multichannel seismic data were processed using Echos and Geodepth software from Paradigm Geophysical. The applied processing sequence can be summarized as follows: trace editing, spherical divergence correction and absorption compensation, predictive deconvolution, normal move-out correction (NMO) with stacking velocities (obtained after iterative analysis and interpretation of Common Offset Sections), stretch muting, stacking, time variant filtering and post-stack time migration. PSDM on selected parts of MS and of CROP (processed by Dal Cin 2014) provided information on interval velocities of MSC units through velocity spectra analysis (on Common Depth Point, CDP, Gathers and Semblance panels).

Results

Deep basins

In the oceanic domain of the Sardo-Provençal basin the deep penetration of MS and CROP profiles allows imaging of the entire stratigraphy, particularly in areas with weak halokinesis (Fig. 3). Application of PSDM on selected segments of data allowed us to obtain reliable interval velocities within MSC and PQ units (Fig. 4).

The interval velocity of 5100 m s\(^{-1}\) for MU may appear relatively high with respect to the mean value of about 4500 m s\(^{-1}\) provided by most Messinian studies from both the West and East Mediterranean (e.g. Montadert et al. 1978; Lofi et al. 2011a, b). The interval velocities of the Levant Basin MU are even lower (Costa et al. 2004; Reiche et al. 2014; Feng & Reshef 2016), as the salt is intercalated with clays (Feng & Reshef 2016). Studies based on laboratory experiments (Jones & Davison 2014) report pure halite seismic velocities of 4500 m s\(^{-1}\), gypsum and anhydrite velocities of 5700 m s\(^{-1}\) and 6500 m s\(^{-1}\), respectively. On the other hand, potassium and magnesium salts, often associated with halite, have lower velocity than halite. An erroneous picking of the lower and upper MU boundaries that includes reflectors from the gypsum composing LU and CU can be excluded. In the absence of lithological information for the deep basin Messinian evaporites in the Western Mediterranean, we infer that a certain amount of high velocity gypsum or anhydrite is present within the main halite body in this area. This mineral composition of salt layers is present in various evaporite-bearing basins, revealing velocities values higher than 4500 m s\(^{-1}\) (Jones & Davison 2014). Moreover, Decima & Wezel (1971) and Roveri et al. (2008, 2014) report the presence of gypsum within the salt unit in the Messinian deep marginal basin in Sicily, that is considered the best onshore analogue of the unsampled Messinian Trilogy in the deep Western Mediterranean basins. We propose that PSDM with MU interval velocity of 5100 m s\(^{-1}\) yields a complete flattening of the base of salt (Fig. 3b,c), compensating for the velocity pull-up effect of the section processed in time domain (Fig. 3a). In the Sardo-Provençal deep oceanic basin, the top of basaltic basement (Zb) is recognized at a depth of c. 8 km below the sea surface (c. 5.1 km below the seafloor) and is overlain by a pre-MSC sequence about 1.7 km thick characterized by poor lateral continuity of reflectors and, in general, reflector strength increasing with depth. The oceanic basement shows moderate relief not exceeding 500 m in the section imaged in Figure 3b and c.

The oceanic basement is not imaged in the data from the Algero-Balearic basin, as penetration of acoustic energy is highly hampered by intense halokinesis.

The three MSC seismostratigraphic units are clearly imaged in the Sardo-Provençal basin (Fig. 3).

LU, MU and UU lay conformably above the pre-MSC sequence. LU, highly reflective, displays an increasing thickness

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Fig. 6. Comparison between two representative profiles across the two investigated margins. (a) WS10 data of the west Sardinian margin and adjacent eastern Sardo-Provençal abyssal plain. (b) SF12 data of the south Balearic margin and adjacent northern Algero-Balearic abyssal plain. Despite the diachronous origins, both the basins were open at the onset of the MSC: their Messinian to Quaternary evolution is thus comparable, as suggested by similar thicknesses of the MSC and PQ units. The Messinian Trilogy is present in both the deep basins and generally thins toward the continental margins with onlapping terminations. Salt deforms and intrudes the overlying UU and Plio-Quaternary (PQ) sequences. Growth strata in the UU indicate that halokinesis locally began during deposition of UU in both the basins. In the Sardo-Provençal basin (a) halokinesis commonly creates allochthonous bodies of MU at the lithological discontinuity between UU and LP (see inset (c)). Salt rollover structures are common on the lower slope of the Sardinia margin. Thin UU and MU, often bordered by the erosional surfaces BES and TES, gradually disappear on the upper slope and they laterally converge to the MES. The structure of the Alberese-Balearic continental margin is characterized by a steep fault scarp that separates a marginal slope basin from the deep basin. Deep MSC units onlap at the foot of the fault scarp (see also Fig. 11) with quite rare rollover structures; (a) and (b) are displayed with the same vertical and horizontal scales.

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from 700 m to about 1 km from west to east, produced by westward reflector divergence. MU is reflectorless with a thickness of about 1 km where undeformed. UU is about 800 m thick and displays high reflectivity except in its upper and lower boundaries. The base of LU occurs at a depth of 3.4 km below seafloor in the undeformed sequence (Fig. 3b and c), possibly deeper if correctly interpreted between salt structures (Fig. 5). Like the oceanic basement, LU is also not recognizable in the dataset from the Almero-Balearic basin other than in a very tentative way due to diffuse halokinesis.

MU often shows chaotic reflections that we ascribe to incorporation of portions of layered sequences during halokinesis or to lateral seismic events (Fig. 5). The thickness is highly variable, with a decreasing thickness trend approaching the Sardinian margin from the west (Fig. 6a). The nature of the eastward-thinning salt is unclear due to the lack of internal reflectors. Salt is expected to thin.

Fig. 7. Qualitative evaluation of the original MU thickness from line SF12 in the Almero-Balearic basin (Fig. 6). (a) Thickness in twt (s) of the deformed MU corresponding to that within the black rectangle in Fig. 6; (b) converted thickness of deformed MU section (a) into depth by using mean interval velocity of 5000 m s\(^{-1}\). (c) Restored MU, along the same length as (a) and (b), resulting in an average thickness of c. 900 m. (a–c) have the same horizontal scale; (b and c) have the same vertical scale. Using a mean interval velocity of 4200 m s\(^{-1}\) for MU (calculated by Costa et al. 2004; Reiche et al. 2014; Feng & Reshef 2016 for the Eastern Mediterranean MU) or of 4500 m s\(^{-1}\) (calculated by Montadert et al. 1978 for the Western Mediterranean deep basin MU) the thickness of restored MU would be about 700 m and 800 m, respectively.

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Fig. 8. Typical deep basin salt structures imaged with different vertical resolution by the four seismic datasets analysed in this study. Seismic images refer to (a) the north Almero-Balearic and (b–d) the Sardo-Provençal basins. The high resolution of both the SF12 (a) and WS10 (b) datasets allows a clear identification of Pli-Quaternary (PQ) and MSC reflectors. Note the thin transparent autochthonous salt layer ‘s’ identified within the Upper Unit (UU). (a and b) show UU composed of an upper alternation of 9–10 high/low amplitude events and a lower low amplitude package. Deep penetration MS (c) (modified, Finetti & Morelli 1973) and CROP (d) data give images of LU base and deeper reflections. In both basins MU generates diapirs piercing the UU and the PQ. PQ is composed of a low amplitude Lower Pliocene (LP) layer overlain by a high amplitude Upper Pli-Quaternary (UPQ) package. In (a and c) note the onlap and pinch-out terminations inner and above the top of the LP (TLP), suggesting that halokinesis was often active during the entire Pliocene. The process is still active as testified by seabed deformation induced by the largest diapirs. Seismic images have the same vertical and horizontal scales.
towards the edge of the evaporitic basin due to lateral onlap. Salt redistribution towards the basin centre may have equally contributed to such thinning.

Interestingly, part of the salt has risen diapirically through the UU and has spread laterally at the base of the Plio-Quaternary sequence forming smaller-scale salt structures (Fig. 6a and c). Because such structures have induced folding in the Plio-Quaternary strata, we infer that salt intruded along the discontinuity between UU and the overlying Lower Pliocene sediments favoured by the changing mechanical properties between indurated gypsum and overlying soft deep-sea clay-rich muds.

In the Algero-Balearic deep basin MU is imaged in a variety of structures and its base can be traced with discontinuity (Fig. 6b). Starting from the deep basin salt distribution interpreted on the seismic profile of Figure 6b, we have converted MU traced in two-way travel times to depth using a mean interval velocity of 5100 ms\(^{-1}\), and

Fig. 9. Comparison between (a) the south Balearic and (b) western Sardinian continental margins (modified from Mocnik et al. 2014). The basement is cut by faults produced by the Oligo-Miocene rifting phases. Horst and graben are filled by continental syn-rift (cOM, cM) deposits with high amplitude seismic response and chaotic internal configuration. Post-rift marine (mOM, mM) deposits are characterized by subparallel continuous and low amplitude seismic packages. (a) In the south Balearic margin the top of the mM is erosive and is overlain by high amplitude packages that we ascribe to the Messinian Bedded Units (BU) (Loiri et al. 2011a). BU is bounded by erosional surfaces at its bottom (BES) and top (TES). The Plio-Quaternary (PQ) sequence directly overlies the TES. (b) In the west Sardinian margin the thin MU and UU are present on the lower slope. Their lower boundary BES represents the erosional truncation of the mM unit. The upper boundary of the UU is the TES and an erosion surface IES is also present within it. In the upper slope the Messinian units converge in the margin erosion surface MES. The MES truncates the post-rift units and is covered by the LP semi-transparent unit. Also the current seafloor is affected by erosion that origins irregular morphology. Seismic images (a) and (b) have the same vertical and horizontal scales.

Fig. 10. Comparison between MSC deposits in (a) the Algero-Balearic basin (modified from Wardell et al. 2014) and (b) the Sardo-Provençal lower slope. Analogies can be recognized in terms of thicknesses and seismic characters of the Messinian Trilogy, which shows its typical seismic facies: the UU (about 150 ms twt thick) package of high/low amplitude alternation, the thin, semi-transparent MU and the thin, highly reflective LU. Seismic images have the same vertical and horizontal scales. The fault pattern affecting UU, especially on the Balearic margin, has been interpreted as volumetric change induced by gypsum to anhydrite transformation and dewatering that propagates into the overlaying Plio-Quaternary muds.
finally we have averaged the salt thickness to obtain a uniform layer resulting c. 900 m thick (Fig. 7). This procedure suffers from approximations induced by uncertain picking of the base of UU and lateral salt flowage affecting its thickness in the analysed cross-section. The resulting restored thickness of the halite layer is, however, strikingly similar and comparable to the 1 km thickness one observed in the undeformed Sardo-Provençal deep basin (Fig. 3).

In both basins salt structures generally induce folding and often pierce through the overlying gypsum and marls (UU) and the Lower Pliocene deep-sea muds (LP). Less frequently they cause intense deformation in the UPQ units and breach through the sea bottom (Figs 3, 5, 6 and 8). The lateral spread of salt at the base of the Plio-Quaternary sequence observed in the Sardo-Provençal basin is not observed in the Algero-Balearic basin.

Similarly to the Sardo-Provençal basin, incipient halokinesis had already locally begun during the deposition of UU in the Algero-Balearic basin (e.g. Fig. 6). Salt deformation proceeded more intensely during the Early Pliocene, as suggested by frequent onlap or pinch-out terminations of high amplitude above the Lower Pliocene semi-transparent reflectors (Fig. 8a–c). A progressive attenuation of salt deformation occurred in the Upper Pliocene–Quaternary (UPQ unit). However, some morphological features on the seafloor of both the basins testify that locally the process is still active (Figs 3, 5 and 8a). UU, where undeformed, attains a rather uniform thickness of about 800 m in both the basins, while it displays highly variable thickness as a consequence of syn-sedimentary halokinesis. A semi-transparent layer within the upper part of UU has been highlighted in the Sardo-Provençal basin (Fig. 8b), which has been labelled ‘s’ according to Geletti et al. (2014). Internal configuration and geometry of the ‘s’ layer suggest it is composed of salt. It rarely exceeds the thickness of 15–20 ms twt (about 50 m, using a seismic velocity of 5100 ms$^{-1}$). The same layer is also found in the Algero-Balearic basin (Fig. 8a), but thinner and without the marked doming structure found in the Sardo-Provençal basin. Due to insufficient vertical resolution the ‘s’ layer is not observed in CROP and MS profiles (Fig. 8c and d).
Above the Messinian sequence the Lower Pliocene (LP) is marked by a low reflectivity unit commonly referred to as muds deposited after the re-establishment of open marine conditions at the base of the Pliocene (Hsü et al. 1973; Rehault et al. 1984; Lofi et al. 2005; CIESM 2008). LP is overlain by a package of higher intensity reflectors related to turbiditic bodies which deposited during the UPQ. Normal faults can be generally identified above the salt diapirs (Fig. 8). The thickness of the Plio-Quaternary sediments appears to be an important factor in generating the salt structures. In both basins the largest diapirc structures are present in the areas of the Plio-Quaternary depocentres (Figs 5 and 6). In the Sardo-Provençal basin this is in the NW of the basin, while in the Algero-Balearic basin it is in the southern part (see isochron maps of Fig. 13b and c).

**Lower slopes**

LU, MU and UU are found on both the south Balearic and western Sardinian lower slopes, where they thin and eventually disappear (Figs 6, 9–11). In many places the current termination does not represent the original depositional termination, as salt detachment and flow toward the basin have displaced the termination basinward (Fig. 6). Rollover structures (Figs 6 and 11) are particularly evident on the conjugate margins of the Sardo-Provençal basin (e.g. Sage et al. 2005; Lofi et al. 2011a; Geletti et al. 2014) as a response to a progressively increasing slope angle of a subsiding continental margin loaded by terrigenous sedimentary input. Salt flow toward the basin is less represented in the data of the northern margin of the Algero-Balearic basin, with rare and weaker rollover structures. The right-lateral tectonic imprint on the basin margin defined by the steep Emile Baudot Escarpment emplaced before the MSC, combined with the very limited fluvial contribution to the sedimentary budget from the Balearic promontory, have not created the geological conditions favourable for the large-scale development of salt rollover structures.

LU can be traced upslope in both deep basins and margins as a thin (some tens of milliseconds twt), highly reflective, layer (Figs 6 and 10). The overlying MU is often deformed, particularly in the Sardinian slope, with salt flow creating salt weld surfaces, block faulting, rollover and sliding of the UU that seems partially still active (Fig. 6, 11a). UU has the typical seismic character represented by an alternation of 9–10 closely spaced high amplitude reflectors (Figs 10 and 11). This yields a thinner UU sequence overlying a thinner MU compared to the deep basins. In the time domain the thicknesses of UU range between 0 and 250 ms (0–390 m from PSDM), and the MU top is generally deeper in the Balearic margin (about 3.9 s twt) than in the Sardinian margin (3.45 s twt). The lateral continuity between LU, MU and UU suggests that during the MSC there was a clear connection between the deep basins and the lower slope basins, where very similar evaporitic sequences in the seismic record were deposited in very different water depths (Fig. 6).

On both continental margins, the Plio-Quaternary is represented mainly by the LP sequence, while only a thin high amplitude reflector package, when present, can be ascribed to the UPQ (Figs 9, 10a and 11b). The total thickness ranges between zero and c. 300 ms twt. The lower boundary of PQ is represented by the TS conformity that locally becomes erosional (TES). On the middle/upper slope the entire MSC is represented by an erosional hiatus (MES) (Figs 6 and 9). The seafloor of the southern Balearic margin is affected by erosion by down-slope sediment transport along the steep EBE (Fig. 6b). The seafloor of the Sardinian margin shows erosional effects by bottom currents and turbidity currents (Geletti et al. 2014; Fig. 9b).

**Discussion**

In Figure 12 we present a one-dimensional synthesis of the seismically-derived stratigraphy of the Sardo-Provençal and Algero-Balearic basins. They have been obtained from prestack depth migration and conversion to depth, respectively.

The abyssal plains of the Sardo-Provençal and Algero-Balearic basins lay at a comparable water depth as they belong to the same Quaternary deep-water turbidite sedimentary system. The main depocentre in this sedimentary system is the Rhone deep-sea fan, outside the area covered by the datasets analysed in this work. The oceanic basement is clearly identified at c. 6.5 s twt in the Sardo-Provençal basin (5.1 km after PSDM; Fig. 3), deeper than the weakly, though consistently identified oceanic basement top at about 5.8 s twt in the Algero-Balearic basin (Fig. 6b and ESCI Profile across the Valencia Trough, Sàbat et al. 1995). Using a similar seismic velocity structure as in the Sardo-Provençal basin (Fig. 4), the depth of the basement in the Algero-Balearic basin is about 4.35 km below the seafloor.

The MSC seismo-stratigraphic units appear very similar in both deep basins. The thickness of MU (measured where undeformed, or restored) is consistent between 0.9 and 0.95 km. LU, where undeformed, is about 800 m thick in both basins. Uncertainty is only about the thickness of LU. In the Algero-Balearic basin there is a marked increase in LU thickness towards the margin, due to reflector divergence probably produced by terrigenous input from
the Sardinian margin during deposition of the lower evaporites. However, because LU shows remarkable similarity between lower slope basins in the two margins, we can assume that the same similarity applies to LU in the deep basins.

The thickness of the PQ is 0.95 – 1 km in the deepest part of both basins. The different depth of the oceanic basement depends on the different thickness of the pre-MSC formations resulting from the different opening ages of the two basins. The time elapsed between the end of the rifting phase and the end of the MSC is 17 Ma for the Sardo-Provençal margin and 10 Ma for the Algero-Balearic margin, resulting in a pre-MSC sequence thickness of 1.7 and 0.97 km, respectively. At the onset of the MSC the basin floors were already filled with a uniform sedimentary layer. Evaporitic deposition during the MSC was even across the two basins, with minor lateral changes in LU in response to local terrigenous sediment input from the Sardinian margin. According to the post-rift thermal subsidence curve (McKenzie 1978), the younger Algero-Balearic basin should have subsided more rapidly than the Sardo-Provençal basin provided the stretching factor β was the same. The fact that the MSC and later evolution of the sedimentary fill is absolutely comparable in the two basins can be explained with a stretching factor in the Algero-Balearic basin lower (therefore with a lower subsidence rate) than the high values of 10 and 3 – 7 proposed for the Sardo-Provençal basin by Steckler & Watts (1980) and Rehault et al. (1984), respectively.

Among the three MSC seismic units, UU is the one that is better imaged in the analysed data and provides two distinctive characters for the two basins. The intra-UU salt layer ‘s’ is present in the deepest part of both basins, with a greater thickness in the Sardo-Provençal basin. The event that caused salt deposition towards the end of the MSC, while the upper evaporite gypsum and clastics were deposited in the deep basins, can be considered a regional event in the Western Mediterranean. The reason for the ‘s’ layer not being identified in other parts of the Western Mediterranean is probably two-fold: (1) the relatively high resolution of the deep-water seismic survey of the datasets analysed in this study; and (2) the possible dilution of gypsum and salt by clastics in the peripheral areas of the Western Mediterranean, with particular reference to the Gulf of Lion depocentre where most of the available information comes from. Following the MSC evolutionary model of Rouchy & Caruso (2006), Ryan (2008) and Lofi et al. (2011b), we infer that the deposition of the ‘s’ layer followed a second, short decrease in the base level. This secondary base level drop is correlatable to the intra-UU erosion (IES), which is well defined on the Sardinian continental slope (see also Geletti et al. 2014). Such unconformity is not present on the South Balearic margin, because the margin is produced by a large tectonic structure pre-dating the MSC that has segmented the margin in isolated marginal slope basins separated by steep fault-scarsps where no MSC evaporites could accumulate. The lateral continuity of the MSC units from deep basin to slope is missing, and the IES is not preserved in the sedimentary record.

The main salt body MU of the MSC is imaged undeformed only in the distal part of the Sardo-Provençal basin. Elsewhere in the deep basins it is deformed by various diapiric structures in the deep basins and rollover structures on the lower slopes.

PSDM provides real dimensions of the large geological structures and salt structures imaged in all the deep central basins. The diapir imaged in the depth-migrated part of the CROP profile (Fig. 5) is almost 4 km high. Lateral salt flow to feed the diapir growth has caused lateral salt weld surfaces, namely the juxtaposition of UU directly on LU. Salt weld is commonly found around salt diapirs in both deep basins (Figs 3, 5, 6, 8, and 13b, c).

Salt detachment and downslope translation as a consequence of margin uplift and tilting is common in sedimentary basins (e.g. Hudec & Jackson 2004). The salt flow towards the basin occurs along a basal detachment and a series of growth faults that cause segmentation of the originally continuous salt layer. Such structures are particularly well imaged in the lower slope of the Gulf of Lions (Gorini et al. 2005; Lofi et al. 2005, 2011a), where not only the margin slope induced by basin subsidence, but also the sedimentary load of the Rhone deep-sea fan sediments have provided the driving force for salt gravity sliding and lateral spreading. Rollover structures are well developed at the base of the Sardinian slope, as the MSC units were continuously deposited both in the deep basins and its margin. The sedimentary load is probably the main driver in the Gulf of Lions, while margin tilting and gravity gliding are the dominant processes here. Only volcanic bodies (Fig. 6a) provide a local discontinuity of the MSC on the Sardinian slope. Less common are rollover structures on the South Balearic margin. The segmentation of the margin in marginal slope basins separated by steep fault scarp of the EBE has prevented the continuous salt deposition from the deep basin to its margin. The only rollover structures are found at the transition between the thin to thick salt basins below the Algero-Balearic abyssal plain.

Conclusions

The Sardo-Provençal and the Algero-Balearic sedimentary basins are floored by oceanic crust opened in different phases of back-arc extension in the Western Mediterranean and were fully open at the time of the Messinian Salinity Crisis (MSC). Therefore, during and after the MSC they were part of one continuous deep-water sedimentary basin. The Hannibal Ridge and a morphological step along the North Balearic Fracture Zone were probably the only submerged dividers between the two basins. The comparison between seismic stratigraphy and the MSC structures obtained by comparable seismic acquisition systems outlines the following characters.

The older basement age in Sardo-Provençal basin is reflected in a thicker pre-MSC sedimentary sequence than in the Algero-Balearic basin (1.7 and 0.97 km, respectively). In MSC and post-MSC times,
the younger Algo-Balearic basin should have undergone a higher subsidence rate than the older Sardo-Provençal basin according to the post-rift thermal subsidence curve, if the stretching factor of the two basin is the same. Because the MSC and later evolution of the sedimentary fill is comparable, a lower stretching factor must have characterized the opening of the Algo-Balearic basin.

The seismic record in the two deep basins is very similar in terms of seismic appearance, thickness and style of deformation of the MSC units. The similarity includes the presence of a thin salt layer within the upper part of the UU and a related intra-UU unconformity interpreted as a secondary base-level drop during the last phase of the MSC.

The style of salt deformation differs in the lower slope, as salt rollover structures are common on the West Sardinian margin, while they are less common on the South Balearic margin. Such difference is thought to be the result of a progressive subsidence and steepening on the Sardinian margin as opposed to a pre-MSC strike-slip system of the Emile Baudot Escarpment on the southern Balearic margin.

In the deep basins, salt structures are common and started to form already during the last phase of the MSC, at the time of deposition of UU. The most intense salt deformation was during the Early Pliocene. A progressive attenuation of halokinesis occurred throughout the Late Pliocene and Quaternary, with some evidence for present-day activity of the largest structures.

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