THE MESSINIAN SALINITY CRISIS IN THE WEST-MEDITERRANEAN BASINS:
COMPARISON BETWEEN TWO RIFTED MARGINS

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Introduction. We present a comparison between two multichannel seismic datasets acquired across the passive margins of the west Mediterranean sea: the west Sardinia continental margin extending in the east Sardo-Provençal basin and the South Balearic continental margin extending in the north-western Algero-Balearic basin.

The two margins bear in common the origin from continental rifting, but underwent different geodynamic histories and are not coeval. The Sardo-Provençal basin opened following the Oligocene-Early Miocene breakup of the European plate and anticlockwise rotation of the Sardinian block. According to Mauffret et al. (2004) this phase ended in the early Miocene (16 Ma), when the opening of the Algero-Balearic basin started to open as a result of rifting between the Balearic Promontory and the African margin until the Tortonian (8 Ma). The Messinian Salinity Crisis (MSC) affected the whole Mediterranean basin, with deposition of evaporitic sequences in the deep basins, lower continental slopes, and in several shallower marginal basins; usually, in the continental margins, the MSC originated noticeable erosional truncations that locally cause important hiatuses in the pre-Messinian sedimentary sequences, covered by the Plio-Quaternary sequence.
The availability of the processed and interpreted seismic dataset of Western Sardinia [WS10 project, partly published by Geletti et al. (2014) and Del Ben et al. (2014)] and the processed and partly interpreted profiles of South Balearic margin (Salt deformation and sub-salt fluid circulation in the Algero-Balearic abyssal plain (SALTFLU) SF12 project, Camerlenghi et al., submitted), allowed us to focus on some analogies in the seismic facies of the sedimentary sequences that deposited after the drifting phases of both basins during the MSC and in the Pliocene and Quaternary.

We paid particular attention to differences and analogies concerning the thickness of the Messinian evaporitic units, evidences of depositional depths, erosive events and discontinuity surfaces. Salt tectonic activity involving the Upper evaporite Unit and the Plio-Quaternary deposits will be discussed based on different kinds of salt-induced deformation in the lower slopes and abyssal plains already identified by Camerlenghi et al. (2009, 2014), Geletti et al. (2014) and Del Ben et al. (2014).

Given the absence of calibrating boreholes in the deep Mediterranean basins and the difficult penetration of seismic energy below the evaporitic layers, the comparison of these datasets is a contribution to the comprehension of the evaporitic deposition, margin erosion, and early-stage salt deformation during the MSC in the Mediterranean sea.

**Geological setting.** The present distribution of the geological domains in the west Mediterranean Sea is the product of mainly extensional processes that followed the Late Cretaceous to Early Tertiary counterclockwise rotation of Iberia and the compression of the Pyrenees until about 20 Ma (Carminati et al., 2004).

Beginning in the Late Oligocene, a rifting phase affected most of the region; during the Early Miocene, a WNW-ESE extension was associated to detachment of the Corso-Sardinia microplate and Balearic promontory from the Iberian plate (Sabat et al., 1995). The Sardo-Provençal basin and Valencia Trough started to open while the southeastern part of the Balearic promontory underwent NW-SE compression originating the Betic-Balearic thrust belt (Gelabert et al., 1992). Following the continental collision, an extensive rifting phase begun initiating the opening of the N-S opening of the Algero-Balearic basin. Between the Alboran block and the Balearic Promontory a right lateral movement generated the transpression along the Emile Baudot Escarpment (EBE) (Acosta et al., 2001).

In the Early Miocene, the Corso-Sardinia microplate started a counter-clock rotation reaching the actual position in the Middle Miocene (Cohen, 1980). The Provençal basin opened as back-arc basin between 19 and 16 Ma (Speranza et al., 2002). The Sardinia Block migrated along the right lateral north Balearic fault Zone and displaced the Balearic Promontory with a coeval rifting in the Valentia Trough. The Algero-Balearic basin has a thin and uniform oceanic crust (Sabat et al., 1995) and the N-S trending Hannibal Ridge is considered the spreading center of the Algero oceanic basin, that ended its activity 8 Ma (Mauffret et al., 2004). The authors consider the NW-SE magnetic anomaly 160 km far from the east side of the Hannibal ridge, as the boundary between the Sardo- Provençal and Algero-Balearic basins.

The sedimentary sequence is characterized by the post drift Messinian Salinity Crisis (MSC), resulted by a complex combination of tectonics, precession controlled oscillations and glacio eustatic processes which progressively contributed to restrict and finally isolate the Mediterranean Sea from the ocean. Collected literature analyzed by CIESM (2008) lead to agreement on beginning of the evaporitic sequence at 5.96 Ma until 5.33 Ma, with re-connection between Mediterranean and Atlantic basins and restoration of water circulation (Hsu et al., 1973).

The “Messinian trilogy” recognized in the West-Mediterranean abyssal plain (Rehault et al., 1984), is characterized by different seismic facies: the Lower evaporite Unit (LU), the salt Mobile Unit (MU) and the Upper evaporite mainly gypsiferous Unit (UU) (Lofi et al., 2011).

In the eastern Sardo-Provençal basin, the Upper Unit has been identified as nine-ten cycles of high reflecting layers interpreted as gypsum with alternation of transparent layers associated to halite lithology (Geletti et al., 2014). The authors have recognized a thicker
intra UU salt layer in the deep basin and a main erosional surface, already locally recognized in some West-Mediterranean margins and called IES (Intermediate Erosional Surface) by Lofi et al. (2011), on the lower slope. Geletti et al. (2014) hypothesized that these two features are coeval and could be originated by a sea level drop during the UU deposition. This represents a still open question about the evidences of more Messinian sea levels drops which produced not only the main salt units of the Messinian trilogy, but eventually also further internal intercalations.

In the Algero-Balearic abyssal plain (Sabat et al., 1995; Camerlenghi et al., 2009, 2014), and in the eastern Sardo-Provençal basin (Geletti et al., 2014; Del Ben et al., 2014) the Messinian evaporite sequences evidence salt domes and diapirs with associated normal faults; the domes and diapirs have been originated by movement of the Messinian salt of the MU and, locally, also by the salt layer inner the UU (Geletti et al., 2014). The halokinetic processes started during the Late Messinian, as testified by some growth strata of the UU, and developed till recent, locally affecting the seabed. The Pliocene-Quaternary sediments showed internal unconformity related to the final emplacement of the diapirs, which are more recently active at the foot of the escarpments.

Messinian evaporite sequence has been recently interpreted in a wide study of Maillard and Mauffret (2013), along seismic profiles from the Ibiza channel to Alicante; they interpreted the Miocene/Pliocene boundary either as an erosional surface that cuts the underlying reflectors and/or dividing two different seismic facies, in that case associated to the Marginal Erosional Surface observed along the Mediterranean margins (MES, Lofi et al., 2011). Sometimes the boundary is represented as the top of chaotic reflections interpreted as MSC-related deposits [Chaotic Unit, clastics and/or evaporites, by Lofi et al. (2011)]. Otherwise the evaporite are well recognizable thanks to high amplitude reflections.

Salt-induced abyssal plain sediment deformation have been recently identified by Camerlenghi et al. (2009) below the EBE in the area south of Ibiza classifying four different kinds of deformational structures: 1) a belt of elongated abyssal plain seahills, 2) anastomosing knolls in the Menorca fan area, 3) abyssal knolls and seahills across the basin and 4) a mud volcano extruding sediments and fluids of likely pre-Messinian origin.

Seismic datasets. The seismic datasets used in this work belong to two different research projects that involved the R/V OGS Explora to investigate the Messinian and post-Messinian sedimentary sequences. A general purpose to explore also the uncalibrated pre-Messinian sequence represents a very difficult goal, due to the high absorption of seismic energy by the evaporite layer that requires higher energization and lower frequency of the seismic source.

For both the multichannel seismic datasets the used acquisition parameters allowed to improve the resolution of the pre-existing profiles in this region (MS and CROP seismic data) and obtain the better compromise between resolution and penetration of investigation.

In 2010, the West Sardinia project (WS10) has been performed within the eastern sector of the Sardo – Provençal basin and on its passive margin (location in Fig. 1). 15 MCS profiles were acquired: seismic source made up of an array two GI-guns with a total volume of 16.3 litres, towed at 4 m depth, shot interval 25 m, 1.5 km length of digital streamer and 120 traces with spacing interval 12.5 m. Seismic processing has been performed using industrial software packages Focus, Geodepth by Paradigm and Promax by Halliburton; Academic grant of Petrel (Schlumberger) have been used (Geletti et al., 2014).

In 2012 a seismic dataset of 12 multichannel reflection profiles, sub-bottom profiler and multibeam bathymetry have been acquired within the Eurofleet project SALTFLU: Salt deformation and sub-salt fluid circulation in the Algero abyssal plain (location in Fig. 1). The used sources for seismic data were made up of two arrays of four GI-guns towed at 3 meters depth and shot interval of 25 meters, 3km length of digital streamer and 240 traces with spacing interval 12.5 meters. The seismic profiles presented in this work are post-stack migrated section (Camerlenghi et al., 2014).
Discussion-dataset comparison. In Fig. 2 the seismic facies of the Messinian UU of the Almero-Balearic (A1-A2-A3) and east Sardo-Provençal (B1-B2-B3) basins have been compared.

The time depth of the top of UU in the Almero-Balearic basin is generally shallower than in the east Sardo-Provençal basin (respectively 4.10 sec TWT and 4.65 s TWT).

In A1 a detail of the seismic profile SF12-03 shows a well reflecting package of about 10 reflectors that depict the UU, here partially deformed by salt tectonic. Also Geletti et al. (2014), interpreted an UU depicted by a package of stratified reflectors with a thickness ranging between 250 and 500 ms TWT along the seismic profiles of the west Sardinia Margin (B1). An average velocity of 3500 m/s, deduced by the velocity spectra analysis, suggests an UU thickness of about 440-880 m. In A1 the UU reaches a thickness of about 300-400 ms TWT, that is 500-700 m assuming the same velocity.

A thin transparent layer has been observed in the shallower part of the UU; this level rarely exceeds a time thickness of 15-20 ms TWT and it could be recognized along most of the SF 2012 seismic profiles. Locally it produces little salt domes (Fig. 2A2, part of SF12-07). Due to its seismic facies and depth position below the UU top, it can be associated to the autochthonous salt layer “s” inner the UU interpreted by Geletti et al. (2014), and evidenced in Fig. 2B2.

The stratified UU overlies a sequence with a transparent seismic facies which is typical of the salt lithology (MU); it exhibits a transparent layer on the foot of the slope, where a negative reflector, related to the high interval velocity of salt, marks its base (blue dotted line in Fig. 2A3). The scattered seismic signal of the upper UU (detail in frame z1) and the gas chimneys
on the overlying Plio-Quaternary sediments suggest the presence of fluids mobilization that seep and rise to the seabed (Camerlenghi et al., 2014). Some normal faults, probably generated by the detachment of the sequence on the salt layer, can favor the mobilization of the salt producing rollover of the UU. More severe rollover processes are evident on the west Sardinia slope (Fig. 2B3), where they produced block faulting and rotation of the UU and the Plio-Quaternary sequence, sometimes reaching the sea bed.

The decollement and movement of salt and of the overlying sequence toward the deep basin represent important contributes to the halokinetic activity that develops at the foot of the escarpments, producing a large number of salt diapirs.

The Plio-Quaternary sequence has a very changeable thickness, specially due to the halokinetics that produces little basins between the diapirs and important thinning on the top and around the same structures. Regionally talking, the Plio-Quaternary sequence is some hundreds of msec in thickness (TWT), sometimes reaching one second (TWT), that is more than 1000 m. In the Sardo-Provençal basin this thickness increases toward north-west, due to

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Fig. 2 – Comparison between the UU and MU MSC sequences of the Algero-Balearic basin (A1, A2, A3) and of the Sardo-Provençal basin (B1, B2, B3). Each comparison are at the same scale. In details A1 and B1 the analogy of the seismic facies of the UU is showed, characterized by a 9-10 package of reflectors; A2-B2 compare the thickness of intra UU halite layers between the basins, which generally doesn’t exceeds 15-20 ms of time thickness and, rarely, forms salt diapirs in the Algero basin as evidenced in the portion of seismic profile SF12-07. A3–B3 compare the UU deformation on the foot of the margins: at the base of the south Balearic margin the UU are mostly affected by possible fluids mobilization producing a specific evaporite seismic facies (as showed in zoom z1); rollover is not so pronounced as in the west Sardinia margin. Location of profiles in Fig.1.
the important sediment supply by the French rivers while in the northern sector of the Algero-Balearic basin the Plio-Quaternary thickness is more regular, with a SE-ward thickening due to the deeper top of the Messinian UU.

The thickness of the Plio-Quaternary sediments is a further important features contributing to the halokinetic process, in fact the larger diapirs are present in the central part of the Sardo-Provençal and Algero-Balearic basins: they can often reach the sea bed with 2-3000 and more meters in height. This phenomenon is particularly evident in the central Sardo-Provençal basin.

To the north of the EBE some salt evidence has been recognized within rise basins (Fig. 3A); this Messinian sequence was deposited in some graben structures that seem to be remnants of the rifting phase. Here a well reflecting sequence of high amplitude reflectors can be ascribed to the UU, with a time thickness of about 100 ms TWT. Below this unit the transparent facies of salt can be distinguished, producing salt domes that are gradually more evident toward the basin (SE). To the north, the UU pinches out and onlaps the relief structures generated by normal faults.

To the upper part of both the slopes of the studied basins we observe some high reflective horizons drastically cut by erosional surface interpret as Top Erosional Surface (TES, Fig. 3B). The reflecting layers are probably a remnant of UU. Also in the middle slope of the West-Sardinia margin Geletti et al. (2014), recognized the erosional truncations of the Marginal Erosional Surface (MES) as a well-defined reflector: locally it is on the top of an eroded high reflecting sequence associated to remnant of evaporite sequence (Fig. 3C).

Fig. 3 – A) Part of the SF12-09 seismic profile. A high reflecting UU covers a thin layer of MU, here evidenced by salt diapirism; the dotted blue line depicts its base. The erosion TES of the high reflecting horizons on the upper part of the slope of the south Balearic margin (B) and on the middle slope of western Sardinia margin (C). PQ is Plio-Quaternary sediments; LP-Lower Pliocene depicted by the typical semi transparent facies, UPQ the higher amplitude reflectors of the Upper Plio-Quaternary sequence. Location of profiles in Fig. 1.
Conclusion. The comparison between the WS10 profiles in the west Sardinia margin and east Sardo-Provençal basin and the SF12 profiles in the south Balearic margin and Algerian-Balearic basin let to make some consideration about the Messinian and post-Messinain geological events that characterize the west Mediterranean sea.

The thickness of the Plio-Quaternary sequence highly depends on halokinetics, that produced local small basins between the diapirs and variable thinning above and around the diapirs. Regionally talking, the sequence in both the basins has generally a thickness of some hundreds of meters, locally reaching 1 s (TWT) that is to say more than 1 km. In the Sardo-Provençal basin the Plio-Quaternary thickness increases toward north-west, due to the sedimentary supply by the French rivers.

The UU is thinner in the Algero-Balearic basin than in the Sardo Provençal basin testifying probable different subsidence rates.

The presence of an intra UU halite layer in both the analyzed basins seems to confirm a further temporary sea level drop during the last MSC in the west Mediterranean basins, as hypothesized by Geletti et al. (2014).

The halokinetic processes are distributed not homogeneously in the region and this depends on several different contributions. First of all the main element is the availability of salt: greater the amount of salt, easier will be the initiation of halokinetics. Another important element is the sedimentary load, generally increasing toward the central part of the deep basins, where we can observe the bigger diapir structures that can reach the sea bed with some thousands of meters in height. Finally, on the lower slope of the margins, in spite of thinner salt layers and sedimentary cover/load, the salt detachment produce small diapirs on the lower slope and several bigger diapirs in the deep basin, at the foot of the slope.

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References


