New onshore/offshore evidence of the Messinian Erosion Surface from key areas: The Ibiza-Balearic Promontory and the Orosei-Eastern Sardinian margin

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New onshore/offshore evidence of the Messinian Erosion Surface from key areas: The Ibiza-Balearic Promontory and the Orosei-Eastern Sardinian margin

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Abstract – As the Messinian sea-level draw down associated with the Messinian Salinity Crisis is still questioned, we propose to show that the widely spread erosion surface affecting the Mediterranean margins is indeed linked to an exondation demonstrated from offshore and onshore data. Our study presents a comprehensive onshore to offshore correlation of the Messinian erosional surface. It is focused on small drainage systems or interfluve areas, outside of evaporite basins or incised canyons, where the Messinian erosion had not yet been studied previously: around Ibiza on the Balearic Promontory and around Orosei on the Eastern Sardinian margin, Tyrrhenian Basin, both areas where new offshore data were recently acquired. We show that the late Messinian erosion formed in subaerial settings, as testified by evidence of continentalization events, and attests for a regression phase that was correlated from the offshore continental slopes to the onshore paleo-platforms in both areas. Characteristics of this erosion in both study areas strengthen the scenario with at least one important low-stand sea-level for the Messinian Salinity Crisis with evaporites subbasins lying at different depths and possibly disconnected.

Keywords: Messinian Salinity Crisis (MSC) / Northwestern Mediterranean / erosion surface / Ibiza / Eastern Sardinian margin

Résumé – Découverte de la surface d'érosion messinienne onshore/offshore dans deux lieux clés : le Promontoire Baléares (Ibiza) et la marge est-sarde (Orosei). Depuis la découverte de la crise de salinité messinienne dans les années 70, le scénario proposant une chute importante du niveau marin associé à la mise en place des évaporites dans les plaines abyssales de la Méditerranée est régulièrement remis en cause. Nous montrons que la surface d'érosion affectant l'ensemble des marges est en effet liée à une émersion que l'on peut suivre à terre. Les observations présentées à terre s'attachent aux zones d'interfluves en dehors des bassins évaporitiques périphériques, là où la surface d'érosion messinienne n'a pas été étudiée : autour de l'île d'Ibiza dans les Baléares et autour d'Orosei sur la marge est-sarde. La surface d'érosion messinienne y est mise en évidence pour la première fois. Les données de sismique haute résolution récemment acquises dans ces deux zones nous permettent de présenter des corrélations terre-mer. Des évènements marquant clairement une continentalisation caractérisent la limite Mio-Pliocène dans les deux régions et atteste une phase régressive que l'on peut suivre des paléo-plateformes continentales à terre aux pentes du domaine offshore. Ces observations apportent des éléments pour étayer un scénario de la crise avec un bas niveau marin et des bassins évaporitiques à différentes paléo-bathymétries, possiblement déconnectés les uns des autres.

Mots clés : Crise de salinité messinienne / Méditerranée nord-occidentale / surface d'érosion / Ibiza / marge est-sarde

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1 Introduction

The Messinian Salinity Crisis (MSC) in the Western Mediterranean Sea resulted first in evaporites precipitation in peripheral shallow basins (“Primary Lower Gypsum”: PLG). Then, evaporite precipitation shifted to the deepest depocentres in the central bathyal domains with a “deep basin trilogy”; Hsü *et al.*, 1973; Ryan and Cita, 1978; Lofi *et al.*, 2011; Manzi *et al.*, 2018), while erosion affected Mediterranean drainage areas with incisions of deep subaerial valleys (Chumakov, 1973; Clauzon, 1973; Barber, 1981; Savoye and Piper, 1991). This erosion is also observed offshore over most of the present-day Mediterranean margins as a widespread surface at the base of the Pliocene-Quaternary series and incising in the pre-MSC series, called the Margin Erosion Surface (MES) (Guennoc *et al.*, 2000; Lofi et al., 2005; Bache et al., 2009; Lofi *et al.*, 2011). It has been related to a drop of debated amplitude of the sea-level during the peak of the crisis, from 5.6 to 5.32 Ma (Cita and Ryan, 1978; Clauzon, 1982; Gautier *et al.*, 1994; Rouchy and Caruso, 2006; Ryan, 2009; Manzi *et al.*, 2013). According to some scenario (CIESM, 2008), this erosion surface should therefore be continuous on the paleo-platforms, and subaerial. However, high amplitude sea-level drawdown is still debated (Hardie and Lowenstein, 2004; Roveri and Manzi, 2006) and new results based mostly on geochemical analysis favor an interconnection of all the Mediterranean subbasins during the MSC, therefore suggesting that evaporites precipitated from the same water-body at high sea-level (Roveri *et al.*, 2014; Gvirtzman *et al.*, 2017; Manzi *et al.*, 2018).

The MES is well documented in the large fluvial systems such as the Rhone, Ebro, and Nile where the incision is observed from downslope, *i.e.* on the continental slopes offshore (Lofi *et al.*, 2005; Bache *et al.*, 2009; Urgeles *et al.*, 2011; Pellen *et al.*, 2019), to upslope, onland, up to Lyon in the Rhone Valley or up to Assouan in the Nile Valley (Chumakov, 1973; Clauzon, 1973; Guennoc *et al.*, 2000).

In the peripheral shallow basins, currently onshore, the MES is also identified but its stratigraphic position remains uncertain and debated (Roveri *et al.*, 2014; Clauzon *et al.*, 2015). Indeed, the offshore MES has been tentatively correlated to several key surfaces identified in onshore successions, each of them having different relationship in regard to the Primary Lower Gypsum (PLG) and to the distinctive Late Miocene units, particularly the Terminal Carbonate Complex (TCC; according to Esteban, 1979; see Clauzon *et al.*, 2015 for a review).

Elsewhere, in small or diffuse drainage systems, or interfluve areas, the MES has rarely been studied (Cornée *et al.*, 2008). To evidence the MES in such places, we aimed to unequivocally identify the erosion, allowing drawing of a complete onshore-offshore sketch.

Offshore, the extension of the MES (*i.e.* the erosion surface down to the transition to the MSC-deposits) has been followed all along the northwestern Mediterranean margins (Fig. 1), in the framework of an integrated study of several key-areas in different settings (Lofi *et al.*, 2011, 2018). In this scientific context and with a land-sea approach, we focused on two areas, respectively, the Balearic Promontory to the West, and the Eastern Sardinian margin in the Tyrrhenian Basin to the East; both areas where the offshore MES has already been studied (Maillard et al., 2014; Driussi *et al.*, 2015; Lymer *et al.*, 2018). Onshore, we document the MES for the first time:

1 around Ibiza on the Balearic Promontory, within the Miocene-Pliocene series outcropping on the NE part of the island, that are for the first time interpreted in the light of the MSC;
2 around Orosei on the Eastern Sardinian margin, Tyrrhenian Basin, where the MES was unknown.

Finally, the correlation of the MES between the offshore continental slopes and the onshore paleo-platforms in both areas can be proposed.

2 Data and method

Offshore seismic lines and maps result from a large seismic database including academic seismic profiles obtained during several scientific cruises and oil-industry profiles, improved by high-resolution seismic profiles acquired recently along the Eastern Sardinian margin and SE Corsican margin during the “METYSS 1” and “METYSS 3” cruises, in June 2009 and April 2011, respectively (Gaullier *et al.*, 2014) and on the Balearic Promontory during the “SIMBAD” cruise in January 2013 (Maillard *et al.*, 2014; Driussi *et al.*, 2015) (Fig. 2). The profiles were acquired on the R/V “Téthys II” (INSU-CNRS/CIRMED) with a source that consisted of a mini-GI (SODERA) air gun and a receiver that was a 6-channel 25-m streamer. Data were processed using the Géovecteur© software package. Locally, we can differentiate between different types of seismic units on the basis of their acoustic facies and geometries. Some of the reflections were tied to wells and enabled to correlate seismic units to stratigraphic layers (Gaullier *et al.*, 2014; Driussi *et al.*, 2015; Lymer *et al.*, 2018). They were extended laterally on the study areas and landward as shallow as possible. On the margins, the pre-MSC units are identified thanks to truncations below a usually high amplitude reflection (Fig. 3). Above, the post-MSC unit linked to the base of the Pliocene shows a nearly transparent seismic facies as observed all over the Northwestern Mediterranean (Fig. 3). It passes progressively upward to higher amplitude parallel reflections. On these bases and from correlation to some industrial wells or deep drilling sites, we could identify the MES on the seismic lines with great confidence. To present offshore maps of the MSC markers in both study areas, we used former works of the same research team (Gaullier *et al.*, 2014; Maillard *et al.*, 2014; Driussi *et al.*, 2015; Lymer *et al.*, 2018; Fig. 2) and added some details, looking carefully on some lines. Time-depth conversion is done using a velocity of 1500 m/s in water and 2000 m/s in Pliocene-Quaternary sediments.

Onshore, we investigated the lateral continuity of the MES through mapping the erosional surface at the base of the marine Pliocene deposits in northeastern Sardinia and by the detailed stratigraphic analysis of the late Neogene deposits in northeastern Ibiza Island (Lézin *et al.*, 2014, 2017; Giresse *et al.*, 2015). In all localities, we undertook a detailed analysis of the stratigraphic records with emphasis on the observed unconformities. Our field work is mainly based on mapping, logging and sampling for biostratigraphy to establish the late

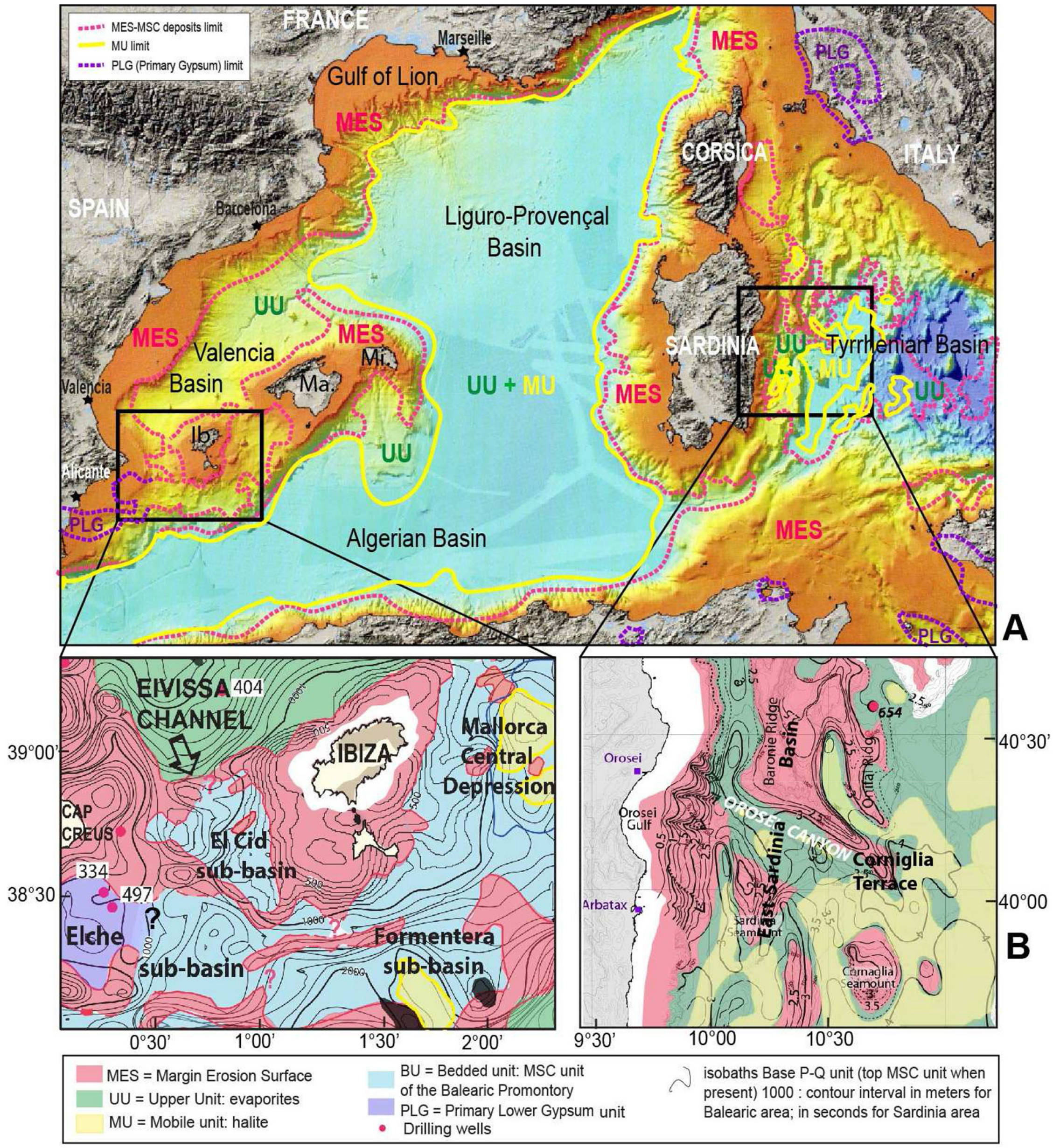

Fig. 1. Extension of the Messinian Salinity Crisis (MSC) markers and the Margin Erosion Surface (MES) in Western Mediterranean Sea. A. Regional bathymetric map (from Brossolo and Mascle, 2008) with the location of the two study areas (black rectangles). Margin Erosion Surface (MES) downslope limit, in pink dotted line, is also the upper limit of the MSC units extension. B. Zooms on the two study areas: maps of Ibiza (left) and East Sardinia (right). Isobaths draw the base of the Pliocene-Quaternary unit in its present-day morphology. UU = Upper Unit; MU = Mobile unit; BU = Bedded unit; PLG = Primary Lower Gypsum unit.

Neogene tectono-sedimentary evolution. These works were partially presented for the Orosei area in Giresse *et al.* (2015) but never analyzed in term of the MSC. For the Ibiza onshore it has never been published.

3 Offshore MSC units and erosional surfaces

In the Western Mediterranean deep basins, the evaporites related to the MSC have been identified as three distinct seismic units also called Messinian "deep basins trilogy" (Hsü *et al.*, 1973; Montadert *et al.*, 1978). This trilogy is composed, from top to bottom, 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") (Lofi *et al.*, 2011). It is an aggrading sequence infilling the topographic preexisting lows. These units thin towards the passive margins of the Western Mediterranean basin, pinch out at about 2 to 3 s twtt-deep, and pass laterally upward to the MES (Lofi *et al.*, 2011, 2018; Bache *et al.*, 2012; Leroux *et al.*, 2015). Another unit has been identified recently in the intermediate-depth basins called Bedded Unit (BU)

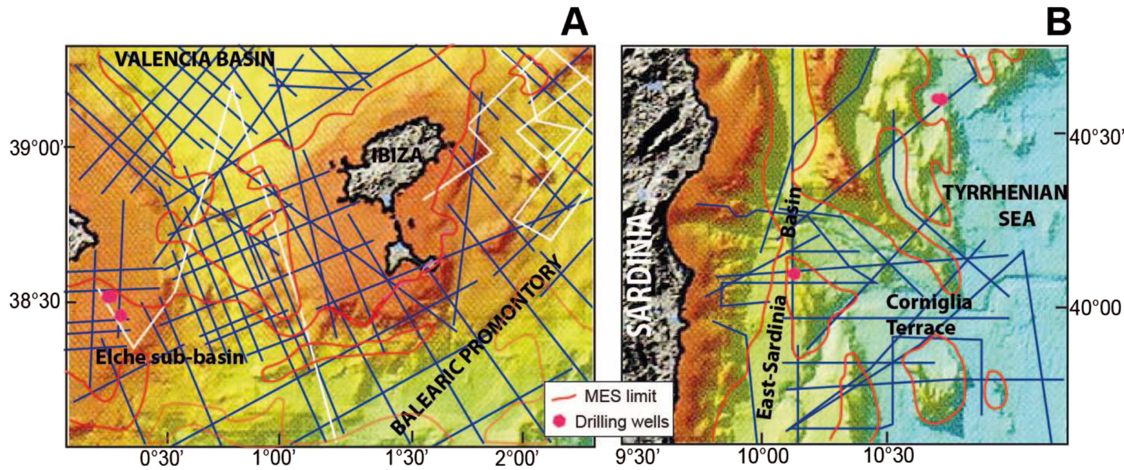

Fig. 2. Position of the seismic lines used in this study on the bathymetric map (after Brosolo and Mascle, 2008). A: for the Ibiza area, white lines: the SIMBAD high resolution lines and dark blue lines: former industrial and academic lines; B: for the Orosei area, dark blue lines: the "METYSS 1" and "METYSS 3" high resolution seismic lines.

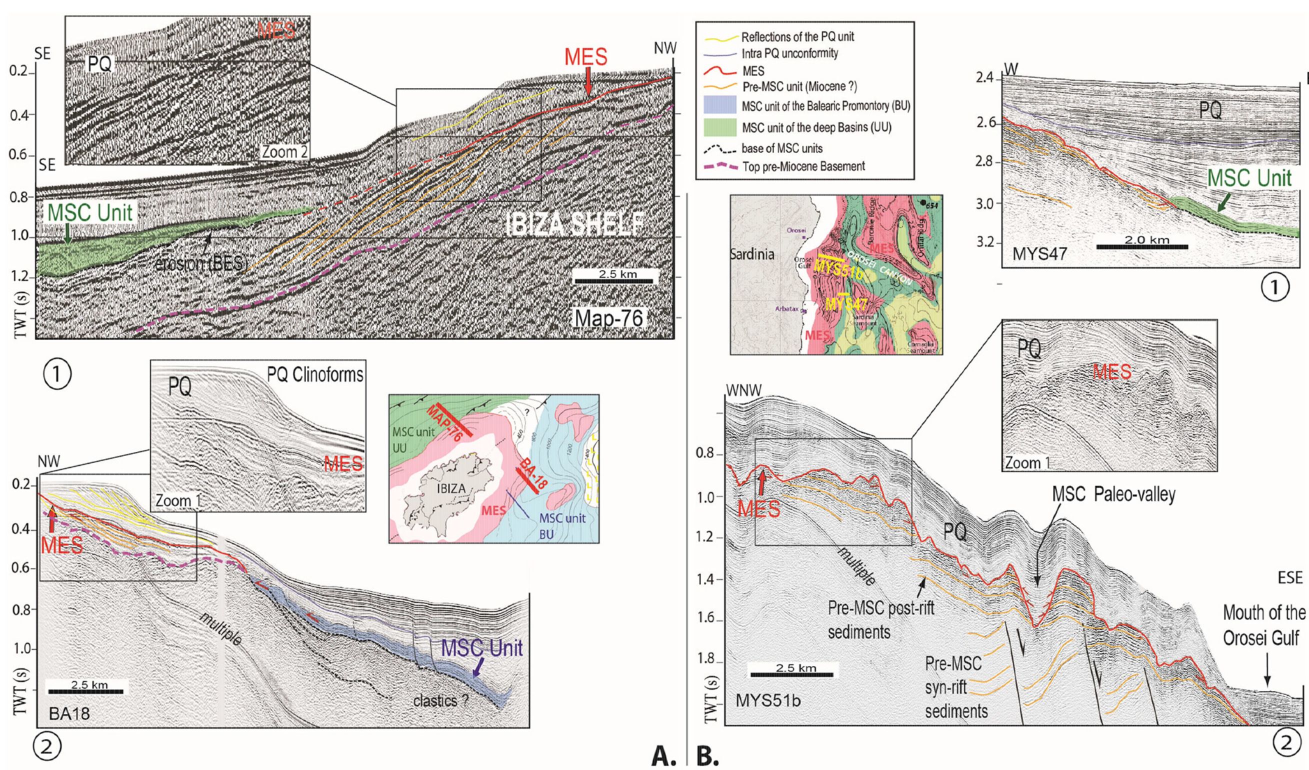

Fig. 3. Seismic lines displaying the Margin Erosion Surface offshore. A. Seismic profiles showing onlap of the MSC unit on the MES, for the Valencia Basin (UU; industrial line, A-1) and the Balearic Promontory (BU; academic Simbad-cruise high-resolution line, A-2). Note that UU is onlapping mostly horizontally and BU is tilting and gliding on a basal decollement surface. B. Seismic profiles showing the MES on the East-Sardinia margin, onlap of MSC unit (UU) on the MES (B-1); rugged morphology of the MES in Orosei valley (B-2). Both areas show truncation of pre-MSC units. Vertical exaggeration of the lines is approximately x2.5 for the pre-MSC unit and x5 for the Messinian to Quaternary units. Each line is located on its respective area map.

(Lofi et al., 2018), located in between the deep basins evaporite units and the peripheral basins filled with the PLG unit (Fig. 1).

The Balearic Promontory is a continental rise (500 km-long, 120 km-wide) which includes the Balearic Islands. Although located between extensional basins, the Valencia continental Basin to the North, the Algerian and the Provençal oceanic basins to the South and East respectively, it is considered as the easternmost prolongation of the Betic thrusts belt (Sanz De Galdeano, 1990; Roca, 2001; Sabat et al., 2011; Fig. 1A). Over the offshore Balearic Promontory, some thin MSC unit (BU) has been recently evidenced (Maillard et al., 2014; Driussi et al., 2015), and appear widely distributed in

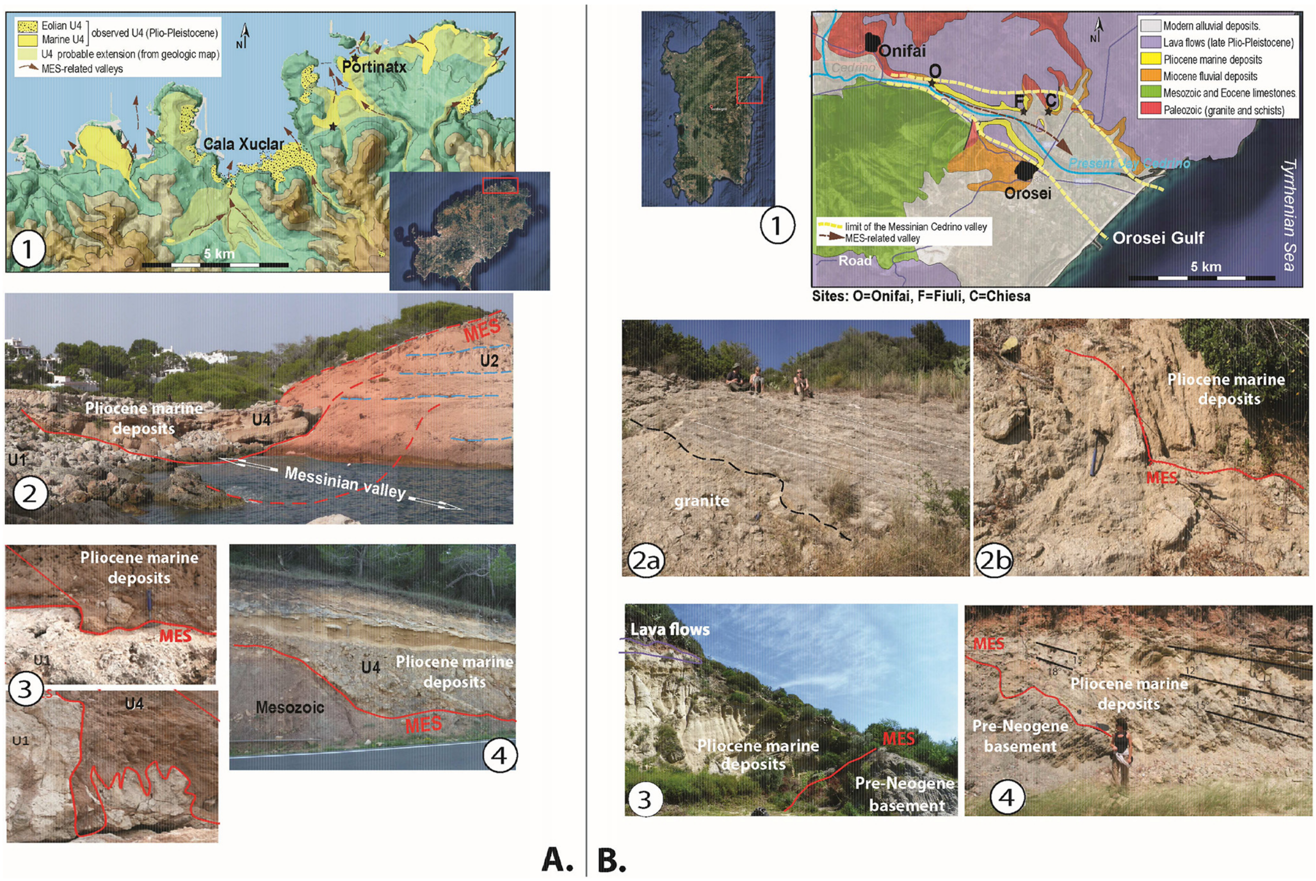

Fig. 4. Pictures displaying the Margin Erosion Surface onshore. A. The Northeastern part of Ibiza Island. A-1: Map showing extension of U4 Plio-Pleistocene unit infilling the Messinian valleys (DEM of present-day topography). A-2: Incision of the MES in U1 and U2 Miocene units at Portinatx (Ibiza Island), showing a small valley filled with Pliocene deposits (location on map 4A-1). A-3: Close-up view of MES in Portinax. A-4: MES incising Mesozoic rocks (black star located on map 4A-1). B. Orosei, Central Eastern Sardinia. B-1: Schematic geological map of the Orosei area with the location of marine Pliocene outcrops (modified from Beccaluva *et al.*, 1983) and location of the MSC valley. B-2a: Chiesa Site (location on map 4B-1): graded beds of poorly sorted torrential deposits on top of the granitic basement (granite covered by a layer of chaotic granitic angular blocks from rock avalanches). Black dashed line: unconformity between Paleozoic basement and Miocene continental deposits (Alpine-Pyrenean unconformity). B-2b: Miocene continental deposits are incised by an erosional surface that is covered by Pliocene marine deposits. This erosional surface is therefore attributed to the MES (in red). B-3: Fiuli Site (location on map 4B-1): Pliocene shallow marine sandy sediments resting in unconformity on top of the pre-Neogene basement (Red line: MES). B-4: View of the MES (red line) below Pliocene marine deposits at Onifai Site (location on map 4B-1).

small intermediate-depth sub-basins (Fig. 1B). On the Alicante margin near Ibiza Island, borehole analyses have shown that this unit corresponds in this sector of the promontory to the PLG (Fig. 1; Ochoa *et al.*, 2015). Although no peripheral evaporites basin has been described in the Balearic Islands, gypsum, possibly correlated to the PLG, was drilled below the airport in the Palma basin in Mallorca Island and extends offshore (Rosell *et al.*, 1998; Mas et al., 2012; Maillard *et al.*, 2014). The MSC-related unit of the offshore Balearic Promontory could then be composed, at least partly, of Primary Lower Gypsum, and thus differ from that of the surrounding deep basins filled with the deep basin evaporites (MU and UU: Fig. 1).

The MES has been particularly well defined on the Valencia margins, where it was mapped and drilled by numerous wells (Mauffret *et al.*, 1978; Lanaja, 1987; Field and Gardner, 1991; Escutia and Maldonado, 1992; Maillard *et al.*, 2006; Maillard and Mauffret, 2006; Urgeles *et al.*, 2011; Pellen *et al.*, 2019). In the Valencia basin, the MSC unit (UU) onlaps the MES at about 2 km-depth on the northern Catalan margin (Garcia *et al.*, 2011; Pellen *et al.*, 2016) but thins towards the Balearic Promontory and drapes the slope of the Balearic Islands, pinching out on the MES at a mean depth of 0.8 s twtt, *i.e.* at about 700 m depth (Fig. 3A-1).

Around Ibiza, the MES exists everywhere as deep as 500 m (Fig. 1B). It truncates pre-MSC units and extends below Pliocene-Quaternary clinoforms building the present-day shelf (Fig. 3A-2). Downslope, it passes to the thin MSC unit (BU) draping all the depression areas of the Promontory. Some clastic units (Lofi *et al.*, 2011) could exist below the MSC unit, as chaotic seismic facies are often observed, as shown in the Valencia Basin (Maillard *et al.*, 2006; Pellen *et al.*, 2016).

From the Valencia basin, the MES can be followed continuously through the Gulf of Lion, the Corsica margins and until the Sardinian passive margins (Fig. 1A; Sage et al., 2005; Cornée *et al.*, 2008; Thinon *et al.*, 2016; Lymer *et al.*, 2018). In the study area (Fig. 1B), the Eastern Sardinian margin deepens rather abruptly from the Sardinia shelf, breaking toward the abyssal Tyrrhenian Basin, crossing the 200–2000 m water depth East-Sardinia Basin parallel to the coast and the wide and flat Cornaglia Terrace with water depths ranging from 2000 m to 3000 m. Offshore of the Orosei Gulf, these domains are incised by the Orosei Canyon. The Tyrrhenian Sea is a back-arc basin related to the eastward migration of the Apennine subduction system from Oligo-Miocene to present-day (Malinverno and Ryan, 1986; Gueguen *et al.*, 1998; Sartori *et al.*, 2001; Doglioni *et al.*, 2004; Jolivet *et al.*, 2006; Prada *et al.*, 2016). Recent observations reveal however that the Eastern Sardinian margin was already segmented in horsts and grabens during the MSC and imply that the MSC occurred after the end of the rifting (Lymer *et al.*, 2018).

On the shelf, the MES progressively deepens from the coast towards the East Sardinia Basin (Lymer *et al.*, 2018; Fig. 1B). There, the MES displays rough and valley-like morphologies (Figs. 1B and 3B-2). The basal-Pliocene unit, characterized by its low amplitude/nearly transparent seismic facies, is directly located above the MES and fills the MSC paleo-valleys. The depth of incision of the MSC valleys is generally less than 100 m (assuming a mean internal velocity of 2000 m/s in the PQ unit). The main MSC paleo-valley has incised the pre-MSC series by approximately 280 m (Fig. 3B-2). Downslope, the MES is markedly smoother (Fig. 3B-1). It passes laterally to the MSC Unit (UU) near the bottom of the East-Sardinia Basin at 2.9 s twtt., *i.e.* at about 2.3 km depth. The MES thus exists much deeper than on the Balearic Promontory, showing an onlap of the UU at a depth compatible to that usually seen around the NW Mediterranean margins (*i.e.* 2 to 3 km, Lofi *et al.*, 2011; Leroux *et al.*, 2019). The clastic unit, which is widely present in other Mediterranean basins, is visible only very locally in our study area, along the flank of some structural highs.

4 Onshore MSC units and erosional surfaces

4.1 Ibiza Island, Balearics

During the late Miocene times (post-Betic phase), only a small area in the NE of Ibiza registered shallow marine sedimentation and transition to continental deposits (Durand-Delga *et al.*, 1993). We identified the following four Late Miocene to Plio-Pleistocene sedimentary units (U1–U4), from bottom to top (Figs. 4A and 5A) (Lézin *et al.*, 2014, 2017).

4.1.1 Description

Unit U1 is mainly composed of fossil-rich limestones (benthic foraminifera, corals, rhodoliths, vermetids, cerithids...) and locally Cnidarians-rich limestones with abundant reworked *Tarbellastrea* sp. accumulated in shallow marine environments (Fig. 5A).

Unit U2 with a conical shape sets up along N70° to N 110° faults. The proximal part of the sedimentary alluvial fans is composed of polygenic detrital material (metric to plurimetric) deriving from Mesozoïc basement erosion. The middle part of the fan is characterized by decimetric layers composed of subangular centimetric pebbles that alternate with conglomerates to normal graded coarse sandstones, pink siltstones with microcodium and root traces (Fig. 5A) and marls with well-preserved benthic foraminifera and reworked planktonic foraminifera. Braided fluvial channels, hydromorph paleosols, and sheet flood deposits attest continental and/or nearshore conditions, while the paleontological content of the argillites with foraminifera indicates marine environment. In the distal part, only shallow marine environment is recorded. Unit U2 is a clastic unit set up by gravitational and fluvial processes in nearshore environment allowing the edification of the coastal alluvial fans. It is controlled by the development of syn-sedimentary extensional faults (Lézin *et al.*, 2017).

Unit U3 is mainly carbonated with oolithic grainstone and microbialites (stromatolites and thrombolites, Fig. 5A) developed in shallow marine environment. These deposits are deformed by synsedimentary large scale boudinage structures (Odonne *et al.*, 2019) and are locally overlain by marly series with roots traces, microcodiums attesting to their continental origin (paleosol).

An important erosion and karstification surface incises these three units (Figs. 4A-2 and 4A-3), down to the underlying Mesozoic units (Fig. 4A-4). This erosion/dissolution surface is locally covered by Unit U4 formed by shallow marine calcarenites with gastropods, benthic and planktonic foraminifera (*e.g. Globorotalia puncticulata* and *Globigerinoides extremus* determined by F. Sierro, see Lézin *et al.*, 2017), red algae or biodetrital sands with well sorted grains, Helix gastropods and cross-beddings with a dip greater than 30° testifying an eolian depositional context (Figs. 4A and 5A).

4.1.2 Interpretation

The Miocene units show common characteristics with other Tortonian-Messinian units known in Mallorca or peripheral MSC Spanish basins such as in Sorbas Basin. Unit 1 presents strong facies similarities with the reef complex previously described in Mallorca Basin (Pomar *et al.*, 1996, Pomar, 2001) and therefore could be Late Tortonian to Lower Messinian in age. From its characteristic facies, Unit 3 can be interpreted as the TCC (Terminal Carbonate Complex) found elsewhere onland Spain (Esteban *et al.*, 1996; Riding *et al.*, 1999; Cornée *et al.*, 2004; Braga *et al.*, 2006; Soria *et al.*, 2008; Roveri *et al.*, 2009; Lugli *et al.*, 2010), and dated from 5.67 to 5.54 my (Bourillot *et al.*, 2010). Both Units 1 to 3 were deposited in shallow water or nearshore environment and record a transgressive general trend.

After the deposition of the TCC (Unit 3), the development of paleosols and the important erosion and karstification surface attests a major relative sea-level fall. The marine U4 was sampled and contains planktonic foraminifera attributed to lower Pliocene (younger than 4.7 my). U4 marine unit records a reflooding, with a sea level close to that recorded during the deposition of the TCC, that must be linked to the regional Zanclean reflooding of the West Mediterranean Basin at the end of the MSC.

The aeolian biodetrital sands have been assigned to the upper to middle Pleistocene in Cala Xuclar (Fig. 4A-1; Del Valle *et al.*, 2016). Moreover, if U4 is mostly found locally onlapping the MES in valleys carved in the above units (Fig. 4A), it also rests as thin layers on top of the Late Miocene cliffs, reaching the altitude of 60 m and attesting for the high relative Pliocene sea-level. According to Miller *et al.* (2005),

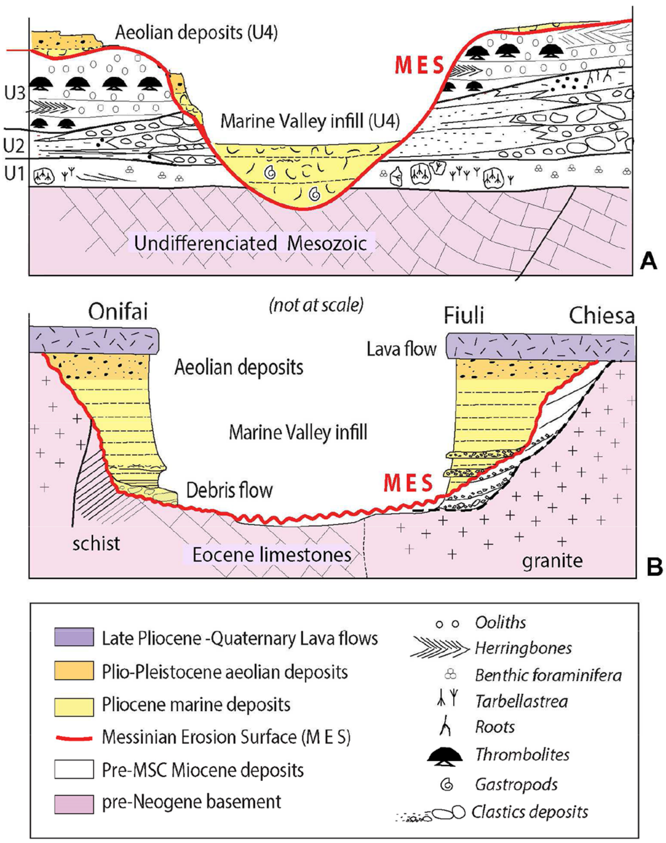

Fig. 5. Schematic representation of onshore stratigraphy illustrating the geometric relationship between pre- and post- MSC units below and above the MES. 4A shows the Ibiza sketch: Late Miocene units laying in unconformity on Mesozoic carbonate basement and the MES drawing a valley filled with U4, as in Portinatx. 4B displays the East-Sardinian sketch: various types of eroded basement, reduced pre-MSC Miocene (?) detritals witnesses of continentalization and well developed marine Pliocene filling the MES. See Figure 3 for locations.

the upper Zanclean sea level was at 20 m above the present day sea-level. Considering these values, a possible uplift of about 40 m should be consider.

We, therefore, assume that the exondation is related to the peak of the Messinian Salinity Crisis, corresponding to the MSC drawdown. The resulting strong erosion and karstification of the Upper Miocene and Mesozoic series are thus the MES (Fig. 4A-3), that has cut some small valleys then filled by the marine part of U4 (early Pliocene). The onshore valleys are correlated to coastal reentrants, called "calas" in Spain, which reflects the present-day landscape (Fig. 4A-1). This onshore Messinian diffuse erosion network, due to the absence of an important drainage system in Ibiza, must be connected to the MES observed on the Ibiza offshore upslope domain.

4.2 Orosei Area, eastern Sardinia

Recent onshore field investigations aimed to identify and characterize the erosion surface below the Pliocene marine deposits in the Orosei area, along the Cedrino River, eastern Sardinia (Fig. 4B).

4.2.1 Description

In this area, the pre-Neogene basement is mainly made of Hercynian granitic rocks and minor schists with locally a Mesozoic to early Cenozoic sedimentary cover (mainly platform limestones) that has been deformed during Pyrenean-Alpine orogeny (Dieni *et al.*, 2008). Pre-Neogene basement along the valley of Cedrino is covered from upstream to downstream by chaotic blocks, followed by accumulations of conglomerate and polygenic or monogenic breccias and arenaceous coarse sandstones reaching up to 40 m in thickness. These clastic deposits evolve upward and laterally (toward the present-day coast-line) to torrential and then fluvial deposits with sequences of channelized sand and rounded pebbles (Figs. 4B-2 and 4). These continental clastic deposits are locally observed unconformable over the Eocene limestones, and they are considered as Miocene in age on the basis of similar facies in other areas of Sardinia (Calvino *et al.*, 1972; Dieni *et al.*, 2008). They are deeply incised by a Paleo-Cedrino valley, and subsequently filled up with marine fine sandy deposits, early Pliocene in age (Giresse *et al.*, 2015; Fig. 5B). The erosion surface crosscuts not only the Miocene clastics but incises also the Mesozoic and Paleozoic basement (pre-Neogene basement, Figs. 4B-3 and 4B-4). Over this major discontinuity, the Pliocene sedimentary unit starts locally with some thin debris-flow deposits. The debris-flow reworked basement blocks including elements of nummulitic Eocene limestones in a fine-grained marine matrix including bioclasts and foraminifera (Fig. 4B-4) or dominated by granitic clasts (Fig. 4B-3). The sedimentation rapidly evolves into a fine sandy marine formation (Fig. 5B), up to 30 m thick, highly bioturbated and containing occasional shelly gravel beds, 20 to 30 cm-thick. It includes mainly oysters, pectens, spines of sea urchins, gastropods and various benthic and planktonic microfauna that permitted to refine the age of the oldest exposed marine deposits over the erosion surface (Fig. 4B-3). The presence and common occurrence of *Globorotalia puncticulata* (FO 4.52 Ma; LO 3.57 Ma; Sierro *et al.*, 2003) in the basal beds of the Pliocene marine formation attests an age younger than 4.52 Ma for this formation (Giresse *et al.*, 2015). These Pliocene deposits are covered by late Pliocene to Quaternary lava flows that allowed the preservation of the Pliocene deposits (Calvino *et al.*, 1972; Beccaluva *et al.*, 1983; Figs. 4B-3 and 5B).

4.2.2 Interpretation

The observed sections show that the main erosion surface corresponds locally to a stratigraphic gap between Eocene and Early Pliocene deposits. The post-tectonic unconformity of the Pyrenean-Alpine orogeny is comprised in this time interval. However, in some localities (*e.g.* "Chiesa", Fig. 4B-2), the pre-Pliocene erosion surface also incises some Miocene continental clastic deposits that are lying in unconformity over the post-orogenic basement. Thus, there are two successive erosion surfaces in the Orosei area: the first one being linked to the end of Alpine-Pyrenean orogeny in Sardinia in the Late Eocene (*e.g.* Dieni *et al.*, 2008), about c.40–35 Ma ago (Fig. 4B-2a), and the second one, stratigraphically positioned between the Miocene and the early Pliocene deposits (Fig. 4B-2b), having developed during the main Messinian event. This second remarkable surface is therefore interpreted as the MES (Fig. 5B).

5 Discussion-implications

5.1 Subaerial exposure and gravity-driven destabilization

The MES is linked to continental processes and thus occurred in subaerial conditions. Both study areas display differences but also similitudes. In Ibiza Island, the major relative sea-level fall is recorded after the deposition of the TCC (U3 unit) and is evidenced by continental markers: the MES and locally the formation of paleosols at the top of the TCC (Lézin *et al.*, 2017). High amplitude sea level change is also considered a likely trigger for gravity-driven instabilities such as bending soft deformation affecting U3 (Odonne *et al.*, 2019). If it is difficult to appraise the exact chronology between the MES, the gravity instabilities in continental context and the paleosols, they all postdate the Late Miocene marine deposits and they are all evidence for subaerial events during a time-interval linked to the low-stand sea-level (MSC peak). Gravitational deformation should be regarded in relation to large-scale processes of margin collapse during Messinian sea-level drawdown, proposed elsewhere in the Mediterranean Basin (Lofi *et al.*, 2005; Del Olmo *et al.*, 2011; Bache *et al.*, 2015; Cameselle and Urgeles, 2017; Micallef *et al.*, 2018). If such subaerial destabilization has been evidenced on the offshore slopes, similar examples from the shelf remain poorly documented, except where PLG evaporites are present in the pre-MSC late Miocene succession, allowing gliding (Cyprus: Orszag-Sperber *et al.*, 2009; Sorbas: Bourillot *et al.*, 2010; Clauzon *et al.*, 2015). Onshore Eastern Sardinia margin, the youngest pre-MSC marine series is Eocene in age. Consequently, we assume that exondation lasted long and that the Miocene continental clastics deposition could have started before the end of the Miocene and thus, it cannot be undoubtedly solely linked to the MSC peak but also to a longer erosion phase. In western Sardinia margin, as in the Oristano Gulf, Late Miocene marine limestones belonging to the TCC exist, and a karstic plateau that developed at their top has also been interpreted as the MES (Cornée *et al.*, 2008). Moreover, similitudes of marine Pliocene infilling the MES in both study areas favor the interpretation of at least the top part of the continental clastic of Orosei as markers of the MSC continentalization time-interval.

In the peripheral basins (Boudinar in Morocco, Sorbas onland in Spain) the MES was also proved to form in subaerial settings above the TCC. Its geometry is only locally well-preserved, when overlain by continental clastics deposited before the Zanclean reflooding (Do Couto *et al.*, 2015; Clauzon *et al.*, 2015; Cornée *et al.*, 2016), with incisions suggesting that a fluvial network shaped the landscape during the peak of the MSC. The debris flows (Fig. 5B) deposited above the erosion surface in Eastern Sardinia seem to be an equivalent to those continental deposits.

Offshore, gravity instabilities are also observed on the Balearic Islands slope domain within the MSC unit (Fig. 3B; Maillard *et al.*, 2014), but they show raft deformation typical of gliding processes that could be explained by an evaporitic nature of the MSC unit (BU in this case). Some thin detrital units have been reported locally on the lower slope (Maillard *et al.*, 2006) interpreted as large-scale marine collapse deposits (Cameselle and Urgeles, 2017). Similar thin and local detrital units are also recorded along the Sardinia margin (Lymer *et al.*, 2018) outside of the deep Orosei valley. In both areas, detritals are poorly developed offshore, mainly because of the absence of large drainage networks from the islands (Sardinia and Balearic Islands). Another reason for this scarcity of detrital deposits could be the onshore destabilization evidenced by the gravity deposits trapping the sediments upstream with poor horizontal displacements. In places where they appear offshore, the clastics are often interbedded within the MSC-units. They pass laterally to the MES, proving once again polygenic character of the erosion onshore and on the slope domains, lasting the entire Salinity Crisis peak.

5.2 Meaning of the depth of the MES

The MES/MSC deposits limit offshore appears from 500 to 1000 m depth on the Ibiza slopes whereas it occurs at about 2000 to 2500 m depth on the Eastern Sardinia margin (Fig. 1B). The depth is also different on each side of the Ibiza Island, deeper on the Valencia side that is connected to deeper basins, shallower on the Balearic side where MSC sub-basins are perched at different depths on the Promontory. These small intermediate-depth sub-basins could have been partially closed and disconnected from the deep basins evaporites (Driussi *et al.*, 2015), at least for precipitation of the MU (Fig. 1), supporting the hypothesis of different depth for the deposition of the evaporites (hypothesis of stepped sub-basins, Cita and Ryan, 1978; Ryan, 2008; Maillard *et al.*, 2014; Roveri *et al.*, 2014; Pellen *et al.*, 2016). Late Miocene onshore deposits of the NE Ibiza Island, currently laying at 0 to 30 m height, formed in the near-shore environment, running out the possibility of large vertical post-MSC motion that could have explained the present-day different depth of the evaporites occurrences on both sides of the island. Possible maximal 40 m uplift of Unit 4 also minimizes the possible vertical movements. This is in accordance with preliminary backstripping results on the Balearic Promontory showing that the pre-MSC paleo-topography was not very different from the present-day bathymetry (Mas *et al.*, 2018; Heida *et al.*, 2019). In Eastern Sardinia, rifting was completed by the beginning of the MSC, and resulted in the isolation of the East Sardinian basin, thus already deep during the MSC. Some post-rift reactivation has occurred locally in that domain but only minor vertical motions have affected the margin after the beginning of the oceanic spreading in the deep basin (*e.g.* Lymer *et al.*, 2018). We have thus to assume that the MSC sedimentary units developed in several terraces set up during the rifting.

Consequently, both study areas support the hypothesis of the existence of sub-basins perched at different depth during the Crisis, possibly infilled with different evaporite successions and possibly in a diachronic way. Together with the subaerial erosion, these are arguments for disconnection of some sub-basins during the acme of the crisis, incompatible with high stand sea level, at least during the entire length of the crisis. To conclude, during the MSC, both areas were moreover in post-tectonic context: post Betic compression for Ibiza and post-Tyrrhenian rifting for the Sardinia Eastern margin. Tectonic deformation exists locally but is regionally weak during the Late Miocene/Pliocene and, unlike proposed explanations (Roveri *et al.*, 2019), vertical movements (uplift/subsidence) are not the main trigger mechanism, at least at large scale, to explain the present-day different depth of the MSC deposits. Nevertheless, isostatic rebound must be taken into account in the MSC scenario (as shown in Rabineau *et al.*, 2014) and vertical movements will be carefully studied in the integrated project SALTGIANT – Understanding the Mediterranean Salt Giant [Marie Sklodowska-Curie Actions – Innovative Training Networks (ITN)].

6 Conclusion

The MES, Margin Erosion Surface of the Messinian Salinity Crisis, is described for the first time onland Ibiza and East Sardinia in the Orosei area, showing its existence onland outside of large river systems and outside of peripheral basins. In both cases, the MES extends offshore and passes laterally to MSC units down the slope, the depth of the transition being different in each margin. This also demonstrates onland the polygenic character of the erosion that has been proposed for the offshore MES.

In both cases, the MES is overlain by marine Pliocene and aeolian Plio-Pleistocene sediments, particularly well observed in the valleys. In the Orosei area, Late Pliocene to Quaternary lava flows permitted to preserve those deposits whereas, in Ibiza, Pliocene marine deposits occurred locally filling small valleys and covering the top of Late Miocene cliffs.

The erosion is incised in various units ranging from pre-MSC unit down to the basement in both cases. Onland Ibiza, incisions affected Mesozoic and overlying marine Late Miocene series identified as regional known units. The erosion is clearly post-TCC. Onland eastern Sardinia, it affected Mesozoic and Paleogene units but marine Late Miocene units are missing.

The MES formed during the MSC peak is a subaerial erosional surface as testified by evidence of continentalization events: karstification of the surface, detritals and continental deposits linked to gravity instabilities, emplacement of aeolian dunes and paleosols onshore. These thin and local continental deposits provide new evidence for a regression phase and, where present, preserved the original geometry of the MES.

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