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Terrestrial colonization of the Balearic Islands: New evidence for the Mediterranean sea-level drawdown during the Messinian Salinity Crisis

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ABSTRACT

More than 40 yr after the discovery of salt giants buried below the Mediterranean deep basin floor, debate on the Messinian Salinity Crisis (MSC) is still continuing about whether there was a large or only moderate drawdown in base level related to the deposition of deep evaporites during its peak. In this paper, we constrain the magnitude of this sea-level drawdown during the MSC. An analysis of the late Neogene faunas of the Balearic Islands, combined with the available geostructural data, shows that a minimum of 800–1200 m drawdown would be required to allow the colonization of the Balearic Islands by new continental-terrestrial fauna during the MSC peak, which provides solid new evidence in favor of a deep desiccated basin in the Mediterranean during the MSC.

INTRODUCTION

The Messinian Salinity Crisis (MSC) was a geological event that affected the entire Mediterranean region as well as global ocean circulation between 5.97 and 5.33 Ma (Krijgsman et al., 1999; Manzi et al., 2013). In the Mediterranean, the crisis was mainly characterized by isolation and/or reduced connection with the Atlantic Ocean, resulting in a new hydrological budget that favored the deposition of vast amounts of evaporites (salt and gypsum) in the marginal basins and abyssal plains, together with considerable erosion of the exposed margins (Hsü et al., 1973; CIESM, 2008).

As soon as the deep Mediterranean evaporites were discovered (Ocean Drilling Program and Deep Sea Drilling Project [ODP-DSDP] drill holes), intense debate arose about the most appropriate scenario for their formation. According to the initial model (so-called "deep desiccated basin"), the Messinian evaporites formed in a deep but desiccated Mediterranean, while the shelves and slopes underwent subaerial erosion due to fluvial rejuvenation triggered by a 1500 m sea-level drawdown (Hsü et al., 1973). This initial model provided a plausible explanation of the observed geological features and became the paradigm for the MSC.

Another model (corresponding to a "deep nondesiccated basin") proposed that the basin was not desiccated but instead completely filled with brine, suggesting that deep-water conditions may have persisted throughout the MSC (Debenedetti, 1976; Schmalz, 1991; Hardie and Lowenstein, 2004). Only a moderate base-level drawdown would be required in this scenario, and both slope erosion and evaporite emplacement would have occurred by density currents in a stratified deep-water environment (Roveri et al., 2014a).

The main criticisms of the deep desiccated basin model focused on the implications of the widely distributed clastic evaporites emplaced by deep-water gravity flows, which had been overlooked in previous studies (Lugli et al., 2015).

As no deep drilling has reached the entire MSC sequence in the Western Mediterranean, the nature of most of the evaporites and erosional surfaces is still unknown. The debate on both models continues and currently represents a scientific challenge (Roveri et al., 2014b). This paper aims to show that a major drawdown of the sea level is required to have allowed terrestrial colonization of the Balearic Islands during the MSC peak.

GEOLOGICAL SETTING

The Balearic Promontory (Fig. 1) is a 500-km-long, 120-km-wide continental rise, including the Balearic Islands, surrounded by the deep Algerian and Valencia/Liguro-Provençal basins (Acosta et al., 2002). It forms part of the northeastern prolongation of the Betic Range into the Mediterranean Sea.

A thin MSC-related unit (Bedded Unit [BU]; Fig. 1) has been recently identified all over the Balearic Promontory, generally 0–100 m thick, but it reaches a thickness of at least 300 m in the Mallorca Central Depression (Driussi et al., 2015). This unit is distributed in small subbasins at depths currently lying between 600 and 2000 m, while its connection with the known MSC units of the deep basins (Upper Unit [UU] and Mobile Unit [MU] in Fig. 1) currently remains uncertain. The other parts of the promontory were subject to erosion during the MSC (Margin Erosion Surface [MES] in Fig. 1).

The Neogene basins on the Balearic Promontory have been relatively stable in terms of vertical movements since the Miocene, so the sedimentary record, both onshore and offshore, is suitable for testing the possible scenarios related to the MSC events (Just et al., 2011; Maillard et al., 2014; Driussi et al., 2015; Mas, 2015).

METHODS

This study links two different methodologies: on one hand, the fauna fossil record (Fig. 2), and on the other hand, geological/geophysical data (Fig. 3). This approach allows the reconstruction of the sea-level drawdown needed to expose terrestrial pathways connecting mainland Europe to the Balearic Islands at the end of the Miocene.

The fossil bones of Pliocene sites in Mallorca were extracted from the rock matrix (bone breccias) by cyclically consolidating the visible bones with Paraloid-B67 resin (5%), and immersing them in 10% acetic acid solution for 48 h, followed by immersion in freshwater for 7 d, and air drying.

Maps and sections were taken from a large seismic database including academic seismic profiles obtained during several scientific cruises and oil-industry surveys, and these data sets were improved by recent high-resolution seismic profiles acquired on the Balearic Promontory during the "SIMBAD" oceanographic cruise (Maillard and Gaullier, 2013). The map and sections (with units in meters) taken from the seismic database assumed a Pliocene–Pleistocene unit velocity of 2290 m/s (Fig. 3). Paleobathymetry was estimated from restoration of the sections at the end of the Miocene before the sea-level drawdown. Post-MSC tectonic deformation was removed, as well as the effects of the Pliocene–Pleistocene unit loading and Miocene unit decompaction, both calculated with

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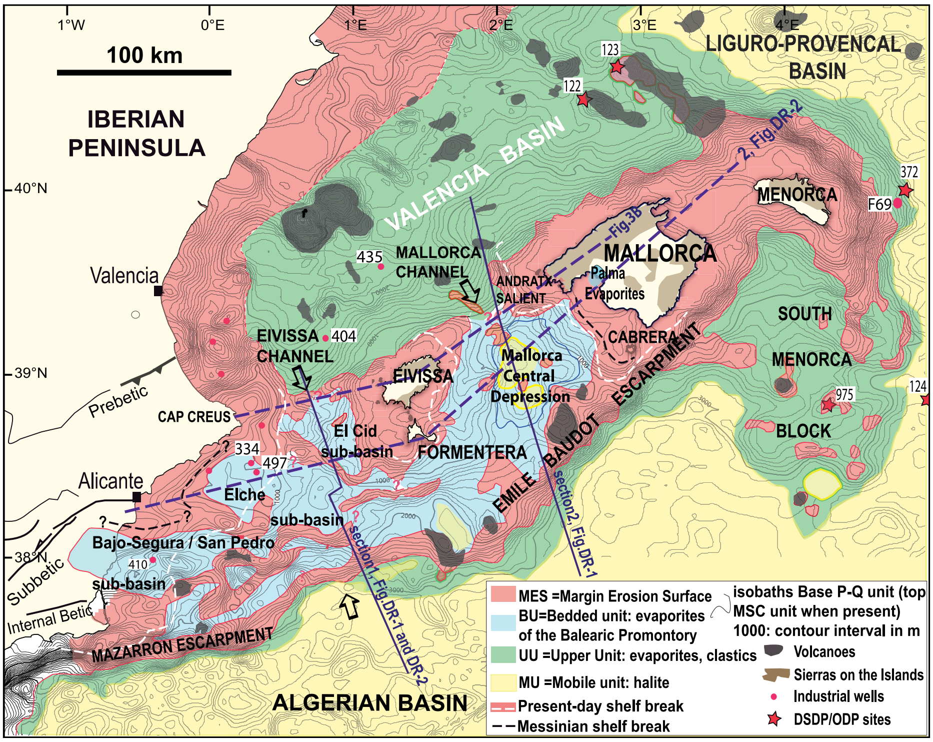

Figure 1. Distribution of Messinian Salinity Crisis (MSC) markers in Balearic Promontory (continental rise, including Balearic Islands). Map shows present-day depth to base of Pliocene–Quaternary (P-Q) unit, as well as (1) extent of MSC-related subbasins containing BU (in blue), and (2) areas affected by MES during erosion of MSC-related units (in red). DSDP—Deep Sea Drilling Project; ODP—Ocean Drilling Program.

a local isostatic model (Fig. DR2 in the GSA Data Repository[1]).

BIOSTRATIGRAPHY, COLONIZATION, AND PALEOBATHYMETRY

Different episodes of faunal colonization can be identified in the Miocene to Holocene fossil record of the Balearic Islands (Fig. 2; Bover et al., 2014). A first episode (the so-called *Gymnesicolagus* faunal assemblage) has been related to the Langhian-Serravallian regression (middle Miocene). A second episode, characterized by a new vertebrate fauna, has been recorded throughout the Pliocene–Pleistocene succession. Then, these new colonizing faunas evolved separately on the different islands (Fig. 2).

The colonization of the Balearic Islands by these new faunas is considered to have occurred during the Messinian, although the phylogenetic links between the mainland species and their insular descendants have not yet been clearly established. The recent discovery of Zanclean deposits on Mallorca and a reappraisal of the Pliocene sites on Menorca and Eivissa (Bover et al., 2014; Quintana et al., 2011; Quintana and Moncunill-Solé, 2014; Torres-Roig et al., 2017) shed new light on the fauna that arrived at the islands during the MSC, and on the chronology of this colonization episode. Evidence supports a very close relationship between the giant hamster *Apocricetus darderi* from the Zanclean section of Mallorca (MN14) and *Apocricetus alberti* from the Iberian Peninsula (MN13; Torres-Roig et al., 2017), providing robust evidence for a MSC-related origin of the Pliocene–Pleistocene faunal assemblage of Mallorca. Additionally, the large-sized gerbil *Debruijnimys* from Eivissa and an undescribed murid from MN14 of Mallorca are included in rodent genera that colonized the Iberian Peninsula during the MSC event. Some other island mammals (the caprine *Myotragus*, the shrew *Nesiotites*, and the leporids *Nuralagus* and *Hypolagus*) have been identified as likely descendants from mainland genera belonging to MN13. In addition, morphological traits (such as gigantism and hypsodonty increase) suggest that this fauna represents an early stage of isolated evolution.

The arrival of these faunas in the Balearic Islands can now be unequivocally related to their dispersal during the Messinian. Their colonization requires the existence of at least one terrestrial route connecting the Iberian Peninsula with the Balearic Islands. The narrow window in time is strongly supportive of the hypothesis of a terrestrial pathway for their appearance in a group and cannot be explained by random drift one-by-one over time from the mainland to faraway islands on flotsam.

Figure 1 shows the present-day depth of the base of the Pliocene–Pleistocene units. The areal extent of the MSC markers reflects the widespread nature of the MES, suggesting that subaerial erosion occurred over the entire Balearic shelf as well as on the structural highs located between the islands in the Mallorca and Eivissa channels (Just et al., 2011; Maillard et al., 2014; Driussi et al., 2015; Ochoa et al., 2015). The MES extends almost continuously from the Iberian Peninsula to the Balearic Islands through structural highs.

A cross section on the northern Balearic margin from mainland Spain (Cap de Creus) to Mallorca (Andratx salient; section 3B; Figs. 1 and 3) following the nearly continuous MES could be considered prime evidence to confirm the existence of a terrestrial connection between mainland Spain and the Balearic Islands. However, some of the bathymetric highs well expressed in the Eivissa Channel are related to post-MSC compression and/or volcanism (Acosta et al., 2001; Lastras et al., 2004), which led to small-scale folds and thrusts and to the large-scale bending observed on northwest-southeast cross sections (section 1; Fig. DR1). This Pliocene to present-day deformation may have produced 200–300 m of vertical uplift (Maillard and Mauffret, 2013). On the other hand, a large amount of post-MSC sedimentary loading (locally in the subbasins; Fig. 3A) could be responsible for subsidence, together with recent normal faulting (sections 1 and 2; Fig. DR1).

The paleogeomorphology of the area before the Pliocene may thus have been quite different. Restoration involves considering superimposed uplift and subsidence effects, where the Pliocene–Pleistocene unit is backstripped, and the late Miocene surface elevation is calculated with local isostatic compensation (Fig. DR2). In the Eivissa Channel, if the effects of post-MSC tectonics (300 m uplift) and unloading of the relatively constant-thickness Pliocene–Pleistocene unit are removed from this section, we can infer a paleodepth of 1000–1200 m maximum. This is in accordance with results showing that at least the upper slope of the Valencia basin was eroded (Urgeles et al., 2011; Cameselle and Urgeles, 2017). The rest of the Eivissa Channel should have been under shallow water during the MSC to allow deposition of the BU in the subbasins, followed by consequent post-MSC deformation (section 1; Fig DR1). The Elche basin, however, lying at around 900 m depth at the end of the Miocene (B, section 2; Fig. DR2), would have emerged with a sea-level drawdown of the order of 1000 m. This would imply that it was already filled by evaporites before the main drawdown. Indeed, the Elche subbasin is correlated with the Primary Lower Gypsum evaporites (Ochoa et al., 2015). In this case, a connection could

[1]GSA Data Repository item 2018173, supplementary Figures DR1 and DR2, is available online at http://www.geosociety.org/datarepository/2018/ or on request from editing@geosociety.org.

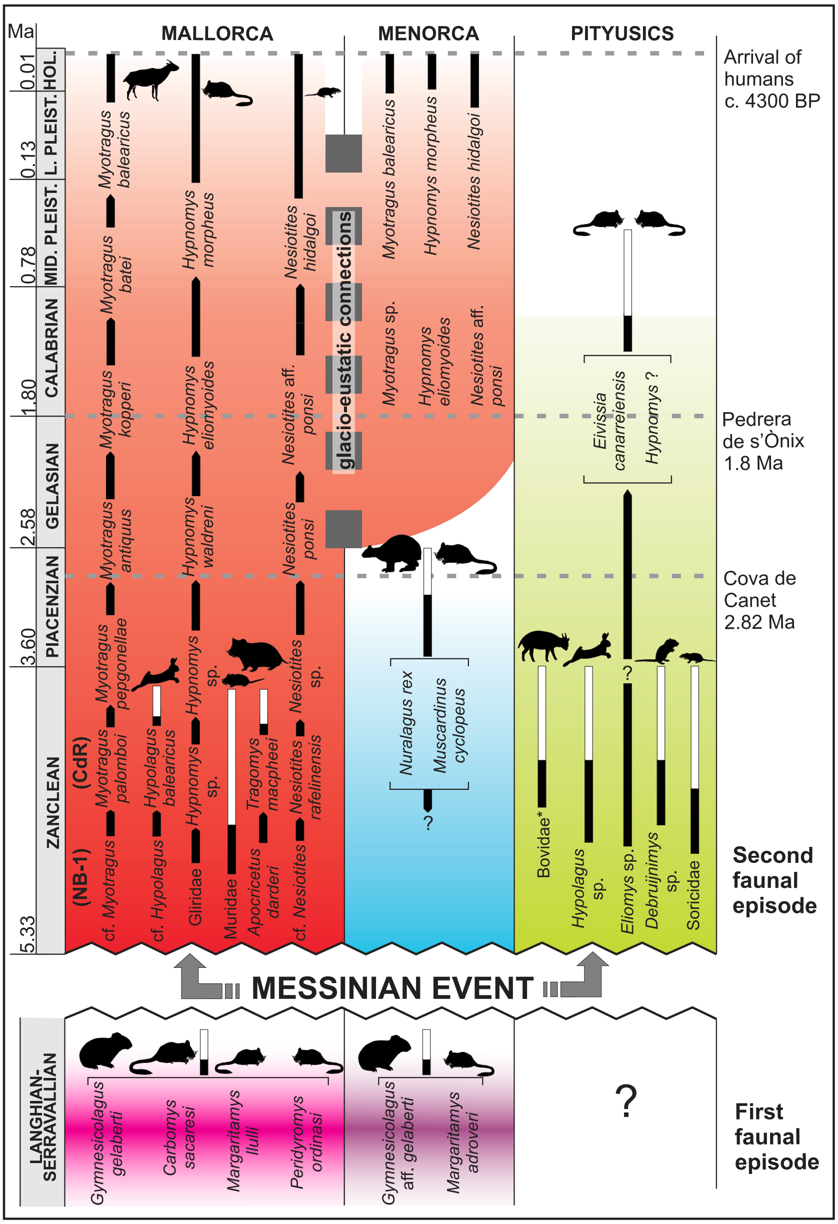

Figure 2. Diagram showing mammalian faunal succession of late Miocene–early Pliocene to Holocene in Balearic Islands. Different insular faunal episodes have been identified, where first episode (*Gymnesicolagus* faunal assemblage) has been related to Langhian-Serravallian regression (middle Miocene). Second episode, characterized by vertebrate fauna that arrived during MSC, is recorded throughout Pliocene–Pleistocene. New faunas evolved separately on different islands: *Myotragus* fauna on Mallorca, *Nuralagus* fauna on Menorca, later replaced by *Myotragus* fauna, and a poorly understood colonizing fauna—affected later by a Pliocene–Pleistocene extinction event—on Pityusic Islands (Eivissa and Formentera). Mallorca and Menorca merged during successive glacial events (gray squares). Gray horizontal discontinuous lines indicate paleomagnetic and radiocarbon ages. NB-1—Na Burguesa-1 faunal assemblage; CdR—Caló den Rafelino faunal assemblage. *Under study by Moyà-Solà and Quintana.

have occurred everywhere between mainland Iberian Peninsula and Eivissa during the MSC. Alternatively, the subbasins were perched and enclosed as small "lakes" of different water depth during the MSC, thus allowing mammalian colonization of the Balearic Islands via the northern Balearic margin (section 3B). This second hypothesis fits with the results in the Central Mallorca Depression, allowing salt deposition in a closed subbasin deeper than the Elche subbasin (B, section 2; Fig DR2).

Following section 3B, restoration reveals that a 1000 m sea-level drawdown would also have caused the emergence of the Mallorca Channel (Fig. 3B), suggesting a sea-level change of at least the same magnitude as the one allowing erosion along the entire path from the Eivissa Channel to Mallorca and implying a continuous terrestrial connection along the northern Balearic margin.

CONCLUSIONS

This analysis of the late Neogene insular fauna of the Balearic Islands, combined with the available structural data, enables us to infer the minimum sea level associated with desiccation of the Mediterranean during MSC, which favored the colonization of the Balearic Promontory by new continental-terrestrial fauna.

The paleobathymetry in the Eivissa and Mallorca Channels connecting the Iberian Peninsula and these islands was already 800–1200 m deep during the late Miocene. We conclude that the Mediterranean sea-level drawdown should have been at least equal to this paleodepth to allow the colonization of the Balearic Islands by terrestrial fauna during the MSC peak. The fauna observed in the Zanclean section of Mallorca provides strong new evidence supporting the deep desiccated basin model.

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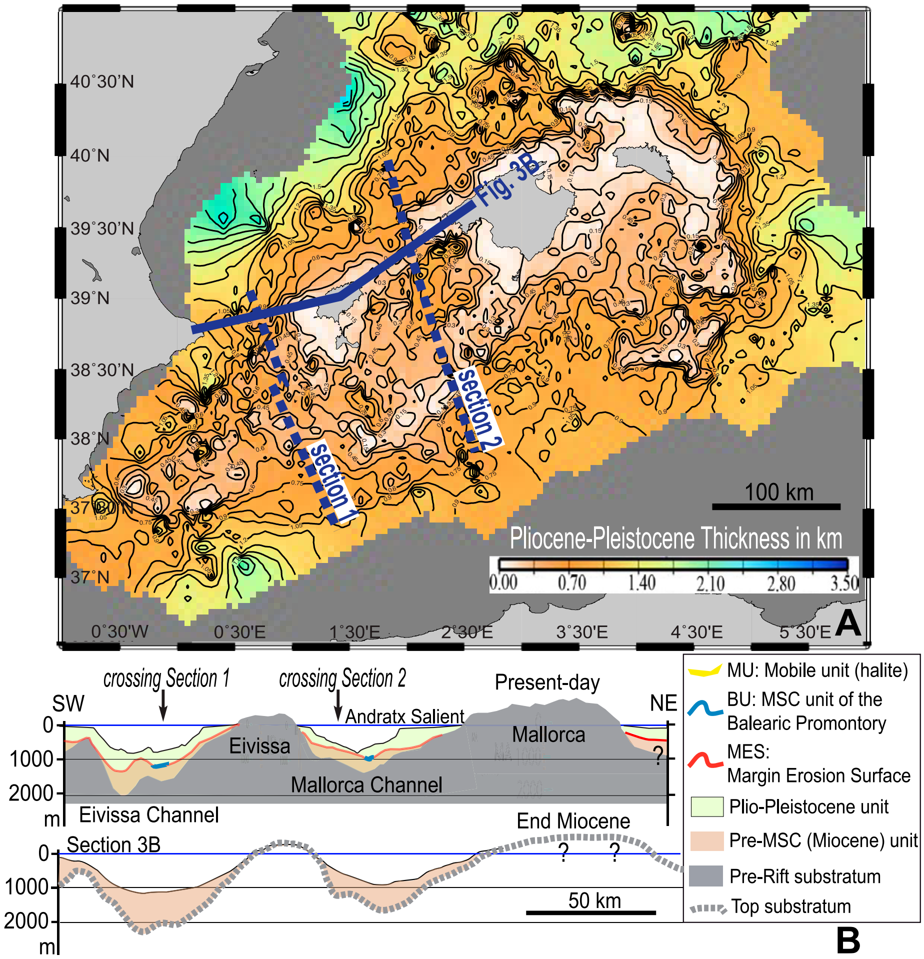

Figure 3. Depths and paleodepths of markers related to Messinian Salinity Crisis (MSC) on Balearic Promontory (continental rise, including the Balearic Islands). A: Map showing thickness of Pliocene-Pleistocene units (post-MSC deposits). B: Along-strike section of Balearic Promontory (for present-day) and restored paleodepth at end of Miocene. Section connects Cap Creus to southwest of Mallorca Island via Eivissa and Mallorca Channels. See comments in text. For restoration method, see text and Figure DR2 (text footnote 1). BU—Bedded Unit.

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