

# Deep-basin evidence resolves a 50-year-old debate and demonstrates synchronous onset of Messinian evaporite deposition in a non-desiccated Mediterranean

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## ABSTRACT

The Messinian salinity crisis (MSC) is perceived as an environmental crisis governed by climatic and tectonic controls, affecting global oceans' salinity and shaping the Mediterranean Sea's biochemical composition. Recently drilled offshore wells in the Levant Basin retrieved a sedimentary record of the deep-basin Mediterranean MSC salt deposits and the underlying pre-evaporite unit. In this study, we have concentrated on the pre-evaporite interval and its transition into the overlying evaporites. Analysis of this data set changes the way these deposits have been perceived since the 1970s, when they were first penetrated in their uppermost part during Deep Sea Drilling Project expeditions. Using sedimentology, seismic interpretation, biostratigraphy, and astronomical tuning, we show that Messinian salt deposition in the Eastern Mediterranean began during stage 1 of the MSC. In contrast to the present paradigm, salt was deposited synchronously with gypsum in the marginal and intermediate-depth basins significantly before the 50 k.y. interval coined as the "MSC acme event", ~400 k.y. after the crisis began. Thus salt precipitation took place in a non-desiccated deep basin, having a restricted but often open connection with the Atlantic Ocean, substantially altering our understanding of the mechanisms governing the deposition of salt giants. A coeval onset of basinal halite and marginal gypsum precipitation calls for a reevaluation of global-scale climatic and oceanographic models of the MSC, taking into account a much older age for the beginning of halite deposition.

## INTRODUCTION

Restriction of Atlantic Ocean connectivity during the Messinian salinity crisis (MSC) resulted in the deposition of up to 3 km of evaporites within deep Mediterranean Sea basins (Hsu, 1973). It has been suggested that deposition of the MSC salt giant has greatly affected the global oceans by sequestering 5% (Ryan, 2008) to 10% (Garcia-Castellanos and Villaseñor, 2011) of their salt content into the Mediterranean. Also, by contributing warm, saline water to northern latitudes, the MSC influenced Atlantic Meridional Overturning Circulation and consequent global climatic shifts (Hernández-Molina et al., 2014). This singular giant evaporite system, one of the largest and youngest in Earth's history, is repeatedly used as a cornerstone for explaining evaporite deposition during Earth's history.

One of the oldest controversies related to the MSC concerns the magnitude and timing of sea-level lowering and desiccation, where several models for evaporite formation have been suggested. Some have proposed that salt was precipitated in deep basins under a deep-water environment (Schmalz, 1969), while other scenarios promote a desiccated shallow-water environment (Hsu, 1973). A hybrid model has been proposed, with

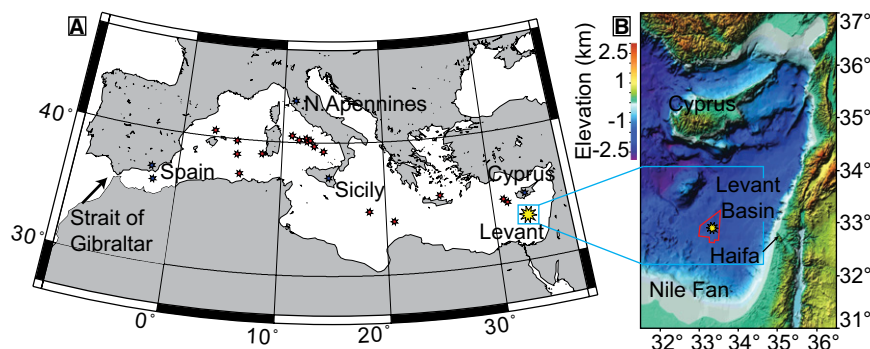
early brine formation in the deep Mediterranean preceding substantial drawdown, followed by massive salt precipitation accompanying gateway closure (Ryan, 2008; Garcia-Castellanos and Villaseñor, 2011; Lofi et al., 2011). However, both the hybrid and shallow-water models essentially start from the following consensus age model for the MSC, based on inferred correlations between the deep and marginal basins. Correlation of Mediterranean evaporite sequences deposited in marginal to intermediate basins (CIESM, 2008; Roveri et al., 2014) and their isotopic signatures (Flecker and Ellam, 2006) demonstrated that partial connectivity with the Atlantic persisted throughout the first phase of gypsum deposition, lasting for 370 k.y. (MSC phase 1: Primary Lower Gypsum [PLG], 5.97–5.6 Ma). At this stage, while gypsum was deposited in proximal settings, euxinic shales and dolostones were thought to have been deposited in the deep basins. The thick salt unit is interpreted as being accumulated during the succeeding MSC acme, a short period of ~50 k.y. (MSC phase 2: Resedimented Lower Gypsum [RLG], 5.6–5.55 Ma).

While the deep-basin salt was penetrated in its uppermost part (Deep Sea Drilling Project–Ocean Drilling Program [DSDP-ODP]; Fig. 1), the risk and vast expense of drilling through the entire salt section has resulted in a critical lack of data. Drilling the deep Mediterranean basins has been repeatedly called for in order to test and validate the various ideas and hypotheses regarding the MSC (Roveri et al., 2014a). In this study, we establish the age of the base of the thick halite deposited in the deep (>1500 m water depth) Eastern Mediterranean by examining the pre-evaporite unit and the transition into the evaporites of the Levant Basin. Our results are based on analysis of the 320 m section found immediately below and through the base of the evaporites (Fig. 1), focusing on one industry well recently drilled in the area. This interval holds the key for providing an indication for the age of the base of the halite in the Eastern Mediterranean. In this work, we question some of the present scenarios for explaining the MSC, such as those related to the synchronicity or diachronism of evaporite deposition across the Mediterranean as well as the way evaporite depositional dynamics are understood.

## MATERIALS AND METHODS

The study area is located ~100 km offshore Israel (Fig. 1). The data set utilized in this study includes modern three-dimensional pre-stack depth-migrated seismic reflection data (Fig. DR1 in the GSA Data Repository<sup>1</sup>), gamma-ray (GR) well logs (Fig. DR2), and well cuttings

<sup>1</sup>GSA Data Repository item 2018060, summary of biostratigraphy data, seismic interpretation, spectral analysis of well logs, X-ray diffraction and scanning electron microscope data, and biostratigraphy, is available online at <http://www.geosociety.org/datarepository/2018/> or on request from [editing@geosociety.org](mailto:editing@geosociety.org).



**Figure 1. A:** Map of Mediterranean Sea marking study area (yellow star); referenced sections (blue stars); and Deep Sea Drilling Project and Ocean Drilling Program wells (red stars), which penetrated halite deposits only at their uppermost part. **B:** Bathymetry map of Levant and surrounding area (Hall et al., 1994). Red polygon outlines three-dimensional seismic cube and well location.

of one deep-water (1600 m below sea level [mbsl]) commercial well (Fig. 1). The pre-evaporite interval was sampled every 9 m, totaling 35 samples. Following lithological and mineralogical description (scanning electron microscopy [SEM], X-ray diffraction [XRD]; Fig. DR3), samples were further investigated for biostratigraphy (Figs. 2 and 3; Fig. DR4). Total organic carbon (TOC) was measured using Rock-Eval 6 pyrolysis at Vinci Technologies (France) on a total of 24 samples (Fig. DR5).

## LITHOLOGICAL COMPOSITION RELATIVE TO PRESENT PARADIGM

Prior to our analysis, we expected two main alternatives for the lithological composition of the pre-evaporite section and the transition into the evaporite unit of the Levant Basin. The first is that of the generally accepted stratigraphic and depositional model of the MSC, in which the deep-basin pre-evaporites are coeval with the marginal gypsum deposits of the PLG and should consist of euxinic shales and/or dolostones (CIESM, 2008; Manzi et al., 2015; Roveri et al., 2014). The second is the presence of an unconformity with erosional features, similar, e.g., to the base of the MSC in nearby Cyprus. There, a composite “Lower Evaporite” unit

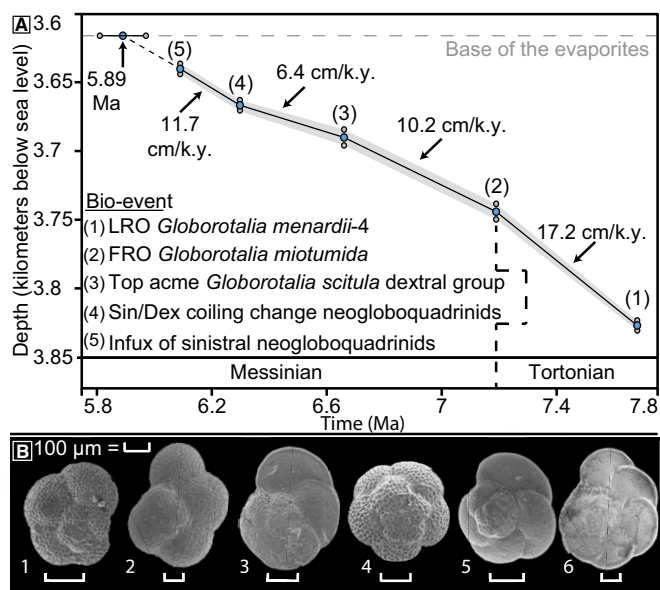
mainly consisting of gypsrudite and gypsarenite emplaced by gravity flows is described (Manzi et al., 2015). This unit is characterized by high lateral thickness variability and a regional-scale unconformity showing a strong erosional character locally associated with an angular discordance.

The pre-evaporite interval studied here (3885–3616 m below sea level [mbsl]; Fig. 3; Fig. DR1) is seismically characterized by subhorizontal and subparallel continuous high-amplitude reflections, implying a stratified and relatively undeformed marine succession. It is composed of fine-grained clastic ocean floor sediments, primarily shale. Minor amounts of white to light gray, hard limestone and very fine- to fine-grained consolidated sandstones are outlined in Figure 3. Shale samples are organic rich (>1 wt% TOC) and reach peak values of 4 wt% TOC immediately underlying the base of evaporite deposition (Fig. DR5). Lower values of GR are associated with silt- and carbonate-rich sediments, while higher GR corresponds to shale- and organic-rich sediments (Fig. 3). The main evaporite facies consists essentially of pure halite (Fig. DR3) overlying an ~2-m-thick basal anhydrite bed. This has been shown in the past using geophysical methods (Feng et al., 2016), and confirmed here using XRD and SEM analysis (Fig. DR3).

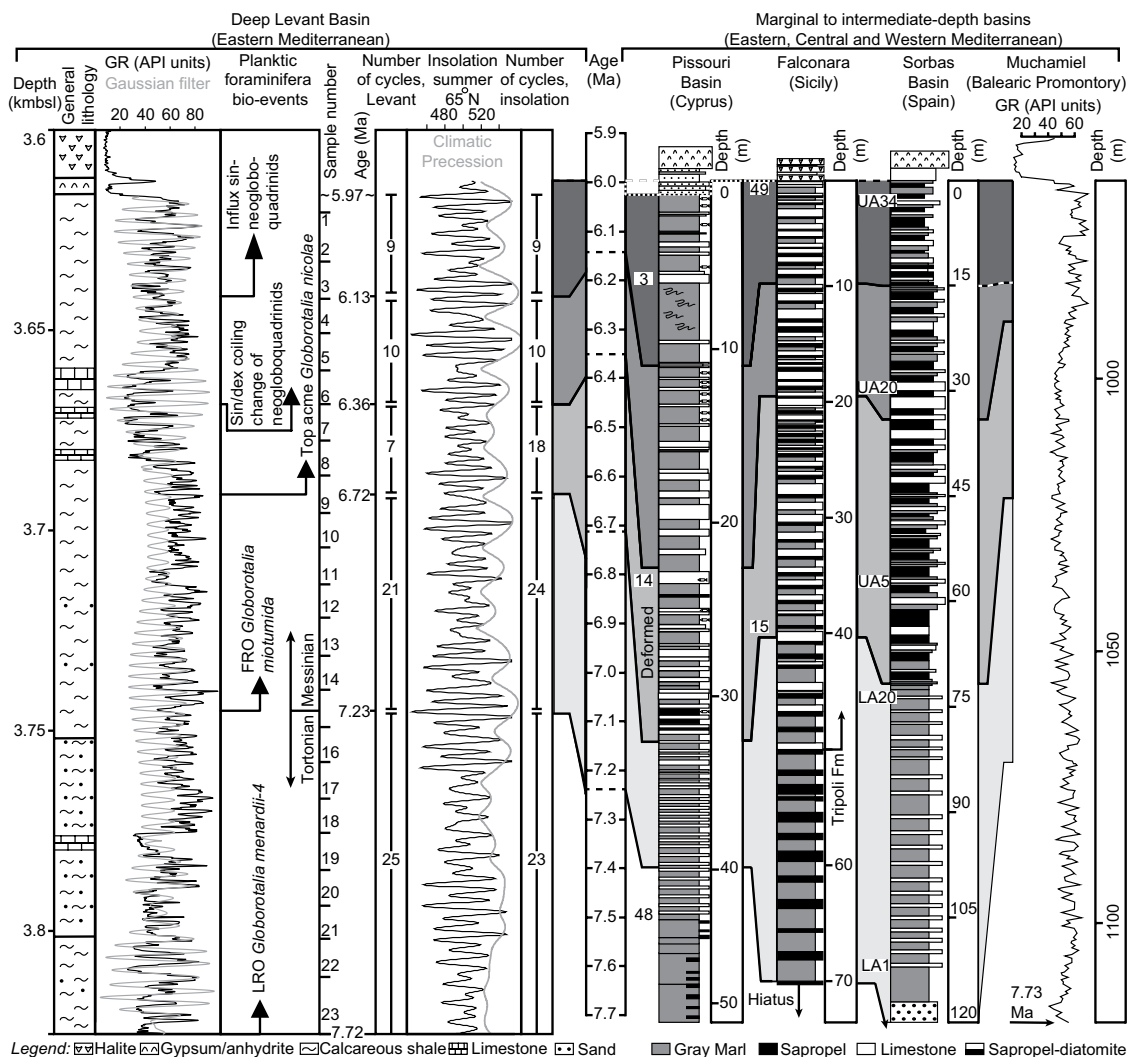
Consequently, our observations oppose a “chaotic” sedimentation and unconformity scenario for the base of the MSC in the deep Levant due to the consistent recovery of the drilled record, lack of any indication of truncation in the seismic section (Fig. 3; Fig. DR1), and no sedimentary evidence indicating substantial reworked or transported deposits in this interval. A stratigraphic investigation into the age and duration of the pre-evaporites provides further indication of continuous sedimentation across the base of the evaporites.

## BIOSTRATIGRAPHY AND ASTRONOMICAL TUNING

This study applies the Mediterranean planktonic foraminiferal biostratigraphic zonation of the late Tortonian to Messinian (Hilgen and Krijgsman, 1999; Hüsing et al., 2009; Krijgsman et al., 1999; Sierro et al., 2001). A number of reliable biostratigraphic events are recognized, providing five age calibration points as well as sedimentation rates for each of the dated intervals (Figs. 2 and 3; Fig. DR4; Table DR1 in the Data Repository). These events are, in stratigraphic order, the Last Regular Occurrence of *Globorotalia menardii*-4 (3827.5 mbsl; 7.718–7.726 Ma, mean 7.722 Ma), the First Regular Occurrence of *G. miotumida* (3745 m; 7.240–7.246 Ma, mean 7.243 Ma), the top acme of *G. scitula* dextral group (*G. nicolae*) (3691 m; 6.716–6.717 Ma, mean 6.716 Ma), the main sinistral-to-dextral coiling change in the neogloboquadrinids (3668 m; 6.348–6.377 Ma, mean 6.363 Ma), and the first influx of sinistral neogloboquadrinids above the main coiling change (3641 m; 6.11–6.144 Ma, mean 6.127 Ma). In addition, observed dominance of dextral coiled neogloboquadrinids in the uppermost two samples below the base of the evaporites (Table DR1) supports the age of 6.127 Ma for the underlying influx of sinistral coiled neogloboquadrinids (Fig. DR4). Moreover, the occurrence of foraminifera immediately underlying the base of the evaporites supports the notion that this interval is within “normal marine” settings, prior to the inhospitable high-salinity conditions.



**Figure 2. A:** Tortonian–Messinian age-depth curve based on planktonic foraminiferal bio-events, marked by blue circles and numbered according to bio-event legend. Mean sedimentation rates are shown for each interval. Gray boundaries represent depth uncertainty. Dashed line leads to extrapolated age of base of evaporites. Depth value used in this work is true vertical depth relative to mean sea level (TVDSS). **B:** Scanning electron microscopy images of planktonic foraminifera used for biostratigraphy: 1—*Neogloboquadrina* sp.; 2—*Sphaeroidinellopsis seminulina*; 3—*Globorotalia miotumida*; 4—*Globoquadrina altispira*; 5—*G. scitula*; 6—*G. menardii*-4. LRO—Last Regular Occurrence; FRO—First Regular Occurrence; Sin—sinistral; Dex—dextral.



**Figure 3. Lithology, well-log spectral analysis, biostratigraphic events, and astronomical tuning of pre-evaporites in the Levant, correlated to sections across the Mediterranean.** Note high correspondence between Levant well-log derived cycles and those appearing in the 65°N summer insolation curve (Laskar et al., 2004), other than the interval between 6.72 and 6.36 Ma (see discussion in text). While lithological sections are presented in depth domain, insolation curve is in time domain. Data from Cyprus (Krijgsman et al., 2002), Sicily (Hilgen and Krijgsman, 1999; Hüsing et al., 2009), Spain (Manzi et al., 2013; Sierro et al., 2001), and Balearic Promontory (Ochoa et al., 2015) include their own depth scale and cycle numbers as black text on white rectangles. Note synchronous onset of evaporite deposition across the Mediterranean from marginal through intermediate to deep basin. kmsl—km below sea level; GR—gamma ray; API—American Petroleum Institute; sin—sinistral; dex—dextral; FRO—First Regular Occurrence; LRO—Last Regular Occurrence.

Upward extrapolation of average sedimentation rates for the remaining 25.5 m from the last depth to which an age could be assigned (3641.5 m; 6.127 Ma) to the base of the evaporites, using the full range for the last two reliable bio-events (Fig. 2) and taking into account the depth uncertainty of the cutting samples, results in an age range of 5.98–5.81 Ma for the top of the pre-evaporites (Fig. DR4). These ages are, within uncertainty, consistent with the age of the top of the pre-evaporitic part of the Messinian elsewhere in the Mediterranean (Fig. 3).

Next, we used the GR well log for tuning our data to astronomical target curves (Laskar et al., 2004), calibrating between the two data sets with the biostratigraphic ages. The usage of well-log data for astronomical tuning of Tortonian–Messinian deposits has been demonstrated repeatedly by previous authors, and a phase relationship between sedimentary processes and orbital cycles has been shown to occur in Neogene sediments across the Mediterranean (Hilgen and Krijgsman, 1999; Ochoa et al., 2015; Sierro et al., 2000). Clay-rich sediments with higher organic content may be equivalent to sapropelic layers, which, according to these authors, formed at times of increased precipitation. Silt- and carbonate-rich sediments (low GR) are compatible with deposition under dry conditions, when runoff and terrigenous supply were reduced during precession maxima/summer insolation minima.

Spectral analyses of the log data from the base of the dated sediment section at 3825 m to the base of the evaporite unit at 3616 m indicates statistically significant periodical signals (Fig. DR2). According to our biostratigraphic age model, it is clear that the identified ~2.5 m cycle represents climatic precession. This cycle thickness was therefore used for fitting

Gaussian bandpass filters on the well log (Fig. 3). The results confirm our initial age model by indicating a very similar number of cycles filtered within most of the Levant pre-evaporite section and those of the 65°N summer insolation curve (Laskar et al., 2004), widely used for Miocene astronomical calibrations across the Mediterranean. The limestone-rich interval between 6.72 and 6.36 Ma is problematic, as fewer cycles seem to be present between bio-events 3 and 4 relative to other Mediterranean sections. This might be attributed to the lithological shift in this interval (Fig. 3). However, it seems that the discrepancy in the number of cycles in the 6.72–6.36 Ma time interval is a regional feature reported also by Krijgsman et al. (2002) from the Pissouri section in nearby Cyprus (Fig. 3).

## RECALIBRATING MEDITERRANEAN-WIDE CORRELATIONS

Considering that the top of the pre-evaporites represents an age consistent with 5.97 Ma, but significantly older than 5.6 Ma, leaves us with two different options for the age of the base of the salt unit. The current ideas about the MSC, with the salt being deposited in a short period of ~50 k.y. during the MSC acme (CIESM, 2008; Roveri et al., 2014), would imply a major hiatus of ~370 k.y. (i.e., missing the PLG equivalent unit) at the base of the salt. While an equivalent hiatus has been postulated by Manzi et al. (2015) for Cyprus, convincing arguments from the deep Levant Basin are missing. We consider a hiatus in the deep basin unlikely in view of the lateral continuity of seismic reflectors below and at the boundary itself (Fig. DR1), as also demonstrated repeatedly by published regional seismic sections (e.g., Feng et al., 2016; Roberts and Peace, 2007) and elsewhere in the deep domain of the Mediterranean (Lofi et



al., 2011). An astronomical calibrated age of ca. 5.97 Ma for both the top of the pre-evaporite and the base of evaporite facies was identified in other successions across the Mediterranean (Fig. 3), providing evidence for a major synchronous step in MSC development. Our results suggest therefore that the studied section is in fact conformal and salt formation began around the onset of the PLG in the marginal basins.

## REFORMING MEDITERRANEAN AND GLOBAL MODELS FOR EVAPORITE DEPOSITIONAL SYSTEMS

Models presented over the past 40 years concerning the offshore MSC deposits remained only speculative in the absence of a sedimentary record from the deep Mediterranean. Our analysis of cuttings and well-log data from recent industry drilling shows that halite started to precipitate in the deep basins at around the onset of the PLG at 5.97 Ma (Fig. 3). This precipitation progressively culminated into thick halite deposits in the deepest depocenters, as mapped by Steinberg et al. (2011). At that time, sea level was still high and the oceanic connection with the Atlantic prevailed (Flecker and Ellam, 2006). Our results do not exclude a possible evaporative drawdown and sea-level lowering at the acme of the MSC (Bertoni and Cartwright, 2007; Lofi et al., 2011; Ryan, 2008). However, the Levant record indicates that salt started to deposit in deep waters, so that deep-water settings occurred during at least a part of the salt emplacement. This calls for a different mechanism other than substantial desiccation for explaining the deep-basin deposition of halite.

A coeval initiation of basinal halite and marginal gypsum precipitation also calls for a revaluation of the commonly accepted stratigraphic models for the MSC (CIESM, 2008; Roveri et al., 2014), as well as of global-scale climatic and oceanographic models of the MSC, taking into account a possibly much older age for the initiation of halite deposition. A box model of the MSC has recently showed the possibility of synchronous deposition of deep-basin halite and shallower deposition of gypsum during Atlantic connectivity (Simon and Meijer, 2017). In this work, we prove for the first time using a sampled section of the Mediterranean that this scenario is correct, at least for the eastern part of the Mediterranean. Our data are not consistent with a scenario of desiccation prior to evaporite precipitation in the deep Mediterranean, adding a new physio-chemical alternative to our understanding of evaporite depositional systems.

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