

## Chronological constraints and consequences for the Messinian Salinity Crisis

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### ABSTRACT

The Messinian Salinity Crisis of the Mediterranean resulted from a complex interplay between tectonic gateway closure and climate evolution. Recent astrochronological constraints show that 1) the onset of Lower Gypsum at 5.96 Ma is not related to glacio-eustatic sealevel lowering but its timing can best be attributed to the influence of the 400-kyr eccentricity cycle on regional climate superimposed on a tectonic trend; 2) the evaporite cycles are controlled by precession induced regional climate changes rather than by obliquity forced glacio-eustatic sealevel change; 3) the main desiccation phase between the Lower and Upper Evaporites coincides with the twin peak glacials TG12-14 suggesting a glacio-eustatic control; 4) the Pliocene flooding of the Mediterranean is not related to a glacio-eustatic sealevel rise. Simple quantitative analyses were used to evaluate controversial water level scenarios for the Mediterranean "Lower Evaporites". The results indicate that a shallow-water scenario for the Lower Gypsum units would imply unrealistic salt thicknesses on the order of 3 km. Some outflow to the open ocean must have persisted, implying that the Mediterranean was a deep-water basin during Lower Gypsum formation. Potential precipitation of gypsum in the deep-Mediterranean basins will critically depend on the availability of oxygen and thus on the stratification of the water column. The model results furthermore indicate that the deep Mediterranean halite units could have been deposited under shallow conditions, assuming that they correspond to the ~80 kyr time interval between the onset of glacial TG12 and the termination of TG14, when Mediterranean outflow to the Atlantic was blocked.

### INTRODUCTION

The Messinian Salinity Crisis is recognized as one of the key events in Earth's history attracting a great deal of scientific interest and fueling imagination with huge waterfalls during the reflooding of the Mediterranean following desiccation. During the crisis vast amounts of evaporites were deposited when the Mediterranean became progressively isolated from the world ocean; these evaporites are locally sandwiched in between deep marine sediments of Tortonian and Zanclean (Pliocene) age. Scientific debate focused on whether the isolation of the Mediterranean was caused by a (dominant) tectonic or glacio-eustatic control and on the depositional environment of the evaporites (e.g. Clauzon *et al.*, 1996; Hsü *et al.*, 1977; Rouchy and Caruso, 2006; Roveri and Manzi, 2006). Controversies exist concerning the presence of deep versus shallow basins in the pre-Messinian Mediterranean and on deep versus shallow water during Messinian evaporite deposition. Geophysical observations of oceanic crust beneath the western Mediterranean, benthic

foraminiferal data showing deep-water species and geographical studies showing canyon formation at the margins have confirmed the deep basin hypothesis for the pre-Messinian setting. By contrast, the controversies on the depositional environment of the so-called “Lower Evaporites” units have yet not been resolved. It became increasingly clear that only a high-resolution age model based on astronomical tuning would provide the necessary means to unravel the intricate and fascinating history of the Messinian Salinity Crisis (Hilgen *et al.*, 2007; Sierro *et al.*, this volume).

### CHRONOLOGY FOR THE MESSINIAN IN THE MEDITERRANEAN BASIN

The classic Messinian sequence in the Mediterranean as described from Sicily (Decima and Wezel, 1973; see Roveri *et al.*, this volume) starts with cyclic alternations of open marine marls and sapropels, passes via diatomites into the Lower Evaporites (gypsum, evaporitic limestone and halite), and ends, above an erosional surface and sometimes angular unconformity, with the Upper Evaporites (gypsum, marls) and fresh to brackish water deposits of Lago Mare facies. Here we define the MSC as the interval of evaporite deposition and Lago Mare sedimentation in the Mediterranean.

#### Messinian pre-evaporite sequences

Continuous pre-evaporite sequences from all over the Mediterranean were subjected to integrated high-resolution stratigraphic studies in order to obtain a cyclostratigraphic framework and develop an astronomical age model that would allow accurate dating of the onset of the MSC. The first preliminary attempts were based on simple cycle counts in the successive lithostratigraphic units of the Mediterranean Messinian (Hilgen *et al.*, 1995; Vai, 1997). The tuning of the complete pre-evaporite Messinian resulted in an age of 7.25 Ma for the base of the Messinian and of 5.96 Ma for the onset of evaporite formation and, hence, the salinity crisis proper (Hilgen and Krijgsman, 1999; Krijgsman *et al.*, 1999a); these ages are now generally accepted. Cyclostratigraphic correlations between the Mediterranean sections are rather straightforward and were confirmed by high-resolution planktonic foraminiferal biostratigraphy (Figure 1). Astronomical tuning of Messinian pre-evaporite cycles to successive insolation peaks generally shows a good to excellent fit between the characteristic sedimentary cycle patterns and the astronomical target curve, including precession/obliquity interference patterns in the insolation curve (Hilgen and Krijgsman, 1999; Sierro *et al.*, 2001). Alternating thick/thin beds consistently correlate with high/low amplitude variations in insolation, proving that no sedimentary cycles are missing and that alternative correlations can be excluded. Additional paleoclimatic studies revealed that the sedimentary cycles of the Messinian pre-evaporites reflect - precession induced - changes in (circum) Mediterranean climate (e.g. Sierro *et al.*, 1999; and this volume).

#### The “Lower Evaporite” units

The resultant astrochronology shows that the transition to the evaporites occurs at exactly the same sedimentary cycle (Krijgsman *et al.*, 1999a). It proves that the MSC is a synchronous event over the entire Mediterranean, the onset of which is dated astronomically at  $5.96 \pm 0.02$  Ma. Cyclostratigraphically, the pre-evaporitic marl-sapropel cycles are replaced by gypsum-marl cycles of the Lower Gypsum, indicating that the evaporite cyclicity is related to precession controlled oscillations in (circum) Mediterranean climate as well. As a consequence, gypsum beds correspond to precession maxima (insolation minima) and relatively dry climate (Krijgsman *et al.*, 2001). The tuning of the evaporites themselves, proved to be more problematical, even though they are arranged in a cyclic fashion as well. This tuning, which is based on cycle counts rather than on cycle patterns, hinted at the presence of an hiatus of ~60-90 kyr in marginal basins during which sealevel was significantly lowered in the Mediterranean (Krijgsman *et al.*, 2001). The total amount of cycles in the Lower and Upper Evaporites also exclude an obliquity control and, hence, that glacio-eustatic sealevel changes are responsible for the evaporite cyclicity. The total number of evaporite (gypsum) cycles in the Lower Evaporites of Spain (17 cycles) and Italy (16 cycles) is in good agreement and implies a total duration of approximately 350-370 kyr. Deposition of the Lower Gypsum is thus independent of the paleogeographic and geodynamic setting of the individual basins. Moreover they require a continuously marine environment (see Lugli *et al.*, this volume), excluding a relative sea level fall exceeding the paleodepth of the marginal basins (i.e. < 200 m). It should be noted here that all the information on the Lower Evaporite units comes

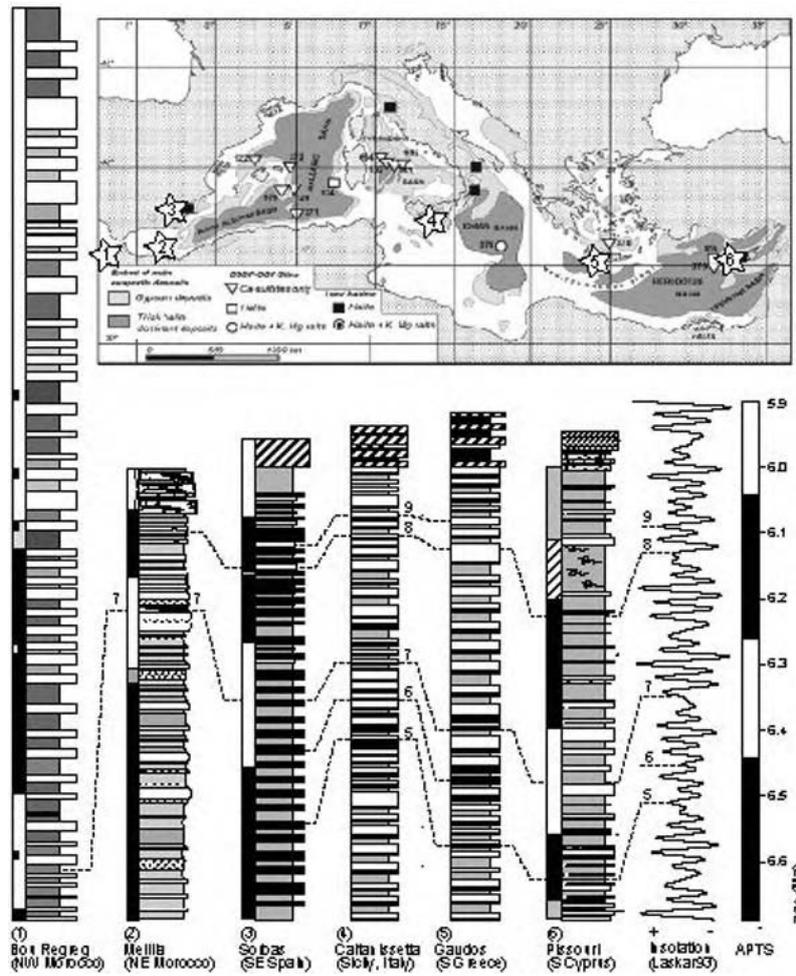


Fig. 1. Cyclostratigraphic correlation of the Messinian pre-evaporite sections of the Atlantic and Mediterranean on a W-E transect, and confirmed by biostratigraphic data (numbers correspond to biostratigraphic levels according to Krijgsman *et al.*, 1999a; 5=last occurrence (LO) *G. conomiozea* group, 6=first common occurrence (FCO) *Turborotalita multiloba*, 7=sinistral/dextral coiling change *Neogloboquadrina acostaensis*, 8=first influx sinistral neogloboquadrinids (90%), 9=second influx sinistral neogloboquadrinids (40%)). Inset map shows the locations of key sections used to construct the astrochronological framework for the Messinian: 1) Bou Regreg; 2) Melilla; 3) Sorbas; 4) Sicily; 5) Gaudos; 6) Cyprus. It also shows the distribution and extent of the Messinian evaporites in the Mediterranean with location of the DSDP-ODP sites that recovered evaporitic deposits (modified after Rouchy and Caruso, 2006).

from basins indicative of a marginal setting during the Messinian. Researchers have traditionally assigned the “N” reflectors (below the salt) as the deep basin equivalents of the marginal Lower Evaporites (Lofi *et al.*, 2005; and this volume), but there is thus far no direct evidence of repetitive gypsum/marl cycles in the very deep basins (e.g. Roveri and Manzi, 2006).

**The “Upper Evaporite” units**

Complete isolation and possible desiccation was only established after deposition of the Lower Gypsum, when the Mediterranean water level dropped more than 1,000 m as evidenced by incised canyons of the Rhone, Ebro, Po and Nile rivers in the Mediterranean margins. Deposition of the Upper Evaporite unit, overlying erosional surfaces, took place in a non-marine, deep Mediterranean basin forming a large Lago Mare. The post-evaporite units of the Mediterranean latest Messinian also display a marked cyclicity, comprising in general seven to eight sedimentary cycles. The total number of sedimentary cycles is in good agreement with the total number of precession peaks, whereas there is clearly not enough time for a 40 kyr obliquity control, thus excluding glacio-

eustasy. As the average periodicity for precession in Neogene times is 21.7 kyr, the Upper Evaporite units have a duration of approximately 175 kyr.

Unfortunately, the tuning of the Upper Evaporites is not fully certain because it is based on counting and tuning the number of supposedly precession related Upper Evaporite cycles from the Miocene-Pliocene boundary downward which itself is well tuned. Only the Upper Evaporites at Eraclea Minoa reveal a pattern that can be recognized in the astronomical target curve. Tentatively calibrating the post-evaporite cycles to the insolation curve leaves only a small “Messinian gap” (between 5.59 and 5.50 Ma) during which the desiccation of the Mediterranean, deposition of halite, and the accompanying isostatic rebound processes (tectonic tilting and erosion) must have occurred (Hilgen *et al.*, 2007).

Recent studies in northern Italy indicate that the Colombaccio Formation with its characteristic limestone beds that were initially listed as being the full equivalent of the Upper Evaporites, covers only a significantly reduced time span. It is now suggested that it corresponds to the younger part of the Upper Evaporites only (Roveri and Manzi, 2006). The older part of the Upper Evaporites is contained in part by the underlying Formazione di Tetto. This unit has been deposited in a deep basin equivalent of the marginal rimmed basins in which the Lower Evaporites were deposited. The older part of the post-evaporite sequences consists of reworked evaporites and supposedly covers the Messinian gap inferred from marginal basins, suggesting that the deep basins in Northern Italy did not experience any desiccation event (Roveri and Manzi, 2006).

## CONSEQUENCES FOR THE MESSINIAN SALINITY CRISIS SCENARIOS

### No glacio-eustatic control for the onset of the MSC

Although it was initially tempting to link the onset of evaporite formation to peak glacial stages TG20 and 22 as suggested by Hodell *et al.* (1994), improved age control showed that this is not the case (Hodell *et al.*, 2001). In fact the onset of the MSC evaporites at 5.96 Ma coincides with the glacio-eustatic sealevel rise following glacial stage TG32 and can be related to the influence of the 400-kyr eccentricity cycle on regional climate and, hence, Mediterranean water budget, which occurs superimposed on the ongoing trend in tectonic isolation of the basin. The isotope records in particular portrayed a late Messinian interval marked by heavy values and high-frequency fluctuations, the latter reflecting dominantly obliquity-controlled glacial cyclicity. The glacial series reveals two prominent peak glacials TG20 and 22 in the lower reversed Gilbert, with astronomical ages of 5.75 and 5.79 Ma. This interval corresponds to the *Globorotalia margaritae* acme in the Bou Regreg area (Krijgsman *et al.*, 2004). The glacial interval ends with two more distinct obliquity steered glacials TG12 and 14 (with astronomical ages of 5.548 and 5.582 Ma), followed by the marked stepwise deglaciation from TG12 to TG 9 (5.445 Ma) recognized in all oceanic basins. This deglaciation is associated with an overall glacio-eustatic sealevel rise; it is marked by invasions of the warm water planktonic foraminiferal species *Globorotalia menardii* and *Neogloboquadrina dutertrei* in the Bou Regreg area on the Atlantic side of Morocco and signifies a key event in Messinian paleoceanographic history (van der Laan *et al.*, 2006).

### Depositional environment of the Lower Evaporites

Knowing the chronology of the MSC events, we can quantitatively investigate by means of budget calculations the influence of the Mediterranean-Atlantic water connection on the depositional environment of the “Lower Evaporites” (see also Flecker, this volume). Since the Mediterranean is characterised by an excess of evaporation over precipitation and river input, complete disconnection from the Atlantic Ocean will lead to desiccation and evaporite deposition. Quantitative analysis of complete disconnection shows that, without inflow from the Atlantic Ocean, the sea level of the Mediterranean drops fast and will reach a level of –2,500 before 10 kyr (Meijer and Krijgsman, 2005). In addition, stable intermediate water levels would require a very specific and constant balance between inflow, precipitation, and evaporation. We can estimate the thickness of the deposit that would accumulate in the time span represented by the Lower Gypsum (i.e., at least 360 kyr) in a configuration of continuous inflow and fully blocked outflow. This scenario results in a fast initial rise of average salinity until halite saturation is reached (Figure 2). The blocked-outflow scenario is in conflict with data on the Lower Gypsum in several ways: (1)

halite formation is only slightly (<20 kyr) delayed with respect to gypsum accumulation, (2) the calculation predicts most of the sequence to consist of halite, and (3) the total model-predicted thickness of the evaporites is much larger than the 500-700 m estimated from seismic profiles (Lofi *et al.*, this volume). It follows that the deep-basin, shallow-water scenario can be regarded as unrealistic. The results of these calculation hint that it is likely that Mediterranean water was continuously able to flow back to the Atlantic, suggesting that no (major) sea level lowering took place at the onset of the Messinian Salinity Crisis and that the “Lower Evaporites” were consequently deposited in a deep-water Mediterranean basin. This scenario would require the Atlantic connection to become modified to such extent that inflow would still be able to continuously compensate for the net water loss in the Mediterranean, but that outflow of Mediterranean water (and salt) into the Atlantic becomes restricted. In that case, the amount of salt precipitation in the Mediterranean would critically depend on, amongst other factors, the amount of outflow, which is probably a direct consequence of the configuration of the Strait geometry, and on the amount of stratification in the Mediterranean (Meijer, 2006). In addition, the role of precession-induced changes in the freshwater budget must be addressed. Imagine we start from a Mediterranean basin in which the efficiency of transport through the Atlantic gateway has been reduced to such extent that the average basin salinity has reached a level halfway the middle of the gypsum saturation range (130-160 g/l). It can then be shown that a reduction of the freshwater loss to about  $0.75 \times$  the starting value (which we take to be the present-day value) would bring salinity below the range of gypsum saturation.

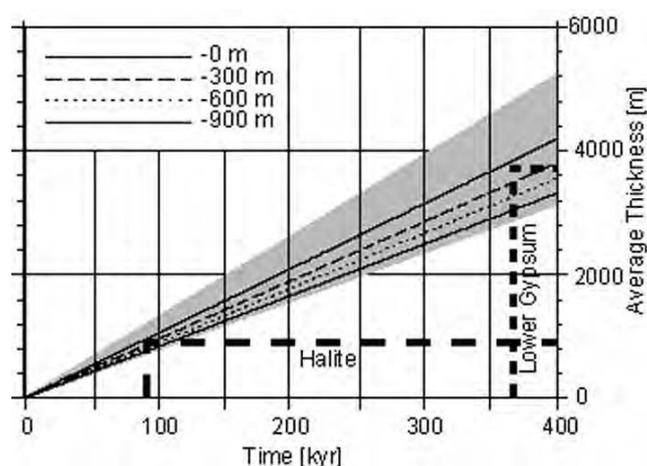


Fig. 2. Evaporite thickness as a function of time, calculated for the case of fully blocked outflow. The calculation has been done for a range of values for Mediterranean sea level. The solid line corresponds to sea level at the present-day position, the dashed lines to a sea level 300, 600 and 900 m lower. The shaded band comprises results for all intermediate positions of sea level. Estimated model thickness for Lower Gypsum and halite is according to our astrochronological ages.

### A glacio-eustatic cause for the Mediterranean desiccation phase

Increased time control suggested that the base of the Upper Evaporites is intimately linked with the beginning of the major stepwise deglaciation between TG12 and TG9 from 5.55 to 5.45 Ma, or more correctly to the first step of the deglaciation between 5.55 and 5.52 Ma (van der Laan *et al.*, 2006). This leaves the option that the hiatus, or so-called Messinian gap, between the Lower and Upper Evaporites observed in marginal basins is linked to the last two peak glacials TG12-14 of the Messinian glacial interval. The reason why glacio-eustatic sealevel lowering associated with twinned glacials TG14-12 resulted in the final desiccation of the Mediterranean rather than the even more prominent peak glacials TG22-20 is explained by the additional influence of the ongoing trend in tectonically driven/induced isolation. This scenario suggests a strong link between Messinian glacial history and associated glacio-eustatic sealevel change and the final desiccation/drawdown of the Mediterranean and the subsequent refill at the base of the Upper Evaporites and Lago Mare. If our correlation holds, it may explain why repetitive (marginal)

marine influxes are reported from the Lago Mare (Carnevale *et al.*, 2006), although indications exist that the dominant environmental conditions were not fully marine but dominantly hyposaline. In this way it may even be argued that the “Pliocene” flooding already started at the base of the Upper Evaporites. The exact duration of the deep Mediterranean halite deposits is still unclear, but the stratigraphic similarity with the Sicilian sequence suggests it is deposited between the “Lower” and “Upper Evaporites”. The resulting duration for the halite unit is consequently estimated at ~80 kyr which indicates a total thickness of ~1,000 m in the box model scenario (Figure 2). This is a rather realistic figure which indicates that Mediterranean-Atlantic return flow may have become cut off at the beginning of the Messinian halite deposits in the deep Mediterranean basins.

#### **End of the MSC: Pliocene flooding of the Mediterranean**

The Messinian glacial history and closing stages of the MSC made it tempting to link the Pliocene reflooding of the Mediterranean to a significant sea-level rise resulting from deglaciation. Hodell *et al.* (1994) incorrectly linked the main flooding event to the TG12-9 transition through linear extrapolation of the sedimentation rate in the Salé drill hole. However increased time constraints revealed that the M/P boundary was significantly younger. Suc *et al.* (1997) therefore attributed the Pliocene flooding to the abrupt deglaciation associated with TG5 which occurs in the M/P boundary interval and is particularly evident in the record from ODP site 846 (Shackleton *et al.*, 1995b). Close inspection of the benthic isotope record of the Loulja section (Bou Regreg area) tuned to precession revealed that the M/P boundary (as currently formally defined in the Mediterranean) does not coincide with any major deglaciation (van der Laan *et al.*, 2006). This outcome renders credibility to alternative scenarios such as the headward erosion of fluvial incisions in the Gibraltar area (Blanc, 2002; Loget *et al.*, 2006). It is also consistent with indications for marine influences in the Lower Evaporites.

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