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# A modeling perspective on spatial and temporal variations in Messinian evaporite deposits

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ABSTRACT

During the Messinian Salinity Crisis (MSC), evaporite-dominated sequences formed in marginal and deep basins of the Mediterranean Sea. In the marginal basins, the onset of the MSC is synchronous and a single depositional framework fits all sequences. In contrast, MSC sequences of the western and eastern deep basins appear to comprise a different number of units and differ greatly in thickness. Even though there exist numerous scenarios for deposition in the marginal and deep basins, the link between the two settings is difficult and scenarios are rarely quantitatively supported. We employ a simple box model for the Messinian Mediterranean to examine the causes of (1) spatial variation in thickness and (2) differences in the time of onset of deposition. Model results are compared with actual observations on the MSC sequences. The results show that a large connection between the western and eastern basin is necessary for, and some degree of water column stratification is conducive to, synchronous onset of the MSC in the marginal basins. Moreover, halite deposits in the deep basins are likely to be coeval and have formed in ≈60 ka after a (further) restriction of the Atlantic–Mediterranean connection during the MSC, but without a significant sea level drop. A difference in the net salt gain per unit volume caused the different halite deposition rates in the two basins. A scenario with only a simple restriction of the Atlantic–Mediterranean connection during the Late Miocene – without significant changes in the Mediterranean sea level, the fresh water budget, or the size of the Strait of Sicily – is able to explain the synchronous onset of the MSC, the synchronous marginal evaporite formation and the differences in the deep basinal sequences.



## 1. Introduction

During the Messinian Salinity Crisis (MSC, 5.96–5.33 Ma Lourens et al., 1996; Krijgsman et al., 1999) deposition took place in two distinct settings in the Mediterranean: marginal and deep basins. In (former) marginal basins all around the Mediterranean, Messinian sequences start with up to 16 distinct cycles of gypsum intercalated with marl/carbonates. A duration of ≈360 ka has been calculated for their formation by linking the cycles to precession driven climate changes (Krijgsman et al., 1999). This first phase of the MSC, the so-called Primary Lower Gypsum phase (PLG, 5.96–5.61 Ma), is followed by the second phase of the MSC, the halite phase (5.61–5.55 Ma) which is characterized by widespread erosion of the PLG deposits, redeposition of the eroded gypsum, and formation of a halite unit in deep marginal basins in Sicily, Calabria and Cyprus (Roveri et al., 2008a). The third and last phase recognized in marginal basins is the Upper Evaporite phase (5.55–5.33 Ma) which generally consists of non-evaporitic shallow marine deposits and the brackish water Lago Mare deposits, but is named after local primary gypsum deposits in Sicily.

In the archetypal deep basin setting of the Gulf of Lions, the seismically-imaged Messinian sequence also consists of three evident units which have been tentatively matched with the marginal basin units: the Lower Unit, the Mobile Unit which consists of halite, and the Upper Unit (Lofi et al., 2005). A fourth unit, the Chaotic Unit, is a diachronous unit thought to consist of marginal erosion products (Lofi and Berné, 2008). This deep basin trilogy, however, is not representative for both the western (WMed) and the eastern Mediterranean (EMed) basin. Differences between the WMed and EMed deep basinal sequences encompass (1) the presence of the Lower and Upper Unit in the WMed, which are thought to be absent or merely locally developed in the EMed, (2) large differences in the total thickness of the MSC sequences and (3) an internal layering in the Mobile Unit of only the EMed. õAlthough recognized as one of the outstanding issues of the Messinian Salinity Crisis (CIESM, 2008), these differences are as yet unexplained. The presence of sill(s) between the Mediterranean basins and differences in local climate and river discharge have been postulated as possible explanations. However, thus far, these postulates have endured without any quantitative support.

Contrary to the differences in deep basinal settings, the MSC record of the PLG phase in marginal basins is very similar. Cyclostratigraphy has shown the onset of gypsum deposition to be synchronous among marginal basins throughout the Mediterranean (Krijgsman et al., 1999).

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Recently, a new facies interpretation of the PLG deposits and the redefined stratigraphic position(s) of the Calcare di Base deposits have led to the proposition of a single depositional framework for all Mediterranean marginal basins (Lugli et al., 2010; Manzi et al., 2011) explaining the similarities in the PLG deposits.

Can we arrive at a scenario, based on physics and in a quantified fashion, that links the deposits from the marginal basins, similar in WMed and EMed, to the deep basin sequences, which strongly differ between WMed and EMed? Using a relatively simple box model of the Late Miocene Mediterranean, we will examine the factors controlling (1) the timing of onset of gypsum and halite deposition, (2) the duration of halite deposition, and (3) the evaporite thicknesses formed in the WMed and EMed basins individually. Factors studied are the restriction in the Atlantic Mediterranean connection (AMC) and in the Strait of Sicily, the strength of water column stratification, and changes in the amount of river input received by the two basins. By comparing model results with observational constraints on the timing of onset of gypsum deposition, gypsum thicknesses, and halite thicknesses, we will provide quantitative constraints on the role of sills, climate and the influence of water column stratification during the first two phases of the MSC.

The next section will describe the observations used to constrain the model results. Despite the fact that the model used is relatively simple in setup, the results are not simple and will be introduced gradually in the following sections: Section 3 describes the basic setup of the model and its boundary conditions, Section 4.1 gives a general overview of the mechanisms affecting the model results before Sections 4.2 and 4.3 focus on the application to the MSC. The results are followed by a discussion of the implications of the model results on the MSC in Section 5.

## 2. Observational constraints

### 2.1. Sea level

The synchronous onset of PLG deposition across basins with different palaeogeographical and geodynamic settings (Krijgsman et al., 1999), the facies of the gypsum (Lugli et al., 2010), and the absence of erosional features (Roveri et al., 2008b), indicate a fully subaqueous environment during the whole PLG phase. This implicitly rules out any sea level drop larger than the depth of the marginal basins (≈200 m) during this time interval (Krijgsman et al., 1999).

After deposition of the PLG, marginal sequences all have an erosional surface, the well-known Messinian Erosion Surface, topping the primary gypsum deposits, suggesting either tectonic uplift in a Mediterranean-wide tectonic phase (CIESM, 2008), a sea level drop exceeding the depth of the marginal basins, or a combination of both. The thickness of the halite sequences in the Sicilian foredeep basins, postdating the PLG phase, and the lack of subaerial erosion features in Apennine deep(er) water settings suggest sea level lowering was also modest during their deposition. The volume of deep basinal halite deposits, which cannot be explained without a supply of salt from the Atlantic, is another argument for a basin at global sea level during (at least part of) the halite phase (Krijgsman and Meijer, 2008; Topper et al., 2011).

Hence, observational evidence for the PLG and halite phase, the first ≈410 ka of the MSC, allows for the assumption of a constant sea level.

### 2.2. Marginal basins

The synchronous onset of gypsum deposition in both Mediterranean basins has been established by Krijgsman et al. (1999, 2002) with an uncertainty of one precessional cycle (≈20 ka). Strictly speaking, the lack of gypsum in the first depositional cycles of some Apennine basins means that the onset is diachronous (Dela Pierre et al., 2011). However, this seems to be the local effect of a relatively large continental runoff in a restricted basin (Lugli et al., 2010). The fact that gypsum is present in younger depositional cycles suggests that either an increasing Mediterranean salinity was able to overcome the dilution by continental runoff, or the runoff decreased during the PLG phase. As a constraint on the model results we will use the synchronous character of the first occurrence of gypsum in WMed and EMed marginal basins.

The thickness of the PLG deposits varies significantly among sequences between, but also within, the WMed and EMed. The largest observed thickness of PLG deposits in the WMed, 130 m, is near Sorbas (Krijgsman et al., 2001; Braga et al., 2006); for the EMed, this is 227 m in the Vena del Gesso (Lugli et al., 2007). In other marginal sections only several tens of meters or no primary gypsum at all is preserved (e.g. Fortuin and Krijgsman, 2003; Matano et al., 2005). Because of the large lateral variation, due to differences in deposition and preservation/erosion, we will only use gypsum thickness observations as an order-of-magnitude constraint on the model results.

### 2.3. Deep basins

When linking the marginal sequence to the deep basinal sequence, the Lower Unit is often taken as the equivalent of the marginal PLG. However, the nature and age of the Lower Unit are still unknown (Lofi et al., 2005). The Lower Unit is clearly distinct from the underlying sequence of supposedly earlier Miocene age (Lofi, pers. comm.), but only visible in the Gulf of Lions and probably the Algerian margin (Lofi et al., 2011). At a basinal scale, the extent and thickness are unknown. Lower Unit thickness estimates depend strongly on the lithology chosen for time-to-thickness conversion of the seismics. Thicknesses calculated with an assumed gypsum lithology are higher than for shale/clastics because of gypsum's higher seismic velocity (Lofi et al., 2005).

Deposits of the Chaotic Unit laterally grading into the Lower Unit, suggest that the Lower Unit may also be an erosional product from the margin. In this view, coarse material of the Chaotic Unit is deposited in a proximal position, while fine material in more distal positions gives rise to the parallel seismic reflections of the Lower Unit (Lofi et al., 2011). If true, the WMed deep basin trilogy would reduce to a bipartite sequence with no obvious equivalent of the marginal PLG, but only a Mobile Unit and an Upper Unit. Continuing this line of thought, the only difference between the deep basinal sequences of the WMed and EMed would be the thickness of the Mobile Unit, which is higher in the EMed, and the thickness of the Upper Unit, which is below seismic resolution in the EMed. This postulate matches well with the idea of primary gypsum formation only in the marginal basins (Manzi et al., 2007); a mechanism explaining the absence of gypsum formation in the deep basins has already been proposed (de Lange and Krijgsman, 2010).

The unknown nature and extent of the Lower Unit makes it impossible to put constraints on either the gypsum volume or the thickness as deposited during the first phase of the MSC. The synchronous onset of PLG formation in both basins, as observed in the marginal basins, remains the only constraint for the first 360 ka of the MSC.

Putting absolute age constraints on the deep basinal halites is difficult. Bottom and top erosional surfaces in the deep WMed and EMed are, in all probability, coeval because they are linked to the fast processes of partial desiccation and refilling of the Mediterranean (Meijer and Krijgsman, 2005; Garcia-Castellanos et al., 2009). Therefore, units enclosed between bottom and top erosional surfaces must have been deposited during the sea level lowstand of the MSC. However, the halites in both the WMed and EMed are in between the deep water continuations of these erosional surfaces. These surfaces are conformable and enclose the entire MSC sequence (Lofi et al., 2011). Based on these surfaces alone, the age of the halites can only be constrained to somewhere within the MSC interval.

If the deep basinal halites are time equivalent with the Sicilian halites, their deposition can be placed between the top of the PLG (≈5.61 Ma) and the start of the Upper Evaporites (≈5.55 Ma). This