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Depositional environments of the Mediterranean “Lower Evaporites” of the Messinian salinity crisis: Constraints from quantitative analyses

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ABSTRACT

We use simple quantitative analyses to evaluate controversial water level scenarios for the Mediterranean “Lower Evaporites” of the Messinian salinity crisis. Our results indicate that a shallow-water scenario for the Lower Gypsum units – with Mediterranean water level lower than the sill at Gibraltar – 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. Since glacio-eustatic fluctuations do not seem to have had a major influence on Lower Gypsum deposits, Mediterranean water level was even substantially higher than the Gibraltar sill. Our analyses furthermore show that precessional changes in the freshwater budget may explain the observed cyclic lithological changes of gypsum and non-evaporitic sediments. Potential precipitation of gypsum in the deep Mediterranean basins would have critically depended on the availability of oxygen and thus on the stratification of the water column. Finally, our results indicate that the deep Mediterranean halite units could have been deposited under shallow conditions, assuming that they correspond to the ~70 kyr time interval between glacials TG12 and TG14, when Mediterranean outflow to the Atlantic was blocked.

1. Introduction

The depositional environment of the evaporites that have been deposited all over the Mediterranean basin during the Messinian salinity crisis (MSC) has been discussed from the time of their discovery until today (e.g. Hsü et al., 1978; Clauzon et al., 1996; 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 (Hsü et al., 1973; Nesteroff, 1973). Geophysical observations of oceanic crust beneath the western Mediterranean (Montadert et al., 1978), biostratigraphical data revealing deep-water species (Hsü et al., 1978) and geographical studies showing canyon formation at the margins (Clauzon, 1973) have convincingly confirmed the deep-basin theory for the pre-Messinian setting. By contrast, the controversies on the depositional environment of the so-called “Lower and Upper Evaporites” units have yet not been resolved. Hypotheses for “Lower Evaporite” deposition (Fig. 1) range from: A) very shallow waters and major draw down (>1000 m) of the Mediterranean Messinian sea level (Hsü et al., 1973; Rouchy and Saint-Martin, 1992; Rouchy and Caruso, 2006), via B) shallow waters by a minor (~150 m) sea level lowering – with evaporite deposition only at silled marginal basins – (Clauzon et al., 1996; Roveri and Manzi, 2006), to C) hardly any sea level lowering and the Mediterranean water level similar to the Atlantic level (Krijgsman et al., 1999b; Lu, 2006).

The debate on the depositional environment of the MSC evaporites has so far mainly concentrated on paleontological, sedimentological, geochemical and geological field data and on correlations to the glacio-eustatic sea level curves, but the results and interpretations of many studies are not conclusive. One of the key issues related to the present Messinian debate concerns the lack of knowledge of the water exchange between the Atlantic Ocean and the Mediterranean. As is generally recognised, inflow of Atlantic water is essential to allow the formation of kilometre-thick evaporite sequences in the Mediterranean, but it is still unknown where and when these connections actually persisted (e.g. Krijgsman, 2002). Here we use simple quantitative analyses to explore some of the implications of different scenarios for evaporite deposition. The analyses give quantitative estimates of evaporite thickness and will be used to discuss the conflicting hypotheses for the depositional environment of the Lower Gypsum and halite deposits of the “Lower Evaporites” of the MSC.

2. Chronostratigraphy of the Messinian salinity crisis

The classic Messinian sequence in the Mediterranean as described from Sicily (Decima and Wezel, 1973) starts with cyclic alternations of

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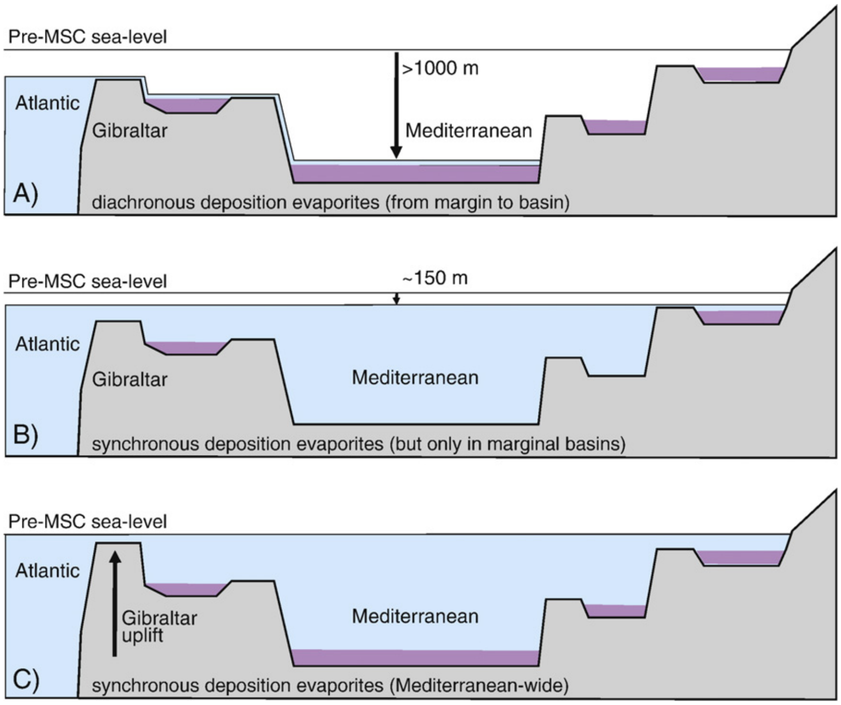
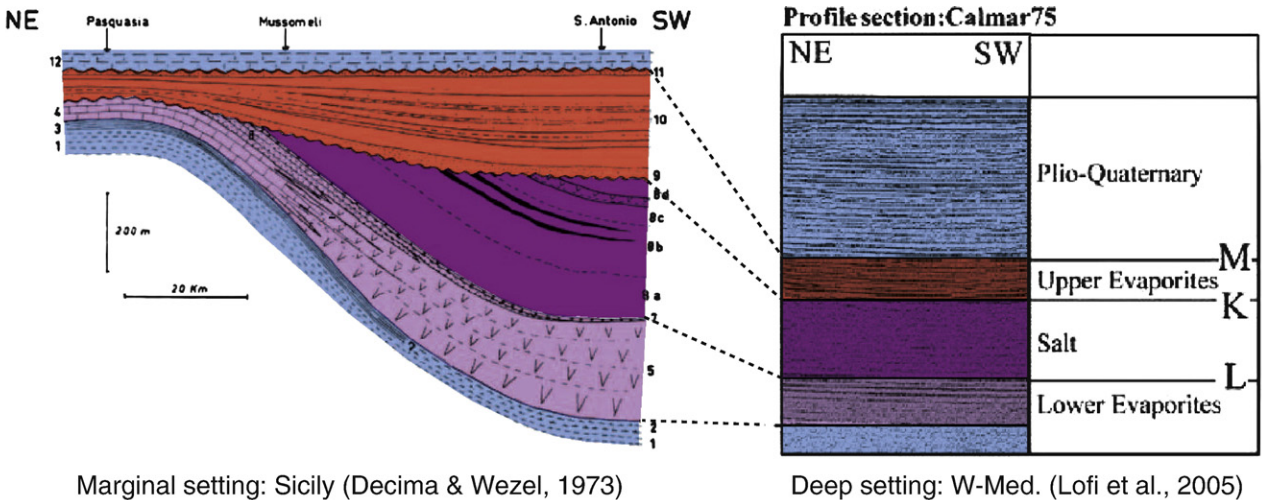


Fig. 1. Different scenarios for the depositional environment of the so-called "Lower Evaporites" of the Mediterranean Messinian Salinity Crisis. Hypotheses range from: A) very shallow water and major draw down (>1000 m) of the Messinian sea level (Hsü et al., 1973; Rouchy and Caruso, 2006), via B) shallow water achieved by a minor (~150 m) sea level lowering – with evaporite deposition only in marginal basins – (Clauzon et al., 1996; Roveri and Manzi, 2006), to C) hardly any sea level lowering, but uplift in the Gibraltar region, restricting exchange and a the Mediterranean water level similar to the Atlantic level (Krijgsman et al., 1999b; Lu, 2006).

open marine marls and sapropels, passes via diatomites into the "Lower Evaporites" (evaporitic limestone, gypsum, marls 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 (Fig. 2). The stratigraphic relationships between the Calcare di Base, Lower Gypsum and halite units of the "Lower Evaporites" are, however, not clearly defined and are still under revision (Roveri et al., 2006b). The Sicilian deposits have been regarded as examples of a deep basinal setting because paleobathymetric reconstructions of the pre-evaporite sections Falconara-Gibliscemi in the Caltanissetta Basin reveal water depths of approximately 1200 m in the early Messinian (Kouwenhoven et al., 2003). In addition, the seismic-facies interpretations of the evaporitic sequences of the deep west-Mediterranean basins exactly mimic the Sicilian sequence (Fig. 2: Lofi et al., 2005). The evaporitic succession of Sicily is therefore regarded as indicative for a relatively deep peripheral basin containing the best analogue MSC succession of the deep Mediterranean basins (Rouchy and Caruso, 2006). Researchers have traditionally assigned the reflectors below the salt as the deep basin equivalents of the "Lower Evaporites", but there is thus far no direct evidence of repetitive gypsum/marl cycles in the very deep basins (Lofi et al., 2005; Roveri and Manzi, 2006). The regional terminology may also create some confusion since the Sicilian "Lower Evaporites" comprise Lower Gypsum, Calcare di Base as well as halite (salt) units, while the term "Lower Evaporites" in the seismic profiles corresponds to the unit below the salt. It has



Marginal setting: Sicily (Decima & Wezel, 1973)

Deep setting: W-Med. (Lofi et al., 2005)

Fig. 2. Correlation of the evaporitic sequences of the Messinian on Sicily (after Decima and Wezel, 1973) to the seismic cross-sections of the deep western Mediterranean basins (after Lofi et al., 2005). Remind that the Sicilian "Lower Evaporites" comprise the Lower Gypsum, Calcare di Base and halite units, while the seismic "Lower Evaporites" only correspond to the unit below the halite.

furthermore been suggested that the “Lower Evaporites” on Sicily and in the seismic profiles comprise large elements of clastic sediments and reworked evaporites (Lofi et al., 2005; Roveri et al., 2006b; Ryan, 2007).

By contrast, the Sicilian “Lower and Upper Evaporites” units have alternatively been considered as relatively shallow marginal basin sequences, both entirely pre-dating the deep Mediterranean evaporites (Clauzon et al., 1996; Clauzon et al., 2005).

2.1. The Messinian pre-evaporites

The construction of an astronomical time scale for the Messinian (Hilgen et al., 1995; Krijgsman et al., 1999b) was a major step forward in the understanding of the depositional and paleoenvironmental processes leading to the crisis and solved many of the ongoing chronological controversies (Fig. 3). Astronomical tuning of the sedimentary cyclicity in the Messinian deposits allowed a direct

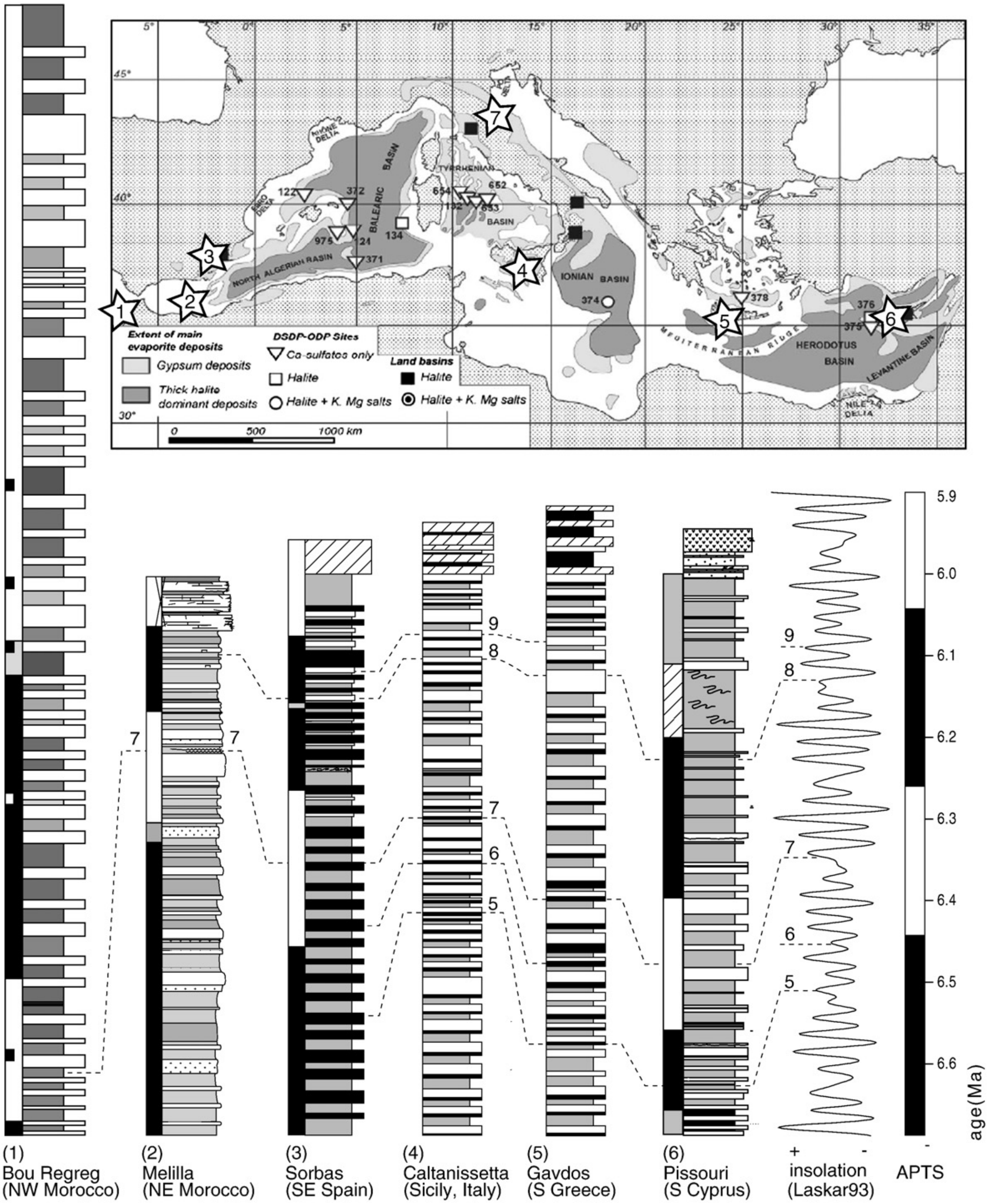


Fig. 3. Cyclostratigraphic correlation of the Messinian pre-evaporite sections of the Atlantic and Mediterranean on a W–E transect, and confirmed by biostratigraphic data. Inset map shows the locations of key sections used to construct the astrochronological framework for the Messinian: 1) Bou Regreg (Krijgsman et al., 2004); 2) Melilla (Van Assen et al., 2006); 3) Sorbas (Krijgsman et al., 1999b); 4) Sicily (Krijgsman et al., 1999b); 5) Gavdos (Krijgsman et al., 1999b); 6) Cyprus (Krijgsman et al., 2002; 7) Northern Apennines (Manzi et al., 2007) confirmed by biostratigraphic data (numbers correspond to biostratigraphic levels; 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 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).

comparison of MSC sequences all over the Mediterranean and of Mediterranean sequences to the Atlantic record (Hodell et al., 2001; Krijgsman et al., 2004). Detailed cyclostratigraphic, biostratigraphic and magnetostratigraphic investigations of the pre-evaporite sequences showed that the transition to evaporitic conditions occurred at 5.96±0.02 Ma, synchronously between the western and eastern Mediterranean (Krijgsman et al., 2002). Paleobathymetric estimates, based on benthic foraminifera from pre-evaporite sequences of various Mediterranean basins, indicate depths of 1200 m for the Caltanissetta basin (Kouwenhoven et al., 2003), 400 m for the Sorbas basin (Krijgsman et al., 2006), and between 200 and 400 for the Pissouri basin on Cyprus (Kouwenhoven et al., 2006). This suggests that the paleogeographic setting of the different Mediterranean subbasins was not a controlling factor for the timing of evaporite deposition. Messinian astrochronology furthermore showed that the onset of evaporite formation was not linked to peak glacial stages TG20–22 as earlier suggested (Hodell et al., 1994). In fact the onset of the MSC evaporites at 5.96 Ma coincides with the glacio-eustatic sea level 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 (Van der Laan et al., 2005; Hilgen et al., 2007).

2.2. The Lower Gypsum of the Messinian salinity crisis (5.96–5.59 Ma)

Age control on the MSC evaporites is less straightforward because biostratigraphy is hampered by harsh hypersaline environments and magnetostratigraphy is impossible since the entire evaporitic process occurred in a single reversed magnetic chron. The Lower Gypsum from the marginal settings have similar internal compositions and reveal a distinct sedimentary cyclicity (Dronkert, 1976; Vai and Ricci Lucchi, 1976). Cyclostratigraphic correlations provide comparable numbers of sedimentary cycles; ~17 cycles in the Sorbas basin of SE Spain and >16 cycles in the Vena del Gesso basin of NE Italy (Krijgsman et al., 2001). Cyclostratigraphically, the pre-evaporitic marl-sapropel cycles are

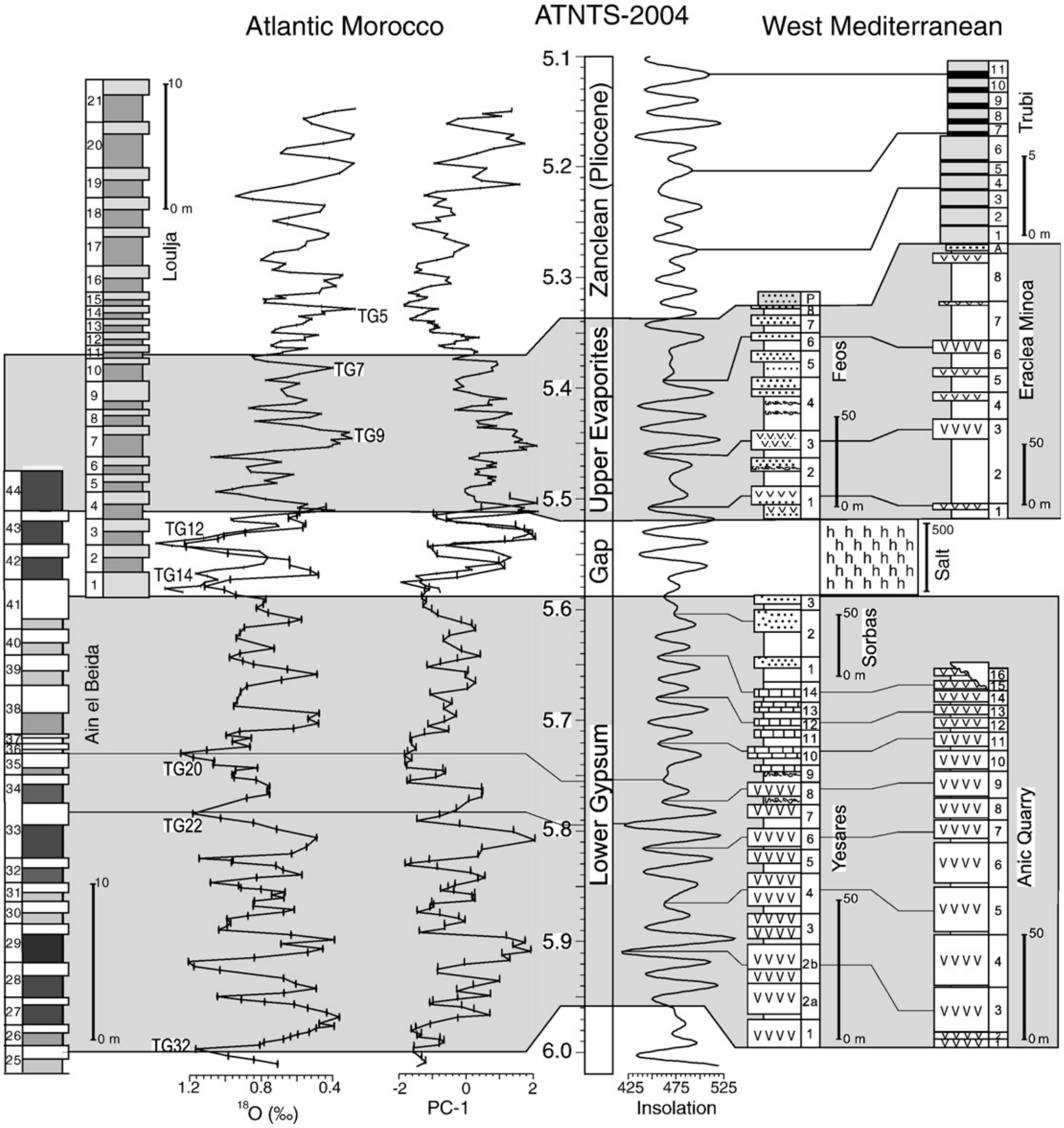


Fig. 4. Astronomical tuning of Messinian key sections located on the Atlantic margin of Morocco and in the Mediterranean (modified from Hilgen et al., 2007). The benthic oxygen isotope and geochemical (Principal Component of geochemical element (ICP) data) records of Ain el Beida (Van der Laan et al., 2005) and Loulja (Van der Laan et al., 2006) of the Moroccan Bou Regreg region (location 1 in Fig. 3) show the astronomical correlation of the marked glacial and interglacial stages. The Mediterranean sections of Yesares, Sorbas and Feos come from the Sorbas and Nijar basins of SE Spain (location 3) (Krijgsman et al., 2001; Fortuin and Krijgsman, 2003), the Anic Quarry (location 7) is in the Northern Apennines (Vai and Ricci Lucchi, 1976) and Eraclea Minoa (location 4) on Sicily (Lourens et al., 1996; Hilgen et al., 2007). Shading marks the intervals of Lower and Upper Evaporites, respectively. The deep halite unit corresponds to the Messinian Gap in the Mediterranean margins and is probably linked to the two peak glacials TG12 and 14 of the Messinian glacial interval (Van der Laan et al., 2005).

gradually replaced by gypsum-sapropel cycles of the Lower Gypsum unit, indicating that the evaporite cyclicity is related to precession-controlled oscillations in (circum) Mediterranean climate as well, with gypsum beds corresponding to precession maxima (insolation minima; Fig. 4) and relatively dry climate. The most logical tuning of these cyclostratigraphic patterns to the astronomical curves results in a total duration of ~360 kyr and an age of <5.6 Ma for the top of the Lower Gypsum, although this calibration is not as straightforward as for the pre-evaporites (Krijgsman et al., 2001; Hilgen et al., 2007). It must be noted here that these cyclostratigraphic age constraints have been derived from gypsum sequences of marginal settings. The Falconara section on Sicily, representative of a deep basinal setting, shows a transition to cyclic evaporitic dolostones of the Calcare di Base (e.g. McKenzie et al., 1979; Blanc-Valleron et al., 2002) at the age of 5.96 Ma (Krijgsman et al., 1999b). Deep settings in the Northern Apennines indicate deposition of anoxic shales, while Lower Gypsum precipitation took place at marginal settings (Manzi et al., 2005; Roveri et al., 2006a; Manzi et al., 2007).

2.3. The massive halite of the Messinian salinity crisis (5.59–5.52 Ma)

If the interpretations of the seismic profiles of the deep Mediterranean basins are correct (Fig. 2), the massive halite deposits, with clear evidence of desiccation in the upper levels of Sicily (Lugli et al., 1999), are entirely post-dating the Lower Gypsum evaporites and pre-dating the Upper Evaporites. The stratigraphic interval comprising the Upper Evaporites, up to the Pliocene flooding of the Mediterranean (5.33 Ma), consists of typical non-marine deposits displaying at least eight precession cycles (Fortuin and Krijgsman, 2003; Roveri et al., 2006a), although marine influxes have been reported as well (Carnevale et al., 2006). Tentative astronomical tuning of the Upper Evaporite sequences reveals that the massive halite units correspond to the time interval between ~5.59 and ~5.52 Ma (Fig. 4), linked to the last two peak glacials TG14–12 of the Messinian glacial interval (Van der Laan et al., 2005; Hilgen et al., 2007). The reason why glacio-eustatic sea level lowering associated with the twinned glacials TG14–12 may have resulted in the end of Lower Gypsum formation, rather than the even more prominent peak glacials TG22–20 is explained by the additional influence of the ongoing trend in tectonically driven isolation (Hilgen et al., 2007). The halite time interval is probably characterised by erosion and angular unconformities at marginal settings (Butler et al., 1995; Fortuin and Krijgsman, 2003; Roveri and Manzi, 2006) and by a more complex system comprising reworked clastic evaporites in northern Italy (Roveri et al., 2001; Manzi et al., 2005).

3. Quantitative analyses on the Mediterranean water and salt budget

Several studies have recently been directed to achieve quantitative modelling insight into the processes that played a role during the Messinian salinity crisis (Blanc, 2000; Meijer and Krijgsman, 2005; Blanc, 2006; Meijer, 2006; Gargani and Rigollet, 2007). In this paper, we will investigate by means of budget calculations the influence of the Mediterranean–Atlantic water connection on the depositional environment of the Lower Gypsum and halite of the MSC. The calculation focusses on the hypothesis that these units were deposited in a deep basin, shallow-water configuration of the Mediterranean (Fig. 1A; Hsü et al., 1973; Hsü et al., 1978; Rouchy and Saint-Martin, 1992; Rouchy and Caruso, 2006). According to the palaeobathymetric estimates that underlie the hypothesis, this “shallow-water environment” for the evaporites of Spain, Italy and Cyprus suggests Mediterranean water levels to be significantly below zero level. The exact level of the water column is not that relevant, more important is the notion that the Mediterranean sea level must have been far below the Atlantic level which allowed water and salt to come in but also implies water could not go out anymore. 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 quickly and reaches a level of −2500 in less than 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.

Here we estimate the thickness of the deposit that would accumulate in the time span represented by the Lower Gypsum unit (i.e., at least 360 kyr) in a configuration of continuous inflow and fully blocked outflow. This analysis may be considered an elaboration of remarks in the discussion in Meijer (2006). For the sake of simplicity the Mediterranean is considered a single basin and the present-day bathymetry is adopted. Taking also present-day values for evaporation, precipitation and river discharge it is straightforward to calculate the inflow of Atlantic water required to keep the Mediterranean sea surface at a given level. This inflow is then held fixed and assumed to continuously bring in water with a normal salinity of 35 g/l. In the Mediterranean basin the following is considered to take place: once the average salinity has reached the saturation value for gypsum (set at the average value of the gypsum saturation range of 130–160 g/l, i.e., 145 g/l) all subsequently incoming $CaSO_4$ is taken to be deposited as gypsum. Since $CaSO_4$ represents only a small fraction of the incoming salts the salinity will keep rising at nearly the same rate. At an average salinity of 350 g/l, saturation for halite is reached and all subsequent incoming NaCl is considered to precipitate on the seafloor. We use a typical composition of seawater as reported in Figure 3.18 of Leeder (1999). Incoming salt mass is converted to sediment thickness taking characteristic densities of gypsum and halite (2300 kg m^{-3} and 2200 kg m^{-3}, respectively) and assuming the precipitate to be distributed evenly across the entire water-covered area.

The results of the calculation are shown in Figs. 5 and 6 where Fig. 5 zooms in on the first 25 kyr. The top panel of Fig. 5 gives the evolution of

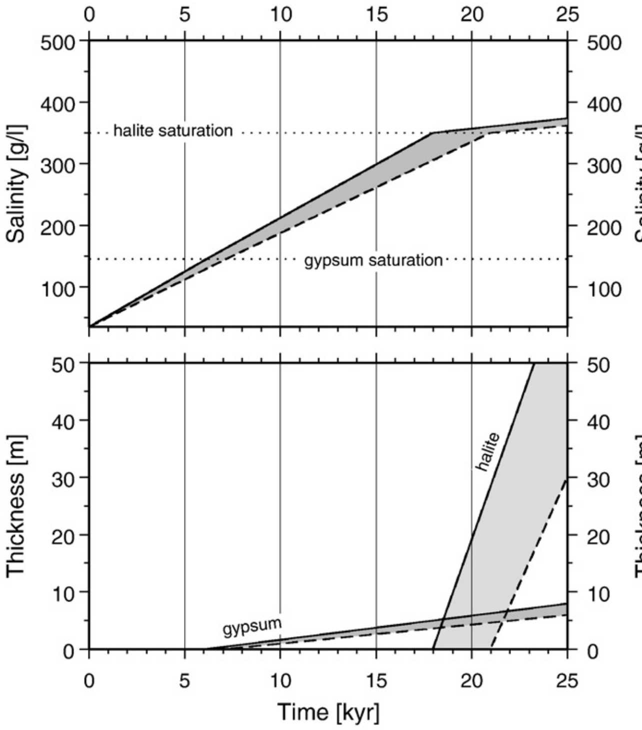


Fig. 5. Salinity (top panel) and evaporite thickness (bottom panel) as a function of time, calculated for the fully blocked-outflow scenario. The calculation has been done for a range of values for Mediterranean sea level. The solid line corresponds to sea level at the present-day position, the dashed line to a sea level 900 m lower. The shaded band comprises results for all intermediate sea level positions.

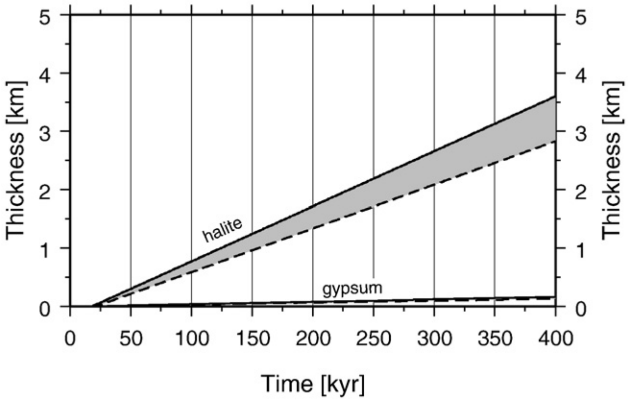


Fig. 6. As bottom panel of Fig. 5 but showing a longer time span.

average salinity and the bottom panel illustrates the growing average thickness of gypsum and halite. The calculation has been done holding sea level constant at its present-day position (solid lines) and under the assumption of stabilisation at lower levels: the bottom limit of each shaded band corresponds to stabilisation of sea level at 900 m below present; the shaded area comprises results for all intermediate sea level positions.

3.1. Depositional environment of the Lower Gypsum

The top panel of Fig. 5 shows a fast initial rise of average salinity until halite saturation is reached. As anticipated, the passing of gypsum saturation has no perceptible effect. Since the precipitation of salts more soluble than halite has not been incorporated, the average salinity increases steadily beyond the point of halite saturation. The bottom panel of Fig. 5 clearly shows the start of accumulation of gypsum and halite. As follows most clearly from Fig. 6, the blocked-outflow scenario here quantified 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 that most of the sequence consists of halite, and (3) the total model-predicted thickness (~3000 m) of the evaporites is much larger than observed in the field (100–150 m according to Dronkert, 1976 and Vai and Ricci Lucchi, 1976) and from seismics (maximum of 500–700 m including potentially reworked elements; e.g. Lofi et al. 2005 and minimum of 0 m assuming that deep settings only contain anoxic shales; e.g. Manzi et al. 2007). These conclusions can be shown not to be significantly affected by uncertainties in basin geometry and evaporite density. Adopting a value for net evaporation that is less than the present-day value leads to a reduction in the rate by which salinity increases with time and thus in a reduction in the thickness of evaporites that accumulate over a certain time span. However, the accumulated deposit will still be dominated by halite. One might suggest that perhaps net evaporation was so small that the average salinity passed the level of gypsum saturation but stayed below the level of halite saturation. To achieve this for the Lower Gypsum means to stay below halite saturation for a period up to 360 kyr. This is found to require a reduction of the net evaporation to about 5% of the present-day value. Reductions to this extent have recently indeed been argued on the basis of climate simulations for the Late Miocene (Gladstone et al., 2007). Were these low values of net evaporation persistent throughout deposition of the Lower Evaporites, however, the thickness of accumulated gypsum would only have been about 5 m, much less than is observed.

It follows from the above that the deep-basin, shallow-water scenario can be regarded as unrealistic (as previously pointed out by Sonnenfeld, 1985 and older work referred to in that paper). The results of our calculation hint that it is essential that Mediterranean water was continuously able to flow back to the Atlantic during Lower Gypsum formation. This would entail a larger inflow (compensating not only for net evaporation but also for the outflow) which would bring in $CaSO_4$ at a faster rate. At the same time, the presence of a return flow could keep salinity below the value of halite saturation.

3.2. Depositional environment of the massive halite

Although the exact duration of the deep Mediterranean halite deposits is still unclear, the stratigraphic similarity with the Sicilian sequence suggests it is deposited between the “Lower” and “Upper Gypsum”. Increased time control on the Atlantic isotope records suggests that this so-called “Messinian gap” between the Lower and Upper Gypsum observed in marginal basins, during which the massive halite was deposited in the deep basins, is linked to the last two peak glacials TG12–14 of the Messinian glacial interval (Van der Laan et al., 2005). The resulting duration for the halite unit is consequently estimated at ~70 kyr (Fig. 4). Our quantitative analysis of the blocked-outflow scenario indicates that in this period of time we may expect the accumulation of a halite mass equivalent to a uniform layer of about 700 m thick across the entire present-day basin floor (Fig. 6). The observed thickness of the halite unit in the seismics from the western Mediterranean basin is 600–1000 m, while at least 1500 m have been reported from the eastern Mediterranean basin (Lofi et al., 2005). Combined with the areal extent of halite as indicated by the distribution map of Rouchy and Caruso (2006; here reproduced at the top of Fig. 3), a thickness of 1000 m in the western basin and 1500 m in the eastern basin can be shown to be equivalent to a uniform layer, spread out across the entire present-day seafloor, of about 370 m. If instead we take a higher estimate reported in literature for the thickness in the eastern basin, 3500 m (e.g., Blanc, 2006), we find an equivalent uniform thickness of 715 m. These values are of the same order as found with our simple calculation of Fig. 5, which we interpret to indicate that, indeed, the scenario of fully blocked Mediterranean–Atlantic outflow could offer an explanation for the Messinian halite deposits. The model would need to be refined, for example by considering separate subbasins (as in Blanc, 2006), to warrant more detailed conclusions. Nevertheless, the fact that the calculated thickness is on the high side of the “observed” range (700 m versus 370–715 m), might indicate (1) that substantial erosion or dissolution of the evaporites has occurred, (2) that Mediterranean sea level was below the present level during halite deposition (see dashed line in Fig. 6), (3) that evaporation was less than here assumed (perhaps in response to the high concentration of salts in Mediterranean water), or (4) that halite formation took less time than the ~70 kyr here assumed.

4. Discussion

4.1. Restricted outflow scenario

The results of our model calculations show that no (major) sea level lowering took place at the onset of the MSC and that the Lower Gypsum units were consequently deposited in a deep-water Mediterranean basin (Fig. 1B and C) (Clauzon et al., 1996; Krijgsman et al., 1999b; Roveri et al., 2001). A deep-water model is furthermore in agreement with sedimentological observations of continuously subaqueous marine environments for the evaporites of Spain and Italy, excluding a relative sea level fall that exceeds the paleodepth of these basins (i.e. excluding a fall of more than 400 m). The deep-water 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. As a consequence, the salinity of the Mediterranean rises until it reaches the level where gypsum will precipitate from a giant Mediterranean-wide brine (Fig. 2C), or only at silled marginal basins

(Fig. 2B). A true box model of the restricted outflow scenario indicates that near complete separation from the Atlantic is required to reach saturation unless Mediterranean waters are strongly stratified (Meijer, 2006).

In the case of continuous inflow and restricted outflow, the amount of salt precipitation in the Mediterranean will critically depend on, amongst other factors, the amount of outflow, which is probably a direct consequence of the configuration of the strait, and on the amount of stratification in the Mediterranean (Meijer, 2006). Field evidence suggests that the distinct sedimentary cyclicity of the Lower Gypsum units is related to precession-controlled variations in regional climate. Since glacio-eustatic fluctuations do not seem to have had a major influence on Lower Gypsum cyclicity, Mediterranean water level must even have remained at a level substantially higher than the Gibraltar sill.

4.2. Processional forcing of the Mediterranean water budget

The possible role of precession-induced changes in the freshwater budget is addressed in Fig. 7. As a starting point we take, as in the above, the present-day basin shape and current freshwater budget. Next, we reduce the efficiency of transport through the connection to the Atlantic Ocean until the average salinity of the Mediterranean basin has reached gypsum saturation (the required reduction follows e.g. from Figure 6 of Meijer, 2006 and amounts to about 4 orders of magnitude). To be precise, we define a starting configuration in which Mediterranean salinity is stable in the middle of the range of gypsum saturation, 145 g/l. Keeping the efficiency of strait transport fixed, Fig. 6 shows how the average salinity of the Mediterranean varies as a function of the imposed net freshwater loss (i.e., evaporation minus precipitation minus river discharge, $E-P-R$). The latter variable is expressed as a fraction of the value in the starting configuration. Hence, the starting configuration itself corresponds to the point denoted by the diamond in Fig. 7: fraction of $E-P-R$ is unity and average salinity equals 145 g/l. It follows from Fig. 7 that a reduction of the freshwater loss to about 0.75× the starting value (i.e., 0.75× the present-day value) would bring salinity below the range of gypsum saturation. Variations to this extent are probably not too large to be associated to the precession cycle. Using an intermediate complexity climate model, Meijer and Tuenter (2007) find the net water loss from the Mediterranean Sea at precession minimum to amount to approximately 0.8× the present-day value. A reduction to this extent would bring salinity close to the lower limit of the saturation interval (see dashed line in Fig. 7). Fig. 7 thus illustrates that a precessional change in the freshwater budget may indeed result in cyclic sedimentation of gypsum and non-evaporitic sediments. Of course the reduction in freshwater loss required for non-evaporitic sedimentation is less when we assume the salinity in the starting configuration to have been closer to the lower limit of the gypsum saturation range.

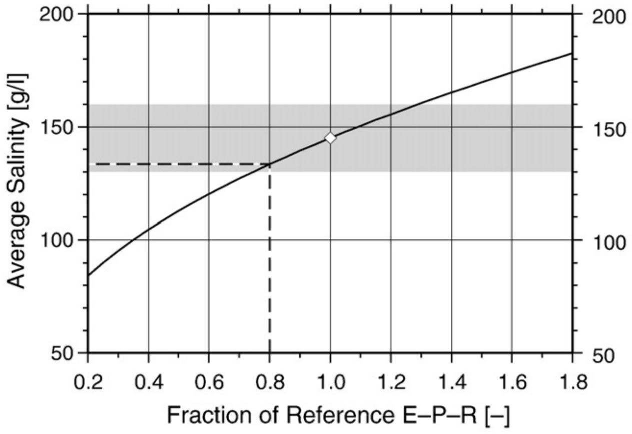


Fig. 7. Average salinity of the Mediterranean Sea as a function of the net freshwater loss for the case of severely restricted exchange with the Atlantic Ocean (i.e., both in- and outflow are restricted). The net freshwater loss; evaporation (E) minus precipitation (P) minus river input (R) is expressed as a fraction of the reference value which is defined as the present-day value. The efficiency of exchange with the Atlantic Ocean has been reduced to such extent that with the present-day net water loss (unity on the horizontal scale) the basin attains a salinity midway the gypsum saturation field (indicated by the diamond; the gypsum saturation field is shown by shading). The dashed line indicates the response to a reduction in net freshwater loss as may be approximately associated with the precession cycle.

4.3. Depositional environments in the deep Mediterranean basins

The remaining key question of the Messinian salinity crisis is what happened in the deep Mediterranean basins during marginal evaporite deposition? Detailed stratigraphic reconstructions in the Northern Apennines indicate that the Lower Gypsum of the Vena del Gesso has formed in a marginal basin, restricted by tectonic processes from a deep basin where deposition took place of mainly mud and clay, indicative of anoxic environments barren of biological activity (Roveri et al., 2001; Manzi et al., 2005; Roveri and Manzi, 2006). The Falconara (Sicily) and Metochia (Greece) sections, which are the key sections of the astronomical time frame for the Messinian salinity crisis, are considered to be of deep-water settings and also do not show gypsum deposits, but a transition to evaporitic limestones and dolostones (McKenzie et al., 1979; Krijgsman et al., 1999b; Blanc-Valleron et al., 2002).

Our modelling results indicate that the most logical scenario for the Lower Gypsum unit is evaporite formation occurring Mediterranean-wide, resulting from a Mediterranean with restricted outflow to the Atlantic. Evidence for the hypothesis of a 150 m sea level lowering, triggering the onset of the evaporites in marginal silled basins (Clauzon et al., 1996; Clauzon et al., 2005) is rather poor, especially since oxygen isotope records from the Atlantic show no evidence for any sea level fall at the corresponding age (Hodell et al., 2001; Krijgsman et al., 2004; Van der Laan et al., 2005). In contrast, the onset of the Lower Gypsum formation took place synchronously over the western and eastern Mediterranean basins at high sea level.

Evaporite formation was furthermore shown to critically depend on the geometry of the basin and especially on the 3D configuration of the sill (Meijer and Krijgsman, 2005). The onset of Lower Gypsum formation is recorded, at the same age, from relatively shallow-marine (200–400 m deep) paleoenvironments in the Sorbas/Nijar basins of southeast Spain (Krijgsman et al., 2001), the Vena del Gesso basin in the Northern Apennines (Krijgsman et al., 1999a; Roveri et al., 2001; Manzi et al., 2007), the marginal basins of Sicily (Roveri et al., 2006b), Greece and Cyprus (Krijgsman et al., 2002). This suggests that a change in the water and salt fluxes at the Mediterranean–Atlantic sill near Gibraltar was the dominant factor for Lower Gypsum precipitation. Otherwise, it requires similar sill geometries for all these subbasins, which we consider as highly unlikely.

The absence of gypsum in the deep settings could also be explained by the presence of anoxic paleoenvironments. Gypsum is a mineral composed of calcium sulfate dihydrate ($CaSO_4\,2H_2O$), so anoxic environments would be less favourable for gypsum precipitation and preservation than oxic environments (e.g. Sloss, 1969). Gypsum precipitation may thus have been restricted to relatively shallow levels in the Mediterranean basin, if the Mediterranean water column was stratified during Lower Gypsum deposition. This could also explain the precessional control for the sedimentary cyclicity of the Lower Gypsum, since the classic marl/sapropel cycles of the Messinian pre-evaporites also indicate that oxic/anoxic conditions (i.e. gypsum/no gypsum) changed with precession maxima/minima in all Mediterranean basins (Fig. 3).

The precipitation of gypsum from a Mediterranean brine could thus be related to the availability of oxygen and consequently to the stratification of the water column. This may provide another explanation for deposition of primary gypsum at relatively shallow environments only, and the absence of gypsum in the deeper anoxic levels, like in the Northern Apennines (Manzi et al., 2007). The sea level fall at the onset of halite precipitation has likely caused massive erosion of the marginal gypsum deposits, explaining the large amount of reworked evaporites in the deeper settings (Manzi et al., 2005; Roveri et al., 2006a,b), while silled marginal basins are the only places where the Lower Gypsum units were not removed by erosion.

5. Conclusions

Our simple quantitative analysis shows that unrealistic salt thicknesses on the order of 3 km should have been present in the Mediterranean subsurface, when deposition of the Lower Gypsum units (5.96–5.59 Ma) of the Messinian salinity crisis had taken place in shallow-water or blocked-outflow scenarios. We conclude that restricted outflow to the Atlantic Ocean must have persisted during Lower Gypsum formation, implying that the Mediterranean must have been a deep-water basin. The arguments for a shallow-water scenario mainly come from observations of marginal evaporites, and are not per definition in conflict with a deep-water scenario, since shallow-water environments evidently could have been present at marginal settings.

The restricted outflow scenario implies that Mediterranean water level remains in concert with the Atlantic at a level substantially higher than the Gibraltar sill, since glacio-eustatic fluctuations do not seem to have had a major influence on Lower Gypsym deposits. We furthermore calculate that the observed cyclic lithological changes of gypsum and non-evaporitic sediments may result from precessional changes in the freshwater budget.

Increased time control on the Atlantic isotope records suggests that the massive halite could be linked to the last two peak glacials TG12–14 of the Messinian glacial interval (~5.59–5.52), resulting in an approximate maximum duration of ~70 kyr (Van der Laan et al., 2005). Our quantitative analyses indicate that this would correspond to a thickness of ~700 m in the modelled scenarios of shallow water and blocked-outflow. This is in agreement with the observed thickness in seismic profiles, indicating that Mediterranean Atlantic outflow may have become cut off at the beginning of halite deposition.

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