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Mediterranean Sea level variations during the Messinian salinity crisis

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[1] The Mediterranean Basin has not always been connected to the Atlantic Ocean. During the Messinian salinity crisis (MSC), the Mediterranean Sea became progressively isolated by a complex combination of tectonic and glacio-eustatic processes. When isolated, the Mediterranean water level depends on the hydrological flux and is expected to vary significantly. The amplitude and number of large water level fluctuations in the isolated Mediterranean is still controversial, despite numerous geological investigations. The observation of 3–5 surfaces of erosion in the Nile delta (Eastern Basin) provides new elements for understanding the dynamics of the MSC. Our model demonstrates that numerous water level falls of short duration may explain the preservation of a discontinuous river profile at ~ -500 m and ~ -1500 m in the Western Basin, as well as the existence of deep surfaces of erosion in the Eastern Basin. **Citation:** Gargani, J., and C. Rigollet (2007), Mediterranean Sea level variations during the Messinian salinity crisis, *Geophys. Res. Lett.*, 34, L10405, doi:10.1029/2007GL029885.

1. Introduction

[2] The Messinian salinity crisis (MSC) is synchronous over the entire Mediterranean basin, dated to have started at 5.96 million years ago [Krijgsman *et al.*, 1999]. The beginning of the MSC does not correspond to a major peak in the open-ocean benthic $\delta^{18}\text{O}$ signal [Krijgsman *et al.*, 1999; Hodell *et al.*, 2001], which is commonly interpreted to reflect glacio-eustatic sea-level changes. The MSC was thus not associated with a major climate change [Warny *et al.*, 2003]. Furthermore, the tectonic uplift (~ 1 km) that was assumed to have occurred between 6.3 and 4.8 Myr ago in the area of the present Gibraltar Strait, argues in favour of a dominantly tectonic origin for the Messinian crisis [Duggen *et al.*, 2003]. Isolation from the Atlantic Ocean was established between 5.59 and 5.33 million years ago [Krijgsman *et al.*, 1999], causing a large fall in Mediterranean water level of 1500–2500 m [Ryan *et al.*, 1973; Barber, 1981; Clauzon, 1982; Guennoc *et al.*, 2000]. The MSC finished when eastward regressive erosion opened the Gibraltar Strait [Blanc, 2002]. Despite the progress in our knowledge about the chronology of the MSC, some uncertainties still exist. For instance, we don't know precisely the number of Mediterranean water level falls and their amplitude, during the isolation phase.

[3] Based on sedimentological analyses, seismic line observations and paleoriver reconstructions, it is suggested that at least two significant falls of Mediterranean water level [Rouchy and Saint-Martin, 1992] took place in the Western [Gargani, 2004; Lofi *et al.*, 2005] and in the Eastern [Druckman *et al.*, 1995] Basin. The amplitude of these sea level falls was estimated to be in the order of ~ 500 m and ~ 1500 m in the Western Basin, by analyses of the slope break of the paleorivers profiles [Gargani, 2004].

[4] Various erosional surfaces (3–5) are observed in seismic profiles along the Egyptian margin at a depth between -2500 and -3000 m (Figure 1). Considering the Plio-Quaternary subsidence that ranges between 750–1000 m (see Figure 1b), northwards of the Egyptian Hinge Line, these surfaces must have been formed during the MSC at a depth of 1500–2250 m beneath the present-day sea level of the Eastern Mediterranean basin. So far, these data are not explained by previous theories or models.

2. Model and Methods

[5] To understand the history of Mediterranean water level fluctuations in more detail, it is necessary to take into account precipitation, evaporation and river discharge [Blanc, 2000; Meijer and Krijgsman, 2005], but also eustatic variations and uplift rate of the threshold between the Atlantic Ocean and the Mediterranean Sea. Basically, the model sums the water inflow and outflow into the Mediterranean basins [Meijer and Krijgsman, 2005]. At a given time, the Mediterranean basin can be connected or not to the Atlantic Ocean. This depends from the sea level of the Atlantic Ocean $Z_{\text{Atlantic}}(t)$ and from the altitude of the threshold area $Z_{\text{threshold}}(t)$ between the Atlantic Ocean and the Mediterranean Sea. The glacio-eustatic variations $Z_{\text{Atlantic}}(t)$ are in competition with the uplift rate $U_{\text{threshold}}$ of the threshold area between the Atlantic Ocean and the Mediterranean Sea to allow the Atlantic water to flow into the Mediterranean Basin. If $Z_{\text{Atlantic}}(t) > Z_{\text{threshold}}(t)$ ($Z_{\text{threshold}}(t) = U_{\text{threshold}} \cdot t + Z_{\text{init}}$, where t is the time and Z_{init} the initial altitude of the threshold), the Mediterranean sea is connected to the Atlantic. In consequence, the Mediterranean Sea level is identical to the Atlantic Sea level $Z_{\text{Mediterranean}}(t) = Z_{\text{Atlantic}}(t)$. If $Z_{\text{Atlantic}}(t) < Z_{\text{threshold}}(t)$, the Mediterranean is isolated from the Atlantic. Under this condition, the Mediterranean Sea level $Z_{\text{Mediterranean}}(t)$ depends from the water budget. The water budget is calculated at each time step (1 kyr) taking into account the temporal variations of the water inflow (precipitation, river discharge) and outflow (evaporation). Basically, the variation of the volume of the Mediterranean is given by $\Delta V_{\text{Mediterranean}}(t) = [P(t) + E(t) - Q(t)] \cdot A(Z_{\text{Mediterranean}}(t)) \cdot t$, where $P(t)$, $Q(t)$ and $E(t)$ are respectively the precipitation rate, the river discharge and the evaporation rate by unit area. $A(Z_{\text{Mediterranean}}(t))$ is the area of the Mediterranean Sea

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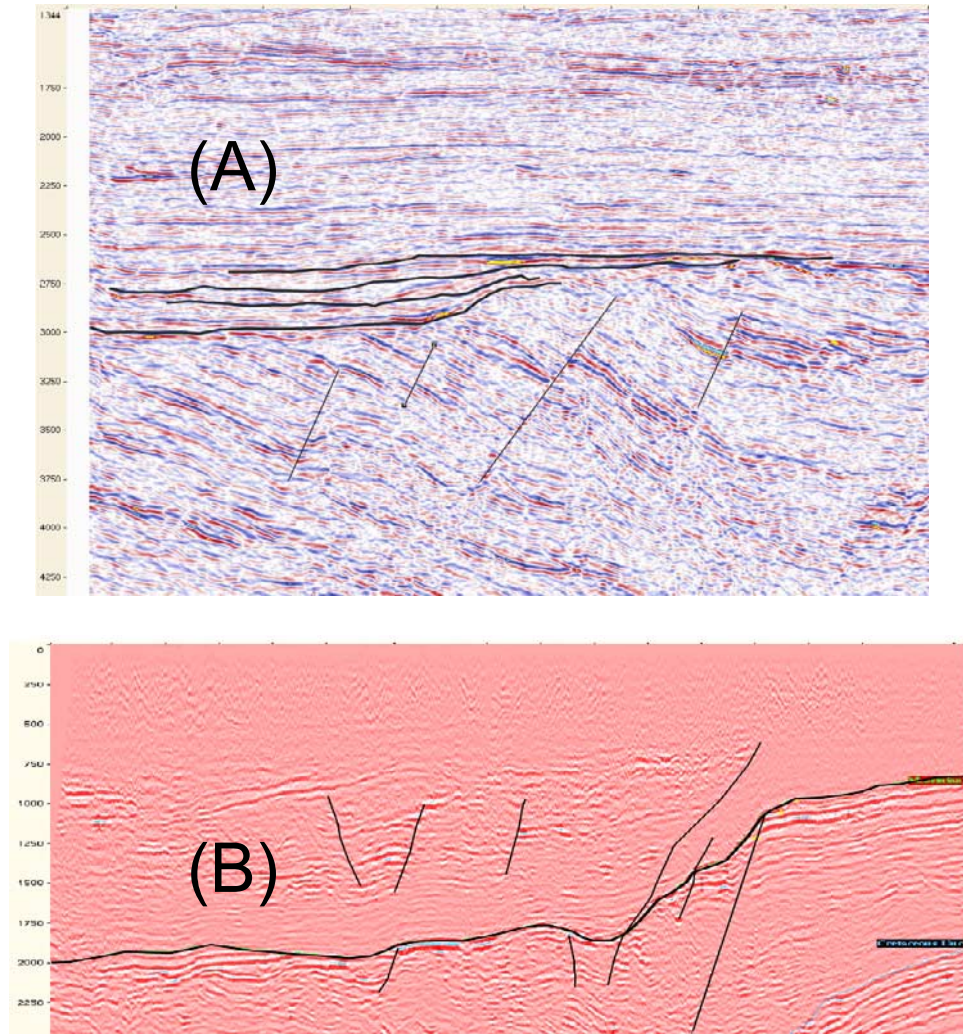


Figure 1. Seismic line of the Egyptian margin showing (a) surfaces of erosion (horizontal scale: 1 horizontal grid = 1250 m) and (b) the 750–1000 m of post messinian tectonic along the hinge line of the Egyptian margin (horizontal scale: 1 horizontal grid = 2000 m).

when the sea level is $Z_{\text{Mediterranean}}(t)$. The area of the Mediterranean Sea $A(Z_{\text{Mediterranean}}(t))$ is approximates by the linear relation:

$$A(Z_{\text{Mediterranean}}(t)) = (Z_{\text{Mediterranean}}(t) - Z_0)/a \quad (1)$$

where a and Z_0 are two constants. This approximation is close to the geometry used by *Meijer and Krijgsman* [2005]. Considering this geometry for the Mediterranean Basin, the area variation with time is of the form $A^2(Z_{\text{Mediterranean}}(t + 1)) = A^2(Z_{\text{Mediterranean}}(t)) - 2\Delta V_{\text{Mediterranean}}(t + 1)/a$. The Mediterranean sea level $Z_{\text{Mediterranean}}(t)$ is calculated at each time step using equation (1).

[6] The Western and the Eastern Basin may have become independent during water level lowstand, separated by the Sicily threshold $Z_{\text{Sicily-thr}}(t)$. When the sea level of the Western Basin is smaller than the Sicily threshold ($Z_{\text{W-Med}}(t) < Z_{\text{Sicily-thr}}(t)$), the variation of the sea level in the Western and Eastern Basins became independent. The area variations of the Western and

Eastern Basin are simulated respectively by the equations $A(Z_{\text{W-Med}}(t)) = (Z_{\text{W-Med}}(t) - Z_{0W})/a_W$ and $A(Z_{\text{E-Med}}(t)) = (Z_{\text{E-Med}}(t) - Z_{0E})/a_E$, where Z_{0W} , Z_{0E} , a_W , a_E are constants giving the geometry of the Western and Eastern Basins.

[7] Oxygen isotopic-based sea-level estimates for the open-ocean suggest variations of amplitude between -50 m and $+50$ m during the MSC [*Miller et al.*, 2005]. To model the temporal glacio-eustatic variations (open ocean) $Z_{\text{eustatic}}(t)$, an insolation curve is used [*Gargani et al.*, 2006] even if this approximation may produce some discrepancy with real sea level variation. The amplitude of the simulated glacio-eustatic variation is comprised between -50 m and $+50$ m.

[8] The hydrological flux (precipitation, evaporation) estimated by a palynological analysis for the Messinian times [*Fauquette et al.*, 1999; *Fauquette et al.*, 2006] suggests that climatic and hydrological conditions are close to the present one. It is not necessary to suppose extreme hydrological fluxes to obtain a significant water level fall. A value comprised between 0.5 and 1 m/yr for Evaporation

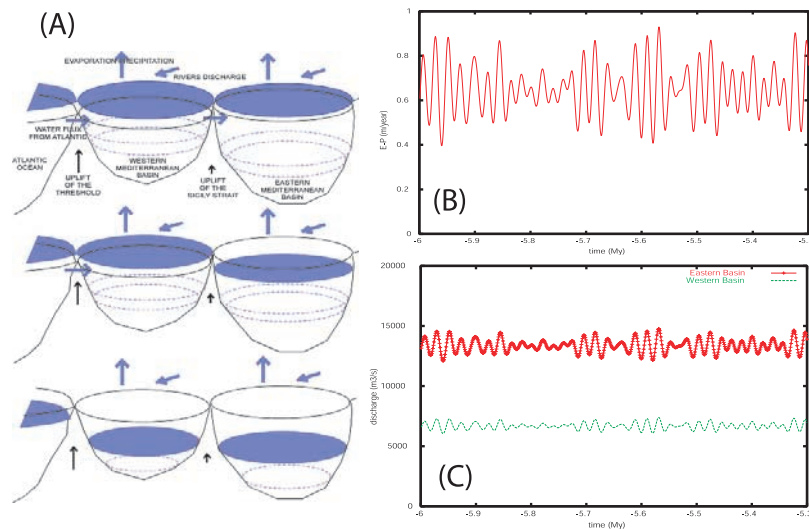


Figure 2. As no major climate change has been documented during the MSC [Warny *et al.*, 2003], the same range of value can be considered for the evaporation, precipitation, and rivers discharge during the MSC as during the present time. Small climatic variations can be expected, due to the variation of insolation, as during the Quaternary times. We use the insolation curve (65°N, July 1st) to simulate the temporal variation of open ocean sea level as well as of E-P (Evaporation-Precipitation) and the variation of river discharge [Gargani *et al.*, 2006]. We assume that the variations of the hydrological flux with time, due to global climate change, are no more than 25% from the present value. (a) Conceptual model. (b) Evaporation E minus Pluviometry P in the Mediterranean Basin during the MSC. The mean temperature and precipitation were of the same order during the MSC as today. In the present time, E-P range between 0.5 and 1 m/an [Meijer and Krijgsman, 2005]. The evaporation and precipitation by unit area are considered identical in the Western and Eastern Basins [Meijer and Krijgsman, 2005]. (c) River discharge in the Western and Eastern Basin. We conserve the same order of the present river discharge [Meijer and Krijgsman, 2005].

minus Precipitation is considered (Figure 2). The river discharge is around 15000 m³/s in the Eastern basin and 7500 m³/s in the Western basin. The variation of evaporation, precipitation and river discharge due to astronomical forcing are approximated using the temporal variation of the insolation curve. The amplitude of these variations is assumed to be of $\pm 25\%$ of the average value.

3. Results and Discussion

[9] According to our modelling, numerous and brief water level fluctuations may have occurred at ~ -500 m, then at ~ -1500 m in the Western Mediterranean Basin (Figure 3) associated with an uplift rate of 0.667 mm/yr [Duggen *et al.*, 2003] of the threshold between the Atlantic Ocean and the Mediterranean Sea (possible values range from 0.75 mm/yr to 0.3 mm/yr). The abrupt increase in the ratio of continental- versus marine-derived palynomorphs that indicates that restriction of Atlantic inflow intensified at 5.4 Myr [Warny *et al.*, 2003] could be interpreted adequately by this approach. This scenario can also explain the slope break observed in the rivers paleoprofiles of the Gulf of Lions: our model suggests that numerous sea level falls at various depths have happened. The model furthermore allows interpretation of the 3–5 phases of erosion observed on the Egyptian margin (Eastern Basin), as well as the large regressive erosion that affected the River Nile starting from a lowstand at ~ -2000 m during the MSC. The 3–5 phases of erosion are a consequence of climatic variations that affected evaporation, precipitation

and river discharge when the Mediterranean was isolated from the Atlantic Ocean. Roveri and Manzi [2006] have suggested that 3–4 cycles could be recognized across the different Mediterranean basins. Furthermore, the existence of fossil fishes in the upper interval of the ‘Lago-Mare’ event in Cava Serredi (Tuscany, Italy) implies an intra-Messinian marine refilling [Carnevale *et al.*, 2006]. The eight ‘Lago-Mare’ cycles in the sediment of the Nijar Basin (SE Spain) also suggests a repeatedly fluctuating water level instead of one major desiccation event during the Late Messinian episode [Fortuin and Krijgsman, 2003]. The ~ -2000 m lowstand duration has certainly been long enough to allow 3–5 phases of erosion, as well as to allow the incision of numerous messinian valleys on the Egyptian margin. Our results suggest that it may have a duration of 60–80 kyrs. To our knowledge, this duration is not constrained by isotopic method. The different detritic fans observed in the Nile delta (Qawasim and Abu Madi) may also be a consequence of the change of location and of duration of the erosion due to the various Mediterranean water level falls during the MSC.

[10] The duration and the number of lowstand of the Mediterranean Sea level depend of the altitude and of the uplift rate of the “Gibraltar” and Sicily thresholds (see auxiliary material).¹ The amplitude of the Mediterranean Sea level in the Western and Eastern Basins depends from the water budget. An approximation of $\pm 25\%$ of the value of

¹Auxiliary materials are available in the HTML. doi:10.1029/2007GL029885.

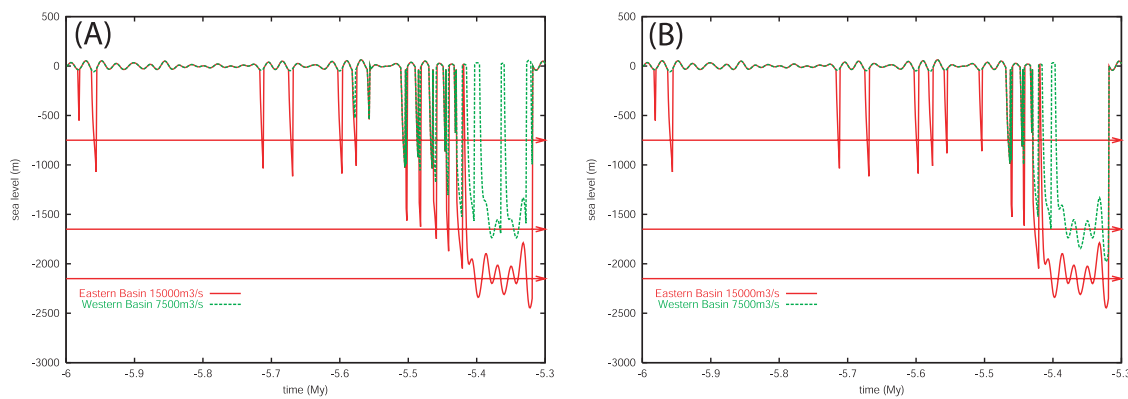


Figure 3. Mediterranean water level variation for the Western (green line) and the Eastern Basins (red line). The uplift rate $U_{\text{threshold}}$ is of (a) 0.30 mm/yr and (b) 0.667 mm/yr (1 km in 1.5 Myr) [Duggen *et al.*, 2003] for the area between the Atlantic Ocean and the Mediterranean Sea. We consider a small rate of uplift (30 m/Myr) for the Sicily threshold during the MSC [Patriat *et al.*, 2003]. A calibrated insolation curve calculated at 65°N, July 1st, is used to simulate the glacio-eustatic variations of amplitude comprised between -50 m and $+50$ m, during the MSC [Miller *et al.*, 2005], due to global climate change. We also use the insolation curve to simulate the hydrological flux [Gargani *et al.*, 2006]. The geometry of the two basins is taken into account as in the study of Meijer and Krijgsman [2005]. We assume a bathymetry $Z_{\text{init}} = -380$ m for the threshold between the Mediterranean Sea and the Atlantic Ocean, and of -35 m for the threshold between the Western and the Eastern Basins. This model allows an interpretation of the existence of 3–5 cycles in the sediments, as well as the observable lowstands in rivers profiles. $a_W = 4461.5 \cdot 10^{-12} \text{ m}^{-1}$, $a_E = 2275.8 \cdot 10^{-12} \text{ m}^{-1}$, $a = 1628 \cdot 10^{-12} \text{ m}^{-1}$, $Z_{0W} = -3123$ m, $Z_{0E} = -3613$ m, $Z_0 = -3581$ m.

evaporation, precipitation and river discharge induce an uncertainty of $\pm 10\%$ on the estimation of the sea level equilibrium. This approach allows an estimate of the consequences of climate (water inflow and outflow) and of the uplift rate of the various thresholds on the Mediterranean Basin during the Messinian times.

4. Conclusion

[11] Our model suggests that numerous sea level fall of large amplitude may have happened during the Messinian salinity crisis in accordance with seismic data. It explains why 3–5 phases of erosion are observed in the deep basin. It could be the starting point for a better understanding of the dynamics of the various Mediterranean sub-basins. For example, our approach could provide indications about the mean salinity, the sedimentation rate (evaporates, detritic) and about the geodynamics of the Mediterranean margin and thresholds.

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