GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L10405, doi:10.1029/2007GL029885, 2007

Mediterranean Sea level variations during the Messinian salinity crisis

Julien Gargani[1,2] and Christophe Rigollet[3]

Received 3 March 2007; revised 17 April 2007; accepted 25 April 2007; published 31 May 2007.

[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 δ^{18}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 ($\sim$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 $\sim$500 m and $\sim$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 $Z_{Atlantic}(t)$ and from the altitude of the threshold area $Z_{threshold}(t)$ between the Atlantic Ocean and the Mediterranean Sea. The glacio-eustatic variations $Z_{Atlantic}(t)$ are in competition with the uplift rate $U_{threshold}$ of the threshold area between the Atlantic Ocean and the Mediterranean Sea to allow the Atlantic water to flow into the Mediterranean Basin. If $Z_{Atlantic}(t) > Z_{threshold}(t)$ ($Z_{thresshold}(t) = U_{threshold}.t + Z_{init}$, 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 $Z_{Mediterranean}(t) = Z_{Atlantic}(t)$. If $Z_{Atlantic}(t) < Z_{threshold}(t)$, the Mediterranean is isolated from the Atlantic. Under this condition, the Mediterranean Sea level $Z_{Mediterranean}(t)$ 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 $\Delta V_{Mediterranean}(t) = [P(t) + E(t) - Q(t)].\ A(Z_{Mediterranean}(t)).t$, where P(t), Q(t) and E(t) are respectively the precipitation rate, the river discharge and the evaporation rate by unit area. $A(Z_{Mediterranean}(t))$ is the area of the Mediterranean Sea

---

[1] Laboratoire Géodynamique des Rifts et des Marges Passives, Université du Maine, Le Mans, France.

[2] Now at Institut Français du Pétrole, Rueil-Malmaison, France.

[3] Gaz de France, Saint-Denis, France.

0094-8276/07/2007GL029885$05.00

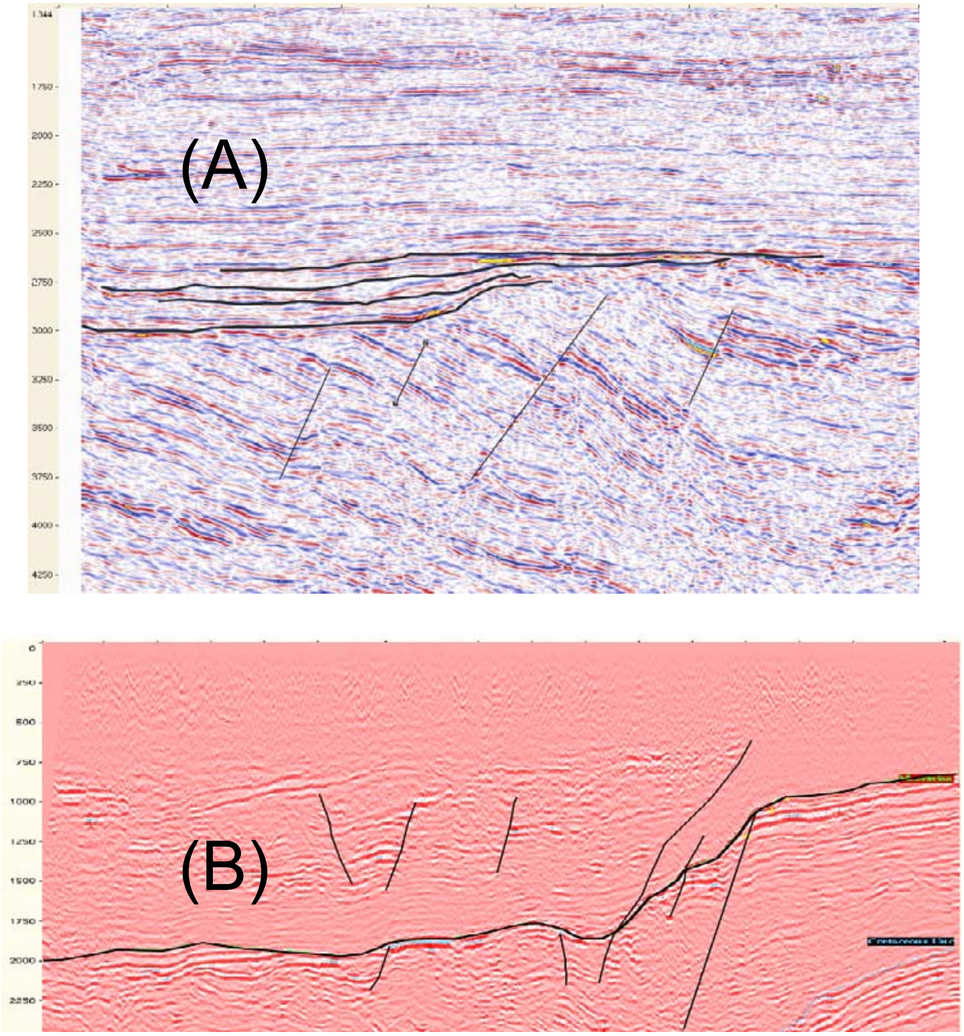

Figure 1. Seismic line of the Egyptian margin showing (a) surfaces of erosion (horizontal scale: 1 horizontal grid = 1250 m) and (b) the 750–1000 m of post messinian tectonic along the hinge line of the Egyptian margin (horizontal scale: 1 horizontal grid = 2000 m).

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

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

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 $A^2(Z_{\mathrm{Mediterranean}}(t+1)) = A^2(Z_{\mathrm{Mediterranean}}(t)) - 2\Delta V_{\mathrm{Mediterranean}}(t+1)/a$. The Mediterranean sea level $Z_{\mathrm{Mediterranean}}(t)$ 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 $Z_{\mathrm{Sicily\text{-}thr}}(t)$. When the sea level of the Western Basin is smaller than the Sicily threshold ($Z_{\mathrm{W\text{-}Med}}(t) < Z_{\mathrm{Sicily\text{-}thr}}(t)$), 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 $A(Z_{\mathrm{W\text{-}Med}}(t)) = (Z_{\mathrm{W\text{-}Med}}(t) - Z_{0W})/a_W$ and $A(Z_{\mathrm{E\text{-}Med}}(t)) = (Z_{\mathrm{E\text{-}Med}}(t) - Z_{0E})/a_E$, 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) $Z_{\mathrm{eustatic}}(t)$, 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

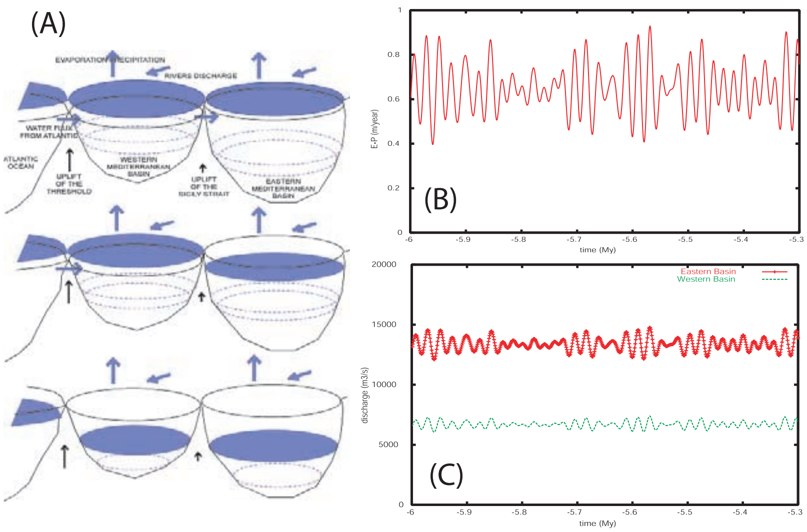

Figure 2. As no major climate change has been documented during the MSC [*Warny et al.*, 2003], the same range of value can be considered for the evaporation, precipitation, and rivers discharge during the MSC as during the present time. Small climatic variations can be expected, due to the variation 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 m^3/s in the Eastern basin and 7500 m^3/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 ±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 ±25% of the value of

---

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

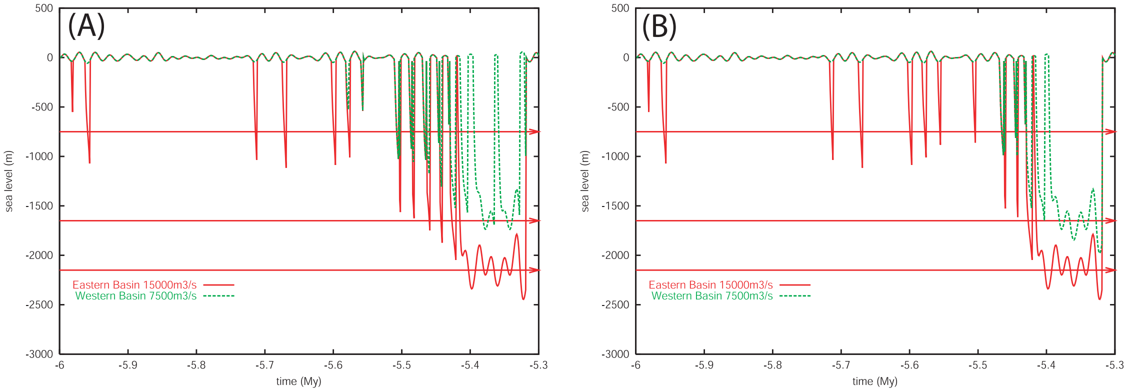

Figure 3. Mediterranean water level variation for the Western (green line) and the Eastern Basins (red line). The uplift rate $U_{threshold}$ is of (a) 0.30 mm/yr and (b) 0.667 mm/yr (1 km in 1.5 Myr) [*Duggen et al.*, 2003] for the area between the Atlantic Ocean and the Mediterranean Sea. We consider 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 $Z_{init} = -380$ 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. $a_W = 4461.5 \cdot 10^{-12}$ m^{-1}, $a_E = 2275.8 \cdot 10^{-12}$ m^{-1}, $a = 1628 \cdot 10^{-12}$ m^{-1}, $Z_{0W} = -3123$ m, $Z_{0E} = -3613$ m, $Z_0 = -3581$ m.

evaporation, precipitation and river discharge induce an uncertainty of ±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.

[12] **Acknowledgments.** We would like to thank Paul Meijer and an anonymous reviewer for constructive comments. Nicolas Nosjean and Wout Krijgsman are also acknowledged for discussion.

References

Barber, P. M. (1981), Messinian subaerial erosion of the Proto-Nile Delta, *Mar. Geol.*, *44*, 253–272.

Blanc, P.-L. (2000), Of sills and straits: A quantitative assessment of the Messinian salinity crisis, *Deep Sea Res., Part I*, *47*, 1429–1460.

Blanc, P.-L. (2002), The opening of the Plio-Quaternary Gibraltar Strait assessing the size of a cataclysm, *Geodin. Acta*, *15*, 303–317.

Carnevale, G., W. Landini, and G. Sarti (2006), Mare versus Lago-mare: Marine fishes and the Mediterranean environment at the end of the Messinian salinity crisis, *J. Geol. Soc. London*, *163*, 75–80.

Clauzon, G. (1982), Le canyon messinien du Rhône: Une preuve decisive du desiccated deep-basin model (Hsü, Cita et Ryan, 1973), *Bull. Soc. Géol. Fr.*, *24*, 597–610.

Druckman, Y., B. Buchbinder, G. M. Martinotti, R. Siman Tov, and P. Aharon (1995), The buried Afiq Canyon (eastern Mediterranean, Israel): A case study of a tertiary submarine canyon exposed in late Messinian times, *Mar. Geol.*, *123*, 167–185.

Duggen, S., K. Hoernie, P. van den Bogaard, L. Rüpke, and J. Phipps Morgan (2003), Deep roots of the Messinian salinity crisis, *Nature*, *422*, 602–606.

Fauquette, S., J.-P. Suc, J. Guiot, F. Diniz, N. Feddi, Z. Zheng, E. Bessais, and A. Drivaliari (1999), Climate and biomes in the west Mediterranean during the Pliocene, *Paleogeogr. Palaeoclimatol. Palaeoecol.*, *152*, 15–36.

Fauquette, S., et al. (2006), How much did climate force the Messinian salinity crisis? Quantified climatic conditions from pollen records in the Mediterranean region, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *238*, 281–301.

Fortuin, A. R., and W. Krijgsman (2003), The Messinian of the Nijar Basin (SE Spain): Sedimentation, depositional environments and paleogeographic evolution, *Sediment. Geol.*, *160*, 213–242.

Gargani, J. (2004), Modelling of the erosion in the Rhone Valley during the Messinian crisis (France), *Quat. Int.*, *121*, 13–22.

Gargani, J., O. Stab, I. Cojan, and J. Brulhet (2006), Modelling the long-term fluvial erosion of the River Somme during the last million years, *Terra Nova*, *18*, 118–129.

Guennoc, P., C. Gorini, and A. Mauffret (2000), La surface d'érosion messinienne dans le golfe du Lion, *Géol. Fr.*, *3*, 67–97.

Hodell, D. A., J. H. Curtis, F. J. Sierro, and M. E. Rayno (2001), Correlation of late Miocene to early Pliocene sequences between the Mediterranean and North Atlantic, *Paleoceanography*, *16*(2), 164–178.

Krijgsman, W., F. J. Hilgen, I. Raffi, F. J. Sierro, and D. S. Wilson (1999), Chronology, causes and progression of the Messinian salinity crisis, *Nature*, *400*, 652–655.

Lofi, J., C. Gorini, S. Berné, G. Clauzon, A. Tadeu Dos Reis, W. B. F. Ryan, and M. S. Steckler (2005), Erosional processes and paleo-environmental changes in the western Gulf of Lions (SW France) during the Messinian salinity crisis, *Mar. Geol.*, *217*, 1–30.

Meijer, P. T., and W. A. Krijgsman (2005), Quantitative analysis of the desiccation and re-filling of the Mediterranean during the Messinian salinity crisis, *Earth Planet. Sci. Lett.*, *240*, 510–520.

Miller, K. G., et al. (2005), The Phanerozoic record of global sea-level change, *Science*, *310*, 1293–1298.

Patriat, M., N. Ellouz, Z. Dey, J.-M. Gailuer, and H. Ben Kilani (2003), The Hammamet, Gabès and Chotts basins (Tunisia): A review of the subsidence history, *Sediment. Geol.*, *156*, 241–262.

Rouchy, J. M., and J. P. Saint-Martin (1992), Late Miocene events in the Mediterranean as recorded by carbonate-evaporites relations, *Geology*, *20*, 629–632.

Roveri, M., and V. Manzi (2006), The Messinian salinity crisis: Looking for a new paradigm?, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *238*, 386–398.

Ryan, W. B. F., et al. (1973) Initial reports of the Deep Sea Drilling Project, *Rep. 13*, U.S. Gov. Print. Off., Washington, D. C.

Warny, S. A., P. J. Bart, and J.-P. Suc (2003), Timing and progression of climatic, tectonic and glacioeustatic influences on the Messinian salinity crisis, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *202*, 59–66.

J. Gargani, Institut Français du Pétrole, 1-4 Avenue du Bois-Préau, F-92852 Rueil-Malmaison, France. (julien.gargani@libero.it; julien.gargani@ifp.fr)

C. Rigollet, Gaz de France, 361 Avenue du Président Wilson, F-93211 Saint-Denis, France.