

# Modeling the magnitude and timing of evaporative drawdown during the Messinian salinity crisis

William B. F. Ryan

Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY, USA, 10964

email: billr@ldeo.columbia.edu

---

**ABSTRACT:** The Mediterranean and Red Sea salt layers of Messinian age reach up to 3 km in thickness in the subsurface of the modern abyssal plains and are rare to absent on the contemporary margin rims. Deposition of the full evaporite suite of carbonates, sulfates, halite, potash, dolomitic marl and debris from pervasive margin erosion took place during a regional Late Miocene salinity crisis once the restriction of two-way water flow through the portal from the Atlantic reached a threshold that triggered a rise in salinity everywhere sufficient for precipitation to commence on a regional scale. For the first 0.35 my of the crisis the surface of the Mediterranean remained more or less at the level of the global ocean except possibly during brief episodes when brine reflux ceased as the consequence of sea-level fall in the exterior Atlantic. Evaporative drawdown on a large scale is an intra-salinity-crisis phenomenon and coincides with the precipitation of the bulk of the halite that makes up the giant flowing salt layer observed in reflection profiles. We present an integrated quantitative model that reproduces the closure of the Atlantic spillway, evaporative drawdown and eventual opening of the Gibraltar Strait for the Pliocene refilling. The model incorporates time-varying global eustasy, solar insolation, mixing of brine across sills between the Mediterranean and Red Sea depressions and water flow through subsurface aquifers. The model accounts for the precipitation of more than one million km<sup>3</sup> of halite alone in just a few precession cycles. The closure results from the weight of the growing brine body and salt deposit that depresses the basin center and elevates its rims. Ground water leakage under high pressure from the Atlantic into the nearly empty Mediterranean corrodes and opens fissures in the Gibraltar barrier leading to eventual break through at this particular location followed by a run-away flood.

---

## INTRODUCTION

A huge layer of salt, sulfate evaporites and detritus of Messinian age lies beneath the floor of the modern Mediterranean Sea and to a lesser volume in the Red Sea. The wide distribution of this deposit came to light in the 1960's with seismic reflection profiles that revealed domes, resembling salt diapirs, rising upwards through the sediment overburden (Hersey 1965; Knott et al. 1966; Phillips and Ross 1970; Ryan et al. 1971). As techniques of subsurface imaging improved with more powerful sound sources and more sensitive digital recording, the entire cross-section of the abyssal Messinian deposit was resolved (Montadert et al. 1970; Finetti and Morelli 1972; Lowell and Genik 1972; Mauffret et al. 1973; Miller and Barakat 1988; Cernobori et al. 1996; Bertoni and Cartwright 2006). In the Mediterranean basins the evaporite succession consists of a basal N-Reflector, a transparent (weakly-reflective) internal layer that exhibits lateral flowage (*la couche fluante* of Auzende et al. 1971) and an upper band of reflectors referred to as the M-Reflectors because of their pan-Mediterranean distribution (Biscaye et al. 1971). In the Red Sea a widespread but thinner band of equivalent S-Reflectors blankets the flowing salt layer (Knott et al. 1966). There the salt, evaporites and clastics combine to a reported thickness reaching 3 km (Davies and Tramontini 1970; Ahmed 1972; Guennoc et al. 1988; Ross et al. 1973; Stoffers and Ross 1974; Bosworth and McClay 2001). Orszag-Spencer et al. (1998) report that the bulk of the Red Sea evaporites may be of earlier Serravalian and Tortonian age. Nevertheless, it is apparent that the salt drilled in the central rift valley by the *Glomar Challenger* is of Messinian age and that the Red Sea shared the same Pliocene terminal flooding as the Mediterranean (Girdler and Whitmarsh 1974).

## Surprising discoveries from deep-sea drilling

Drilling into the M-Reflectors on Leg 13 and into the S-Reflector on Leg 23B of the Deep Sea Drilling Project recovered dolomite-bearing dark clay, anhydrite (finely-layered, wavy, nodular and with some primary crystalline selenite), and banded halite including potassium and magnesium salts precipitated from highly concentrated brines (Ryan, Hsü et al. 1973a; Stoffers and Kühn 1974). Three key and diagnostic features presented themselves: 1) gypsum and anhydrite (mostly lithified) in repetitive beds of many meters in thickness separated by mud that contained micro-fauna and flora (Hajos 1973) and isotope signatures (Fontes et al. 1973; Lloyd and Hsü 1973; Friedman and Hardcastle 1974) indicative of fresh-to-brackish subaqueous environments (Ruggieri 1967); 2) gypsum and anhydrite beds with nodular and "chicken-wire" features regarded as burial diagenesis above the shoreline (Hsü et al. 1973a); 3) alternations between primary cloudy halite with brine inclusions and secondary transparent halite indicative of alternating cycles of precipitation and dissolution (Hsü et al. 1973b; Stoffers and Kühn 1974); and 4) an abrupt contact between the youngest evaporite strata and the overlying Pliocene marine marls that displays a sudden change from shallow lake beds or alluvium to a deep seabed drowned by marine water (Cita 1972, 1973; Cita et al. 1973; Cita and Gartner 1973; Blanc 2002).

## Formulation of the initial desiccation hypothesis

The discovery of the subtidal and supratidal *sabka* facies with analogs in the modern coast of the Persian Gulf (Shearman 1963) and the preservation of fossilized algal remains and desiccation cracks led the shipboard team and post-cruise experts to propose alternating cycles of submersion for the mud, finely-

laminated sulfates and banded halite followed by emersion during the growth of nodular textures and eventual chicken-wire fabrics (Friedman 1973; Hsü et al. 1973c; Stoffers and Kühn 1974; Schreiber and Tabakh 2000). The implications of an intermittently desiccated sea were enormous and controversial (Drooger 1973). The coastal facies implied that the edges and occasionally even the interiors of the abyssal deeps had been alternately wet and dry (Hsü 1973).

As preposterous as the deep-basin desiccation hypothesis was and as resistive as objections have been (Nesteroff 1973; Selli 1973; Debenedetti 1976, 1982; Sonnenfeld and Finetti 1985; Dietz and Woodhouse 1988; Hardie and Lowenstein 2004; Manzi et al. 2005), a large amplitude evaporative drawdown (Maiklem 1971) of the sea is needed at sometime during the salinity crisis to account for the deep incisions of river valleys crossing the Mediterranean's tectonically passive margins (Clauzon 1973; Clauzon 1978; Barber 1981; Ryan 1978). The magnitude of the Nile valley incision indicates more than 1.5 km of base level change (Chumakov 1973). This value soon expanded to 2 km using methods of backstripping applied to exploration boreholes in the Gulf of Lions (Ryan 1976). The Messinian seabed depth in the Red Sea restores to >1 km when taking into account the continuing thermal subsidence of its oceanic lithosphere.

#### Persistent questions

But when did the evaporative drawdown of the sea surface occur? Did it begin relatively late in the salinity crisis (Ruggieri 1967; Ruggieri and Sprovieri 1974, 1976; Clauzon et al. 1996; Krijgsman et al. 1999a) in time to set the stage for the lakes with their hyposaline faunas? Or did evaporative drawdown commence at the beginning of the salinity crisis to account for all (or nearly all) the evaporitic deposits, both early and late, forming in shallow water (Hsü et al. 1977, 1978; Rouchy 1982a, b; Rouchy and Caruso 2006)? Under what conditions did the thick flowing salt layer precipitate — either from a stable brine surface in relatively deep water, as the surface fell, in shallow playa lakes after near total desiccation of the former sea, or in ephemeral puddles on exposed salt flats? What role does evaporitic drawdown play in the formation of other saline giants (Hsü 1972)? Did external glacio-eustatic sea-level drop trigger the Messinian salinity crisis (Kastens and Mascle 1990)? To what degree did the tectonic activity in the compressive margin settings of the Apennines, Sicily and Spain mix up the stratigraphic relationships between the evaporites and the deposits that hosts them (Roveri et al. 2003; Roveri and Manzi 2006)?

#### Additional evidence from abyssal settings

Drilling in the Mediterranean on later DSDP legs and subsequent expeditions of the Ocean Drilling Program has confirmed the cyclic nature of the beds of gypsum and anhydrite of the Upper Evaporite Series with evidence of periodic exposure (Garrison et al. 1978) as well as their association with fresh to brackish microfossils, both in the eastern and western Mediterranean (Hsü et al. 1978; Cita et al. 1978; Iaccarino and Bossio 1999). Strontium isotopic measurements on the sulfates indicate that the Upper Evaporite Series that comprise the M-Re-flectors experienced repeated solution and re-precipitation in the presence of continental waters (Clauer 1976; Müller and Mueller 1991; Flecker and Ellam 2006). Although halite of many meters thickness was recovered from the edges and in the centers of the abyssal plains in the Mediterranean and at the rim of the Red Sea's modern axial cleft, the reflection profiles show

that all the holes were terminated before sampling to any significant depth into the flowing salt layer. Drilling on later legs showed that terminal marine flood occurred simultaneously across the entire Mediterranean (Iaccarino et al. 1999; McKenzie 1999). Salt pans on the floor of the Red Sea's axial valley experienced a similar abrupt drowning (Stoffers and Ross 1974), except that the biostratigraphic resolution there is currently not as precise as in the Mediterranean.

#### Observations from marginal settings

Evaporites and salt of the same late Miocene age as the abyssal deposits appear in outcrops, subsurface boreholes and mine shafts at numerous locations around the edge of the Mediterranean. These sites all share in common a tectonically-active convergent margin setting at the time of deposition. The depocenters that were in upper plate configurations range from elongate and relatively narrow troughs in the interior of the Betic cordillera of southeast Spain (e.g., Sorbas-Nijar, Fortuna basins) to those in Tuscany (e.g., Volterra basin) and Cyprus (e.g., Pissouri, Polemi and Mesaoria basins). The depocenters along the subducting plate boundaries include trenches, accretionary prisms and forearc troughs of the Apennine arc (e.g., Vena del Gesso, Romagna, Marche and Abruzzi basins in the Adriatic trough, Crotne-Spartivento basin in Calabria and the Caltanissetta trough in Sicily). Outcrops in the Ionian Islands, Crete and Gavdos are linked to uplift resulting from convergence in the Hellenic forearc.

In Sicily, the Cattolica gypsum beds in the lower group of the Gessoso-Solfifera Series (Ogniben 1957; Decima and Wezel 1971; Richter-Bernburg 1973) appear in a stratigraphic position sometimes partly-interbedded with but mostly above an initial evaporative limestone called the Calcare di Base (Decima and Wezel 1971; Decima et al. 1988). This succession is common in margin settings. Based on the magnetostratigraphy of numerous outcrops from Spain to Cyprus, Krijgsman et al. (1999a) assign an age of 5.96 my to the Calcare di Base and the onset of the salinity crisis. However, in observing the widespread distribution of the Calcare di Base in numerous sub-basins, some argue for a prolonged diachronous deposition of the Lower Evaporite series of several hundred thousand years linked to gradual Mediterranean regression (Butler et al. 1999), and others propose a slight diachronism of no more than a few precession cycles (Rouchy and Caruso 2006).

#### Differences between margin and abyssal evaporites

The evaporative limestone and gypsum deposits of the Lower Evaporite Series that are found in marginal settings in proximity to early Messinian reefs have primary and diagenetic features that researchers have used in order to place their depositional environments in relatively shallow-water and mostly (if not entirely) in subaqueous conditions, and certainly not abyssal. Consequently the surface of the Mediterranean must have remained at or very close to the level of the external Atlantic for the duration of this series in order to keep these margin regions submerged for the ~350 ka interval of the this series (Clauzon et al. 1996; Krijgsman et al. 1999a, b). Thus it is not possible for similar shallow-water environments to have occurred simultaneously at the edges of the already-deep Mediterranean abyssal plains. If there had been a major high-amplitude and evaporitic drawdown during this relatively-long interval, either rapid or gradual, one would expect to see corresponding erosional gaps and/or depositional hiatus in the *in situ* margin deposits developed during the interval of their emergence high above the deeper shores of briny lakes occupying the basin floors. Such

TABLE 1

Boundary conditions for modeling the Mediterranean and the Red Sea salinity crisis.

	Western Med	Eastern Med	Red Sea	Total
Surface Area ( $\text{m}^2 \times 10^{12}$ )	0.82	1.68	0.45	2.95
Volume of water ( $\text{km}^3 \times 10^6$ )	1.28	2.63	0.23	4.13
Evaporation ( $\text{m}^3/\text{yr} \times 10^{12}$ )	1.0	2.8	0.93	4.73
Evaporation (m/yr)	1.22	1.67	2.07	4.96
Volume of salt ( $\text{km}^3 \times 10^6$ )	0.5	1.5	0.25	2.25
Calculated mass of salt ( $\text{kg} \times 10^{18}$ )	1.08	3.24	0.54	4.86

gaps are conspicuously absent in the descriptions of the autochthonous Lower Evaporite exposures throughout the circum-Mediterranean. This is not to say that during the time of the Lower Evaporite deposition, these marginal deposits always remained undisturbed or in place. It is without dispute that slices of the gypsum banks slumped from time to time downslope into deeper-water as the consequence of slope instability and contemporaneous tectonic activity. Such occurrences of gypsum-bearing olistostromes, debris flows and the turbidites generated by the density-flows are frequently observed in outcrops within the modern landscape of the Central Sicilian Basin (Roveri and Manzi 2006) and Apennine foredeep (Ricci Lucchi 1973; Roveri et al. 2003).

Therefore, if there were any *in situ* evaporite precipitates in the deeper parts of the Mediterranean during this time period of the first half of the Messinian salinity crisis and contemporaneous with the gypsum banks on the margins, they correspond to the thin anhydrite beds of the finely-laminated Balitino facies (Ogniben 1957) and thin halite beds intercalated with thick euxinic shales as described by Richter-Bernberg (1973) and Selli (1973) from the Central Sicilian Basin and aforementioned allochthonous debris flows and turbidity currents that transported originally primary margin materials to the basin aprons and floors (Roveri and Manzi 2006).

Thus, as argued by Krijgsman et al. (1999a, b) and Rouchy and Caruso (2006), it is not necessary to require a repetitive period of relatively shallow-water evaporite formation in the basin settings (Clauzon et al. 1996) before the onset of the continuous halite precipitation that created the >1km-thick layer of flowing salt on the basin floors revealed in reflection profiles (Montadert et al. 1970; Finetti and Morelli 1972, Ryan 1978; Montadert et al. 1978).

So, if absent from the abyss, how far offshore did the banks of the primary Lower Evaporite gypsum (mostly bedded selenite) extend across the Mediterranean margins? At a minimum, we can reconstruct in Sicily a total thickness of the Lower Evaporite Cattolica gypsum beds exceeding 200m. Therefore, either most of the accommodation space below wave-base must already have been in existence in the form of a relatively deep outer continental shelf and upper slope prior to the salinity crisis, or contemporary subsidence must have taken place at quite extraordinary rates to keep up with the accumulation. The picture that fits this total thickness constraint is precipitation (most-likely bottom growth crystal nucleation) of selenite taking place across variable water depths from the sub-tidal shore to the shelf edge and upper slope. Simultaneous precipitation of substantially lesser amounts banded anhydrite and early halite took place in the abyss within a setting of predominate euxinic shale and the accompanying clastics shed from the margins by slope instability (Ricci Lucchi 1973; Richter-Bernburg 1973;

Ruggieri and Sprovieri 1976; Debenedetti 1982; Sonnenfeld 1985; Manzi et al. 2005; Manzi et al. 2007).

### A model to reproduce simultaneous deep- and shallow-water deposition

The numerical model for this task starts from realistic initial salinity and hypsometry and proceeds through successive time steps from 7.0 to 5.0 my so as to encase the entire salinity crisis from its pre-evaporitic euxinic shale with rhythmic diatomites to the early evaporitic limestone, the first cycle gypsum beds and subsequent thick halite, followed by the second cycle gypsum beds containing freshwater fauna and finally the pelagic marl that heralds the return to normal marine conditions.

The approach is similar to the one taken by Blanc (2000) involving major basins separated from each other by sills. Our model does not distinguish if the water supplied from the Atlantic crosses Spain or Morocco, but only that the spillway transects a rim of the Mediterranean susceptible to uplift by flexure of the surrounding lithosphere. We compare the model output to published scenarios of salinity crisis to evaluate how well the model output tracks the observed succession of Messinian deposits in both margin and abyssal settings

## METHODS

### Computing the volume of the salt layer

The boundary conditions are assembled by first compiling seismic reflection profiles gleaned from journal publications, drilling reports, site surveys, geophysical databases and the opportunity to examine proprietary data of exploration companies. From the thickness of the entire evaporite deposits sandwiched on the profiles between the recognizable basal Reflector "N" to top-most Reflector "M", an isopach map was drawn, digitized and gridded into a volume that linked cumulative thickness with surface area. Two-way travel time was converted to meters using average compressional-wave velocities of 4.2 km/s for the flowing salt and 3.5 km/s for the N-, M- and S-Reflector packages. Salt thickness in the Red Sea is poorly documented and comes primarily from citations in journal articles and trade magazines. Our Red Sea budget is not large and includes what can reasonably be considered to the Messinian deposits.

The resulting volumes (Table 1) were tabulated for the western and eastern Mediterranean and for the Red Sea regions. The volumes are generous by not distinguishing between the precipitates and interleaved detritus. Thus our summations provide maximum volumes. More conservative calculations from a future denser set of profiles and by removing the clastic component may reveal a total of the precipitates reduced by 75% to 50%. Our objective was to place a maximum limit on the volume of the deep basin salt and evaporite deposits because this

volume translates into discerning the necessary time for salt to be supplied from the Atlantic.

### Computations of salt flux

The second step was to develop equations to account for water exchange between the external Atlantic and the interior seas, starting with the same initial geographic boundary conditions and hydrological data as used by Blanc (2000). The principal differences between his model and the one present here are: 1) the use of a realistic hypsometry (Meijer and Krijgsman 2005) for the area versus volume versus depth properties of each region rather than the assumption of a simple truncated cone; 2) rates of evaporation that take into account the environmental lapse rate; 3) rainfall and river input that vary through precession cycles instead of constant values; 4) an Atlantic input modulated by global eustasy using  $\delta^{18}\text{O}$  isotopes from Atlantic and equatorial Pacific drill cores as proxies for ice volume change (Shackleton et al. 1995; Zhang and Scott 1996); and 5) calculations in Matlab® instead of a Microsoft Excel® spreadsheet.

Salt is subtracted from the brine as it precipitates and segregates as a solid in the repository of the deposit. This repository partly dissolves when the waters freshen. Salinity fluctuates as the consequence of time-variable evaporation rates and freshwater inputs. The salt reflux from interior to exterior basins over the intervening sills is calculated and incorporated into the model. We allow the brine layer to stratify (Blanc 2006) and thus maintain a high evaporation rate on its surface even as net salinity rises. The growing weight of the brine layer and deposit is taken into account as a forcing agent for uplift of the surrounding regions and the corresponding feedback to the shoaling of the Atlantic spillway.

As water levels drop, the atmospheric temperature increases with a dry lapse rate of  $\sim 6.5^\circ\text{C}/\text{km}$  while the brine's high heat of vaporization requires more thermal energy for evaporation as pressure increases. Once drawdown begins and erosion takes effect on the exposed margins, the shelf area shrinks from canyon cutting and mass wasting. Debris flows transport these materials to the basin floors to flatten them, altering the shape of the depressions from more rectangular in cross-section to more trapezoidal. This substrate modification changes the hypsometry and feeds back to the surface area versus drawdown amplitude relationship. Salt deposition that is mostly confined to the basin floor flattens the relief. As the salt layer thickens, it reduces accommodation space. Overall subsidence occurs from the isostatic loading of the depocenter by the products eroded from the margins as well as by the concentrating brine and the salt deposit.

### Hypsometry

Using an approach similar to that of Meijer and Krijgsman (2005) the current bathymetric configuration of the Mediterranean was relied on to create a model of its hypsometry. Knowledge of the seafloor shape and relief allowed the shrinking surface area during episodes of evaporative drawdown to be tied quantitatively to the magnitude of sea-level fall and visa versa. Our results are similar to those of Meijer and Krijgsman (2005). The difference is our initial boundary condition does speculate on a substantially different Mediterranean configuration in Messinian time than today considering the slow ( $<10\text{ km}/\text{ma}$ ) convergence rate between the African and European plates. The most important adjustment is to subtract the volume of Messinian salt and Plio-Quaternary sediments from the mod-

ern configuration at the start of the model run. This results in a deeper pre-Messinian Mediterranean.

### Paleo-climate

An important boundary condition is a central-Mediterranean dry climate during the salinity crisis little different than today's environment (Suc and Bessais 1990). However, from the inferred change in salinity of the Mediterranean during the course of late Quaternary precession cycles that has influenced the formation of periodic sapropel layers (Vergnaud-Grazzini 1977; Rossignol-Strick 1983; Rohling and Hilgen 1991; Sprovieri et al. 1996a, b), the model uses time-varying river flow, especially for the Nile, corresponding to the particular phase of precession-controlled solar insolation (Rossignol-Strick et al. 1982; Rossignol-Strick 1983;). The solar insolation has been calculated by Laskar et al. (2004). Modeling the sedimentary cycles of the pre- and post-evaporite marine strata requires input of the time-varying solar insolation within the circum-Mediterranean region (Hilgen et al. 1995; Sprovieri et al. 1996a, 1996b, 1999; Vai 1997; Krijgsman et al. 1999a, b; Sierro et al. 1999).

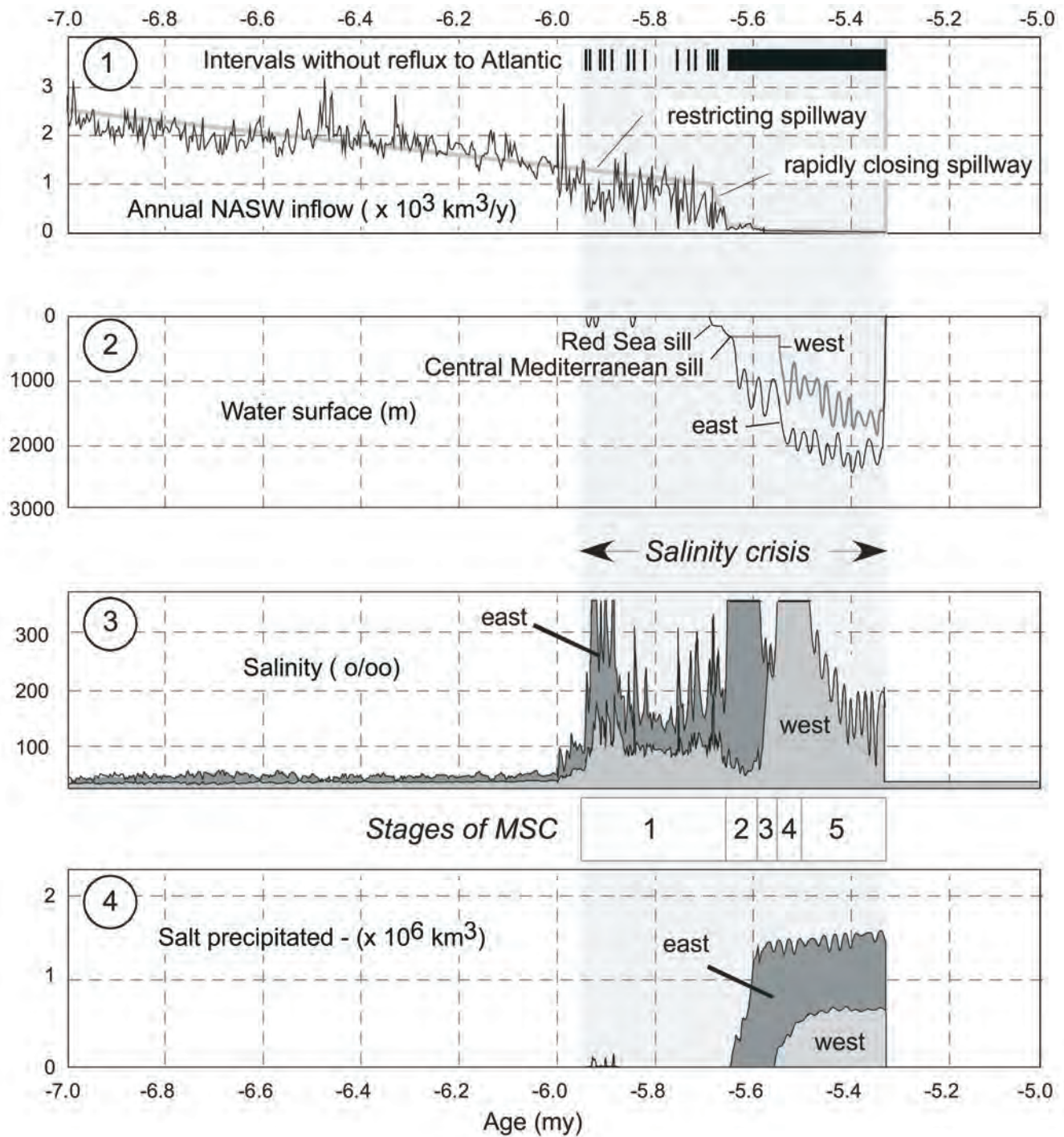
## MODEL RESULTS AND DISCUSSION

### Model behavior

The model calculations begin at 7 ma with an Atlantic influx set at about 50% of the modern value. As the long-term input takes on a decreasing trend (thick straight line in text-fig. 1, top panel), we observe high-frequency fluctuations (thin line) as the result of incorporating the effects of global eustasy in changing the geometry of the spillway. The amplitudes of global eustatic variation at this time in the late Miocene were adopted from Shackleton et al. (1995) because the 80 to 100 m amplitudes of Zhang and Scott (1996) seem excessive since they are comparable to those of the Late Quaternary when massive ice sheets covered substantial areas of the northern hemisphere. Ice sheets of similar magnitude are undocumented for the latest Miocene.

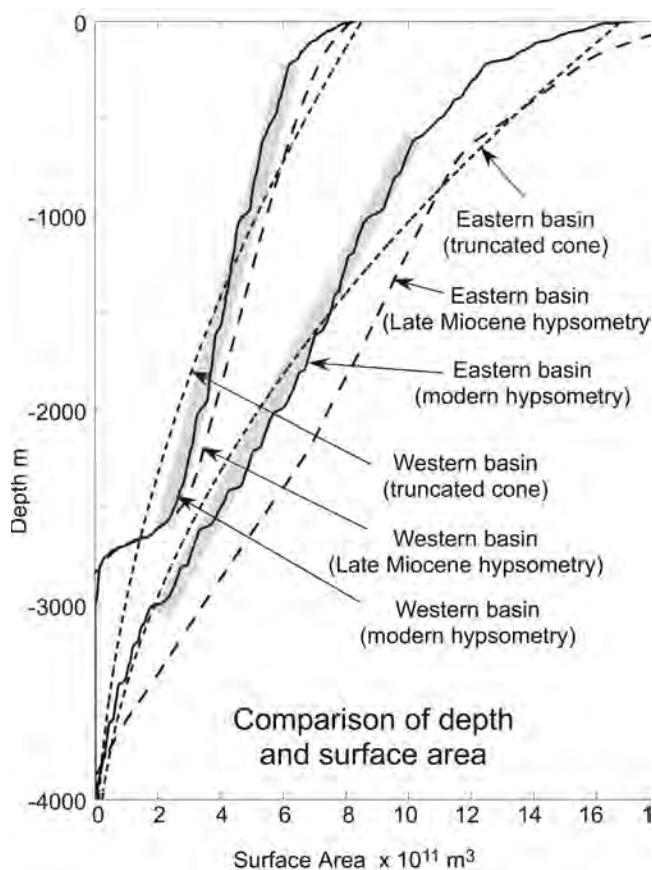
The model's clock was started in order to place the onset of the salinity crisis *senso stricto* at 5.96 my. At this moment the model output displays the first abrupt rise in the calculated salinities sufficient for the onset of widespread gypsum precipitation in the marginal regions (text-fig. 1, third panel). Salinities rise higher in the east than in the west due to the presence of the the mid-Mediterranean interior sill.

The threshold at which decreasing Atlantic input causes Mediterranean salinities to rise abruptly from normal values occurs when the flux through the spillway drops below  $1.1 \times 10^3 \text{ km}^3/\text{a}$ . At this point the reflux of saline Mediterranean water back to the Atlantic becomes restricted episodically and in phase with Atlantic eustasy. The fluctuating salinities belong to Stage 1 in the model output and correspond to the time interval of the deposition of the Calcare di Base and Cattolica gypsum beds in Sicily (Decima and Wezel 1971; 1973), the Vena del Gesso gypsum beds in the northern Apennines (Vai and Ricci Lucchi 1977), the banded-stacked selenite in the Mesaoria basin of Cyprus (Robertson et al. 1995) and the Yesares Formation gypsum in Spain (Dronkert 1976). The total calculated volume of the evaporite deposit (mostly sulfate at this point) is small. However, some of the restrictions in brine reflux are sufficiently to produce intermittent evaporative drawdown in the model output. The water-level fall is not large because it is limited to the elevation of the sill in the spillway to the Red Sea. However, these brief drawdown events are sufficient along with rising pressure on the substrate due to the increasing net salinity (and



TEXT-FIGURE 1

Model output from 7.0 to 5.0 my. Panel 1 shows the Atlantic input modulated by global eustasy. The thick gray line is the gradual reduction of Atlantic inflow that is entered in to the model and the thin black line is the calculated Atlantic supply adjusted for varying global eustasy. Black bars are periods of restricted brine reflux. Panel 2 shows the calculated water surface for both the eastern (black) and western (gray) Mediterranean regions. Panel 3 displays the calculated salinities and panel 4 the volume of salt precipitated. Stage 1 corresponds to the first cycle gypsum beds in Sicily, Stage 2 and 4 to massive halite precipitation in the east and west, respectively, Stage 3 to the recharge of the western region to saturation, and Stage 5 to the second cycle gypsum beds in Sicily. DSDP and ODP drilling only sampled the stage 5 deposits.



TEXT-FIGURE 2

Comparisons of the truncated cone assumption for the area-depth-volume properties of the eastern and western Mediterranean (short dashed lines) and more realistic properties from calculations based on current bathymetry (solid lines) and the hypsometric results of Meijer and Krijgsman (2005) (long dashed lines). The shaded slopes are parts of the curve where shrinkage in surface area results in greater drawdown than predicted by the truncated cone assumption.

thus density of the Mediterranean water body) to start to trigger mass-wasting on slopes and the delivery of debris flows to the basins (Lofi et al. 2005). The mounting load of this early sediment stripped from the margins and delivered to basin centers (~1 km in thickness in the Balearic Basin south of the Gulf of Lions) is more than sufficient to initiate a flowage of the mantle away from the basin centers and towards the margins and generate a peripheral bulge. The model uses this bulge, further amplified by the increasing weight of the brine and accumulating halite (Major and Ryan 1999), to uplift the spillway to the point where it eventually shuts down the Atlantic input.

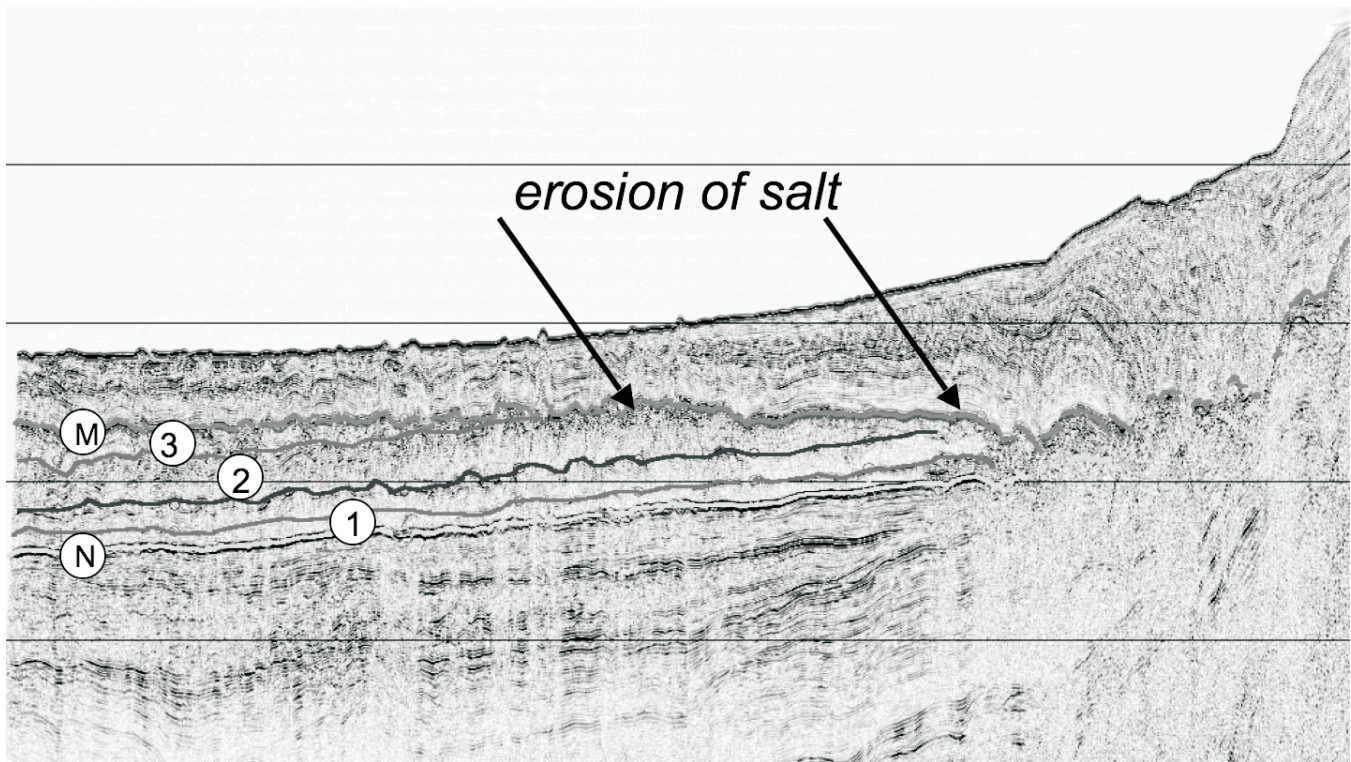
The point at which Atlantic input plus the discharge of Mediterranean rivers and rainfall in the Mediterranean watershed can no longer keep up with evaporation over the surface area of the entire Mediterranean is reached with an Atlantic input of  $1 \times 10^3 \text{ km}^3/\text{a}$ . It is important to point out that the critical input of  $1 \times 10^3 \text{ km}^3/\text{a}$  at which drawdown begins is significant because this value is still a very large flux. For example, considering that the incoming salinity is ~4%, the water delivered to the Mediterranean from this time on brings in  $40 \text{ km}^3/\text{a}$  of perma-

nent salt. Thus the model only needs 55 thousand years of continuing input to deliver to all of the combined Mediterranean and Red Sea salt with its maximum and most-likely over-estimated volume of  $2.2 \text{ million km}^3$ . Some related phenomenon (i.e., feedback) must begin to reduce the Atlantic input rate once drawdown commences so as not to completely fill both seas with salt. It is simply not possible to have a sustained period of drawdown at the flux rate that initiates the drawdown.

The model produces its first high-amplitude drawdown at the start of the rapid closure (text-fig. 1, panel 2). At this time, the entire eastern Mediterranean and Red Sea have reached saturation sufficient for halite precipitation (~350 g/l). The amount of salt in the brine is already >30% of the total volume measured in the deposit. The salt accumulation phase in the eastern Mediterranean and Red Sea belongs to stage 2 of our model output. The model calculations show that the duration of this stage can last no more than 3 precession cycles at a steadily dwindling rate of water supply.

The model shows that western Mediterranean does not concentrate to halite saturation while Atlantic water transits the western region on its route to the east and Red Sea. Thus stage 3 in the model output represents the time required for the brine in the western region to rise towards halite precipitation once water is no longer delivered to the east. As the result of a much-reduced Atlantic inflow, drawdown commences in the west in stage 4. With this diminished influx rate from the Atlantic, the growth of the salt deposit in the west is correspondingly slower than in the east and more precession cycles are required. For the model to deliver all the measured volume of salt in the west, the barrier to the Atlantic is required to leak continuously, although at a very slow rate, equivalent to a single terrestrial river, until the Gibraltar Strait opens at 5.33 ma.

The model reveals that evaporative drawdown is not a one-way excursion of the water level (text-fig. 1, panel 2). The precession-modulation of solar insolation assures rising and falling water levels at the precession periodicity. The amplitude of the excursions (up to 1 km) is a function of both the magnitude of the change in solar insolation from one cycle to the next and also the evolving shape of the basins (narrower shelves, broader basin floors as margin erosion and basin center deposition continue, respectively). The effects of hypsometry predict that the western basin approaches nearly full desiccation prior to the Pliocene flood. Also as the water bodies freshen once the Atlantic input is greatly reduced, the water evaporates more effectively per unit of solar energy. The rising and falling water levels belong to stage 5 of our model output. The dry-wet cycles during stage 5 could correspond to the cycles of carbonate precipitation in the Colomacci Formation in the northern Apennines (Colalongo et al. 1976) as well as to the cycles of the Pasquasia gypsum beds in the Eraclea Minoa outcrop in Sicily (Decima and Wezel 1973; Nesteroff 1973). The very deep drawdown at the end of stage 5 could account for the widespread Arenazzolo Formation that is extant over the whole of central Sicily and the Feos fluvial sands spread across the Nijar Basin of Spain. At this time, just before the Zanclean flood, alluvial conglomerates appear in a heavily-eroded landscape now uplifted in Crete, Gavdos and Cyprus (Rouchy et al. 1980; Orszag-Sperber et al. 1980; Delrieu et al. 1993; Robertson et al. 1995) and on alluvial fans in the subsurface of the Po Plain (Rizzini et al. 1978).



TEXT-FIGURE 3

Seismic reflection profile off the margin of the Levant showing the three internal layers of the flowing salt deposit bounded on the top and bottom by the M- and N-Reflectors. Horizontal scalelines are separated by 0.5 seconds two-way travel time. Thickness of the Messinian deposit at the seaward end of the profile exceeds 1 km. The roof of the salt layer has been extensively eroded and dissolved along the base of the slope.

### Consequences of real hypsometry

Evaporation is a function of solar energy, the surface area of the water, its salinity and its temperature. In the truncated cone assumption of Blanc (2000, 2006) for the shape of the Mediterranean basins the rate of change in surface area decreases regularly with evaporative drawdown (text-fig. 2). Realistic hypsometry presents a different picture and greater amplitudes as shown by Meijer and Krijgsman (2005). The dropping water level reduces surface area, but proceeds more slowly across the broad shelves than that of the truncated cone when using the realistic hypsometry. As the shelf edge is reached, the surface area is reduced at a lesser rate with each increment of sealevel fall when compared to the truncated cone until the base of the slope is reached. From then on every further step of drawdown involves more and more reduction of surface area, inhibiting complete desiccation of the basin floor. The model shows that for drawdown to reach the lowest slopes and basin edges, the evaporation rate per unit area illuminated by the sun must increase substantially while drawdown proceeds. The adiabatic lapse rate has one such a positive feedback through the increased atmosphere temperature with drop in elevation and by clearer skies from a reduction in moisture delivered from the the shrinking surface area. The solar energy has a greater evaporative efficiency in the absence of clouds. On the other hand increasing salinity reduces the water activity and creates a negative feedback. The effect of this negative feedback is somewhat compensated by density stratification of the brine that exposes the least salty water at the water surface where evaporation takes place.

### Consequences of variable climate

The model reveals that changes in rainfall over the Mediterranean and its watersheds at insolation maxima can double and even triple the rate of freshwater supply for several thousand years and lead to rising water levels even with the same rates of evaporation. This effect is greatest in the eastern Mediterranean due to the Nile River input. Increases in evaporative loss during insolation minima (cold periods with marked Mediterranean aridity) enhance drawdown after it has started. In summary, once water drains off the shallow margins, brine stratification, adiabatic heating, reduced cloud cover and the steeper hypsometric gradient all have feedbacks to enhance the potential amplitudes of drawdown even beyond those proposed by Blanc (2000, 2006) and Meijer and Krijgsman (2005).

### Consequences of Atlantic eustasy

If the fluctuations of  $\delta^{18}\text{O}$  of benthic foraminifera in the Pacific between 6 and 5.3 my with an amplitude of  $\pm 0.25\text{‰}$  are the consequences of ice volume changes, they correspond a maximum  $\pm 30$  m change in global sea level (Shackleton et al. 1995). When eustasy of this proportion is applied to the cross-section for the Atlantic portal, the effect on Mediterranean reflux to the Atlantic is substantial once the Atlantic inflow drops below a threshold. Periodic flux reduction is even greater with the  $\pm 50$  m amplitudes proposed by Zhang and Scott (1996). The model calculations generate pulses in Mediterranean salinity and brief water level excursions during stage 1 of the salinity crisis. Such brief and climatically-modulated eustatic excursions could be responsible for the reported cannibalistic erosion across the tops of some of the individual selenite beds in the Vena del Gesso in

the northern Apennines (Vai and Ricci Lucchi 1977), although the interpretation of brief exposure has been placed into doubt (Roveri et al. 2003).

### Sensitivity of salinity to brine reflux

During the time of gradual closing of the entry portal prior to stage 1, the magnitude of the dissolved salt that enters the sea per unit of time remains more or less balanced by reflux back to the ocean at a lesser rate, but carrying the same amount of salt in the form of more saline water. As reflux diminishes, the deficiency between salt entering and leaving accounts for the amount stored in the brine (Blanc 2006). Thus Mediterranean salt content rises in proportion to the imbalance between inflow and outflow. The more restricted the orifice, the less water is exchanged by two-way flow and the higher the contrast between the salinity of entry and exit waters. The model reveals that the value of inflow from the Atlantic at which reflux is becomes restricted is very sensitive to even modest changes in global eustasy (<10m) and slight changes of Mediterranean evaporation/precipitation (10%). Under the influence of eustasy and variable climate alone, our model is unable to reproduce the prolonged a steady state of reduced reflux and salinity increase to the levels of saturation for sulfate or halite as proposed by Debenedetti (1976; 1982) and Sonnenfeld (1985) for deep-water formation of the entire deposit. Instead the model generates a tipping point the moment the spillway becomes sufficiently restrictive that reflux is interrupted. Salinity rises markedly, and the salinity crisis commences abruptly. Stratification causes the salinities of the deep waters increase to a greater extreme than surface waters. This tipping point is probably the reason why the onset of the salinity crisis is so visible as an abrupt facies change in outcrops at margin locations where it can be observed.

### Comparisons of model output to observed geochemical signals

**Strontium contents:** Since the strontium content in primary gypsum is proportional to brine concentration, the amount measured in the gypsum in the Mediterranean evaporites can be used to deduce salinity variations in the mother brines. Rosell et al. (1998) report that the strontium profile from the first cycle gypsum deposit of the Sorbas basin in Spain has homogeneous contents, reflecting deposition under conditions of hydrological stability and thus relatively deep waters as revealed in stage 1 of our model output. It is only in the second cycle gypsum beds in this basin and those in the outcrop at Eraclea Minoa in Sicily that correspond to stage 5 that the content becomes highly variable. There each gypsum bed shows strontium increasing markedly from its base to top as salinity concentrates due to the thinning of the brine layer.

**Strontium isotopic ratios:** Strontium isotope measurements on gypsum from numerous locations in the Caltanissetta Basin of central Sicily show that all of the first cycle Caltolica gypsum beds have the expected global “oceanic” composition ( $^{87}\text{Sr}/^{86}\text{Sr} = 0.70891\text{--}0.70897$ ), whereas the second cycle Pasquasia gypsum beds fall within a grouping of significantly lower values (0.70868–0.70878) suggestive of a dilution of the brine by continental waters once the Atlantic spillway has closed (Keogh and Butler 1999). The composition of the second cycle materials is surprisingly uniform. Therefore, during stage 5 many regions were bathed by the same water mass under varying concentrations of dissolved strontium. Rising and falling water levels would assure interconnection of all sub-basins. Flecker and Ellam (2006) also report “oceanic” compositions in first cycle Messinian material collected from the Mediterranean’s

northern margins. However, contrary to further restriction of the Atlantic spillway according to our model and the models of Blanc (2000, 2006) to initiate the salinity crisis, they propose a burst in Atlantic water supply (i.e., a transgression) as the triggering agent for evaporative conditions. According to their reasoning, a large Atlantic supply is needed to change the composition of the Mediterranean’s strontium reservoir from any pre-evaporitic “continental” signature to “oceanic” for the first gypsum bed. However, a reduction in salt reflux relative to salt influx has the same effect by concentrating the “oceanic” end-member. With no reflux to the Atlantic, all the dissolved strontium that enters the Mediterranean remains there until it is removed by precipitation. Essentially, the marine strontium reservoir grows in proportion to rising salinity. Since marine water carries >40 times the amount of strontium per liter than typical river water, the “oceanic” composition dominates the Mediterranean reservoir once reflux no longer balances input.

**Bromine contents and paleotemperatures:** The halite at the edge of the Balearic Basin recovered in DSDP Leg 13 belongs to stage 5 in our model output. Bromine concentrations vary by 60% across individual halite bands representing annual deposits (Kühn and Hsü 1974). Only near total desiccation could reduce the brine layer to such a small thickness for this large change to occur in a single year.

Similar to the computations of Blanc (2006), our model shows a rise in Mediterranean and Red Sea salinity over a sustained period during stage 1 before the Atlantic input decreases to the level capable of triggering the first large-scale evaporative drawdown. Thus the volumes of the Mediterranean and Red Seas combined were able to store  $>1 \times 10^6 \text{ km}^3$  of solute in brine concentrated to 325–350 g/l. A single large amplitude drawdown of brine at this level of saturation would deliver up to 50% of the entire salt deposit. The presence of hopper crystals with fluid inclusions on cube corners in cumulates of banded halite in the Realmonte salt deposit of the Caltanissetta Basin suggests crystal nucleation at the brine/air interface as the brine body shrinks. At this concentration a surface level fall of 0.5 m during a single arid season would be sufficient to precipitate one of the 10–20 cm thick halite bands exposed in the walls of the Realmonte Mine in Sicily (Lugli 1999). The observed uniform bromine contents across these bands require a homogeneous concentration with a large buffer against the annual fluctuations in composition. Deep brine bodies also maintain the observed stable bottom temperatures (Lugli and Lowenstein 1997). Only after drawdown approaches completion does the volume and thicknesses of the brine body reduce to magnitudes capable of producing annual variations in the bromine signal and bottom temperatures variations with the observed amplitudes of 10°C for the terminal sodium and potash salts (Lugli 1999).

### Buffer for brine composition in margin settings

As previously mentioned, the margins of the Sorbas Basin in Spain provide the substrate for 13 cyclic beds of first cycle primary selenite, all with homogeneous marine strontium contents (Rosell et al. 1998). These beds must have been deposited on a seabed not far below the level of the Atlantic due to their close proximity to late Miocene carbonate reefs (Dronkert 1976; Rouchy and Saint Martin 1992). Yet precipitation in relatively shallow water should not result in homogeneous compositions, unless these setting were not separate and isolated small basins but instead the margins of the broader interconnected Mediterranean, filled with a large, thick and homogenous brine pool

that effectively sheltered the strontium and bromine concentrations from the influence of eustasy and climate cycles.

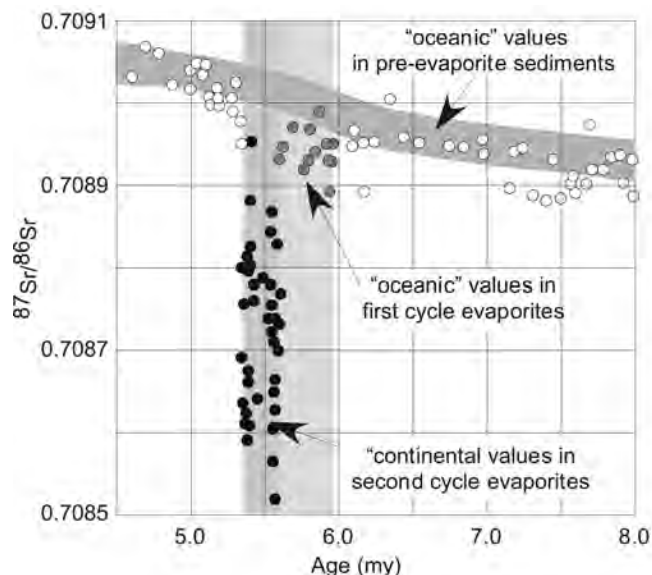
#### What the model output says about the substrate below the flowing salt layer

Drill cores from locations in the deeper axis of the Caltanissetta Basin in Sicily that reach below the base of the thick halite deposits reveal a sterile, brine-saturated mud with scattered crystals of evaporite minerals and thin laminated beds of anhydrite. According to Decima and Wezel (1972, 1973) and Richter-Bernburg (1973) the sterile mud is interleaved with abundant clastic gypsum that displays graded bedding and flute casts that are signatures of deposition from turbidity currents. Such gypsum detritus can only be sourced from already existing banks on nearby rims. The mass flow deposits have thicknesses of >150 m (the limit of drilling) and apparently provide the foundation for the subsequent thick initial halite deposit of almost pure NaCl. In the interpretations of Richter-Bernburg (1973) and Selli (1973) the halite is a coeval deposit with the selenite. The model output confirms this by showing that the halite precipitation only gets underway for significant volume accumulation at the end of selenite deposition when the surface of concentrated brine begins to fall and the selenite banks emerge. Small incipient drawdown during stage 1 may momentarily expose the bank tops, but evidence of emergence of the Cattolica gypsum beds is not supported by more recent and thorough observations (Stefano Lugli and Marco Roveri, personal communication 2006).

#### Model output and the intra-Messinian unconformity

The modern landscape in central Sicily presents numerous outcrops of materials either re-deposited downslope from the basin rim or formed by dissolution and collapse of exposed salt with its interbeds of marl and clastics (Rouchy and Caruso 2006). However, sediments transported down slope are rare in the thick halite of the Realmonte Mine but common in the underlying strata. In field outcrops one gains the impression of a first stage of continuous deposition of successive primary selenite beds on the basin edges, a second stage of exposure of these banks to stream and coastal erosion to produce gypsum gravel and sand, a third stage of massive downslope transport of this detritus along with materials from the slope to the basin floor in gravity flows, and finally a filling of the basin by rapidly-accumulating banded halite of a substantial thickness to subdue the overall relief. Millions of years later as the halite is exposed to meteoric waters, it dissolves and additional breccias are formed to make the modern landscape even more chaotic.

The output of the model generates the conditions for margin erosion at the beginning of stage 2 in the east and at the beginning of stage 4 in the west. The timing of drawdown is determined by the interplay of eustasy, climate, and growth of the peripheral bulge caused by the increasing weight of the growing salt layer. The change in base level accompanying drawdown not only exposes the shallow rims to erosion by waves and later deep incisions by rivers, but also exposes the roof of the halite layer itself to solution. Drawdown produces a widespread unconformity on the margins that splits into two horizons (Ryan and Cita 1978) when reaching the basin floor—one extending beneath the salt layer and recording the arrival of material displaced from the margin as drawdown commenced and the other capping the halite and recording the completion of initial drawdown.



TEXT-FIGURE 4

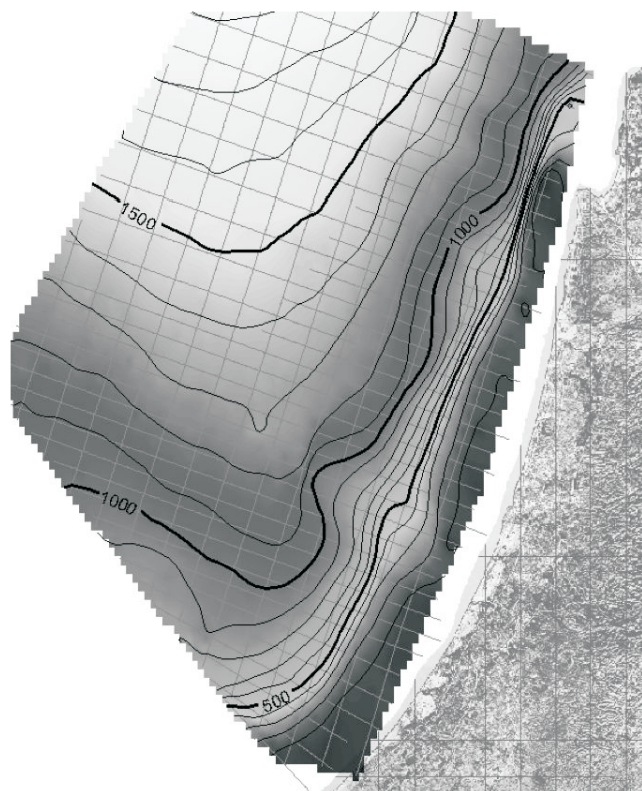
Strontium isotope measurements after Flecker and Ellam (2006). White circles are measurements on pre- and post-evaporite Mediterranean materials. Gray circles belong to the first cycle gypsum beds and the solid black circles to the second cycle gypsum beds. The dark gray wavy band represents the variation in global ocean measurements. The slightly sub-“oceanic” values for cycle 1 indicate brine stratification with the bulk of the water supplied from the Atlantic with minor river contributions. The wide-ranging “continental” values reflect complete closure of the Atlantic spillway.

In the Realmonte mine, an exposure surface separates the salt deposit into two parts: 1) a thick lower unit composed of cumulates of halite with minor amounts of kainite indicating precipitation from a thick stratified water body that shoals during its accumulation to subaerial exposure, and 2) an upper unit that indicates precipitation in shallow, saline lakes (Lugli 1999). One can observe 6-meter deep fissures in the mineshaft located along the contact between the two units. These fissures outline giant polygons interpreted as expansion cracks caused by complete desiccation of the interface surface (Lugli and Schreiber 1997; Lugli et al. 1999).

Intra-Messinian age erosion surfaces and their debris are not only ubiquitous in the deeper regions of the Mediterranean (Ryan and Cita 1978), but also common in marginal settings. The products of erosion are found in the Sergnano gravel under the Po Plain (Rizzini and Dondi 1978), the Qawasim Formation fluvial-clastics beneath the modern Nile delta (Rizzini et al. 1978), the Feos Formation alluvial conglomerates in the Nijar Basin of Spain (Fortuin et al. 2000) and the mega-rudites and breccias of the same time interval in Crete and Cyprus that are scattered between the first and second cycle gypsum units (Delrieu et al. 1993; Robertson et al. 1995).

#### Role of sills

Blanc (2000, 2006) was first to point out the importance of sills in creating diachronous deposits in the east and west. In our model, the shallowest sill separates the Mediterranean from the



TEXT-FIGURE 5A  
Present bathymetry of the SE corner of the eastern Mediterranean. Depths in meters.

Red Sea. The very high (e.g. 2.07 m/a today) net evaporation of the Red Sea assures that this depression experienced an extreme drawdown, while the surface of the Mediterranean remained pinned at the entrance spillway. If the Red Sea drawdown occurred in the “wet” phase of the solar insolation cycle, salt delivery lasted longer, because in the arid phase the much larger surface area of the eastern Mediterranean would dominate evaporative loss. The model shows that in a period as brief as a precession cycle, the Red Sea could have accumulated all of its Messinian salt and then transformed into a landlocked playa lake.

In order to adjust the Atlantic input to account for 75% of the salt delivered across the sill to the eastern Mediterranean and 25% retained in the western Mediterranean, the model is required to reduce the rate of Atlantic input to a mere trickle over the next 50 ka. Continued Atlantic influx accounts for all of the salt layer volume of the entire eastern Mediterranean including the Adriatic and Aegean Seas in 3 precession cycles. The salt deposit in the Levant corner of the eastern Mediterranean reveals 3 internal layers in reflection profiles that may correspond to these cycles (text-fig. 3).

When the Atlantic input drops to  $1.1 \times 10^3 \text{ km}^3/\text{yr}$  the evaporation over the surface of the western Mediterranean is sufficient to initiate drawdown there. The abandoned eastern Mediterranean becomes one more landlocked depression. Its  $^{87}\text{Sr}/^{86}\text{Sr}$  composition takes on the “continental” signature (text-fig. 4). The salt layer in the southern east corner and beneath the Messina abyss-

sal plain reveals extensive dissolution across its upper surface corresponding to an environment dominated by fresh water (text-fig. 5) and possible emergence. However, on the basis of fluid inclusions in the halite from central Sicily its recycling may have occurred while still under the influence of normal seawater (Garcia-Veigas et al. 1995).

The much-reduced Atlantic input requires just a few more precession cycles to supply the approximate  $0.5 \text{ million km}^3$  of salt beneath the abyssal plain of the western Mediterranean. Closure of the Atlantic spillway then seals the fate of the entire Mediterranean to become a vast inland lake with surfaces that rise and fall according to varying solar insolation. The calculations show amplitudes of water level fluctuations exceeding 1 km and a drawdown amplitude of sufficient magnitude to expose the edges of the abyssal plains.

The model output gives the same east to west progression of evaporitic drawdown first recognized by Blanc (2000), yet with a greater magnitude and a faster rate caused by more realistic hypsometry, brine stratification, and adiabatic effects. In addition, as salt deposition flattens the floor, a larger surface area is created at a near constant depth, which then allows fluctuating evaporation and precipitation to have an amplifying effect on the expansion and shrinkage of the lakes.

#### Correspondence between the model calculation and other observations

*Apparent shoaling from Tripoli Fm. to the Calcare de Base:* Variations in global eustasy during the early salinity crisis are of the right magnitude to produce brief salinity spikes at the periodicity of the oceanic eustatic cycles. The widespread and simultaneous appearance of evaporitic limestone on the Mediterranean margins has been puzzling, because its apparent desiccation cracks (Decima et al. 1988) suggest a sudden upwards shallowing from the Tripoli diatomaceous mud often assigned to outer shelf to the upper slope setting. A brief drawdown would expose the Mediterranean’s rim and expose its marls to desiccation. Such an event would be experienced everywhere.

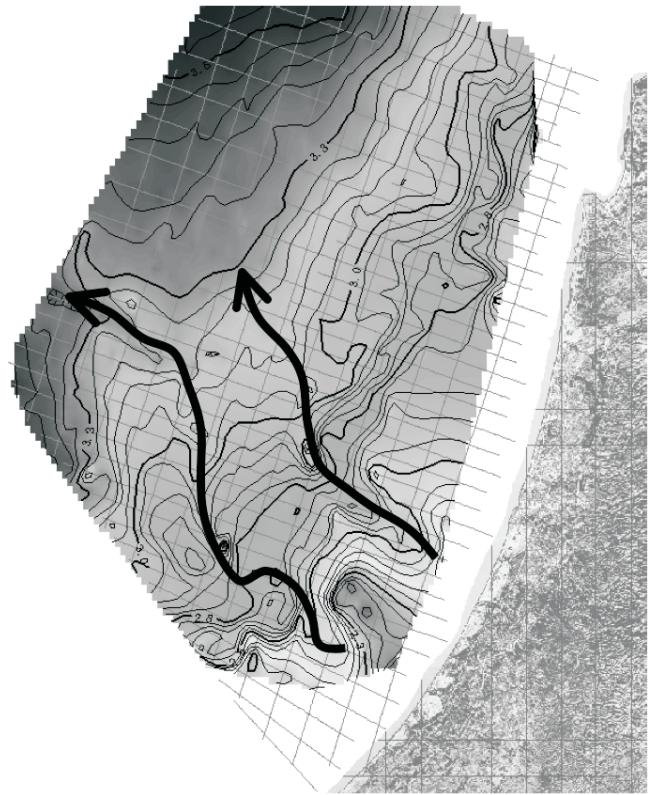
*Cyclic deposits of the Tripoli Formation:* Our model indicates a period of rising salinity during deposition of the Tripoli Formation in good agreement with the stable isotope data of the carbonates (Bellanca et al. 2001; Blanc-Valleron et al. 2002). The grey marls alternating with reddish laminitic sapropels and diatomites in the Falconara and Gibliscemi outcrops in Sicily (Sprovireri et al. 1996) and other rhythmic diatomites in southern Spain, Gavdos Islands south of Crete and Cyprus appear during this interval of gradual closing of the Atlantic inlet. The model produces freshening during solar insolation maxima. Freshening is amplified in the east due to the Nile River contribution. The diatomite beds correlate with the freshening phase of each salinity cycle.

*Absence of pre-salt clastic deposits in the east:* The model initiates massive halite precipitation as soon as the first substantial drawdown gets underway. The clastics derived from exposures of the slope and incision of river valleys must be in the basal salt layer because the salt sits directly upon an erosional unconformity (Ryan 1978; Bertoni and Cartwright 2006). The deep-sea fan upon which the salt deposit in the Levant region is a pre-Messinian depositional apron with a preserved channel-levee complex (text-fig. 5).

*Thick pre-salt clastic deposit in the west:* The model delays the initiation of drawdown in the western Mediterranean until the Atlantic influx is sufficiently diminished to balance the much-reduced evaporation over the reduced surface area in the west. However, the Mediterranean surface has already dropped to the mid-Mediterranean sill exposing the shelf of the Gulf of Lyon and its upper slope (Blanc 2000; Lofi et al 2005). The salinity increase seen in the model output would have setup a large inverted density contrast between existing pore waters of the shelf and slope sediments below and the developing Mediterranean brine above. Pore waters of less density than the brine would be expected to ascend buoyantly out of the substrate in a process of spring sapping capable of triggering widespread mass wasting in the sub-aqueous environment. A seismic reflection profile across the Gulf of Lyon shelf and slope (text-fig. 6) reveals an extensive margin unconformity and a wedge beneath the salt layer corresponding in volume to the missing sediment.

*Widespread intra-Messinian gravels and conglomerates:* The widespread unconformity seen in Sicily, Northern Apennines, Crete, and Cyprus, separating the early and later stages of the salinity crisis (Ricci Lucchi 1973; Rizzini and Dondi 1978; Rizzini et al. 1978; Fortuin and Krijgsman 2003; Orszag-Sperber et al. 1980; Robertson et al. 1995; Roveri et al. 2003) might simply be the response of erosion induced by the large base level change accompanying evaporative drawdown rather than the expression of a pan-Mediterranean tectonic event as proposed by Roveri et al. (2003) and Manzi et al. (2005). It is interesting that in all the circum-Mediterranean locations with exposures of the Messinian evaporites, the mega-breccias, conglomerates, and gypsarenites appear right after the first stage gypsum beds and contain components derived from these beds. Caution must be observed that some of the mega-breccias may result from collapse after dissolution of the subsequent salt (Rouchy 1982a, b; Rouchy and Caruso 2006), although the clastics within the breccias had to have been intercalated in the salt as the consequence of from upslope erosion. The apparent close coincidence between the arrival of massive reworked materials and the onset of salt precipitation is nevertheless remarkable. Re-deposited gypsum is particularly evident in the northern Apennines foredeep trough (Ricci Lucchi 1973). This trough is spared from halite deposition by its location upstream from sills separating it from the downstream Ionian Basin. Our model shows that once the surface of the eastern Mediterranean dropped below the Apennine sill, the combined river input from the Alpine, Apennine, and Dinarides drainage would transform the upstream Apennine foredeep trough into a lake for accumulating the cyclic white lacustrine limestone of the Colombacci Formation, whose precipitation also appears to be modulated by varying solar insolation.

*Gibraltar as the site for eventual reconnection with the Atlantic:* Without special intervention the model creates a smaller volume of salt in the western basin than observed. This happens because the input rate of Atlantic water is already so low in order to start the drawdown in the west that the input must then continue without further reduction for some considerable time. However, margin uplift from brine loading in the basin center has already started and the rate of closure has already accelerated. Rather than interfering with the model to sustain input, another source of Atlantic saltwater is tapped. That source could be subsurface water leaking in from the Atlantic through a permeable barrier as a result head loss in the desiccated interior basin. The necessary rate of continued influx to produce the



TEXT-FIGURE 5B

Deep-sea fan with channels and levees buried directly under the Messinian evaporite and salt deposit. Elevations in seconds two-way travelttime.

observed salt over time volume is  $0.1 \times 10^3 \text{ m}^3/\text{a}$ . The model has two choices: either surface spillway or leaked in marine water through aquifers.

If water delivery was by a surface conduit one might expect that the flow, similar in magnitude to a major circum-Mediterranean river such as the Ebro in Spain, would enlarge its opening by erosion leading to a run-away flood. On the other hand the flux rate has the order of magnitude that can be sustained by an aquifer experiencing a pressure drop from one end to the other. During the salinity crisis the Chaine Calcare continued uninterrupted from the Rif mountain belt of Morocco into Spain. Limestone is well-suited to act as a groundwater aquifer with an interesting property of dissolving in the presence of unsaturated seawater. To explore its role as a possible aquifer, the hydraulic conductivity for fractured limestone of  $0.001 \text{ m/s}$  was entered into the calculations with a pressure drop of  $1 \text{ km}$  for an aquifer  $50 \text{ km}$  in length,  $10 \text{ km}$  in width, and  $1 \text{ km}$  in height. The calculations reveal a flux sufficient to deliver the necessary additional salt over  $100 \text{ ka}$ . The late stage gypsum beds in the drill cores from the Balaeric rise show evidence of sustained marine input for their sulfate. Those from the eastern Mediterranean show no evidence of continued marine supply. Limestone corrosion by salt water should eventually lead to a runaway condition as pore spaces open by further dissolution. Enlarged subterranean caverns will eventually collapse. Is it a mere coincidence that the portal which opens to create the terminal Zanclean flood is directly through the hard limestones of the

Chaine Calcare and that the exposure of these limestones in the remaining mountains show extensive karst development?

## CONCLUSIONS

Due to the exceptionally high excess evaporation over the Mediterranean and Red Seas, the flux of water from the Atlantic necessary to balance this loss is so large that once drawdown begins, salinity rises abruptly to saturation and salt accumulates at a very fast rate. If the input remained unchecked, the measured volume of salt would appear in just a few precession cycles. Thus even with a closing spillway, the halite stages of the salinity crisis are brief. Model calculations produce sulfate saturation several hundred years prior to the initial drawdown. Thus the first cycle evaporites are most likely to have precipitated across a wide range of water depths out of a Mediterranean Sea rich in brine and remaining at the level of the Atlantic except for minor excursions. Precession-modulation of evaporation and precipitation produces the observed amplitudes of water level fluctuations needed to account for the second cycle gypsum/mud beds belonging to the Upper Evaporite series and recovered in deep-sea drill cores from basin floors, aprons, and accretionary prisms. The computations predict the long isolation of the eastern Mediterranean in an evaporative lacustrine environment and the slightly shorter isolation of the western Mediterranean. The isostatic loading of both the brine water body and the accumulating layer of detritus and salt produces a peripheral bulge that the model uses to rapidly close the Atlantic spillway through a positive feedback. Seepage of Atlantic water through a limestone aquifer or through tectonic fractures (J. M. Rouchy, personal communication) may have set the stage for the catastrophic opening of the Gibraltar Strait.

The original desiccation hypothesis for the formation of saline giants, such as the Messinian Mediterranean, needs modification to include an early stage of brine concentration without substantial drawdown, a brief mid-stage of massive salt precipitation accompanying closure, and a terminal stage of near total isolation when water levels oscillate with high amplitude as the consequence of the effects of time varying solar insolation on regional climate. The Mediterranean desert belongs to the late stage. Catastrophic flooding is destined to eventually terminate the isolation, either by stream capture as proposed by Blanc (2002) or by enlargement of aquifer pathways.

It is interesting that the deposition of the giant Luan salt deposit in the late Triassic Gulf of Mexico ended with mudstones, siltstones, sandstones, and conglomerates of the Eagle Mills formation associated with lacustrine, alluvial fan, and braided and meandering stream depositional environments that were buried suddenly by marine limestone of the Smackover Formation. Perhaps the same mechanism of margin uplift also closed the spillway into this depressed basin in a timely manner to prevent it from fully filling with salt. The salt deposition Elk Horn basin in western Canada and the Zechstein Basin in northern Europe also terminated in a fluvial and alluvial phase before completely filling with evaporates as if the spillways into these depressions were also rapidly closed shortly after the commencement of evaporative drawdown.

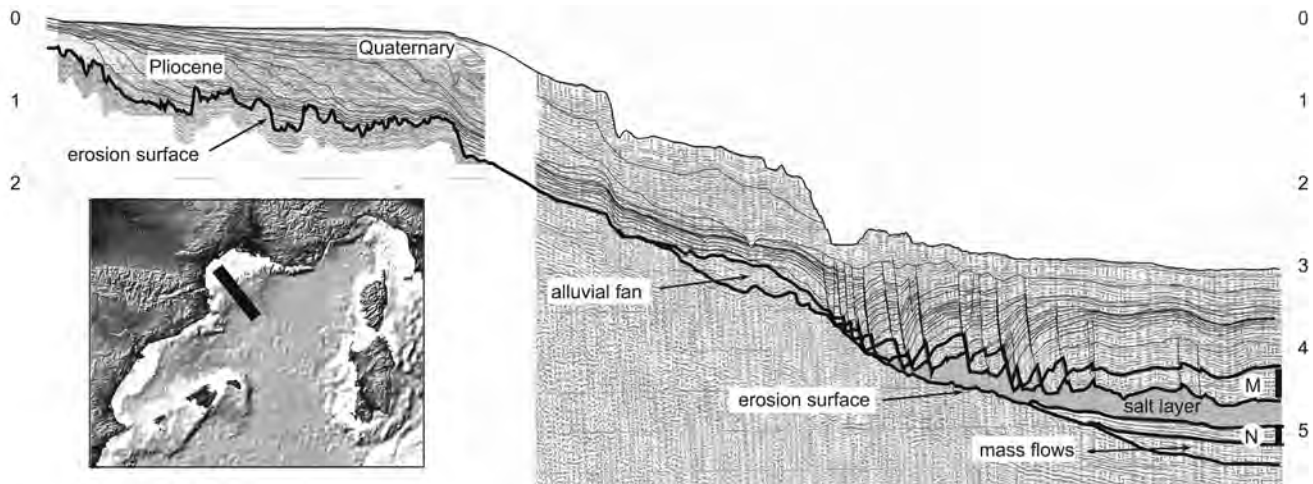
## ACKNOWLEDGMENTS

The exchange of ideas with Maria B. Cita, Kenneth J. Hsü, Yossi Mart, Michael Steckler, David Graindorge, Jennifer Lofi, Gregory Mountain, Alberto Malinverno, Walter C. Pitman III, Charlotte Schreiber, Wout Krijgsman, Franco Ricci-Lucchi and Paul-Louis Blanc has been very insightful. I thank Kimmy

Szeto for his labor in programming the equations into MatLab, Cecilia Baum for extensive assistance with literature search and manuscript preparation, and Chris Scholz and Martin Stute for their encouragement and suggestions. Jean Marie Rouchy provided an extremely helpful review of the manuscript and deserves special thanks. The U.S. National Science Foundation supported the modeling effort via grant NSF OCE 02-41964.

## REFERENCES

- AHMED, S. S., 1972. Geology and petroleum prospects in eastern Red Sea. *Bulletin of the American Association of Petroleum Geologists*, 56: 707-719.
- AUZENDE, J.M., BONNIN, J., OLIVET, J.-L., and PAUTOT, G., 1971. Upper Miocene salt layer in the western Mediterranean. *Nature Physical Science*, 230: 82-84.
- BARBER, P. M., 1981. Messinian subaerial erosion of the proto-Nile delta. *Marine Geology*, 44: 253-272.
- BELLANCA, A., CARUSO, A., FERRUZZA, G., NERI, R., ROUCHY, J.M., SPROVIERI, M., and BLANC-VALLERON, M.-M., 2001. Sedimentary record of the transition from marine to hypersaline conditions in the Messinian Tripoli Formation in the marginal areas of the Sicilian Basin. *Sedimentary Geology*, 139: 87-106.
- BERTONI, C. and CARTWRIGHT, J.A., 2006. Controls on the basinwide architecture of late Miocene (Messinian) evaporites on the Levant margin (Eastern Mediterranean). *Sedimentary Geology*, 118-119: 93-114.
- BISCAYE, P. E., RYAN, W.B.F., and WEZEL, F.C., 1972. Age and nature of the pan-Mediterranean subbottom reflector M. In: Stanley, D., Ed., *The Mediterranean Sea*, 83-90. Stroudsburg, PA: Dowden, Hutchinson, and Ross, Inc.
- BLANC, P.-L., 2000. Of sills and straits: a quantitative assessment of the Messinian Salinity Crisis. *Deep-Sea Research*, 47: 1429-1460.
- , 2002. The opening of the Plio-Quaternary Gibraltar Strait: assessing the size of a cataclysm. *Geodinamica Acta*, 15: 303-317.
- , 2006. Improved modelling of the Messinian Salinity Crisis and conceptual implications. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 238: 349-372.
- BLANC-VALLERON, M.-M., PIERRE, C., CAULET, J.-P., CARUSO, A., ROUCHY, J.M., GESPUGLIO, G., SPROVIERI, R., PESTREA, S., and DI STEFANO, E., 2002. Sedimentary, stable isotope and micropaleontological records of paleoceanographic change in the Messinian Tripoli Formation (Sicily, Italy). *Palaeogeography Palaeoclimatology Palaeoecology* 185: 255-286.
- BOSWORTH, W. and MCCLAY, K., 2001. Structural and stratigraphic evolution of the Gulf of Suez Rift, Egypt: a synthesis. *Mémoires de Muséum national d'Histoire naturelle*, 186: 567-605.
- BUTLER, R.W.H., MCCLELLAND, E. and JONES, R.E., 1999. Calibrating the duration and timing of the Messinian salinity crisis in the Mediterranean: linked tectonoclimatic signals in thrust-top basins of Sicily. *Journal of the Geological Society of London*, 156: 827-835.
- CERNOBORI, L., HIRN, A., MCBRIDE, J.H., NICOLICH, R., PETRONIO, L., and ROMANELLI, M., 1996. Crustal image of the Ionian basin and its Calabrian margins. *Tectonophysics*, 264: 175-189.
- CHUMAKOV, I.S., 1973. Pliocene and Pleistocene deposits of the Nile Valley in Nubia and Upper Egypt. In: Ryan, W.B.F. and Hsü, K. J.,



TEXT-FIGURE 6

Interpreted seismic reflection profile across the Gulf of Lions shelf, slope and basin floor showing the pervasive Messinian erosion surface (heavy black line) descending under the landward edge of the salt layer. The wedge of sediment beneath the N-Reflectors is debris shed from the margin accompanying the first drawdown event near the beginning of stage 1. This deposit is subaqueous in origin and was delivered from the shelf and slope by instabilities generated when the Mediterranean brine became heavier than the pore waters. Its timing could correspond to the rapid "shoaling" observed in the passage from the Tripoli Formation to the Calcare de Base. The alluvial fan contains further sediment shed from the shelf and slope following the major drawdown. Considerable amounts of redeposited marl and mud are interbedded in the evaporites making up the thick M-Reflectors. The salt layer has experienced subsequent flowage from the margin towards the basin center. Vertical scale is seconds of two-way travel time (3 seconds corresponds to a seafloor depth of 2150m).

Eds., *Initial Reports of the Deep Sea Drilling Project*, volume 13: 1242-1243. Washington DC: US Government Printing Office.

CITA, M.B., 1972. Studi sul Pliocene e sugli strati di passaggio del Miocene al Pliocene. I. Il significato della transgressione Pliocenica alla luce delle recenti scoperte nel Mediterraneo. *Rivista Italiana di Paleontologia e Stratigrafia*, 78: 527-599.

———, 1973. Mediterranean evaporite: paleontological arguments for a deep-basin desiccation model. In: Cita, M.B., Ed., *Messinian Events in the Mediterranean*, 206-228. Amsterdam: North Holland Publishing Company.

CITA, M.B. and GARTNER, S., 1973. The stratotype Zanclean. Foraminiferal and nannofossil biostratigraphy. *Rivista Italiana di Paleontologia Stratigrafia*, 79: 503-558.

CITA, M.B., WRIGHT, R.C., RYAN, W.B.F., and LONGINELLI, A., 1978. Messinian paleoenvironments. In: Hsü, K.J. and Montadert, L., Ed. *Initial Reports of the Deep Sea Drilling Project*, volume 42a: 1003-1035. Washington, DC: US Government Printing Office.

CLAUER, N., 1976.  $^{87}\text{Sr}/^{86}\text{Sr}$  composition of evaporitic carbonates and sulphates from Miocene sediment cores in the Mediterranean (D.S.D.P., Leg 13). *Sedimentology*, 23:133-140.

CLAUZON, G., 1973. The eustatic hypothesis and the pre-Pliocene cutting of the Rhône Valley. In: Ryan, W.B.F. and Hsü, K.J., Eds., *Initial Reports of the Deep Sea Drilling Project*, volume 13: 1251-1256. Washington, DC: US Government Printing Office.

———, 1978. The Messinian Var Canyon (Provence, Southern France)- Paleogeographic implications. *Marine Geology*, 27: 231-246.

CLAUZON, G., SUC, J.P., GAUTIER, F., BERGER, A., and LOUTRE, M.-F., 1996. Alternate interpretation of the Messinian salinity crisis: controversy resolved? *Geology*, 24: 363-366.

COLALONGO, M.L., CREMONINI, G., FARABEGOLI, E., SARTORI, R., TAMPIERI, R. AND TOMADIN, L., 1976. Paleoenvironmental study of Colombacci Formation in Romagna (Italy): the Cella section. *Memoria Società Geologica Italiana*, 16: 197-216.

DAVIES, D. and TRAMONTINI, C., 1970. The deep structures of the Red Sea. *Philosophical Transactions of the Royal Society of London*, 267: 181-189.

DEBENEDETTI, A., 1976. Messinian salt deposits in the Mediterranean: evaporites or precipitates? *Bollettino Società Geologica Italiana*, 95: 941-950.

———, 1982. The problem of origin of the salt deposits in the Mediterranean and of their relations to other salt occurrences in the Neogene formations of contiguous regions. *Marine Geology*, 49: 81-133.

DECIMA, A. and WEZEL, F.C., 1971. Osservazioni sulle evaporiti messiniane della Sicilia centro-meridionale. *Rivista Mineralogica Siciliana*, 22: 172-187.

———, 1973. Late Miocene evaporites of the Central Sicilian Basin. In: Ryan, W.B.F. and Hsü, K.J., Eds., *Initial Reports of the Deep Sea Drilling Project*, volume 13: 1234-1240. Washington, DC: US Government Printing Office.

DECIMA, A., MCKENZIE, J.A. and SCHREIBER, B.C., 1988. The origin of "evaporative" limestones: An example from the Messinian of Sicily (Italy). *Journal of Sedimentary Petrology*, 58: 256-272.

DELRIEU, B., ROUCHY, J.M., and FOUCAULT, A., 1993. La surface d'érosion finimessinienne en Crète centrale (Grèce) et sur le pourtour méditerranéen: rapports avec la crise de salinité méditerranéenne, *Comptes rendus de l'Académie des sciences de Paris*, 316: 527-533.

DIETZ, R.S., and WOODHOUSE, M., 1988. Mediterranean theory may be all wet. *Geotimes*, May: 4

- DRONKERT, H., 1976. Late Miocene evaporites in the Sorbas Basin and adjoining areas. *Memoria della Società Geologica Italiana*, 16: 34-361.
- DROOGER, C. W., 1973. The messinian events in the Mediterranean: a review. In C.W. Drooger, Ed., *Messinian Events in the Mediterranean*, 263-272. Amsterdam: North Holland Publishing Company.
- FLECKER, R. and ELLAM, R.M., 2006. Identifying Late Miocene episodes of connection and isolation in the Mediterranean-Paratethyan realm using Sr isotopes. *Sedimentary Geology*, 188-189: 189-203.
- FINETTI, I. and MORELLI, C., 1972. Wide scale digital seismic exploration of the Mediterranean Sea. *Bolletino Geofisica Teorica e Applicata*, 4: 291-342.
- FONTES, J.-C., LETOLLE, R., NESTEROFF, W.D., and RYAN, W.B.F., 1973. Oxygen, carbon, sulfur and hydrogen stable isotopes in carbonate and sulfate mineral phases of Neogene evaporites, sediments, and in interstitial waters. In: Ryan, W.B.F. and Hsü, K. J., Eds. *Initial Reports of the Deep Sea Drilling Project*, volume 13: 788-794. Washington DC: US Government Printing Office.
- FORTUIN, A.R. and KRIJGSMAN, W., 2003. The Messinian of the Nijar Basin (SE Spain), sedimentation, depositional environment and paleogeographic evolution. *Sedimentary Geology*, 160: 213-242.
- FRIEDMAN, G. M., 1973. Petrographic data and comments on the depositional environment of the Miocene sulfates and dolomites at Sites 124, 132, 134, Western Mediterranean. In: Ryan, W.B.F. and Hsü, K. J., Eds., *Initial Reports of the Deep Sea Drilling Project*, volume 13: 695-707. Washington, DC: US Government Printing office.
- FRIEDMAN, I. and HARDCASTLE, K., 1974. Deuterium in interstitial waters from Red Sea cores. In: Whitmarsh, R.B., Weser, O. E. and Ross, D. A., Eds., *Initial Reports of the Deep-Sea Drilling Project* volume 23: 969-970. Washington, DC: US Government Printing Office.
- GARCIA-VEIGAS, J., ORTI, F., ROSELL, L., AYORA, C., ROUCHY, J.M., and LUGLI, S., 1995. The Messinian salt in the Mediterranean: geochemical study of the salt from the Central Sicily Basin and comparison with the Lorca Basin (Spain). *Bulletin de la Société Géologique de France*, 166: 699-710.
- GARRISON, R., SCHREIBER, B. C., BERNOULI, D., FABRICIUS, F., KIDD, R., and MELIERES, F., 1978. Sedimentary petrology and structures of the Mediterranean evaporitic sediments in the Mediterranean Sea. In: Hsü, K.J. and Montadert, L., Ed., *Initial Reports of the Deep Sea Drilling Project*, volume 42a: 571-612. Washington, DC: US Government Printing Office.
- GIRDLER, R.W. and WHITMARSH, R.B., 1974. Miocene evaporites in Red sea cores, their relevance to the problem of the width and age of the oceanic crust beneath the Red Sea. In: Whitmarsh, R.B., Weser, O. E., and Ross, D. A., Eds. *Initial Report of the Deep Sea Drilling Project*, 23: 821-847. Washington, DC: US Government Printing Office.
- GUENNOC, P., PAUTOT, G., and COUTELLE, A., 1988. Surficial structures of the northern Red Sea axial valley from 23°N to 28°N: time and space evolution of neo-oceanic structures. *Tectonophysics*, 153: 1-23.
- HAJOS, M., 1973. The Mediterranean Diatoms. In: Ryan, W.B.F. and Hsü, K. J., Eds. *Initial Reports of the Deep Sea Drilling Project*, volume 13: 944-970. Washington DC: US Government Printing Office.
- HARDIE, L.A. and LOWENSTEIN, T.K., 2004. Did the Mediterranean dry out during the Miocene? A reassessment of the evaporite evidence from DSDP Legs 13 and 42A cores. *Journal of Sedimentary Research* 74: 453-461.
- HERSEY, J.B., 1965. Sediment ponding in the deep sea. *Bulletin of the Geological Society of America*, 76: 1251.
- HILGEN, F. J., KRIJGSMAN, W., LANGEREIS, C.G., LOURENS, L.J., SANTARELLI, A., and ZACHARIASSE, W.J., 1995. Extending the astronomically calibrated (polarity) time scale into the Miocene. *Earth and Planetary Science Letters*, 136: 495-510.
- HSÜ, K.J., 1972. Origin of saline giants: a critical review after the discovery of the Mediterranean Evaporite. *Earth-Science Reviews*, 8: 371-396.
- , 1973. The desiccated deep-basin model for the Messinian events. In: Drooger, C.W., Ed., *Messinian Events in the Mediterranean*, 60-67. Amsterdam: North-Holland Publishing Company.
- HSÜ, K. J., CITA, M. B., and RYAN, W.B.F., 1973a. Origin of the Mediterranean evaporites. In: Ryan, W.B.F. and Hsü, K. J., Eds. *Initial Reports of the Deep Sea Drilling Project*, volume 13: 1203-1231. Washington DC: US Government Printing Office.
- HSÜ, K. J., RYAN, W. B. F., and SCHREIBER, B.C., 1973b. Petrography of a halite sample from hole 134 – Balearic Abyssal Plain. In: Ryan, W.B.F. and Hsü, K. J., Eds., *Initial Reports of the Deep Sea Drilling Project*, volume 13: 708-712. Washington DC: US Government Printing Office.
- HSÜ, K. J., RYAN, W. B. F., and CITA, M.B., 1973c. Late Miocene desiccation of the Mediterranean. *Nature*, 242: 240-244.
- HSÜ, K. J., MONTADERT, L., BERNOULLI, D., CITA, M.B., ERIKSON, A., GARRISON, R., KIDD, R.B., MELIERES, F., MULLER, C., and WRIGHT, R., 1977. History of the Mediterranean salinity crisis. *Nature*, 267: 399-403.
- , 1978. History of the Mediterranean salinity crisis. In: Hsü, K.J. and Montadert, L., Eds., *Initial Reports of the Deep Sea Drilling Project*, volume 42A: 1053-1078. Washington, DC: US Government Printing Office.
- IACCARINO, S. and BOSSIO, A., 1999. Paleoenvironment of uppermost Messinian sequences in the western Mediterranean (Sites 974, 975, and 978). In: Zahn, R., Comas, M.C., and Klaus, A., Eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, volume 161: 529-542. College Station, TX: Ocean Drilling Program.
- IACCARINO, S., CASTRADORI, D., CITA, M.B., DI STEFANO, E., GABOARDI, S., MCKENZIE, J.A., SPEZZAFERRI, S., and SPROVIERI, R., 1999. The Miocene-Pliocene boundary and the significance of the earliest Pliocene flooding in the Mediterranean. *Memoria Società Geologica Italiana*, 54: 109-131.
- KASTENS, K. and MASCLE, J., 1990. Did a glacio-eustatic sea-level drop trigger the Messinian salinity crisis. *Proceedings of the Ocean Drilling Program, Scientific Results*, volume 107: 3-26. College Station, Texas: Ocean Drilling Program.
- KNOTT, S. T., BUNCE, E. T., and CHASE, R.L., 1966. Red Sea seismic reflection. *The world rift system*, Geological of Survey Canada Paper 66-14:5.
- KEOGH, S.M. and BUTLER, R.W.H., 1999. The Mediterranean water body in the Late Messinian: interpreting the record from marginal basins on Sicily. *Journal of the Geological Society of London*, 156: 837-846.
- KRIJGSMAN, W., HILGEN, F. J., RAFFI, I., SIERRO, F.J., and WILSON, D.S., 1999a. Chronology, causes and progression of the Mediterranean salinity crisis. *Nature*, 400: 652-655.

- KRIJGSMAN, W., HILGEN, F.J., MARABINI, S. and VAI, G.B., 1999b. New paleomagnetic and cyclostratigraphic age constraints on the Messinian of the Northern Apennines (Vena del Gesso Basin, Italy). *Memoria Società Geologica Italiana*, 54: 25-33.
- KÜHN, R. and HSÜ, K.J., 1974. Bromine content of Mediterranean halite. *Geology*, 2: 213-216.
- LASKAR, J., ROBUTEL, P., JOUTEL, F., GASTINEAU, M., CORREIA, A.C.M., and LEVARD, B., 2004. A long term numerical solution for the insolation quantities of the Earth. *Astronomy and Astrophysics*, 428: 261-285.
- LLOYD, R. M. and HSÜ, K. J., 1973. Preliminary isotopic investigations of samples from deep-sea drilling in the Mediterranean Sea. In: Ryan, W.B.F. and Hsü, K. J., Eds., *Initial Reports of the Deep Sea Drilling Project*, volume 13: 783-787. Washington DC: US Government Printing Office.
- LOFI, J., GORINI, C., BERNE, S., CLAUZON, G., DOS REIS, A.T., RYAN, W.B.F., and STECKLER, M.S., 2005. Erosional processes and paleo-environmental changes in the western gulf of Lions (SW France) during the Messinian Salinity Crisis. *Marine Geology*, 217: 1-30.
- LOWELL, J. D. and GENIK, G. J., 1972. Sea-floor spreading and structural evolution of the southern Red Sea. *Bulletin of the American Association of Petroleum Geologists*, 56: 247-259.
- LUGLI, S., 1999. Geology of the Realmonte salt deposit, a desiccated Messinian basin (Agrigento, Sicily). *Memoria Società Geologica Italiana*, 54: 75-81.
- LUGLI, S., and LOWENSTEIN, T.K., 1997. Paleotemperatures preserved in fluid inclusions in Messinian halite, Realmonte Mine (Agrigento, Italy): Abstract in Cita, M.B., and McKenzie, J.A., Eds., *Neogene Mediterranean Paleoceanography*, p. 44. Erice, Sicily, Italy: Società Geologica Italiana.
- LUGLI, S., and SCHREIBER, B.C., 1997. Giant polygons in the Messinian salt of the Realmonte Mine (Agrigento, Sicily): Implications for modeling the "salinity crisis" in the Mediterranean, Abstract in Cita, M.B., and McKenzie, J.A., Eds., *Neogene Mediterranean Paleoceanography*, p. 46. Erice, Sicily, Italy: Società Geologica Italiana.
- LUGLI, S., SCHREIBER, B.C., and TRIBERTI, B., 1999. Giant polygons in the Realmonte mine (Agrigento, Sicily): evidence for the desiccation of a Messinian halite basin. *Journal of Sedimentary Research*, 69: 764-771.
- MAIKLEM, W.R., 1971. Evaporative drawdown — a mechanism for water-level lowering and diagenesis in the Elk Point Basin. *Bulletin of Canadian Petroleum Geology*, 19: 487-503.
- MAJOR, C.O., and RYAN, W.B.F., 1999. Eratosthenes seamount: Record of late Miocene sea-level changes and facies related to the Messinian salinity crisis. *Memoria Società Geologica Italiana*, 54: 47-59.
- MANZI, V., LUGLI, S., RICCI LUCCHI, F., and ROVERI, M., 2005. Deep-water clastic evaporites deposition in the Messinian Adriatic foredeep (Northern Apennines, Italy): Did the Mediterranean ever dry out?. *Sedimentology*, 52: 875-902.
- MANZI, V., ROVERI, M., GENNARI, R., BERTINI, A., BIFFI, U., GIUNTA, S., IACCARINO, S., LANCI, L., LUGLI, S., NEGRI, A., RIVA, A., ROSSI, M., TAVIANI, M. 2007. The deep-water counterpart of the Messinian Lower Evaporites in the Apennine foredeep: the Fananello section (Northern Apennines, Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 251: 470-499.
- MAUFFRET, A., FAIL, J.P., MONTADERT, L., SANCHO, J., and WINNOCK, E., 1973. Northwestern Mediterranean sedimentary basin from seismic reflection profile. *Bulletin of the American Association of Petroleum Geologists*, 57: 2245-2262.
- MCKENZIE, J. A., 1999. From desert to deluge in the Mediterranean. *Nature*, 400: 613-614.
- MEIJER, P. TH., and KRIJGSMAN, W., 2005. A quantitative analysis of the desiccation and refilling of the Mediterranean during the Messinian Salinity Crisis. *Earth and Planetary Science Letters*, 240: 510-520.
- MILLER, P.M., and BARAKAT, H., 1988. Geology of the Safaga Concession, northern Red Sea, Egypt. *Tectonophysics*, 153: 123-136.
- MONTADERT, L., SANCHO, J., FAIL, J.P., DEBYSER, J., and WINNOCK, E., 1970. De l'âge tertiaire de la série salifère responsable des structures diapiriques en Méditerranée occidentale (Nord-Est des Baléares). *Compte Rendu de l'Académie des Sciences, Série D*, 271: 812-815.
- MONTADERT, L., LETOUZEY, J., and MAUFFRET, A., 1978. Messinian event: seismic evidences. In: Hsü, K.J. and Montadert, L., Eds. *Initial reports of the Deep Sea Drilling Program*, volume 42a: 1037-1050. Washington, DC: US Government Printing Office.
- MULLER, D.W. and MUELLER, P.A., 1991. Origin and age of the Mediterranean Messinian evaporites: implications from Sr isotopes. *Earth and Planetary Science Letters*, 107: 1-12.
- NESTEROFF, W.D., 1973. Pétrographie des évaporites messiniennes de la Méditerranée. Comparaison des forages JOIDES-DSDP et des dépôts du Bassin de Sicile. In: Drooger, C.W., Ed., *Messinian Events in the Mediterranean*, 111-123. Amsterdam: North-Holland Publishing Company.
- OGNIBEN, L., 1957. Petrografia della Serie Solifera e considerazioni geologiche relative. *Memoria Descritta Carta Geologica Italiana*, 11: 275-292.
- ORSZAG-SPERBER, F., ROUCHY, J.-M., BIZON, G., BIZON, J.J., CRAVATTE, J. and MULLER, J., 1980. La sédimentation messinienne dans le bassin de Polemi (Chypre). *Géologica Méditerranéenne*, 7: 91-102.
- ORSZAG-SPERBER, F., HARWOOD, G., KENDALL, A. and PURSER, B.H., 1998. A Review of the evaporates of the Red Sea-Gulf of Suez rift. In: Purser, B.H. and Bosence, D.W.J., Eds. *Sedimentation and Tectonics of Rift Basins: Red Sea-Gulf of Aden*, 409-426. London: Chapman and Hall.
- PHILLIPS, J.D. and ROSS, D.A., 1970. Continuous seismic reflection profiles in the Red Sea. *Philosophical Transactions of the Royal Society of London, A*, 267: 143-152.
- RICCI LUCCHI, F., 1973. Resedimented evaporites: indicators of slope instability and deep-basin conditions in Periadriatic Messinian (Apennines Foredeep, Italy). In: Drooger, C.W., Ed., *Messinian Events in the Mediterranean*, 142-149. Amsterdam: North-Holland Publishing Company.
- RICHTER-BERNBURG, G., 1973. Facies and paleogeography of the Messinian evaporites in Sicily. In: Drooger, C.W., Ed., *Messinian Events in the Mediterranean*, 124-141. Amsterdam: North-Holland Publishing Company.
- RIZZINI, A. and DONDI, L., 1978. Erosional surfaces of Messinian age in the subsurface of the Lombardian Plain (Italy). *Marine Geology*, 27: 303-325.

- RIZZINI, A., VEZZANI, F., COCOCETTA, V., and MILAD, G., 1978. Stratigraphy and sedimentation of a Neogene-Quaternary section in the Nile Delta area. *Marine Geology*, 27: 327-348.
- ROBERTSON, A.H.F., EATON, S., FOLLOWS, E.J. and PAYNE, A.S., 1995. Depositional processes and basin analysis of the Messinian evaporites in Cyprus. *Terra Nova*, 7: 233-253.
- ROHLING, E.J., and HILGEN, F.J., 1991. The eastern Mediterranean climate at times of sapropel formation: A review. *Geologie en Mijnbouw*, 70:253-264.
- ROSELL, L., ORTI, F., KASPRZYK, A., PLAYA, E. and PERYT, T.M., 1998. Strontium geochemistry of Miocene primary gypsum: Messinian of southeastern Spain and Sicily and Badenian of Poland. *Journal of Sedimentary Research*, 68: 63-79.
- ROSS, D.A., WHITMARSH, R.B., ALI, S.A., BOUDREAUX, J.E., COLEMAN, R., FLEISHER, R.L., GIRDLER, R., MANHEIM, F., MATTER, A., NIGRINI, C., STOFFERS, P. and SUPKO, P.R., 1973. Red Sea Drillings. *Science*, 179: 377-380.
- ROSSIGNOL-STRICK, M., NESTEROFF, W., OLIVE, PH., and VERGNAUD-GRAZZINI, C., 1982. After the deluge: Mediterranean stagnation and sapropel formation. *Nature*, 295:105-110.
- ROSSIGNOL-STRICK, M., 1983. African monsoons, an immediate climate response to orbital forcing. *Nature*, 304: 46-49.
- ROUCHY, J.-M., ORSZAG-SPERBER, F., BIZON, G., and BIZON, J.J., 1980. Mise en évidence d'une phase d'émersion finimessinienne dans le bassin de Pissouri, Chypre: une modalité de passage Miocène-Pliocène en Méditerranée orientale. *Compte Rendus Academie des Sciences Paris*, 291: 729-732.
- ROUCHY, J.-M., 1982a. La crise évaporitique messinienne de Méditerranée; nouvelles propositions pour une interprétation génétique. *Bulletin, Muséum national d'Histoire naturelle*, 4(3-4): 107-136.
- , 1982b. La genèse des évaporites messiniennes de Méditerranée. *Mémoires de Museum National d'Histoire Paris*, 50: 1-277
- ROUCHY, J.M. and SAINT MARTIN, J.-P., 1992. Late Miocene events in the Mediterranean as recorded by carbonate-evaporite relations. *Geology*, 20: 629-632.
- ROUCHY, J.-M. and CARUSO, A., 2006. The Messinian salinity crisis in the Mediterranean basin: A reassessment of the data and an integrated scenario. *Sedimentary Geology*, 188-189: 35-67.
- ROVERI, M. and MANZI, V., 2006. The Messinian salinity crisis: Looking for a new paradigm? *Palaeogeography Palaeoclimatology Palaeoecology*, 238(1-4): 386-398.
- ROVERI, M., MANZI, V., RICCI LUCCHI, F., and ROGLEDI, S., 2003. Sedimentary and tectonic evolution of the Vena del Gesso basin (Northern Apennines, Italy): Implications for the onset of the Messinian salinity crisis. *Bulletin of the Geological Society of America*, 115(4): 387-405.
- RUGGIERI, G., 1967. Miocene and later evolution of the Mediterranean Sea. In Adams, C.G. and Ager, A.V., Eds., *Aspects of Tethyan Biogeography*, 283-290. London: Systematics Association 7.
- RUGGIERI, G. and SPROVIERI, R., 1974. The Lacustrine faunas in Sicily and the desiccation theory of the Messinian Salinity Crisis. *Lavori Istituto Geologico Palermo*, 13: 3-6.
- RUGGIERI, G. and SPROVIERI, R., 1976. Messinian salinity crisis and its paleogeographical implications. *Palaeogeography Palaeoclimatology Palaeoecology*, 20: 13-21.
- RYAN, W.B.F., 1976. Quantitative evaluation of the depth of the western Mediterranean before, during and after the Late Miocene salinity crisis. *Sedimentology*, 23: 791-813.
- , 1978. Messinian badlands on the southeastern margin of the Mediterranean Sea. *Marine Geology*, 27: 349-363.
- RYAN, W.B.F. and CITA, M. B., 1978. The nature and distribution of Messinian erosion surfaces: indicators of a several-kilometer-deep Mediterranean in the Miocene. *Marine Geology*, 27: 193-230.
- RYAN, W.B.F., HSÜ, K. J., et al., 1973. *Initial Reports of the Deep Sea Drilling Project*, volume 13. Washington, DC: US Government Printing Office, 1447p.
- RYAN, W.B.F., STANLEY, D. J., HERSEY, J.B., FAHLQUIST, D.A., and ALLAN, T.D., 1971. The tectonics and geology of the Mediterranean Sea. In: Maxwell, A., Ed., *The Sea*, 387-492. New York: Wiley-Interscience 4.
- SCHREIBER, B.C. and TABAKH, M.E., 2000. Deposition and early alteration of evaporites. *Sedimentology*, 47:1-25.
- SELLI, R., 1973. An outline of the Italian Messinian. In: Drooger, C.W., Ed., *Messinian Events in the Mediterranean*, 124-141. Amsterdam: North-Holland Publishing Company.
- SHACKLETON, N. J., HALL, M.A., and PATE, D., 1995. Pliocene stable isotope stratigraphy of site 846. *Proceedings of the Ocean Drilling Program, Scientific Results*, volume 138: 337-355. Washington, DC: US Government Printing Office.
- SHEARMAN, D. J., 1963. Recent anhydrite, gypsum, dolomite, halite from the coastal flats of the Arabian shore of the Persian Gulf. *Proceedings, Geological Society of London*, 1607:63.
- SIERRO, F.J., FLORES, J.A., ZAMARRENO, I., VAZQUEZ, A., UTRILLA, R., FRANCÉS, G., HILGEN, F.J. and KRIJGSMAN, W., 1999. Messinian pre-evaporite sapropels and precession induced oscillations in western Mediterranean climate. *Marine Geology* 153: 137-146.
- SONNEFELD, P., 1985. Models of Upper Miocene evaporite genesis in the Mediterranean region. In: Stanley, D.J. and Wezel, F.C., Eds., *Geological Evolution of the Mediterranean Basin*, 323-346. New York: Springer-Verlag.
- SONNEFELD, P. and FINETTI, I., 1985. Messinian evaporites in the Mediterranean: a model of continuous inflow and outflow. In: Stanley, D.J. and Wezel, F.C., Eds. *Geological Evolution of the Mediterranean Basin*, 347-553. New York: Springer-Verlag.
- SPROVIERI, R., DI STEFANO, E., CARUSO, A., and BONOMO, S., 1996a. High resolution stratigraphy in the Messinian Tripoli Formation in Sicily. *Paleopelagos*, 6: 415-435.
- , 1996b. High resolution chronology for late Miocene Mediterranean stratigraphic events. *Rivista Italiana Paleontologia e stratigraphica*, 102: 77-104.
- SPROVIERI, R., BELLANCA, A., NERI, R., MAZZOLA, S., BONANNO, A., and SORGENTE, R., 1997. Astrochronology of the Tortonian/Messinian stratigraphic interval in the Mediterranean basins. *Neogene Mediterranean Paleogeography*, Erice, Sicily, Italy. *Memoria Societa Geologica Italiana*, 54: 7-25.
- SPROVIERI, M., BELLANCA, A., NERI, R., MAZZOLA, S., BONANNO, A., PATTI, B., and SORGENTE, R., 1999. Astronomical calibration of late Miocene stratigraphic events and analysis of precessionally driven paleoceanographic changes in the Mediterranean basin. *Memoria Societa Geologica Italiana*, 54: 7-24

- STOFFERS, P. and KÜHN, R., 1974. Red Sea evaporites: a petrologic and geochemical study. In: Whitmarsh, R.B., Weser, O.E. and Ross, D.A., Eds., *Initial Report of the Deep sea Drilling Project*, volume 23:849-865. Washington, DC: US Government Printing Office.
- STOFFERS, P. and ROSS, D. A., 1974. Sedimentary history of the Red Sea. In: Whitmarsh, R.B., Weser, O. E., and Ross, D. A., Eds., *Initial Report of the Deep Sea Drilling Project*, volume 23:821-847. Washington, DC: US Government Printing Office.
- SUC, J.-P., and BESSAIS, E., 1990. Pérennité d'un climat thermique en Sicile avant, pendant, après la crise de salinité messinienne. *Compte Rendus, Academie des Sciences Paris*, 294: 1003-1008.
- VAI, G.B. and RICCI LUCCHI, F., 1977. Algal crusts, autochthonous and clastic gypsum in a cannibalistic evaporite basin: a case history from the Messinian of the Northern Apennines. *Sedimentology*, 24:211-244.
- VAI, G.B., 1997. Cyclostratigraphic estimate of the Messinian stage duration. In: Montanari, A., Odin, G.S., and Coccioni, R., Eds., *Miocene Stratigraphy- An integrated approach*, 463-476. Amsterdam: Elsevier.
- VERGNAUD-GRAZZINI, C., RYAN, W.B.F. and CITA, M.B., 1977. Stable isotopic fractionation, climate change and episodic stagnation in eastern Mediterranean during late Quaternary. *Marine Micropaleontology*, 4: 353-370.
- ZHANG, J. and SCOTT, D.B., 1996. Messinian deep-water turbidites and glacioeustatic sea-level changes in the North Atlantic: Linkage to the Mediterranean Salinity Crisis. *Paleoceanography*, 11: 277-297.

