Decoding the Mediterranean salinity crisis

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ABSTRACT

This historical narrative traces the steps to unravel, over a span of 40 years, an extraordinary event in which 5% of the dissolved salt of the oceans of the world was extracted in a fraction of a million years to form a deposit more than 1 million km³ in volume. A buried abyssal salt layer was identified with reflection profiling and sampled during the Deep Sea Drilling Project, Leg 13. The dolomite, gypsum, anhydrite and halite in the drill cores paint a surprising picture of a Mediterranean desert lying more than 3 km below the Atlantic Ocean with brine pools that shrank and expanded by the evaporative power of the sun. The desert drowned suddenly when the Gibraltar barrier gave way. The explanation of 'deep-basin, shallow-water' desiccation and the notion of a catastrophic Zanclean flood had a mixed reception. However, the hypothesis became broadly accepted following subsequent drilling expeditions. Nevertheless, as experts examined the evaporate facies and sequences of equivalent age in the terrestrial outcrops, weaknesses appeared in the concept of repeated flooding and drying to account for the magnitude of the deposits. The 'Rosetta Stone', used to decipher conflicting interpretations, turns out not to be the deposits but the erosion surfaces that enclose them. These surfaces and their detritus – formed in response to the drop in base level during evaporative drawdown - extend to the basin floor. Evaporative drawdown began halfway through the salinity crisis when influx from the Atlantic no longer kept up with evaporation. Prior to that time, a million years passed as a sea of brine concentrated towards halite precipitation. During the later part of this interval, more than 14 cyclic beds of gypsum accumulated along shallow margins, modulated by orbital forcing. The thick salt on the deep seabed precipitated in just the next few cycles when drawdown commenced and the brine volume shrank. Upon closure of the Atlantic spillway, the remnants of the briny sea transformed into salt pans and endorheic lakes fed from watersheds of Eurasia and Africa. The revised model of evaporative concentration now has shallow-margin, shallow-water and deep-basin, deep-water precursors to desiccation.

Keywords Desiccation, evaporates, Lago-Mare, Mediterranean, Messinian, salt.

INTRODUCTION

A vast salt deposit beneath the floor of the Mediterranean (Fig. 1) was not in itself a surprise at the time of the first deep-sea drilling in 1970. Seismic reflection profiles already had revealed diapiric structures (Fig. 2) similar to salt domes (Hersey, 1965; Ryan *et al.*, 1971). Six of the Deep

Sea Drilling Project (DSDP) Leg 13 sites were targeted specifically to understand the distribution of the salt (Mauffret, 1970; Montadert *et al.*, 1970; Auzende *et al.*, 1971), its cover of 'M' reflectors (Biscaye *et al.*, 1972) and its lateral unconformity on margins. Yet, less was known about either the age or the process by which the salt had formed.



Fig. 1. Distribution today of the Messinian-age salt and evaporites, locations of drill sites from which materials or intersected unconformities related to the MSC, and locations of margin settings discussed in the text were recovered.

The Gessoso Solfifera Formation in Sicily has abundant gypsum and salt. Ogniben (1957) attributed its origin to isolation of the Mediterranean from the Atlantic during the Late Miocene. Its brackish to freshwater Paratethyan fauna introduced the concept of a pan-Mediterranean Salinity Crisis (MSC) (Selli, 1960; Decima, 1964; Ruggieri, 1967).

As to the mechanisms of ocean floor salt formation, there were two popular models: (i) deposition in shallow, subsiding and isolated rift valleys as continents split apart (Pautot *et al.*, 1970); or (ii) precipitation in deep depressions separated from an external ocean by an entrance bar (Schmalz, 1969). The first is called the 'shallow-water, shallow-basin' model and the second the 'deep-water, deep-basin' model (Hsü, 1972a,b, 1973; Hsü *et al.*, 1973a,b).

However, those embarking on the *Glomar Challenger* drill ship were unaware of a 1 km deep incision of a fluvial network extending from the Mediterranean to more than 300 km into the interior of France. This downcutting, described in a publication about the Rhône Valley by Denizot (1952), would contribute to the birth of a third model – the 'shallow-water, deep-basin' model. To account for the river incision, Denizot wrote: "There was a regression of the sea at the end of the Miocene ... with the connecting passageways across Spain and Morocco closed and the Gibraltar Strait not yet opened ... the Mediterranean at that moment completely isolated ... reduced to a lagoon and evolving independently according to climatic influence ... there was a drop in sea level ... following the Strait of Gibraltar opened ... the sea invaded the fluvial network" (translation by M.B. Cita in Clauzon, 1973).

A similar deep fluvial incision had also been found in Egypt (Chumakov, 1967, 1973) where marine deposits of Pliocene age indicated that the sea had invaded a 1200 km artery notched into the interior of Africa during the MSC. While searching for oil in Libya in the late 1960s, geophysicists chanced upon yet other fossil drainage systems of Late Miocene age reaching far inland before disappearing under the Sahara Desert (Barr & Walker, 1973).

DISCOVERIES FROM THE FIRST DEEP-SEA DRILLING

Ubiquitous erosion

Introduction to the Mediterranean sub-sea archive of the MSC begins 100 km east of the Gibraltar Strait (Ryan *et al.*, 1973). Here, in the Alboran Basin, the *Glomar Challenger* sampled



Fig. 2. (A) Reflection profile in the Balearic Basin of the Western Mediterranean showing the flowing salt layer (yellow) covered by the 'M' Reflectors (red) and underlain by the 'N' Reflectors (green), adapted from Ryan (1973). The salt ('couche fluante' of Montadert *et al.*, 1970) deforms under the weight of its cover to produce anticlines and salt domes. Unit I is Pliocene to Pleistocene in age and spans the past $5\cdot33$ Myr. Unit II represents the MSC with a duration of only 0.63 Myr. Unit III encompasses the early pre-evaporite Messinian and reaches back to the Burdigalian stage of the Miocene epoch at *ca* 22 Ma. Other letters correspond to the notations used by other research groups. (B) Nearby profile closer to the margin showing a wedge of chaotic strata (blue) sandwiched between the 'N' Reflectors and the flowing salt layer. This deposit is interpreted as detritus eroded from the margins. The *Glomar Challenger* sampled only the 'M' reflectors.

through a subsurface unconformity that is widespread throughout the Mediterranean. Pliocene marl was found on a surface, truncating significantly older Miocene marl. Momentary bouncing of the drill string hinted at a hard ground or lag deposit along the contact. The marl above and below was deposited in a setting similar to the present bathymetry. The gap corresponded to hundreds of metres of the pre-MSC Miocene sea floor washed from a pathway descending eastward from the Gibraltar Strait to the edge of the abyssal salt layer in the North Algerian Basin (Olivet *et al.*, 1973).

In the Valencia Trough, the same erosion surface was encountered as in the Alboran Sea. However, at the transition from slope to trough floor, the surface here splits into two horizons: one channelling the top of the evaporites and salt

(Pautot *et al.*, 1973) and the other truncating the strata directly underneath the salt. The two surfaces merge over bedrock volcanoes protruding through the salt (Mauffret, 1970; Mauffret *et al.*, 1973).

The first sample of MSC deposits was a surprise. It consisted of thick gravel from a channel on the upper erosion surface. The lack of a firm mud matrix prevented further drilling. The gravel had just four components: (i) basalt; (ii) Middle Miocene biogenic limestone; (iii) dwarfed shallow-water molluscs and benthonic foraminifera (Ammonia beccarii, Elphidium macellum) along with a lone shark tooth; and (iv) fragments of selenite. Without having to drill further, material from the volcanoes was recovered, as were their pelagic cover, an evaporating lagoon, the remains of creatures that lived there in waters of unusual salinity and the streambed that had brought them together. The evaporating lagoon and its strange fauna belonged to the strata sandwiched between the two erosion surfaces.

Fresh to brackish water

Fortunately, deeper coring into this sandwiched deposit was possible at the foot of the south-east margin of the Balearic Islands. Recovery began with 25 m of barren dolomitic marls possessing thin beds of laminated, siliceous and bituminous mud (Fig. 3A) that hosted diatoms, silicoflagellates, ebridians, archaeomonads, phytolitharia and sponge spicules (Dumitrica, 1973a,b,c; Hajos, 1973). Identical fauna had once thrived in a vast lake sea ('lac mer' or 'Lago-Mare') spread across Eastern Europe and Western Asia during the Miocene. According to Hajos (1973): these "taxa characteristic of stagnant brackish and landlocked salinas and lagoons are present in such great numbers as to suggest reduced salinity, shallow water depth, and a landlocked environment". It became obvious that these unexpected sediments in deep Mediterranean basins belonged to a salinity crisis of gigantic proportions.

The diatoms were predominantly littoral planktonic forms accompanied by freshwater, euryhaline, benthonic and epiphytic species in considerable numbers to indicate episodes of sunlight illuminating a lakebed. The dolomitic marls also contained sand layers with detrital gypsum (Fig. 3B), reworked foraminifera of mixed ages in allochthonous interbeds and occasional dwarfed specimens of *Globigerina*, *Globigerinita* and *Globorotalia* of Late Miocene age. Some beds were pure detrital gypsum. The dolomitic marls passed downward to laminated anhydrite consisting of the typical laminated 'balatino' facies (Fig. 3C) of the Gessoso Solfifera Series in Sicily with tiny nodules of anhydrite (Fig. 3D) in layers separated by dark laminae (Fig. 3E), interpreted by some researchers as the remains of algal mats (Ogniben, 1957; Hardie & Eugster, 1971; Decima & Wezel, 1973; Friedman, 1973). The anhydrite occurred in cyclic beds, a metre to several metres in thickness. Each anhydrite bed was separated by more dolomitic marl with freshwater fauna/ flora in thin bituminous layers. As coring continued, the anhydrite beds became nodular (Fig. 3F) and then massive with a chicken-wire texture. At least five cycles of dolomitic marl and anhydrite were encountered in the 70 m drilled. Nodular anhydrite, especially with the chicken-wire lattice structure, is considered by numerous experts to be indicative of subaerial diagenesis of soft material in which the nodules are formed by displacement growth within the host sediment (Murray, 1964; Friedman, 1973; Schreiber, 1973), although some researchers believe that it can form in varied subaqueous environments (Hardie & Lowenstein, 2004).

Sabkhas

Following the discovery of modern nodular and chicken-wire anhydrite in supratidal flats of the Persian Gulf, it had been accepted generally that the environment of formation is the subaerial capillary zone above the groundwater table of the coastal sabkha (Shearman, 1966; Shearman & Fuller, 1969). The wavy and crinkly textures may have formed on an exposed algal mat-coated tidal flat as suggested by Hardie & Eugster (1971) for similar beds in the Gessoso Solfifera Series in Sicily. However, an important observation is the remarkable lateral continuity over many tens of kilometres of individual reflectors that correspond to the dolomitic marl–anhydrite cycles.

The significance of a cyclic deposit that covered large areas of the nearly flat Balearic Basin floor but was absent on the steeper slopes was considered. Could the landscape have resembled a Death Valley with ephemeral salt lakes on its floor? Did the cyclic mud indicate periodic flooding followed by desiccation of the lakes to cause the alteration of original laminated anhydrite to nodular and chicken-wire textures in the shallow subsurface of its shores? Were the allochthonous components derived from slopes that had become exposed? Maiklem (1971) coined the phrase 'evaporative drawdown' for this



Fig. 3. Photographs of MSC deposits recovered by deep-sea drilling from the Upper Evaporites at the base of the Menorca margin in the Western Mediterranean. (A) Finely laminated dark, euxinic mud hosting freshwater diatoms. (B) Detrital gypsum with ripple-induced cross-bedding. (C) Laminated 'balatino' primary anhydrite interpreted as seasonal cycles of precipitation. (D) Thin-section image showing the radial growth of anhydrite laths that create the tiny anhydrite spheres. (E) Thin-section image of dark organic material between wavy anhydrite laminae. (F) Displacement growth of large anhydrite nodules that initiate the 'chicken-wire' texture. Black scale bars are 1 cm. White scale bars are 1 mm.

process that left evaporites of shallow-water origin on the floor of an originally deep and subsequently nearly completely dried depression. Maiklem's proving ground was the Elk Point Basin of mid-Devonian age in Western Canada.

Divides

If salt precipitation in the Mediterranean took place only beneath a thin layer of brine, how did the Atlantic supply of salt water travel beyond the closest depression in the Mediterranean and continue over interior divides to other depressions more distal from the Atlantic that yet contain salt layers as thick as those in the vicinity of the Atlantic portal? The crest of the Mediterranean Ridge in the Ionian Sea was one such barrier where reflection profiles revealed only a thin MSC deposit that turned out to be mostly dolomitic marl of the same type found between the anhydrite beds in the Balearic Basin and containing diatoms of both fresh and brackish water. A rip-up conglomerate suggested an episode of possible exposure. A nearby cleft incised through the thin MSC deposits provided the opportunity to reach pre-Messinian strata. This material contained foraminifera representative of a fully marine bathyal setting except that the species in the cleft drill cores were slightly older than those recovered from the pre-MSC strata in the Alboran Sea. Did the absence of substantial amounts of anhydrite or gypsum on the barrier crest confirm that anhydrite, gypsum and halite only formed on basin floors; or had originally thick deposits covered the whole seabed but were eroded from the high region during subsequent evaporative drawdown?

In the Hellenic Trench on the Aegean Sea side of the Ridge barrier, unusually elevated salinities (> 150‰) were discovered in the interstitial waters squeezed from the cores. It meant that subsurface salt was indeed present there and that the brine sea had to have been sufficiently deep to transport solutes across the Ridge divide. Hence, in order to feed interior basins with brine, the concept of repeated filling and drying of the Mediterranean took shape (Hsü, 1973; Hsü *et al.*, 1973a,b).

Lakes

On the flank of the Strabo Mountains, an assemblage of ostracods (*Cyprideis pannonica*) and benthonic foraminifera (*Ammonia beccarii*

tepida) adaptive to the hypohaline milieu (Benson, 1973a,b) was discovered. An identical assemblage appears in the topmost Gessoso Solfifera Series in Sicily where it has been correlated to the 'lac mer' fauna of the Paratethys (Decima, 1964; Ruggieri, 1967; Ruggieri & Sprovieri, 1974, 1976). Conclusive evidence of the abrupt drowning of lakes and exposed land at the conclusion of the MSC was obtained during drilling in the Tyrrhenian Sea where silty clay rich in pollen and spores and mud with freshwater fauna were covered abruptly by deep-sea marine oozes.

Salt at last

The massive salt deposit that had proven elusive until the very last drill site of the expedition was right where the reflection profiles placed it - in the deep confines of the Balearic Basin. The banded halite consists of couplets comprising thick light layers and thin dark layers, with the individual bands ranging from a few millimetres to 40 mm in thickness. The halite crystals are euhedral in shape (Fig. 4A). These so-called 'cubic hopper crystals' (Delwig, 1955) have abundant fluid inclusions that make them appear cloudy when viewed in thin sections compared with their inclusion-free translucent rims. The halite bands are subaqueous cumulates resulting from precipitation at the brine-air interface. The dark layers are predominantly without rims and the lighter layers have sizable clear rims suggestive of overgrowth as brine chemistry changed, perhaps on a seasonal basis. The crystals with clear rims are interlocked in the deposit, indicating a process of growth occurring on or within the seabed. Although cumulates themselves are not

water-depth diagnostic, intercalations of detrital silt and sand display eroded top surfaces. Shrinkage had cracked one such layer of silt and sand interbedded within the halite (Fig. 4B). The absence of any mud matrix and the composition of the salt matrix suggest transport of the sand by wind and settling in brine dissolved from primary bischofite (i.e. magnesium chloride). The top surface is split by a crack filled with clear halite cement (Fig. 4C) and interpreted as evidence of nearly complete basin desiccation (Hsü, 1972a,b; Hsü *et al.*, 1973c).

Terminal flood

The flooding that ended the MSC was permanent. The overlying biogenic ooze of Early Pliocene age possesses an assemblage of benthonic foraminifera (including *Oridosalis unbonatus*) living in normal sea water and in a bathyal setting (Benson, 1973a; Cita, 1973, 1975). The abrupt passage from Lago_Mare deposits below to Pliocene ooze above was recovered at three drill sites (Western, Central and Eastern Mediterranean). The presence of the marine ostracod species *Agrenocythere pliocenica* suggests water depths greater than 1 km and bottom water temperatures near 8 °C (Benson, 1972, 1973b).

Key findings from the first drilling

• Elements belonging to the MSC have fauna and features indicative of intermittent shallow and occasionally subaerial environments, as well as periodic deeper subaqueous environments and salinities ranging from hypersaline to slightly brackish.



Fig. 4. Photographs of halite from the Balaeric Basin at the foot of the Sardinia margin. (A) Large and semi-opaque hopper crystals with brine inclusions sampled from the light bands. (B) Banded translucent halite above a sand layer truncated by erosion and expanded by a desiccation crack (arrow). (C) Thin-section image showing halite in the desiccation crack 'd' in the form of clear crystals without inclusions. Black scale bar is 1 cm. White scale bars are 1 mm.

• The great variability in the isotope measurements and brine chemistry informs about settings that fluctuated from salty brine seas to dried playas. Freshwater from rain and streams left signatures in the negative carbon and oxygen isotope values of the carbonates (Lloyd & Hsü, 1973). However, the crystallization water in the sulphate must have been supplied originally from an Atlantic source (Fontes *et al.*, 1973).

• The recovered MCS sediments are sandwiched between deep-water marine sediments.

• The recovered anhydrite, gypsum and dolomitic marl are all younger than the abyssal salt layer.

• The salt layer is present today in depressions that were in existence at the time of the MSC.

• The dolomitic marl with its diatom-rich bituminous mud belongs to a brackish and freshwater terminal stage of the salinity crisis as described previously by Ruggieri (1967). Some Mediterranean lakes were more than a kilometre deep, submerging the Mediterranean Ridge and leaving shorelines on the Strabo Mountains.

• The MSC ended by an abrupt and permanent drowning of lakes, their shores and their terrestrial margins, by marine water pouring in from the Atlantic.

INITIAL RECEPTION TO THE DESICCATION HYPOTHESIS

As stated by Hsü et al. (1973b), "the idea that an ocean the size of the Mediterranean could actually dry up and leave a big hole thousands of meters below worldwide sea level seems preposterous indeed". So it was anticipated that, when a desiccation hypothesis was presented in 1973 to 170 other researchers attending a colloquium held in Utrecht, titled Messinian Events in the Mediterranean, the announcement would create quite a controversy. A 'dry Mediterranean' presented insurmountable conflicts with other interpretations for the origin of its evaporites (Drooger, 1973). The first objection voiced at the colloquium was to the 'big hole'. For example, it seemed less outrageous to dry up Messinian depressions 'only 200 to 500 m deep' (Nesteroff, 1973). Consequently, it was proposed that the post-MSC bathymetry came about by collapse of the sea floor ('effondrement') following the MSC (Leenhardt, 1973).

The issue of a 'big hole' did not have to be untenable. The ocean crust imaged beneath the floor of the Mediterranean by seismic refraction and reflection (Le Pichon et al., 1971; Ryan et al., 1971; Finetti & Morelli, 1972) and displaying magnetic anomaly stripes (Bayer et al., 1973) had been formed by volcanic eruptions and dyke injections during sea floor spreading at a divergent plate boundary. Ocean crust forms along the axis of the mid-ocean ridges typically at depths below 2.5 km. Sea floor spreading centres are even deeper in back-arc basins. Furthermore, ocean crust subsides as its lithosphere cools and contracts. The Balearic and Tyrrhenian Seas were already being discussed as back-arc basins (Boccaletti & Guazzone, 1974). The Eastern Mediterranean was a remnant of the Mesozoic Tethys (Dewey et al., 1973), with slivers of its oceanic crust and upper mantle cropping out in Cyprus.

Nonetheless, the issue of depth needed to be quantified in order to be convincing. In a presentation in Utrecht, Rvan (1973) discussed recent commercial exploration in the Gulf of Lions where an extensive erosion surface had again been recognized. Similar to the gap in the Alboran Sea, erosion separated marine Miocene from overlying Early Pliocene strata. The horizon in the Gulf of Lions was littered with gravel belonging to fluvial and alluvial deposits. The nonmarine interval did not receive wide attention until it was pointed out by Delteil and co-workers in 1972 (at a meeting of the Mediterranean Science Commission (CIESM) in Athens) that this surface was the equivalent of Reflector 'M' and that erosion continued all the way downslope and beyond the edge of the salt layer (Fig. 5A).

Presumably, the drastic change in base level in the Mediterranean that led to incisions of the Rhône and Nile river valleys and occasional deserts on the floor of the Balearic Basin had also led to washing of the sediment from the margin of Europe. The boreholes in the Gulf of Lions (Cravatte et al., 1974) were the evidence necessary to calculate the magnitude of the base-level drop. Ryan (1976) and Watts & Ryan (1976) tackled this subject by developing a method called 'backstripping'. The key assumption was that the mantle below the rifted southern edge of France cooled by the same conductive heat loss as observed in the mantle beneath the mid-ocean ridge. Thus, sea floor subsided in proportion to its age as the consequence of thermal contraction. Placing the onset of subsidence at 25 Ma based on the borehole data and using the sediment thickness for each borehole as a starting point, the sediment cover was removed (stripped away) back through time.

Lithosphere rebounds from unloading. The depth of basement at any time in the past



Fig. 5. (A) Tracing of a reflection profile from the shelf-edge in the Gulf of Lions to the floor of the Balearic abyssal plain. Oblique arrows mark successive truncations of pre-MSC sediments by the intra-Messinian erosion surface (the line marked 'M'). Erosion extends under the salt layer to a level around 4.5 km. Salt flowage has disrupted the Pliocene–Quaternary cover. (B) Reconstructed sea floor profiles across the Gulf of Lions margin from the mid shelf to the abyssal plain using the method of 'backstripping'. The shaded area illustrates the thickness of pre-MSC sediment removed from the margin by erosion. The curves represent the present sea floor and the calculated pre-MSC and post-MSC sea floor profiles. The calculations reveal that erosion reached to 3.1 km below the level of the external Atlantic. After water returned with the Pliocene flood, the 'pinch-out' of the salt and evaporite layer lay 2.7 km below the sea surface. Redrawn from Ryan (1976). Note that the profile at the top corresponds only to the right half of the profile at the bottom.

corresponds to the water layer thickness plus the amount of sediment that had accumulated (taking into consideration the effects of subsequent compaction). In this manner, a succession of ancient sea floor profiles across the Gulf of Lions were computed and compared with estimates from microfossils.

The calculations of Ryan (1976) of sea floor depths in the Gulf of Lions just prior to the MSC turned out to be of the same magnitude as estimated by Cravatte *et al.* (1974) based on microfossils. As much as 1.5 km of pre-Messinian sediment had been removed from the outer edge of the margin during the MSC. When stripping away the entire Plio-Quaternary sediment cover from the interior shelf to the edge of the bathyal plain, calculations indicated that erosion had reached to 3.1 km below the surface of the external Atlantic prior to the deposition of the flowing salt layer (Fig. 5B). After the terminal flood, the landward edge of the salt and evaporites lay at 2.7 km below the earliest Pliocene sea surface. Later computations that accounted for the stretching of continental lithosphere during rifting (Steckler & Watts, 1980) confirmed these results. Independently, Clauzon (1982) used the magnitude of the incision of the Messinian Rhône canyon to demonstrate a base level at least as deep as 1.6 km in a dry Mediterranean (i.e. without water and the ensuing subsidence caused by the water load). The depth, indicated by Clauzon, of 2.5 km prior to the salinity crisis for a location at the landward edge of evaporites compares favourably with the 2.7 km calculation of Ryan (1976).

Yet the confirmation of a 'big hole' only made it more incredible that the Mediterranean could actually 'dry up'. Water mass budgets and material-balance considerations show that, with the modern rate of excess evaporation relative to water input from rivers and rain, the Mediterranean could theoretically be empty in 10 000 years if severed completely from the Atlantic. However, one Mediterranean volume of water at Atlantic salinity would produce only a few tens of metres of salt. So the second consistent objection to the desiccation hypothesis voiced at Utrecht was the repeated filling necessary to account for the large volume of the salt layer. How many times in fact did the Mediterranean dry up and refill?

Although the DSDP drilling encountered five cycles of dolomitic marl and anhydrite, there was no indication that the Mediterranean had ever refilled to its brim until after the MSC. Cita (1973) cautioned that the sparse, dwarfed foraminiferal assemblage in the dolomitic marl of the DSDP cores represented abnormal conditions, not open marine. Cita's view that the "Mediterranean evaporates are essentially sterile of marine fossils" was supported strongly by Decima & Sprovieri (1973) in their study of the time-equivalent last seven marl levels in the Gessi di Pasquasia Formation in Sicily. These authors found that all the so-called marine foraminifera were reworked. The only autochthonous species were the fresh and brackish water Cyprideis and A. beccarii tepida. All other microfossils were preserved badly. Shells were broken, partly dissolved and stained by red iron oxides. Furthermore, the assemblages were inconsistent in stratigraphic distribution from sample to sample. Many species were already extinct. In the words of Decima and Sprovieri: "the presence of brackish water environments in basins situated in a distal part of the Mediterranean makes it impossible to realize a direct connection with the Atlantic Ocean during the Late Messinian".

Without such connections, from where did the water come? According to Drooger (1973), who was probing the weakness of the deep basin desiccation model: "The refilling, how did it work? ... Filling up to the brim asks for an enormous and rapid water displacement against a continuous evaporation loss, and the more so with every meter ... why did [the Atlantic water] scour a permanent entrance only the last time? ... the more completely we suppose it desiccated many times during the Messinian, the more remarkable the fact that the obstructing barrier was not demolished well before the Pliocene".

ALTERNATE EXPLANATIONS NOT REQUIRING DESICCATION

The hypothesis of repeated filling and desiccation created many difficulties for those familiar with Messinian deposits on land. The aforementioned Gessoso Solfifera Series is widespread throughout the Central Sicilian Basin (also referred to as the 'Caltanissetta Basin'). The Central Sicilian Basin is a foredeep caught in a convergent tectonic setting between the Hyblean Plateau to the south and the Madonie and Nebrodi Mountains to the north. Salt is encountered rarely in outcrop and is, therefore, investigated more systematically in mines and boreholes.

Across all of the Central Sicilian Basin, an unconformity separates the Gessoso Solfifera Series into lower and upper evaporite deposits (Decima & Wezel, 1971, 1973). The lower group starts with pre-MSC diatomaceous sediment (Tripoli Member) passing upwards to carbonates (Calcare di Base Member), the primary evaporites comprising of the Cattolica Gypsum Beds followed by gypsum turbidites, an anhydrite breccia and then halite belonging to the main salt body. The halite is truncated by the unconformity. Above is the upper group, sometimes called the 'Terminal Series' that consists of the Pasquasia Gypsum Beds capped by a sand and conglomerate extant over the whole of Central Sicily (Arenazzolo Formation). The Gessoso Solfifera Series, including its members truncated by erosion, is transgressed by the open marine Trubi Formation of Early Pliocene age. The onset of the Trubi is time-equivalent to the calcareous marls with the acme of Sphaeroidinellopsis recovered in a drill core from the Tyrrhenian Sea (Cita, 1973, 1975). The absence of benthonic microfossils in the very first 'Trubi' pelagic sediments and the succession of their appearances support the assumption of a complete sterilization of the Mediterranean during the MSC (Cita & Gartner, 1973).

At Utrecht, Richter-Bernburg (1973) pointed out that the Calcare di Base is a 'semi-saline carbonatic sediment'. Richter-Bernburg observed cavernous features caused by dissolution of salt with cube-shaped ghosts of halite crystals which were thought to be formed in a water mass that was already highly concentrated with brine. The Calcare di Base was not present everywhere. For example, it formed only on the north-east and south-west elevated rims of the central trough where it reached a thickness of 50 m. Much of the Sicilian Calcare di Base is now breccia linked to solution collapse (karst formation) after emergence. Subsequent investigators measured the oxygen and carbon isotopic compositions of the carbonate and have related the negative values to the influx of meteoric water (Decima *et al.*, 1988). These same investigators have described bedding planes with desiccation cracks and rip-up clasts

and conclude: "The Calcare di Base is primarily a limestone formed in hypersaline waters in the peripheral portions of the Cattolica Basin".

Richter-Bernburg (1973) noted that this Basal Limestone passed down the slope to "gypsum masses of several hundreds of metres in thickness". The gypsum overlapped the limestone only on the edge of the platforms and rested directly on the Tripoli Member in the deeper trough. To one experienced in the European Zechstein, the gypsum in the form of selenite was 'somewhat mysterious'; their giant swallowtail crystals initially suggested secondary diagenesis. Richter-Bernburg writes: "However, studying the sequences and mapping profile after profile, we more and more realize the primary character of this remarkable rock".

Selenite crystals nucleate on the bottom mud and grow upward with radial spreading to form vertical cones (Fig. 6). The tops of the selenite beds are not flat. When exposed on bedding planes, the cones look like a field of cabbages (hence the name 'cavoli' in Italian). The beds of selenite alternate with much thinner carbonate marls. The total thickness of all the beds reaches 250 m. The schema of Decima & Wezel (1973) illustrates the Cattolica Gypsum Beds passing under the salt layer in the axis of the trough, whereas Richter-Bernburg (1973) interprets them as building 'a reef-like platform' that thins abruptly to euxinic mud in the trough where drilling led to the recovery of finely laminated 'balatino' anhydrite layers that, when compared with the German Zechstein, appear to be "typical for relatively deep and calm waters ... by the fact that they are found in company of the halite marls in outcrops as well as in boreholes".

Mines provide excellent exposures of salt. Halite occurs in several distinct types of rhythmic bedding. Miners have given nicknames to various halite members in the salt layer. Cyclic repetitions occur at scales of a few centimetres to 2 m. Miners have correlated the general sequence of repetition between wells for distances up to 30 km. Based on drilling close to the edge of the southern Riffadali-Amerina Platform, Richter-Bernburg (1973) writes "the halite has been deposited in fjord-like channels between selenite slopes" and considers the halite "a deep water salt facies, rising from a heavy, concentrated brine that fills palaeomorphological depressions".

Listening to Richter-Bernburg at the Utrecht colloquium, it could be imagined that he was also referring to the configuration of the salt in the deep Mediterranean basins (i.e. confined to depressions and missing on ridge crests and slopes). Except, for Richter-Bernburg: the "Messinian halite, as far as Sicily is concerned, took place in a kind of local salt-trap not far from land ... an open Mediterranean Sea with normal salinity was far away to the south".

The most compelling evidence of pre-existing deep areas became the central theme of Ricci Lucchi (1973) who reported on turbidites cropping out in the Northern Apennine foreland thrust-and-fold belt. Extending for >1000 km along the east Peri-Adriatic margin of the Apennines, this foreland trough had already been inherited from the Early Miocene as a depocentre for turbiditic flysch of the Macigno and Marnosoarenacea Formations. Turbidites that accumulated in the trench were scraped up into allochthonous thrust sheets. Ricci Lucchi presented a schematic cross-section from the palaeo-forearc to the



Fig. 6. Typical vertical, nested cones of long, twin crystals of selenite gypsum (from Richter-Bernburg, 1973). Radial growth creates mounds on the top convex surface called 'cavoli' after the Italian word for cabbages. Repetitive beds of this type of selenite separated by thin marls are common in the Lower Evaporites (e.g. Cattolica Gypsum Beds in the Central Sicilian Basin and the Vena del Gesso in the Northern Apennines).

palaeo-trench and eastern foreland, illustrating a progressive incorporation of trench deposits into the growing accretionary wedge. More than 2 km of clastics with detrital gypsum (Laga Formation) accumulated during the MSC, which was brief. The reconstruction of Ricci Lucchi indicated that the detrital gypsum was derived from erosion of cyclic beds of primary selenite that accumulated along a shelf on the western (interior) side of the accretionary wedge. To get to the trench, the gypsum was carried down the slope by turbidity currents, debris flows and massive slides. Some materials were trapped in thrust-top depressions and the rest continued to the trench floor. The selenite beds on the margin rim, with giant swallowtail crystals, are practically identical to those on the rims of the Central Sicilian Basin (e.g. 14 successive beds in the Vena del Gesso of the Apennines, > 16 to 17 beds in the Cattolica Gypsum Beds of Sicily, all separated by thin carbonate marls).

As in Sicily, the Vena del Gesso beds in the Apennines belong to the lower part of the Gessoso Solfifera Series. These beds were also attributed to a shallow sub-aqueous environment (Ricci Lucchi, 1973; Selli, 1973; Vai & Ricci Lucchi, 1976, 1977). Ricci Lucchi remarked that: "regardless of degree and style of deformation within chaotic gypsum bodies ... the resedimented gypsum fragments and slabs show evidence of preslumping nodular and enterolithic structures suggestive of original anhydrite growing in supratidal flats".

The Laga Formation is a huge sequence of proximal to distal turbidites and displaced slope mud that accumulated in a deep-sea fan. Ricci Lucchi estimated a palaeo-relief of 1 to 2 km between the top and base of this fan. The Laga Basin of Ricci Lucchi would be comparable in depth, and perhaps area, to the present Hellenic Trough south and west of Crete. The Laga Basin sediments were deposited in a lifeless, euxinic and possibly hypersaline realm with no evidence of scavengers, bioturbation or tracks on bedding surfaces. No signs of desiccation of this water body were observed. According to this interpretation, the exposure of the primary gypsum on the rim and mass sliding into the basin was the result of tectonic uplift. However, Ricci Lucchi left room in discussions for base-level drop and suggested two sources for allochthonous materials in the Laga Formation: (i) selenite banks on narrow shelves shattered by earthquakes and pulverized into sand by storm waves; and (ii) detaching selenite drape on slopes for the

slumping of large blocks. Ricci Lucchi noted that even during the primary gypsum precipitation "slope instability accompanied gypsum deposition [by] the intercalation of chaotic gypsum between normal gypsum ... and huge lensoid bodies of chaotic gypsum directly overlying the normal sequence".

Selli (1973) presented an outline of the known Italian Messinian from the Piedmont region to Sicily and gave important new details to the emerging picture. One was the basal bituminous marl of the pre-evaporitic euxinic and stagnant Messinian Sea. The marl was rich in hydrocarbon and pyrite, indicating a long prelude of progressive restriction. Selli focused on the Colombacci Formation of the Peri-Adriatic Trough belonging to the upper (post-halite) evaporite time period of the MSC. The Colombacci has as many as eight thin evaporitic limestones inter-bedded with the turbidites and other clastics. Selli remarked: "Each limestone horizon displays an enormous horizontal continuity independent of the lithologic character of the accompanying terrains". Talking about the cycles in the lower evaporates, Selli noted that before and after each selenite bed "the Messinian waters became well diluted" so that "during these phases not only could the marine oligotypical microfaunas develop, but also a high production of organic matter".

In this evaluation of the shallow-water versus the deep-water models for the precipitation of gypsum, anhydrite and halite, Selli (1973) broke out of the mould of the previous ideas. From Selli's experience, the mud-cracks, chicken-wire textures and stromatolite laminations of the type reported by Hardie & Eugster (1971) in Sicily indicated shallow-water deposition and subaerial diagenesis. On the other hand, "the thick banks of selenite are of a more doubtful origin". Selli elaborated further: "The finely laminated balatino and turbiditic gypsarenites originated more likely in deep waters. To accept the shallow-water model for all evaporates, we are forced to infer either enormous rapid and frequent repeated vertical displacement of the sea floor or equally tremendous eustatic movements of the sea-level".

Boundary conditions that could be agreed upon in 1973

Looking back at the Utrecht colloquium from today's perspective, it appears that practically all of the necessary first-hand observations were in place as boundary conditions for a unifying synthesis. As tabulated by Drooger (1973), the participants reached an agreement on the following issues:

• There is but one set of MSC events to be considered.

• Evaporation of sea water is responsible for the primary sulphates and salt.

• The lateral distribution of the evaporites is of a bull's eye pattern in one or more topographic depressions.

• There is evidence that some evaporation took place under shallow water, at least for the Calcare di Base Member and the sulphates in the Upper Evaporite Pasquasia Gypsum Beds.

• The MSC successions are sandwiched between fully open marine sediments that witness distinctly greater depositional depths.

• A general feeling that the Messinian Mediterranean showed a drop of sea-level relative to the prior Tortonian.

• There were no clear fundamental climatic changes around the Mediterranean coinciding with the MSC.

Obstacles to a consensus model

With this level of agreement, what obstacles prevented an early arrival of a consensus model? As summarized by Drooger (1973), the conflicts arose from the different perspectives and methods used by: (i) the sea-going scientist who approached the MSC with geophysical tools and DSDP cores; and (ii) the land geologist who measured and described sections in outcrops and mines. The former seeks a solution for the entire Mediterranean realm, including the parts under sea today as well as those exposed on land. The latter usually explains the deposits of a single basin. A unified model requires the whole region east of the Atlantic gateway to be influenced by the same sequence of salinity and water-level variations. What works to explain the deposits under the Balearic bathyal plain must work to explain the coeval deposits in Spain, Sicily, the Apennines, Crete and Cyprus. To account for salt and evaporites in these margin settings, the oceanographers called upon uplift by folding and thrusting (Catalano et al., 1975). After all, the margin evaporite settings in Spain, Algeria, Italy, Greece, Turkey and Cyprus are all located in Miocene to Recent convergent plate boundary settings susceptible to crustal shortening and thickening.

For the terrestrial geologists, their deposits were formed in regions peripheral to the main Mediterranean and with its water surface coinciding with the Atlantic. From their perspective, the Mediterranean could have been open marine throughout the entire MSC. In fact Montenat (1973), who investigated the Alicante to Murcia region of South-east Spain, claimed that the terminal Miocene conserved the characteristics of a wide open and normal-salinity ocean (sous un faciès entièrement marin). Montenat reported a continuity of marine sedimentation from the Miocene into the Pliocene (continuité de sedimentation mio-pliocène). For Montenat, as well as Richter-Bernburg (1973) and Selli (1973), the Mediterranean supplied water to evaporating lagoons and salt traps over shallow sills. The concentric bull's eye pattern of the oceanographers was, to the land geologists, a string of silled basins. Neither school could put itself in the shoes of the other.

THE NEXT DRILLING EXPEDITION IN 1975

Two years after the Utrecht colloquium, the Glomar Challenger was back in the Mediterranean for DSDP Leg 42A. Drilling at the foot of the Balearic Island on East Menorca encountered once more the pre-evaporitic and postevaporitic deposits with benthonic foraminifera and ostracods, indicative of substrates belonging to mid-mesobathyal depths (> 1000 m). This finding finally put to rest the hypothesis of rapid Plio-Quaternary subsidence to create the post-MSC bathymetric configuration. Microfossils in the intervening dolomitic marls again included sparse dwarfed planktonic specimens, much reworking of pre-MSC taxa and rich populations of A. beccarii and Cyprideis indicating "stressed ... and shallow euryhaline conditions" (Benson, 1978; Cita et al., 1978a).

Drilling on the crest of the Mediterranean Ridge (Florence Rise) west of Cyprus in the Eastern Mediterranean led to the discovery of the same sandwiching of evaporitic dolomitic marls between normal deep-sea sediments. The dolomitic marls differed only by their stronger induration (marlstone) and their greater abundance of *C. pannonica* (Benson, 1978; Cita *et al.*, 1978a). Stable isotopes confirmed the importance of rain, river and groundwater in diluting residual brines (McKenzie & Ricchiuto, 1978; Pierre & Fontes, 1978; Ricchiuto & McKenzie, 1978).

The evaporites from the Ionian Basin added more support to the hypothesis of repeated "cycles of submergence-desiccation as a result of flooding and subsequent evaporation" (Garrison *et al.*, 1978). Extremely saline phases appeared below the gypsum–mudstone cycles, including laminated to nodular anhydrite and bedded halite containing magnesium and potash minerals (Kuehn & Hsü, 1978). The variable bromine content required evaporation of sea water mixed with waters of continental origin. According to Kuehn and Hsü, abrupt changes in the bromine content signalled precipitation in "nearly-evaporated shallow brine lakes".

Selenite with large swallowtail crystals appeared in the North Cretean Basin of the Aegean Sea; they were capped by a caliche breccia, indicative of probable subaerial exposure prior to the Pliocene flooding. No Lago-Mare dolomitic marl was evident. The primary, sub-aqueous and bottom-growth selenite is without water-depth indicators but overlies selenite dissolution breccias that could indicate periods of exposure or freshening by ground waters (Garrison *et al.*, 1978).

STEPS TOWARDS AGREEMENT

Looking in the outcrop for signals of drawdown

Three months after disembarking from Leg 42A and at the first seminar of IGCP Project 96 (*Messinian Correlation*), M.B. Cita held a meeting in Erice, Sicily in 1978 to bring the sea-going and land geologists together on the same outcrop. The pre-conference field trip led by A. Decima visited many of the classic sites in the Central Sicilian Basin. During the excursion and the subsequent lectures it became more and more evident that the deposits recovered by drilling only corresponded to the Upper Evaporite Series in Sicily, except for halite recovered from the Florence Rise west of Cyprus and from the abyssal plain in the Ionian Sea east of Sicily.

The Realmonte Salt Mine in Sicily displays increased (10 to 40 cm) thickness of the individual dark and light couplets in the Sicilian halite. The entire sequence of annual cycles in Decima's Units A and B could have been deposited in less than 20 kyr. According to Decima (1975), the top of his Unit B was an exposure surface. The bromine content indicated that the vast amount of halite had been precipitated under relatively deep water supplied by pre-concentrated marine sources. Except for the brief exposures, was there any further evidence of significant early evaporative drawdown?

In Utrecht, Sturani (1973) had been sceptical of the desiccation model. However, in the interim, Sturani had revisited outcrops in the northernmost reaches of the Peri-Adriatic Trough near Alba and reported in Erice (Sturani, 1975) a dramatic shift from upper bathyal euxinic shales to carbonates possessing stromatolitic, tepee and desiccation structures that indicated either a substantial sea-level fall at the onset of evaporite deposition, an unrecognized effect of substrate dewatering in a subaqueous setting (e.g. from water/methane venting), or slumping of evaporitic limestone from a shallow margin into deeper settings. In discussions at the conference, this abrupt facies change, from apparent bathyal to probable subaerial, was presented as confirmation of the initial evaporative drawdown predicted by the deep-basin, shallow-water desiccation hypothesis.

M.B. Cita organized a second conference as part of the same IGCP project in 1976 on the shore of Lake Garda in the Italian Alps. The theme was 'Messinian erosion surfaces'. G.B. Vai and F. Ricci Lucchi led the pre-conference field trip in the Northern Apennines to the 14 successive selenite beds of the Vena del Gesso. Their recent discovery of algae-bearing and clastic gypsum was announced (Vai & Ricci Lucchi, 1976, 1977). According to these new observations, each of the primary selenite beds displayed a shoaling-upward sequence. The generalized cycle began with finely laminated bituminous shale representing a deep, quiet lagoon. It then passed upwards to algal limestone of the near-shore, followed by massive swallowtail selenite, banded selenite, nodular gypsum of the exposed flat and, at the top, by chaotic and pebbly gypsum interpreted as "subaerial debris flows building out depositional lobes at the mouths of channels cut into emerged selenite beds and older, clayey formations".

Vai & Ricci Lucchi (1976, 1977) gave the term 'evaporitic cannibalism' to the suspected erosion of the top of each cycle, a process by which emergence caused gypsum detritus from margins to be transported towards basin centres. For each cycle, they envisioned that "an exchange with fresher water was necessary to produce the large masses of gypsum and to prevent the precipitation of more soluble salts". The cause of the cycles might be regional climate variability. Vai & Ricci Lucchi called attention to the ability of the sill at the inlet between the Atlantic and the Mediterranean to simultaneously control both sea-level and

salinity in the consistent synchronization that had been observed in the selenite cycles.

The Northern Apennines apparently contained the same cyclic elements of the MSC found by drilling into the floor of the Balearic and Ionian Basins: repeated submergence and then exposure accompanied by freshening and brine concentration, respectively. Did this mean that these basins shared the same water cover? The answer was no, because the Vena del Gesso belonged to the earlier (pre-salt) MSC and the abyssal gypsum and anhydrite from DSDP drilling to the later (post-salt) MSC. The two periods were cleaved by a widespread unconformity.

As the cycles in the Apennines could not be correlated with those in the drill cores when looking for signals of evaporative drawdown, could one instead correlate the unconformity caused by base-level change in the marginal settings to its coeval unconformity and its eventual lateral conformity in the abyss? This approach using the surfaces that bound sediment successions was being applied in petroleum exploration and would soon be called 'sequence stratigraphy' (Vail *et al.*, 1977).

Using the erosion surfaces

As erosion was the topic of the meeting, several lectures set out a basis for such correlations. An earlier hypothesis, that the Southern Alpine lakes owed their origin to entrenchment during lowstands of the MSC, was revived (Bini et al., 1978; Finckh, 1978). Some lakes are so deep today that even their floors lie well below the bottom of the Adriatic Sea. The canyon cutting dates to the MSC when streams carved more than 1 km into their bedrock. The materials removed spread across a downslope regional unconformity as fluvial and alluvial conglomerates. This basal unconformity and its Sergnano Gravel cover have been mapped beneath the Po Plain by commercial reflection profiles, calibrated by hundreds of exploratory wells (Rizzini & Dondi, 1978). The underlying erosion surface reaches to more than 3 km below the sea-level of today. In a few places, the lower part of the gravel contains bioclastic and sandy calcarenites with marine molluscs, corals and re-worked foraminifera. Other Southern Alpine canyons that incised deeply into folded Mesozoic bedrock have retained their Messinian gravel within their narrow floors (e.g. Pontegana Conglomerate).

Although the Sergnano Gravel Formation represents a widespread alluvial fan and braid plain

some hundreds of metres thick, supplied from the north side of the Peri-Adriatic Trough, the fan and braid plain was itself incised by a second episode of erosion producing a superimposed 'V'-shaped valley system. These younger valleys "show all the elements of a fluvial morphology in its juvenile stage" (Rizzini & Dondi, 1978). The sandy deposits in these valleys and their delta aprons contain brackish faunas similar to those of the Late Messinian Colombacci Formation. In some places, the fluvial valleys sliced through all of the Sergnano Gravel so that Pliocene marine clays equivalent to the Trubi Formation rest directly on Early and Middle Miocene formations. The Pliocene clays also invade the upstream Alpine canyons where they cover the Messinian gravel.

In a second lecture, Rizzini *et al.* (1978) presented a synopsis of the subsurface of the Nile Delta, also explored by commercial reflection profiles and boreholes. Again this team found two remarkable Messinian horizons: an older one abruptly separating "sedimentation of a fairly deep sea" from overlying "fluvial-deltaic clastics (Qawasim Fm.)" and a younger one cutting across the top of these clastics and creating a network of stream valleys draining the margin of Africa and filled by the Abu Madi Formation of fluvial and deltaic sands.

The upper surface represents "a fairly pronounced emersion ... accompanied by ... subaerial erosion", flooded everywhere by sediments of Early Pliocene age. Anhydrite of the Rosetta Formation is present except where it has been cut away by canyons and channels formed during the last episode of erosion. The distribution of the Rosetta anhydrite suggested a lowstand deposit correlative with the Upper Evaporite in the Central Sicilian Basin and deposited after the first intra-Messinian episode of erosion. According to Rizzini et al. (1978): "the deposition of nearly one thousand meters of the Qawasim Fm. in a basin, which up until a very short time before had been fairly deep, seems to indicate a sudden lowering of the average level of the Mediterranean Sea".

Using seismic reflection profiles that extend far out to sea in the distal Eastern Mediterranean, the case was made for at least two erosion surfaces: one early in the MSC that continues from the inner shelf to dive under the main salt layer and the other at the end of the MSC that cuts across the top of this layer (Ryan, 1978). Additional examples of dual surfaces in the Valencia Trough, Balearic Basin and Sirte Basin were also presented (Ryan & Cita, 1978). Using three-dimensional seismic reflection profiling while exploring for hydrocarbons beneath the Nile delta, industry consortia have imaged the channels associated with the youngest of the MSC erosion surfaces. These incisions are relatively straight chutes confined by resistant canyon walls of the Rosetta anhydrite (Wescott & Boucher, 2000). The topmost erosion surface (TES) has also been mapped throughout the Valencia Basin (Maillard & Mauffret, 2006; Maillard *et al.*, 2006), where numerous incised channels of the type drilled by the *Glomar Challenger* in 1973 are noted. The streams and deltas of the terminal MSC are draped everywhere by the first Pliocene marine oozes.

The third Messinian Seminar as part of the IGCP Project 96 took place in Spain in 1977. On the first day of the excursion, a careful preparation of the outcrop in the Vera Basin, where Montenat (1973) had proposed a continuous passage from a marine Miocene to a marine Pliocene, exposed a soil horizon with preserved impressions of roots. Emergence was identified in the terminal MSC just before the Pliocene flooding. Numerous outcrops of the Yesares Formation in the Sorbas Basin (Fig. 7) expose beds of gypsum that are also cyclic (Dronkert, 1976, 1977); they display more than a dozen marl and selenite cycles (Dronkert, 1985). The tall swallowtail crystals of selenite compare favourably

with the Vena del Gesso in Italy. In the nearby Nijar Basin, the Yesares Formation consists of fewer cycles of massive primary selenite, cut by an intra-Messinian erosion event that formed canvons filled by gypsiferous debris of the Yesares Formation. Thick, post-evaporitic conglomerates of the Feos Formation, with exotic blocks from reefs and the metamorphic bedrock, cover this fill (Fortuin et al., 2000; Fortuin & Krijgsman, 2003). In the Nijar Basin, the uppermost beds of the MSC are fluvial deposits confined to channels cut into the conglomerates of the Feos Formation. The fluvial deposits pass downdip to lacustrine marls with ostracods belonging to the Lago-Mare assemblage. Some of the lakebed carbonates are white and reminiscent of those in the Colombacci Formation of the Peri-Adriatic Trough. Interbedded soils are indicators of drying and flooding cycles prior to an abrupt marine inundation at the beginning of the Pliocene (Bassetti et al., 2003, 2004).

Contemporary studies in Crete and Cyprus uncovered a similar sequence: (i) intra-Messinian erosion that shed into depressions a thick apron of breccia containing huge blocks of gypsum (Orszag-Sperber *et al.*, 1980; Rouchy *et al.*, 1980; Delrieu *et al.*, 1993); and (ii) palaeosoils and conglomerates recording the drying of the terminal Lago-Mare lakes to expose their floors and

Fig. 7. Neogene sedimentary basins (light areas) in South-east Spain hosting Late Miocene evaporite deposits. Here, the salinity crisis commenced with the sudden appearance of reefs rich in Porites corals on the basin edges followed by the Yesares Gypsum Beds on the basin rims, slopes and floors that are coeval with the 1st cycle evaporites in Sicily. A subsequent intra-Messinian erosion event incises deep canyons into gypsum banks. Debris from the reefs and banks is found in the canyons and on aprons along the foot of the margins. Adapted from Fortuin & Krijgsman (2003).



margins at the end of the MSC. When Robertson et al. (1995) investigated all the sub-basins in Cyprus containing MSC sediments, the same intra-Messinian breccia were found as in Crete (which was termed a 'mega-rudite') "separating the Lower and Upper Gypsum Units". Robertson and colleagues stated that the mega-rudite was derived from "a regional-scale collapse of the basin margin gypsum and en masse gravity transport towards the depocentres". The similarities of the intra-Messinian stratigraphic position of the Sorbas Member canyon cutting and fill in Spain, the breccia in Crete, the mega-rudite in Cyprus, the Sergnano Gravel beneath the Po Plain in Italy, the Laga Formation turbidites in the Northern Apennines and the Qawasim Formation immature sands in canvon settings beneath the Nile Delta are striking (Table 1).

Cutting of the Nile Canyon

The hypothesis that materials eroded from margins were associated with the evaporative drawdown of the Mediterranean was advanced significantly by detailed seismic surveys onshore and offshore of the Nile Delta. Barber (1981) obtained permission from oil company consortia to interpret ca 10 000 km of proprietary reflection profiles calibrated by more than 50 commercial wells. From Barber's reconstruction, the development of an incised drainage network that removed more than a third of the sediment cover from a former undersea continental slope with a palaeo-relief of 2 km, including most of its original landward shelf and terrestrial delta, may be observed. The remaining scene is composed of terrestrial river valleys, their dendritic streams and their distal deltas. Between the valleys are mesas and buttes, where strata were saved by the protective armouring of basalt and limestone. In the wells, drill cuttings retrieved from the ancient landscape are stained with hematite, a proxy for exposure to the sun, wind and rain.

Far inland from the apex of the pre-MSC delta and beneath the modern city of Cairo, the Messinian Nile had cut a 'V'-shaped gorge down through sandstone, basalt and limestone to a level 1.5 km below its rim. The Nile Canyon descends northward to the seaward limit of the survey where its floor reaches 3.5 km below the sea-level of today. At locations where the eroded strata were less resistant, the buried Nile Canyon displays entrenched meanders. In profiles that cross the canyon, Barber recognized paired rejuvenation terraces that imply "a gradual lowering of base level punctuated with dramatic falls". Moreover, a series of terraces parallel to the strike of the former slope that recorded still-stands of the receding shoreline were noted. As the eroded landscape passed seaward into the subsurface of the Nile Cone, it became the substrate for the Qawasim Formation fluvial and deltaic detritus.

Comparison of sea and land erosion surfaces

Even though Barber (1981) made a compelling case for margin erosion, when did it occur? Did erosion start at the beginning of the MSC during the exposure of the Calcare di Base with its reported desiccation cracks and tepee structures or was the erosion a later intra-Messinian phenomenon? Was the erosion associated with one drawdown or dozens of dryings and fillings?

Ever since the publication of the stratigraphic section of the Gessoso Solfifera Series projected along the axis of the Central Sicilian Basin (Decima & Wezel, 1973), attention has focused on the unconformity that truncates the Lower Evaporites (equivalent to the truncation of the 1st cycle evaporites of Grasso et al., 1997). Although cautioned by Decima & Wezel (1973) that: "the sharp angular unconformity ... was evidence for a tectonic phase", subsequent researchers extended this truncation to a regional sequence boundary (Butler & Grasso, 1993; Butler et al., 1995; Grasso, 1997). On the Sicilian field trips, many outcrops were observed where Messinian valleys were filled with breccias and conglomerates similar to the situations in Spain, Cyprus and the subsurface of the Po Plain and Nile Delta. The valley floor deposits include olistoliths of the Calcare di Base and slabs of selenite from the Cattolica Gypsum Beds. At one location in the Central Sicilian Basin, more than 150 m of graded gypsum sands with pieces of selenite approaching 1 cm in size were drilled below the Cattolica salt without reaching the base of the turbidites. According to Grasso et al. (1997): "the incision of the 1st cycle of Messinian evaporates presumably correlates with the ravinement and canyon formation in other circum-Mediterranean areas".

This interpretation essentially is correct but misses the placement of the thick halite layer. When examining the present margins of the Mediterranean, the ubiquitous erosion surface beneath the shelf and slope splits into two and sometimes even more surfaces when reaching the basin depocentre. It is common to observe the deepest and oldest surface extending beneath

Table 1. Correlat salt layers imaged	ion of the two princip in reflection profiles	oal MSC erosiona s.	l intervals (shaded)) in circum-Medite	erranean outcrops	with deep-sea refle	ectors and deep-	sea evaporate/
Mediterranean layers & reflectors (1)	Spain (Nijar, Sorbas) (2)	Sicily (3)	Northern Apennines (4)	Po Plain (5)	Crete & Gavdos (6)	Cyprus (7)	Levant Margin (8)	Nile Delta (9)
A	Cuevas Fm. calcarenites	Trubi Fm.	Pliocene blue clay	Porto Corsini Fm.	Pliocene marls	Zanclean marls	Yafo Fm.	Kafr el Sheikh Fm.
B (top) Erosion 2 (TES)	Feos Fm. fluvial sands	Arenazzolo Fm. sands	Erosion only on the margin	Caviga Sand Fm.	Conglomerate, soils	Conglomerate, soils	Afiq Fm. sands	Abu Madi Fm. sands
B 'M' Reflectors	Zorreras Member.	Pasquasia gypsum beds	Colombacci Fm. Lago-Mare	Colombacci Fm. Lago-Mare	Upper evaporites gypsum	Upper evaporites gypsum	Be'eri Fm. gypsum	Rosetta Fm. anhydrite
C (Giant salt layer), 'N' reflectors at base of layer	Collapsed Manco Member limestones	Halite layers A-D	Euxinic clay	Euxinic clay	Dissolved	Halite rare but in depocentres	Halite on margin and basin	Not present only in distal basin
D (top) Erosion 1 (BES)	Top of Sorbas Member	Gypsum turbidites	Laga Fm. gypsum turbidites	Sergnano gravel	Intermediate Breccia	Mega-rudite and breccia	Gravels, sands	Qawasim Fm. conglomerate
Ð	Yesares Fm. Gypsum selenite beds	Cattolica gypsum beds	Vena del Gesso on margins, euxinic shale	Vena del Gesso on margins, euxinic shale	Lower gypsum selenite beds	Lower gypsum selenite beds	Mavqi'im Fm. gypsum	Eroded away
D	Porites reefs	Calcare di Base	Calcare di Base	Calcare di Base on margins	Stromatolite limestone	Algal limestone	Mavqi'im Fm. limestone	Eroded away
D	Abad Member marls, sapropels	Tripoli diatomites	Euxinic shales	Verghereto Marl	Calcareous marls	Pakhna Fm. chalk	Ziqim Fm.	Sidi-salem Fm. clay
 Montadert <i>et al.</i>, Dronkert, 1976, 7 Ogniben, 1957; I Ogniben, 1957; I Vai & Ricci Lucc Sturami, 1973; St Delrieu <i>et al.</i>, 19 Rouchy <i>et al.</i>, 19 Cohen, 1988; Dr Rizzini <i>et al.</i>, 19 	 1970, 1978; Auzende <i>e</i> 1985; Fortuin <i>et al.</i>, 200 1985; Fortuin <i>et al.</i>, 200 Decima & Wezel, 1971, 1 ihi, 1976, 1977; Krijgsmi urani, 1975; Rizzini & I urani, 1975; Rizzini & I 03. 080; Orszag-Sperber <i>et a</i> 1093; Nescott & Boucher, 78; Wescott & Bouc	<i>it al.</i> , 1971; Ryan, 1 0; Fortuin & Krijgs 1973; Richter-Bernh an <i>et al.</i> , 1999b; Rc Dondi, 1978; I_i , 1980; Robertson <i>t</i> rini & Cartwright, 2000.	973; Maillard & Mau man, 2003. Jurg, 1973; Decima <i>et</i> overi <i>et al.</i> , 2003. <i>et al.</i> , 1995. 2006.	ffret, 2006; Maillard : <i>al.</i> , 1988; Lugli, 19	<i>et al.</i> , 2006. 99.			

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the salt laver for a lateral distance of 10 km or more. The shallowest and voungest surface intersects the top of the 'M'-Reflectors. The downdip separation of a single (although composite) margin unconformity into two basin surfaces that sandwich the salt and evaporite deposits is exactly what was observed in DSDP Leg 13 when drilling in the Valencia Trough and Balearic Basin. The separation testifies to the polyphase Messinian erosion recognized by Mauffret (1976). To illustrate the separate surfaces, the classic diagram from Decima & Wezel (1973) is reproduced in Fig. 8A. In this figure, an interpreted reflection profile across the Levant Margin in the Eastern Mediterranean (Fig. 8B) and another profile crossing the Valencia Trough and Balearic Basin in the Western Mediterranean (Fig. 8C) are included. Although the top of the abyssal salt (shaded vellow in Fig. 8A to C) is clearly truncated in the Byblos Basin (Ryan, 1978), the first episode of margin erosion (marked '1' and shaded red in Fig. 8) extends beneath the landward edge of the salt layer. In the Western Mediterranean, a huge amount of sediment was removed from the Gulf of Lions (Fig. 9A). Although small detrital aprons are common at the salt edge (Lofi, 2001; Lofi et al., 2003, 2005; Maillard et al., 2006), the bulk of the detritus actually may lie under the salt (Fig 9B). All around the Mediterranean, the abyssal salt layer as a transgressive episode across the surface labelled '1' in Fig. 8 is typically observed (Montadert et al., 1978; Ryan & Cita, 1978).

There is little doubt that the gypsum turbidites in the Central Sicilian Basin (also shaded red in Fig. 8A), as well as those in the Laga Basin of the Northern Apennines, are the detrital products of the 1st cycle marginal evaporites. This detritus was created as soon as the margins began to be exposed significantly. The position of the detritus above the basal 1st cycle beds in the basins indicates that major evaporative drawdown began in earnest only after these marginal gypsum beds were already in place. The extension of erosion below the edge of the abyssal salt layer and the occurrence of turbidites below the halite layer in the Central Sicilian Basin indicate that drawdown coincided with the onset of the massive precipitation of salt from initially deep brines (Debenedetti, 1976, 1982; Ruggieri & Sprovieri, 1976; Van Couvering et al., 1976; Busson, 1990; Benson & Rakic-el Bied, 1991). In a simplified redrawing of the original Decima & Wezel (1971) cross-section, Grasso et al. (1997, fig. 16) missed the significance of the gypsum turbidites and left

them out of the sketch. Instead, the incision of the 1st cycle gypsum was traced to the unconformity on top of the salt. Grasso and colleagues, like many other researchers, have placed the halite layer within the 1st cycle or Lower Evaporite Series, rather than observe it as an independent sequence with its own top and bottom unconformities and related to a large-scale sea-level drop.

Environment of salt deposition

Should the abyssal salt layer be seen as accumulating in a permanently filled Mediterranean with a two-way water exchange with the Atlantic (Debenedetti, 1976, 1982; Sonnenfeld, 1985; Sonnenfeld & Finetti, 1985; Hardie & Lowenstein, 2004), or in a brine sea shrinking from nearly full to nearly empty (Hsü et al., 1978a; Rouchy, 1982a,b,c)? In order to address this question, the Tripoli Formation precursor to the MSC is examined first. Although some researchers view the Tripoli diatomite and the Calcare di Base as coeval deposits with carbonates on anticlines and siliceous mud in synclines and normal marine waters exterior to the silled basins (Richter-Bernburg, 1973; Butler et al., 1995; Grasso et al., 1997), others have proposed that the passage from euxinic shales to stromatolitic limestone was brief and occurred over the whole of the circum-Mediterranean at the same time.

This latter proposal was presented first by W. Krijgsman and F. Hilgen at a Messinian seminar in Erice, Sicily in 1997, titled Neogene Mediterranean Palaeoceanography and organized by M.B. Cita and J.A. McKenzie. At the Falconara and Gibliscemi sections on the south-east margin of the Central Sicilian Basin, Sprovieri pointed directly to the horizon at which the MSC began (Sprovieri et al., 1997, 1999; Hilgen & Krijgsman, 1999). The combined successions at Falconara and Gibliscemi include a total of 49 precessioncontrolled diatomite cycles similar in periodicity to the sapropel cycles in the Trubi Formation of the Early Pliocene (Hilgen et al., 1995, 1999; Krijgsman et al., 1995; Sprovieri et al., 1996). Diatomite deposition started at 7 Ma in Sicily. When visiting the Gibliscemi outcrop, Hilgen & Krijgsman (1999) stated: "the astronomical link has far-reaching implications, since global glacial-eustatic sea-level variations are not involved primarily because glacial cyclicity was dominantly obliquity-controlled during the Messinian". The dominance of the precession frequency



Fig. 8. (A) The NE–SW stratigraphic section of the Solfifera Series in Sicily from Decima & Wezel (1973). The Lower Group (1st cycle evaporites) is labelled '1' to '8', with '8A' and '8B' being the primary bedded salt with intercalations of potash and magnesium salts in '8B' followed by an exposure surface. The upper group (2nd cycle) corresponds to labels '9' to '11'. Note the gypsum turbidites (red) under the halite. (B) Interpreted east–west reflection profile across the Levant Margin and Byblos Basin in the Eastern Mediterranean revealing an extensive erosion surface passing under the salt deposits (from Ryan, 1978). Note the truncation of the top of the salt as also seen in Sicily. (C) Interpreted west–east reflection profile from the Ebro shelf, down the Valencia Trough, and onto the floor of Balearic Basin showing a similar erosion surface passing under the landward edge of the salt (from Ryan & Cita, 1978). The vertical lines with dots are drill sites where the erosion surfaces have been cored. Generally, there are two offshore erosion surfaces: (1) under the salt and (2) at the top of the MSC deposits and prior to the Zanclean flood. The earlier surface (1) is correlated to the deposition of gypsum turbidites in the Central Sicilian Basin. The younger surface (2) is from emersion at the end of the 'Lago-Mare' stage and is time-equivalent with the 'Arenazzolo Formation' in Sicily (no. 11 in panel A).



100 km

meant that the external forcing was primarily from local climate within the Mediterranean drainage. Krijgsman reported that new magnetostratigraphic data pinned the onset of the Calcare di Base in Sicily, Gavdos, Spain and the Northern Apennines within the same precession cycle at 5.96 Ma (Krijgsman *et al.*, 1999a,b).

McKenzie et al. (1979) had previously attributed heavy values of the oxygen isotopes in the carbonates of the Tripoli Formation to a sign of dolomitization by highly evaporated sea water. Extremely negative carbon isotopic compositions denoted an organic source of carbon dioxide attributed to the metabolic activity of sulphatereducing bacteria in anoxic sediments. Did this mean that gypsum was already being precipitated well before the formal onset of the MSC? If so, the precipitates had been preserved in only very small quantities. In a subsequent detailed examination of the Tripoli Formation, Bellanca et al. (2001) uncovered pseudomorphs of gypsum and halite crystals that would be expected during a trend towards hypersalinity. These authors also noted a corresponding decrease in the diversity of calcareous microfossils on the same trend until their complete disappearance at the top of the formation. The salinity ultimately reached sufficient concentration to precipitate evaporites as discrete beds, commencing with the overlying Calcare di Base.

Fig. 9. (A) The former Miocene shelf in the Gulf of Lions denuded by erosion during the MSC. Reflector 'M' marks a surface carved by a network of streams and rivers. The subsequent Pliocene and Quaternary cover has built upwards and outwards to create a modern shelf and a submarine-canvon-dissected continental slope (adapted from Lofi et al., 2005). (B) Reflection profile continuing downslope onto the floor of the floor of the Balearic Basin. The wedge of sediment (shaded) beneath the salt is likely to correspond to the material shed from the Miocene shelf as a consequence of the rising density of brine and its falling surface and their sequential impact on pore-water sapping and slope instability.

W. Krijgsman and G.B. Vai used the 16 to 17 cycles of gypsum in the Lower Evaporites and the seven to eight cycles in the Upper Evaporites of Sicily to propose that, if they were all precessioncontrolled, they would represent more than 80% of the duration of the MSC (Vai, 1997; Krijgsman, 1999; Krijgsman et al., 1999a). For the Northern Apennines, the six cycles in the Calcare di Base, the 14 cycles in the Vena del Gesso and the eight cycles in the Colombacci could add up to the full 0.630 Myr duration of the MSC. Just one or two precession cycles were left for the salt layer in the deep Mediterranean basins (Krijgsman et al., 1999b). Yet the abyssal salt had a volume > 1million km³ that dwarfed the volume of sulphate in all the marginal settings combined (Ryan, 1973; Cita, 1988).

When looking for an explanation as to how so much salt could have been deposited so quickly, it is important to decipher the message from the Tripoli and Calcare di Base Formations: the first precipitates were preceded by a long stepwise advance towards hypersalinity (Pedley & Grasso, 1993; Blanc-Valleron *et al.*, 2002). The surface waters of a density-stratified Mediterranean were being pre-conditioned to the level of saturation for carbonate and sulphate. Even more saline water would evolve in the abyss during the succeeding hypersaline cycles of the Yesares and Cattolica Gypsum Beds.

SETTINGS FOR THE LOWER EVAPORITES

Suggestions of early evaporative drawdown

On the ancient Messinian margins of the Mediterranean, a rather sudden appearance of fringing reefs constructed with salinity-tolerant *Porites* corals is observed (Esteban, 1979; Esteban & Giner, 1980). The reef formation begins at the transition from Tripoli euxinic shale to evaporitic limestone (Rouchy & Saint Martin, 1992; their unit C2). The extraordinary feature of these reefs is the down-stepping progression of the coral bodies and their *Halimeda* sand fringes that document a sustained sea-level drop in excess of 100 m (Pomar, 1991; Pomar & Ward, 1994).

The reefs were never draped by gypsum or other evaporates; they were only covered much later by terrestrial and lacustrine deposits (Esteban *et al.*, 1996). In the meantime, the reefs and their talus were eroded severely and karstified to a subsurface depth exceeding 60 m, as if they had been emerged for a long time well above the adjacent sea. Reefs with *Porites* corals of the same age and the same down-stepping feature as those in South-east Spain (Fig. 7) are common on the Alboran coast of Morocco, the coasts of Calabria, the margins of the Central Sicilian Basin and the Levant and in similar coastal settings in Cyprus.

The reefs indicate a significant evolution in the salinity of the Mediterranean water to a threshold capable of excluding grazers, because coeval reefs of this type are not found outside the Mediterranean. It appears that the MSC was already underway during reef growth; but was the emergence of the reefs a phenomenon of global eustacy? Alternatively, was the drop in the surface of the evolving brine a signal of early MSC evaporative drawdown as suggested by Rouchy (1982c), Rouchy & Saint Martin (1992) and Maillard & Mauffret (2006)? Or had the rise in the salinity of the Mediterranean's brine caused the whole water body to gain such significant density that its growing weight induced a flow of the underlying mantle away from the basin centers and towards the periphery to elevate the reefs?

When recently reassessing the most salient features of the MSC and considering the hydrological requirements for evaporite deposition, Rouchy & Caruso (2006) presented a scenario with the first evaporitic stage accompanied by substantial early drawdown. Accordingly, a base level fall of more than 1000 m not only exposed the reefs but also set the stage for the 1st cycle gypsum and the subsequent halite layer. Therefore, gypsum deposition under shallow-water conditions in the margins preceded gypsum deposition under similar conditions in the deep basins. Rouchy & Caruso (2006) discount the evidence of Krijgsman et al. (1999a) for "the synchronous onset of the Messinian salinity crisis over the entire Mediterranean" in order to explain successive deposits at deeper and deeper elevations. Thus, the time period for the accumulation of selenite beds in margin settings had to be brief, because early drawdown was well on its way towards completion by 5.96 Ma. However, where is the evidence of corresponding margin erosion and the delivery of the detritus to the floor during the shrinking brine sea? As pointed out by Butler (2006), reworked shelf and slope components are not observed within the Lower Evaporites in any region, deep or shallow. Butler continues: "These [early] evaporites are free of detritus and bear witness to the lack of sediment entering the basins". In its place, just thin carbonate marls are found, whether in Spain, Sicily, the Apennines, Crete or Cyprus.

No drawdown at all

In order to avoid the messy and controversial issue of evaporative drawdown altogether, Debenedetti (1976, 1982) simply left the brine surface at the level of the Atlantic throughout the MSC while presenting quantitative arguments to show "that the salt deposits on the bottom of the Mediterranean cannot have originated from repeated stages of total desiccation". Sonnenfeld & Finetti (1985) joined in with a similar "model of brine circulation and evaporite precipitation ... that presumes a steady inflow/outflow regime across a severely restricted entrance strait". Dietz & Woodhouse (1988) concurred that the "Mediterranean [desiccation] theory may be all wet". In their permanent deep-water alternatives to the Hsü et al. (1973a,b) desiccation hypothesis, the independent evidence of erosion surfaces, canyon incision, soil horizons, sabkha facies, detrital gypsum, desiccation cracks, etc., was either dismissed or ignored.

Drawdown, but not early

Clauzon *et al.* (1996) addressed the likelihood of a delayed drawdown with a 'two-step model', in which an early and complete evaporite sequence (Calcare di Base, Lower and Upper Evaporites) took place in just the peripheral basins. The exterior Mediterranean remained connected to and at the level of the Atlantic and may not have been especially briny. Deposition of basin evaporites began in a second period when "the Mediterranean was isolated from the Atlantic Ocean ... its base level dropped about 1500 m, and the Messinian erosional surface truncated the margins". Frequent overflows from the Atlantic then delivered the volume of marine waters necessary for the abyssal evaporites and salt.

The Clauzon et al. (1996) scenario placed, for the first time, the deposition of deep-basin halite coeval with the cutting of canyons. It explained the presence of *in situ* marine faunas in the marls interbedded with early marginal gypsum and their absence in the younger, post-salt marls recovered by the Glomar Challenger. However, the two-step model had its limitations. In the process of correlating the erosion surface with the top of the Upper Evaporites on the margins (e.g. Arenazzolo conglomerates and soils), Clauson et al. (1996) neglected the significance of the intra-Messinian erosional event in the margins, separating the Lower and Upper Evaporites and responsible for the widespread conglomerates, breccias, turbidites and mega-rudites in the circum-Mediterranean. The 'two-step model' does not adequately explain why the Upper Evaporites in the margins occurred in fresh to brackish water while the Mediterranean remained marine.

Krijgsman et al. (1999a) soon recognized the improbability of duplication of two successive evaporitic sequences that both progress from marine to continental. These authors argued instead for a common "deep-water ... Lower Evaporite" period for both the Mediterranean margins and its interior basins. "Desiccation was only established after deposition of the Lower Evaporites ... as shown by incised canyons." Krijgsman et al. (1999a) do not state explicitly that the halite layer is separate from the Lower Evaporites but imply that the halite was deposited most probably during the hiatus observed in the Sorbas and Nijar Basins in Spain. Precipitation of halite in the Nijar Basin may have left its presence in the "chaotic, totally altered dissolution facies" capping the selenite beds of the Yesares Formation (Van de Poel, 1991; Krijgsman et al., 2001; Fortuin & Krijgsman, 2003).

Early drawdown, but of limited magnitude

The possibility that brief episodes of drawdown began as early as the abrupt facies change observed across the contact between the Tripoli euxinic shales and the Calcare di Base limestone cannot be ruled out. However, the stratigraphic gap is only seen in the shallowest regions of the margins in the vicinity of the reefs (Rouchy & Saint Martin, 1992; Fortuin *et al.*, 2000).

Judging from the location of the deep-water Yesares selenite in the Sorbas and Nijar Basins at locations in relatively close proximity to the fringing reefs, Krijgsman et al. (1999a) cite Dronkert (1985) in proposing that any sea-level fall during the early MSC was probably limited to a magnitude of < 200 m. For example, Van de Poel (1991) makes the case for a conformable, although abrupt, contact between the Abad marls (pre-MSC and equivalent to the Tripoli diatomites) and massive Yesares gypsiferous strata in the Nijar Basin depocentre. Any perched and barred marginal basin abandoned by drawdown of the larger external Mediterranean is likely to retain some brine on its basin floor and thus not display the signs of complete desiccation within the actual depocentre. On the other hand, it is interesting that seven exploratory wells on the Valencia Trough margin of Spain show no apparent discontinuity between the first evaporites and the underlying Castellon sands. Erosion is only recognized along the top of the 1st cycle gypsum sequence (Lanaja, 1987).

Isotopic evidence

The strontium isotope composition of all 1st cycle gypsum (Fig. 10) retains an oceanic fingerprint (Müller & Mueller, 1991; Flecker & Ellam, 2006) that would not be expected in a desiccated sea where the marine input must have been so small that its flux combined with rivers did not exceed evaporative loss (Keogh & Butler, 1999). This same oceanic composition in the Messinian Red Sea salt requires that the Atlantic water traversed all intervening sills to reach the distal end of the evaporating system. Any significant drawdown upstream of the Suez Sill would have denied the Red Sea of a salt magnitude equal to that of the Balearic Basin close to the Atlantic portal.

What does the salt in Sicily indicate about its origin and timing?

The Realmonte salt deposit reaches a maximum thickness of 670 m near Agrigento, Sicily (Lugli, 1999). An exposure surface separates the salt into two units: (i) a lower unit (layers '8A' and '8B' in Fig. 8A) composed of cumulates of halite plate crystals with minor amounts of kainite showing evidence of initial precipitation from a stratified water body of substantial thickness, followed by



Fig. 10. Strontium isotopic compositions of Mediterranean carbonates and gypsum as a function of age. The shaded belt represents the global ocean trend. The 1st cycle gypsum lies close to the 'oceanic' values indicating that the primary supply of water to the Mediterranean brine was from the Atlantic. However, the brines that precipitated the 2nd cycle gypsum significantly were supplied by river input from the surrounding continents. Adapted from Flecker & Ellam (2006).

shoaling to subaerial exposure; and (ii) an upper unit (layers '8C' and '8D' in Fig. 8A) characterized by cumulates of halite hopper crystals indicating precipitation in shallow, saline lakes. At the Erice meeting in 1997, S. Lugli led the participants down shafts in the salt mine to a location between layers B and C where he pointed to 6 m deep fissures outlining giant polygons formed during an episode of subaerial exposure (Lugli & Schreiber, 1997; Lugli et al., 1999). The salt in layer C above the exposure surface displayed repetitious halite-mud cycles akin to those drilled beneath the floors of the Ionian Sea (Garrison et al., 1978) and the Red Sea (Stoffers & Kühn, 1974). Maximum homogenization temperatures of primary fluid inclusions in halite above the exposure surface indicated palaeo-temperatures decreasing by as much as 10 °C during each of the repetitive intervals of precipitation and

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dissolution (Lugli & Lowenstein, 1997). The large fluctuations in bottom temperatures are a consequence of new water flowing into a shallow nonstratified water body. Deep brine bodies maintain stable bottom temperatures.

According to Lugli *et al.* (1999), "the salt [exposed on the walls of the Realmonte Mine] represents the basinal facies of the evaporite sequence". The Cattolica Gypsum Beds that were visited the following day were the margin facies.

Then again, if the salt was simply the downslope equivalent of the margin gypsum, it should have occupied the same time window for its accumulation. Light and dark couplets in the Realmonte salt average 15 cm in thickness. The alternation of pure halite with clayey salt represents a seasonal rhythmicity in which the pure layers form during summer dry seasons and the thinner clay laminae form during winter wet seasons (Busson, 1990). If 700 to 800 m of salt in the Central Sicilian Basin had precipitated on a seasonal basis without major interruption, the duration of this entire halite interval should have taken less time than a single precession cycle (ca 22 kyr). In contrast, the Cattolica Gypsum Beds encompass more than a dozen such cycles with a time duration estimated at 370 kyr (Krijgsman et al., 1999a).

Therefore, as first deduced by Rouchy (1982c), the basin equivalent of the margin gypsum must be the bituminous clay reported in the logs of the many boreholes archived at the Ente Mineraria Siciliana. The interval of deposition of halite is simply too short to be coeval with the Cattolica Gypsum Beds. Salt precipitation occupies its own brief stage in the middle of the MSC.

What about salt on the Mediterranean Ridge and Levant Margin?

Shortly before the 1997 Erice meeting, a working group of the International Mediterranean Ridge Seismic Experiment published reflection profiles showing thick Messinian salt in the interior of the Mediterranean Ridge (von Huene, 1997). The Mediterranean Ridge Fluid Flow (MEDRIFF) consortium subsequently announced the discovery of brines trapped because of their high density in pools on the Ridge with the highest salinity ever found in the marine environment (Tay *et al.*, 2002). The brine composition gave clear evidence of bischofite in the Messinian salt and showed that "the Eastern Mediterranean must have been evaporated to near dryness" (Wallmann *et al.*, 1997). Reflection profiles across the pool have revealed 1 to 2 km thick salt bodies preserved in localized depressions within the accretionary prism. When some of the salt dissolved later to form karst-like depressions (Kastens & Spiess, 1984), the released solutes seeped into these sea floor pools where they remain for long periods because of their high density. Salt dissolution also delivered chloride of extremely high concentration into the pore-waters of the sediments in the nearby Hellenic Trench.

The discovery of salt on the Mediterranean Ridge – as thick as the salt beneath the basin floors - led Tay et al. (2002) to conclude that the evaporite deposits near the crest "are unlikely to be coeval with evaporites of the abyssal plain in front of the Ridge". However, Messinian halite belonging to the Mavqi'im Formation has been encountered at much higher elevations in the margin of Israel. Halite is identified in the logs of numerous exploration boreholes by its exceptionally low electrical conductivity. These logs display recognizable marker horizons (Cohen, 1988). Whereas Gvirtzman & Buchbinder (1978) had proposed, from the experience of DSDP Leg 42A drilling, that the Mavqi'im evaporites penetrated in different wells at different elevations might be diachronous and formed by repetitive desiccation and filling, Cohen (1988) found that marker horizons in the Mavgi'im Formation correlate from borehole to borehole across distances > 50 km. Cohen was able to trace beds as thin as 1 or 2 m between holes regardless of whether the salt was encountered at 900 or 1850 m below the sea-level of today. Cohen concluded: "most of the individual beds and members of the Mavqi'im Formation retain their identity in minute details" and finally, "it appears that the Mavqi'im Formation was deposited synchronously within a single [deep-water] basin''.

Finding a Messinian salinity crisis dipstick to measure the magnitude of drawdown

At the second Erice conference, highlights from the Ocean Drilling Program Leg 160 that explored the Eratosthenes Seamount offshore of Israel were presented (Major & Ryan, 1999). Eratosthenes is a Mesozoic carbonate platform, the summit of which became a substrate for reefs during the pre-MSC Messinian. Drilling on the summit recovered a limestone, brecciated during subaerial weathering and dissolution diagenesis. The breccia (initially described as a conglomerate aboard the drill ship) contained fragments of limestone, with the polygonal cracking seen elsewhere in the Calcare di Base Formation (Decima et al., 1988). Where the surface of the plateau has been imaged by sonar it reveals pockmarks resembling karst pits. On the midflank at 0.6 km below the summit of the plateau, the MSC is only represented by soil. Cores from 1.5 km below the summit led to the recovery of dolomitic marl above a single bed of 2nd cycle gypsum and containing the Paratethys C. pannonica ostracod assemblage. The thin (< 10 m) MSC deposit is in erosional contact with Oligocene chalk. At this meeting, Spezzaferri et al. (1998) announced that the Eratosthenes Seamount was draped by nannofossil ooze of the Sphaeroidinellopsis acme zone at the conclusion of the MSC. The Early Pliocene sea abruptly submerged the entire plateau. If any evaporites had ever been present, they had washed away during the emergence by the subsequent erosion that etched gullies and canyons from the summit rim to the plateau base.

Druckman *et al.* (1995) report a terminal MSC base-level fall exceeding 1000 m that resulted "in a subaerial environment in the Afiq canyon [on the margin of Israel], the erosion of the Upper Evaporites on the canyon's shoulder and the subsequent deposition of fluvial sediments (Afiq Formation) corresponding to the Lago-Mare". The rapidly rising Pliocene sea drowned the canyon and set the stage for its eventual burial within a few million years.

Additional boundary conditions from 1973 to 2000

• Compelling, but not universally accepted, evidence for a synchronous onset of the MSC across the entire Mediterranean region at 5.96 Ma.

• The deposition of the first evaporite carbonates and sulphates after a long (> 0.7 Myr) interval of increasing restriction at the Atlantic portal and rising salinity.

• As the salinity increased, it formed stratified brine in the Mediterranean, Red Sea and satellite basins.

• The Lower Evaporite selenite beds precipitated from this marine brine in subaqueous settings with minor interruptions. Strontium isotopes indicate an external ocean water source.

• Polyphase erosion surfaces: one exposing the *Porites* reefs; a second surface cutting across the top of the 1st cycle gypsum on the margins and extending to the basin floor to be later onlapped by the salt layer; a third that interrupts the salt

precipitation in Sicily; a fourth cutting across the top of the salt in the Eastern Mediterranean once brine is no longer able to get beyond intervening sills; and a fifth in the terminal 'Lago-Mare' stageassociated exposure of the lower flanks of the Eratosthenes Plateau as well as the thalweg of the Afiq Canyon.

• The intra-Messinian conglomerates, breccias, gypsum turbidites and mega-rudites in the marginal settings including the Po Plain and Nile Delta are products of the second (intra-Messinian) erosion episode.

• This erosion corresponds to the ultra-deep entrenchment of rivers all around the Mediterranean as the consequence of a regional drop in base level.

• The thick abyssal salt layer is present not just in the basin depocentres, but also on accretionary ridges, on canyon floors and on the slope of the Levant.

• The composition, crystal properties and palaeo-temperature indicate precipitation of the halite beds '8A' and '8B' (Fig. 8) in Sicily from stratified brine under deep subaqueous conditions.

• Key marker horizons in logs indicate the lateral continuity of individual halite and anhydrite beds for tens of kilometres.

• The abyssal salt layer formed in a very short period of time (perhaps only a few precession cycles).

• Upper evaporites and halite beds '8C' and '8D' (Fig. 8) were deposited in an intermittently desiccated Mediterranean and its satellite basins cut off from Atlantic supply.

• The remarkably consistent strontium isotopic compositions within each bed of Upper Evaporite gypsum from location to location (e.g. in Sicily) suggests precipitation from a regionally wide water body fed by rivers.

• The common strontium isotopic compositions of Lago-Mare fauna in the DSDP samples show that the lacustrine systems within the deeper Mediterranean basins (east and west) remained interconnected until the very end of the MSC. Exceptions are lakes in Cyprus and Spain located above the level of the large Mediterranean Lago-Mare lakes and supplied from their own watersheds.

TOWARDS A QUANTITATIVE MODEL

An invited talk in Paris by Ryan (2000) discussed Modelling the Mediterranean's Messinian Salinity Crisis: Chronology, Sedimentary Cycles, Erosion Surfaces and the Role of Sills. Independent efforts to quantitatively assess the MSC had also been made by Blanc (2000) who also needed to account for the large volume of salt in the distal eastern Mediterranean. Blanc wrote: "It appears impossible that sea water or brines could have been transferred to the Eastern Mediterranean after the major withdrawal of the western basin below the level of the internal, Sicily Sill". Blanc's computations produced a three-stage drawdown, commencing when the Atlantic inflow across Morocco (Fig. 11A) decreased below the rate of evaporation minus water from rain and rivers. This first stage drained the shelves and upper slopes until the surface of the brine sea dropped to the level of the sill (Fig. 11B) dividing the east from the west (currently the Sicily Sill, but possibly another gap through the Apennine Arc). In the second stage, greater evaporative loss over the larger and more arid Eastern Mediterranean caused the water there to continue to drawdown. The western sea. upstream of the sill, remained pinned at the sill. The third stage began when the Atlantic supply decreased by another two-thirds. Then evaporative loss upstream of the dividing sill consumed all of the input. Salt deposition in the west continued until the gate from the Atlantic shut.

The salinity in the Mediterranean increased to saturation before the first stage drawdown, leaving time for the growth of subaqueous gypsum banks on the shelf and slope (Blanc, 2000). The precipitation of salt occurred during the second and third stages. A dividing sill across Sicily and through the Apeninne Arc allocated more salt to the eastern basins. However, salt accumulation lasted considerably longer than allowed by the precession cycle chronology (Vai, 1997; Krijgsman, 1999; Krijgsman *et al.*, 1999a) and the amount precipitated in Blanc's calculation greatly exceeds the volume measured.

The intervals of salt deposition in the east and west can be shortened and the amplitude of drawdown increased by using a modern depthversus-area bathymetric distribution instead of the simplified truncated cone adopted by Blanc (2000), as well as by allowing for density stratification of the brine. Because the rate of evaporation is dependent upon surface area, the smaller surface area of Mediterranean slopes, as compared with shelves, would accelerate drawdown once the shelves emerged. By closing the Atlantic spillway at a faster rate than that proposed by Blanc (2000), consistency can be achieved with a duration corresponding to a few precession cycles



and a salt volume in the order of 1 million km³ (Ryan, 1973).

Limits to the magnitude of early drawdown

Blanc (2000) pointed out the critical role of sills in the Mediterranean in controlling the delivery Fig. 11. (A) The Atlantic spillway at the onset of the MSC. Prior connections across Spain have been severed. The basins in South-east Spain are satellites of the Mediterranean and supplied with evolving Mediterranean brine. (B) Sills and spillways connecting the Balearic basin in the west to the Ionian Basin in the east. In Messinian time, the Tyrrhenian Sea had only begun to open part way. The Laga and Central Sicilian Basins were large central regions with convergent margin trenches. (C) The Suez spillway into the Red Sea. At this time the Red Sea rift is considerably more narrow than today, yet it provides a deep trough for thick Messinian salt.

of brine to distal regions. The eastern region of the Mediterranean not only has a larger excess evaporation than the west but it also has a broader surface area over which evaporation took place. Thus, once the Mediterranean surface fell to an interior sill, hypsometry and climate would combine to produce an initial high-amplitude drawdown in the east before the west. However, in calculations, Blanc did not include brine delivery to the Red Sea that also shared the Messinian salinity crisis. Evaporation there led to a Messinian-age salt layer that has been probed by commercial drilling and sampled in 1972 on DSDP leg 23 (Ross et al., 1973; Stoffers & Kühn, 1974). The connection of the Red Sea to the Mediterranean was through the Suez Gulf (Fig. 11C), the relatively shallow floor of which in the north acted as a spillway for brine coming from the Mediterranean. The large rate of evaporation over the surface of the Red Sea ensured that once Mediterranean brine levels fell to the Suez Sill, any brine that had accumulated in the Mediterranean would be delivered to the distal Red Sea and end up in its salt deposit (Fig 12). During this time it is unlikely that early MSC Mediterranean brine levels would have dropped below the Suez Sill, except during brief periods of extreme aridity.

Then, as the Atlantic spillway further constricted, evaporation within the Mediterranean eventually would become sufficient to lower its brine surface to the Sicily Sill, abandoning the Red Sea in a 'continental stage' (Stoffers & Kühn, 1974). Although heights of either the Suez or Sicily Sills are not known, the lack of obvious basal unconformities associated with the contact between the Tripoli Formation and the Calcare di Base implies that early MSC drawdowns were unlikely to have been of extremely high amplitude. It is conceivable that the down-stepping of the *Porites* reefs around the margin of the

Mediterranean is in response to the fall in the Mediterranean brine surface to the Suez Sill. Only one precession cycle would be needed to deliver all the necessary solutes to the Red Sea for its giant salt layer.

Timing of halite precipitation in the Mediterranean

The period of main halite precipitation upstream of the Mediterranean needs to be placed in an overall stratigraphic framework of the MSC. This calibration might be accomplished by assigning the major intra-Messinian erosion event to the zenith of Lower Evaporite deposition and subsequent exposure on the margins. Exposure correlates with the delivery of conglomerates, breccia and mega-rudites into basin settings in South-east Spain, Sicily, the Peri-Adriatic Trough, Crete and Cyprus. The exposure and the accompanying massive erosion on all the circum-Mediterranean margins would be the expected consequence of a dramatic drop in base level. By reasoning that the base-level drop tracks the falling surface of the brine, such a drop would ultimately expose the Realmonte salt Unit B in Sicily and result in the giant desiccation cracks filled with wind-blown red dust that can be observed in the mine shafts. The consequence of this logic is that the halite precipitation that produced Units A and B was driven, most probably, by the large-scale and rapid evaporative drawdown midway through the MSC. For example, if the 0.37 Myr duration of the Lower Evaporites and the 5.96 Ma age for the onset of the MSC are accepted, the massive halite deposition would have started around 5.59 Ma (Krijgsman et al., 1999a).

Evaporative concentration

The concept of 'density-bedding' (i.e. a pronounced vertical density-stratification of the water column) was a critical component of the Richter-Bernburg (1973) deep-water model. As evaporation proceeded, the brine stratified. Deep basins collected the densest brine. The surface layer held the least dense brine. Consequently, the less saline surface layer, therefore, ideally was suited for precipitating carbonate and sulphate minerals along coasts and on the shallow margins, respectively. Furthermore, the evaporative activity of less-saline surface brine would be greater than that of more-saline brine. Consequently, the negative feedback that normally would reduce the rate of evaporation as salinity increased because of the decrease in the activity of water would not be as important as first quantified by Blanc (2000). Hence, density stratification allowed the Mediterranean to become concentrated towards halite saturation prior to drawdown.

Once the Atlantic inflow became too small to balance evaporative loss, shrinkage of the brine volume concentrates it further. This 'evaporative concentration' would be the driving agent to rapidly precipitate the halite. As drawdown neared completion, dissolved magnesium and potassium would be the last to leave solution. All of the Sicilian halite exposed on the walls of the Realmonte Mine below the polygon cracks can be explained quantitatively by 'evaporative concentration'. Any continued input of Atlantic water during drawdown, as well as after its completion, would contribute to the total salt repository.

It is suggested that the term 'evaporative concentration' be adopted from Hardie & Lowenstein (1985) to describe the process in which the shrinkage of a near-saturated brine body in an initially full basin delivers large quantities of salt in a short interval of time. In the case of the Central Sicilian Basin, more than one concentration cycle is needed to re-submerge its saltpan and precipitate the upper salt layers C and D. These younger salt layers display many features of dissolution and reprecipitation (Lugli, 1999). The very low bromine content in the upper salt layers suggests that chlorides were derived from earlier layers A and B through dissolution by meteoric waters after exposure on slopes and basin aprons (Decima, 1978).

Drawdown and shrinkage of pre-concentrated brine bodies result in distribution of salt across much of the sea floor beyond the shelf edge but in thicknesses inversely proportional to elevation above the basin floor. Halite deposits would therefore be thin on slopes, thicker on deep-sea fan aprons and thickest on the abyssal plains. 'Evaporative concentration' can account for the bodies of halite ponded in depressions on the flank of the Mediterranean Ridge. It can explain the presence of relatively thin salt layers in the Adana Basin in South-east Turkey at moderately high elevations (Bridge et al., 2005), thicker salt layers in the slightly deeper Cilicia Basin between Cyprus and Turkey, layers of even greater thickness in the deeper Byblos Basin between the Levant Margin and Eratosthenes Seamount (Bertini & Cartwright, 2006) and the thickest layer



of salt in the ultra-deep Xenophon and Ionian Basins (Smith, 1975; Ryan, 1978).

As soon as halite becomes exposed by desiccation, its crystals begin to dissolve from rain, feeding additional solutes via rivers to shrinking shorelines around the playa lakes. Some of these recycled solutes eventually precipitate in saltpans to form the terminal halite sequences with variable bromine concentrations and fluctuating bottom temperatures. Halite deposits would be preserved preferentially along arid margins such as the Levant and in synclines where residual brine would be impounded in lakes dammed behind their outlets.

For example, the deeper parts of the Northern Apennine foredeep trough never experienced subaerial exposure because its proximity to the Alpine watershed ensured greater supply of freshwater than loss by evaporation once drawdown lowered the Mediterranean surface below the Adriatic outlet. However, drawdown to the level of the Adriatic outlet did succeed in exposing the Vena del Gesso selenite beds on the higher margin. Its gypsum was recycled downslope through 'large submarine valleys' (Ricci Lucchi, 1973). "Largescale, post-depositional collapse of primary evaporitic deposits is a widespread feature" (Roveri et al., 2003). Although drawdown is no more effective than tectonics in producing unconformities, drawdown consistently explains the observed synchronous denudation of both active and passive margins from the Levant to the Gulf of Lions.

Fig. 12. Evolution of brine surfaces during the MSC. (1) Onset with salinity sufficiently high for the widespread colonization of *Porites* reefs and the beginning of large-scale of pore water sapping. Methane oxidizes to carbonate which contributes to the basal limestone. (2) Salinity increases further to the level for bottom growth of selenite on margins and slopes. This period involves 1st cycle gypsum accumulation in all circum-Mediterranean satellite basins pulsed by precession-forced climatic change. If drawdown occurs, it is brief and the magnitude minor. The deep basins accumulate euxinic mud and laminated anhydrite. (3) Evaporation over the whole surface of the Mediterranean and Red Sea exceeds the input from the Atlantic combined with rivers plus rain. The surface of the most arid Red Sea at the distal end of the seaway is the first to experience evaporative drawdown. Evaporative concentration delivers the Red Sea salt. Intra-Messinian erosion commences. The Laga, Nijar and Sorbas basins evolve into shrunken lakes fed from their own watersheds and acquire individual strontium isotopic signatures. (4) As Atlantic supply diminishes further, evaporation of the Eastern Mediterranean is adequate to drop its surface below the Apennine spillway. The Eratosthenes Plateau emerges and remains exposed except for its deepest flanks until the Zanclean flood. (5) The interior of the Eastern Mediterranean drops below its spillway across the Mediterranean Ridge to produce thick salt deposits in the Hellenic Trough followed shortly by salt in the Ionian, Sirte, and Herodotus basins. (6) Soon the surface of the Central Mediterranean falls to expose the selenite banks of the Northern Apennine and Sicilian margins and force the precipitation of the Realmonte Mine halite deposit. The Atlantic input is now so small that the brine surface in the Western Mediterranean descends below the Sicilian sill and starts massive halite accumulation in the Balearic Basin. The Gulf of Lions shelf undergoes extensive erosion by streams and rivers to form the huge incision of the Rhône River valley. (7) With the Atlantic input stopped or reduced to a slow trickle, each basin becomes occupied by its own Lago Mare lakes whose surfaces rise and fall with the precession cycles. Stages 3 to 6 are very brief and over in well under 100 kyr. Sills - Mo, Morocco corridor; Si, Sicilian; Ap, Apennine: MR, Mediterranean Ridge; Su, Suez. Basins – Alb, Alboran; AF, Apennine foredeep; CSB, Central Sicilian.

Shallow-water versus deep-water selenite

A continuity of sedimentation from the Tripoli Formation diatomites through the Calcare di Base and Cattolica Gypsum Beds is demonstrated by the book-keeping of precession cycles calibrated to magnetic reversals (Krijgsman et al., 1999a, 2001). Occasionally, a cycle is missing in one outcrop but it appears in others. It is assumed, therefore, that until the end of the 1st cycle (Lower Evaporite) gypsum, there was no major evaporative drawdown. Normal eustatic cycles of 10 to 40 m amplitude can account for regressions that produced desiccation cracks in the Calcare di Base and the shoaling in the Vena del Gesso primary selenite beds (Vai & Ricci Lucchi, 1977). The abrupt vertical facies change from euxinic shales to selenite results from bottom-growth crystal precipitation on the outer shelf and upper slope seaward of the near-shore carbonate platforms as proposed by Richter-Bernburg (1973). The filaments of blue-green algae and the residues of cyanobacteria observed in laminae within the 'swallow-tail' crystals only require sunlight as present today in the upper few hundred metres of the water column. The epiphytic diatoms in the drill cores attest to substrates below wave action. Substantial depth is also a prerequisite for the accommodation of the 250 m of 1st cycle selenite (Richter-Bernburg, 1973; Roveri et al., 2003). Either sea-level rose steadily at an extraordinarily high rate or deposition began with adequate room for these deposits.

Subaqueous versus subaerial erosion

In reviewing the reflection profiles from all over the Mediterranean, and especially the Gulf of Lions, Montadert et al. (1978) arrived at the conclusion: "The erosional surface and the formation of some canyons was a result of subaerial erosion linked to a major regression along the margins at the same time the salt layer was being deposited in the deep basin[s]". This interpretation that the material delivered to the deeper basin had been supplied primarily by subaerial processes has stood essentially unchallenged for two decades. However, in studying a larger set of reflection profiles covering thousands of kilometres, Lofi (2001) and Lofi et al. (2005) have noted that the detrital aprons at the base of the slope in proximity to the landward edge of the salt layer account for less than 30% of the volume of material removed from the adjacent margins. Furthermore the remainder of the material removed from the margin can not be accounted for either with the salt layer or in the strata of the overlying 'M' reflectors. The missing sediment must reside beneath the salt. These strata (Fig. 2B) have a substantially lower compressional-wave velocity than the salt, attested by the phase-reversal at the base of the salt (Montadert et al., 1978). Similar velocity inversions have been observed in the Eastern Mediterranean (Ryan, 1978).

Although researchers traditionally have assigned the 'N' reflectors directly beneath the salt layer as the basin equivalent of the marginal Lower Evaporites, there is no direct evidence of repetitive gypsum/marl beds in the deepest basins. In the Central Sicilian Basin, salt precipitation apparently is initiated on sterile euxinic mud (Rouchy, 1982c), although tectonic disturbances often obscure this passage. In the Levant, the salt layer smothers a deep-sea fan etched by sinuous channel/levée distributary systems sourced from adjacent submarine canyons (Bertini & Cartwright, 2006).

In the quantitative scenario of Blanc (2000), the first stage of drawdown affecting the Gulf of Lions stopped briefly at the level of the sill to the Eastern Mediterranean. Blanc placed this sill around 0.5 km below modern sea-level based on the gentle (< 0.03%) upstream gradient of the Rhône Valley incision (Clauzon, 1982). A baselevel drop of such magnitude would destabilize sub-sea slopes leading to retrogressive mass wasting into the shelf via headward erosion of incipient valleys and gullies. Slope failure proceeds quickly as the margin buttress of water is replaced by air. Expressions such as "chaotic slumping ... enormous tectonic gravitational sheets of chaotic materials" (Selli, 1973), "gravity sliding ... debris flows ... massive chaotic bodies of gypsum" (Ricci Lucchi, 1973) and "largescale, gravity-driven gypsum-slab sliding and related gravity flow deposits" (Roveri et al., 2003) describe downslope transport of material by subaqueous processes. It is therefore possible that the truncation of pre-Messinian strata by the lower erosion surface in the Valencia Trough and beneath the salt in the Levant was initiated by the scouring action of high-velocity subaqueous flows and not necessarily by rivers, rain or wind.

Changes to the 1973 shallow-water, deep-basin model

A review of the current knowledge of the MSC requires the insertion of an early 'deep-water, deep-basin' and 'shallow-water, shallow-margin' stage not considered in the formulations of the original desiccation hypothesis in 1973. Hsü et al. (1978a,b) corrected this deficiency but still left the possibility of significant lowstands during the 1st cycle. The deposition of the diatomites of the Tripoli Formation takes place under the influence of two-way inflow and outflow through the Atlantic portal (Debenedetti, 1982; Sonnenfeld, 1985; Sonnenfeld & Finetti, 1985). However, as modelled by Blanc (2000), the circulation must evolve to intermittent one-way inflow to account for the rise of salinity to a threshold for the Calcare di Base. No convincing evidence of sustained evaporative drawdown is seen until the intra-Messinian "great erosional unconformity that cuts the lower gypsum unit" (Roveri et al., 2003). Vai & Ricci Lucchi (1977) and Krijgsman *et al.* (1999a) have made a compelling case that the Cattolica Gypsum beds and the Vena del Gesso Beds were synchronous. The early MSC water level remained at the level of the Atlantic except for possible minor excursions when global eustacy might have briefly restricted the Atlantic portal and dropped the Mediterranean surface to the Suez Sill. The departure from previous schemes with early MSC lowstands (Rouchy, 1982a,b; Rouchy & Saint Martin, 1992; Rouchy & Caruso, 2006) is in precipitating the salt during a relatively brief interval accompanying drawdown rather than precipitating the "massive halite (and lower gypsum) in a long period of low-level, high concentrated brines" (Rouchy & Caruso, 2006). As Blanc (2000) pointed out, persistent low-level lakes make it impossible to transport Atlantic-sourced solutes to the distal Eastern Mediterranean basins and deposit thick halite across a wide spectrum of elevations from < 1 km to > 4 km below modern sea-level. Early lowstand is unable to supply marine water from the Atlantic into the Red Sea rift.

Finally, as the major drawdown nears completion, the playa lakes appear. The upper evaporites essentially are strata-derived by clastic reworking, dissolution, re-precipitation and diagenesis of materials belonging to the lower selenite and massive salt with little or no supply of new solutes from the Atlantic except, perhaps, in the westernmost regions. Calcite washed down in marls from exposed slopes becomes converted to dolomite in brackish lakes fed by rivers crossing exposed sabkhas and playas.

Lago-Mare as an environment

The name 'Lago-Mare' calls attention to the fresh and brackish water conditions spread across the broad Mediterranean realm during the terminal MSC. Ruggieri (1967) was among the first to apply this environmental attribute to the Congeria or Melanopsis beds underneath the Arenazzolo fluvial sands and alluvial conglomerates in Sicily. The close association of those salinity-intolerant molluscs with terrestrial materials, such as alluvium, soil, leaves, insects, turtles, root casts, etc., is common elsewhere (Selli, 1973; Sturani, 1973; Orszag-Sperber & Rouchy, 1979). This assemblage occupied the shores of lakes, marshes, river mouths and deltas.

The deep-sea drilling expeditions discovered fresh to brackish water diatoms, benthonic foraminifera, ostracods, etc., in non-bioturbated mud indicative of subaqueous substrates in the more offshore fresh to brackish settings. When examining the depth distribution of the microfossil assemblages in the drill cores, the picture emerges of sterile deep lakebeds in the Eastern Mediterranean, ostracod-rich mud where the lakebed was shallow on the crest of the Mediterranean Ridge and Florence Rise and molluscs along the lakeshores and river mouths. The finding of soil instead of Lago-Mare mud on the flank of Eratosthenes seamount and alluvial pebbles above Lago-Mare sands in the Alboran Sea (Iaccarino & Bossio, 1999) implies that the terminal Messinian lake surface remained well below the level of the exterior Atlantic. Any perched basins, higher up on the margins and fed by their own rivers, also would have been suitable for colonization by the Lago-Mare fauna without being connected to either the broader Mediterranean lakes in the deep basins or other satellite basins.

Did the introduction of the Lago-Mare fauna require a direct water route from the Pontian-age Black Sea (Cita, 1973; Hsü & Giovanoli, 1979; Cita & McKenzie, 1986), or were the fauna simply the result of colonization in a suitable alkaline water body after the connection of the Mediterranean with the Atlantic was severed (Benson & Rakicel Bied, 1991; Orszag-Sperber, 2006)? Although the magneto-stratigraphic records on continuous sections in the Dacian Basin of Romania do not show a break in sedimentation corresponding to the MSC and maintain the precession-forced periodicity of 23 kyr for the Pontian sediment cycles (Vasiliev et al., 2004), there is recent evidence of a base-level drop in the adjacent Black Sea. At a meeting in 2003 in Kiev, Ukraine, V.N. Semenenko and G.N. Orlovsky reported: "A hydrographic network of the Northern Black Sea coastal region formed after regression of the Late Miocene (Early Pontian) basin. It took place in consequence of the Messinian salinity crisis in the Mediterranean Sea ... as a result of lateral erosion, the Pontian basin was dropped into the Mediterranean". Gillet et al. (2003) projected reflection profiles (Fig. 13) across the shelf and slope of the Black Sea displaying a distinct Messinian-age sub-bottom 'ravinement surface'. This intra-Pontian unconformity (IPU) correlates with the gypsum and conglomerate recovered by DSDP Leg 42B (Hsü & Giovanoli, 1979). As the sub-bottom depth of this unconformity extends to the foot of the slope (Fig. 13), the only sink for the



Fig. 13. The Messinian-age (Pontian) erosion surface in the deep Black Sea (Reflector 'M') sampled by DSDP drilling (from Gillet *et al.*, 2003).

missing water was the even lower Eastern Mediterranean or evaporation of the Black Sea Basin itself. It seems logical that some Lago-Mare inhabitants such as the *Loxochonca djaffarovi* assemblage may have travelled through an outlet, others such as *Candona* sp. and *Cypridies* sp. may have been carried to more faraway locations in the Western Mediterranean on the feet of birds (Benson & Rakic-el Bied, 1991). Benthonic foraminifera, including *Ammonia tepida*, may have been already endemic to Mediterranean rivers.

It is within the 2nd cycle evaporites and Lago-Mare deposits that strontium composition changed from its oceanic precursor to one heavily influenced by continental source rocks dissolved in river water (De Deckker et al., 1988; McKenzie et al., 1988; McCulluch & De Deckker, 1989). As a consequence, there is little surprise that the 2nd cycle gypsum layers typically are interbedded with marls washed from the higherstanding exposed seabed. The non-oceanic composition is common to all autochthonous 2nd cycle strata throughout the Mediterranean. While looking at the compositions in the Central Sicilian Basin, Butler (2006) realized "that the gypsum of the 2nd cycle was precipitated from the same, Mediterranean-wide, water body". Such continuity is in agreement with the large lateral extent of the 'M' Reflectors; their passage up and down and across a sea floor of considerable elevation change would only be possible with amplitudes of drawdown and reflooding

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exceeding that of the relief between basin edges and margins. Nevertheless, in more elevated regions such as the basins in South-east Spain and Cyprus, the strontium isotopic composition is not the same as in Sicily and the *Glomar Challenger* cores from the deeper areas (Fig. 14). Therefore, the water in these basins must not have exchanged with the larger Mediterranean lakes. This lack of exchange is the primary evidence to show that the Mediterranean never refilled to its brim during the 2nd cycle of the MSC.

Zanclean flood

The opening of the Gibraltar gateway at the end of the MSC (5.33 Ma) returned the Mediterranean



Fig. 14. Strontium isotopic composition (δ Sr) of ostracods in 2nd cycle deposits relative to the 'oceanic' norm (after McCulluch & De Deckker, 1989). The substantial differences and lack of overlap between the measurements on the drill cores from the deep basins and samples from Cyprus and South-east Spain are evidence that the waters of the Mediterranean did not mix with the satellite basins.

desert to an open-marine sea in less than a few decades (Hsü et al., 1973a; McKenzie et al., 1990; McKenzie, 1999; Blanc, 2002). The imprint of the Zanclean flood is evident at the Capo Rossello outcrop (Cita & Gartner, 1973; Cita, 1975). This section, with its overlying Trubi Formation, has become the template for the astronomical time scale of the Late Neogene (Hilgen & Langereis, 1988, 1993; Hilgen et al., 1999). The same passage between the Miocene and Pliocene is intact in cores from eight deep-sea drill sites from the Alboran Sea to the Eratosthenes Seamount (Spezzaferri et al., 1998; Iaccarino & Bossio, 1999; Iaccarino et al., 1999). Across the boundary, over a scale of a few centimetres, dramatic shifts in colour, grain-size, bioturbation and inorganic to biogenic calcite are measured. The stable isotopes of carbon, oxygen and strontium announce the arrival of fully marine water (Pierre et al., 2006). Over the slower span of the first few tens of metres of ooze, the Pliocene seabed repopulated from west to east with deep Atlantic emigrants including Bythoceratina scaberrina, Parrelloides bradvi and P. robertsonianus (Benson, 1973a,b; McKenzie et al., 1990). Sedimentation rates in the deep-sea Trubi marls are slow above the flood surface and rise by a factor of 6 over a few million years (Cita et al., 1978b, 1999), as sediment from the continents was able to find its way across the margins drowned by the enormous sea-level rise and restore the eroded ramps to shelves with prograding slopes (Ryan & Cita, 1978; Lofi et al., 2003).

Hydrocarbon implications

Slope mud typically has the highest organic carbon content of all marine sediments, except sapropels. The rapid displacement to basin floors of slope mud and shelf sands during drawdown and burial by impermeable salt would set the conditions for hydrocarbon source rocks, reservoirs and seals. When the basin fully desiccated, temperatures > 30 to 45 °C on its floor would turn the Mediterranean into a Death Valley (Hsü, 1972b, 1984). The thick salt layer and its Pliocene to Quaternary cover provide the necessary burial to begin maturation, especially in the young Western Mediterranean. Gasoline-range hydrocarbons have already seeped into thermally unaltered Lago-Mare dolomitic marl on the Sardinian edge of the Balearic Basin (McIver, 1973). In describing the Messinian deep-water accumulations in the Peri-Adriatic region, Selli (1973) informed those attending the Utrecht

meeting, "These are the source rocks from which originated, after fluid migration, the major part of the Italian gas field in the Po Plain".

WHAT TOOK SO LONG?

With so much descriptive information about Messinian sediments on land and beneath the sea already assembled in the 1970s and 1980s, why did it take such a long time to reshape the early model of multiple fillings and dryings of the oceanographers and make it conform to the boundary conditions derived from the study of the marginal basins and quantitative modelling? Four reasons are suggested.

The first reason is a possible confusion generated from the widely accepted stratigraphic reconstruction of the Central Sicilian Basin by Decima & Wezel (1973). This schema (Fig. 8A) shows the lateral transition from early "carbonate facies in the marginal zone" with a "lateral passage to the Cattolica gypsum beds" on the slope as also envisioned by Richter-Bernburg (1973). Complications arise from extending the primary gypsum under the salt in this diagram an interpretation not supported by boreholes (Rouchy, 1982c; Lugli, 1999). Consequently, many publications have included the salt as belonging to the margin setting (Clauzon et al., 1996) despite cautions in the original paper that "the Cattolica deposits were deposited in a relatively deep basin". In addressing "how the evaporites were deposited in this basin", Decima & Wezel (1973) suggest: "it could have been by in situ precipitation, by clastic resedimentation from the marginal zone, or as seems likely to us, by a combination of both".

In this classic publication, the emphasis given to olistostrome-type deposits and gypsum turbidites intercalated in euxinic sediments, that researchers such as Vai & Ricci Lucchi (1976, 1977) used to promote deep-water depositional environments during the MSC, is often overlooked. Such allochthonous facies require a preexisting depocentre not unlike the trench and accretionary wedge settings in modern convergent margins with substantial pre-existing relief to provide the necessary accommodation space for huge sediment thicknesses to be deposited in short intervals of time.

The second reason is the confusion generated by correlating the ubiquitous sub-bottom erosion surface on the Mediterranean margins to the unconformity drawn by Decima & Wezel (1973) across the top of the halite deposits in Sicily (Fig 8A). The illusive downdip unconformity equivalents to the initial Mediterranean-wide erosion event are the gypsum turbidities and debris flows beneath the salt, not the truncation of the salt. The truncation is a natural phenomenon occurring once the brine level in the Eastern Mediterranean falls below the surface of the salt in the Central Sicilian Trough; this happened all along the foot of the margin of the Levant.

The third reason was the lack of a highresolution, reliable chronology. In its absence, researchers have proposed that the lower evaporite gypsum was deposited diachronously in a sequence of silled depressions as sea-level fell in steps (Grasso & Pedley, 1988; Rouchy & Saint Martin, 1992; Butler & Grasso, 1993; Pedlev & Grasso, 1993; Butler et al., 1995; Rouchy & Caruso, 2006). In some of these schemes, the deep Mediterranean remained normal marine (Grasso, 1997; Riding et al., 1998). The astronomical time scale provided by the revolutionary efforts of Hilgen & Krijgsman (1999) and their coworkers now give strong evidence for the onset of evaporitic limestone and gypsum at the same time from Spain to Cyprus and additional support for the Lower Gypsum (selenite) beds in Sicily and the Northern Apennines having been paced by the same climate forcing.

The fourth and final reason was the need for quantitative modelling of water input and subsequent precipitation in basins separated by sills. Models had to reproduce the observed distributions and volumes of evaporites and salt in the brief time span of the MSC instead of the original desiccation model with multiple fillings and dryings.

Issues still unresolved

During the progressive increase in the salinity and density of the Mediterranean Sea brine prior to the threshold for halite precipitation, its evolving weight would induce a progressive loading on the underlying lithosphere. This loading would increase the water depth (as well as the brine volume) of the precursor Ionian and Leventine abyssal plains by nearly a kilometre as halite saturation is reached. The consequence of such basin loading is uplift of the rims and a tilting of the slopes towards the basin centres. Might this over-steepening be the instigator of the observed early erosion of the margins observed in the seismic reflection profiles? Moreover, might much of the material shed from the margins and not volumetrically accounted for within the halite layer and the upper evaporate 'M' Reflectors (Fig. 2) actually reside on the basin floors beneath the salt?

Loss of sediment from the margins and its accumulation in the basins produce a positive feedback for uplift and tilting. Most thinking so far on this problem has been to consider the desiccation an unloading phenomenon (Ryan, 1976; Gvirtzman & Buchbinder, 1978). However, with continued delivery of Atlantic water during evaporative drawdown, the weight of its new salt (with a density of $2 \cdot 2 \text{ g cm}^{-3}$) might have more than counter-balanced the weight of the fresh component of the brine, with a density of 1 g cm^{-3} lost to evaporation. Formal calculations of rim uplift need should take into consideration the weight added by the salt first as it is concentrated in brine and second as it is precipitated as a solid (Major & Ryan, 1999).

In proposing a significant delay in the onset of major high-amplitude drawdown until midway through the MSC there are still problems with the supposed shallow-water-depth signal of the Calcare di Base in Sicily and the other widespread carbonates of equivalent age that herald the onset of the MSC. That this limestone in the Apennines, Piedmont, Crete, Gavdos and Cyprus displays many features common to microbial stromatolites cannot be denied, including structures interpreted as expansion cracks (Schreiber et al., 1976; Rouchy, 1982c; Decima et al., 1988). Consequently, evidence from the Calcare di Base has been used to infer early drawdown. However, this limestone often appears rather abruptly above deposits considered to be relatively deep-water. What seems special about the Calcare di Base is that it changes in thickness and facies from one outcrop to the next, even over short distances. The sediment succession shows no obvious precursor signs of an approaching near-shore, high wave-energy depositional environment. Thus it is enticing to consider the process of evaporative drawdown as the agent to transform the seabed from deep to ultra-shallow (Rouchy & Caruso, 2006). In Gavdos, the Messinian water depth prior to the sudden appearance of the limestone was close to 1 km (Kouwenhoven et al., 1999). Here, the stromatolitic-like limestone is locally an intraformational breccia.

Yet, if drawdown is the primary agent of dramatic facies change, where are the contemporary clastics and avalanche deposits set in place by exposure of all the higher slopes? Why is a marked coeval unconformity not found at the numerous sites investigated with palaeomagnetic stratigraphic methods? The gap, if it exists, stays hidden. The 1st cycle primary gypsum is remarkable for its lack of allochthonous upslope materials in many outcrops.

So what other agent could produce a widespread development of microbial carbonates? One possibility is pore-water sapping as salinity in the overlying water body rises to the level for gypsum precipitation. Under increasing water density in deep areas, the subsurface pore water would begin to experience buoyancy, escape to the sea floor and exchange its pore space with the overlying brine. Such venting would initiate cracks in the sea floor as well as fissures and pipes where the fluid passes through the substrate. Release of methane would accompany the exchange of the fluids. The escape of buoyant pore-water out of the seabed, especially where the inverse density gradient between porewater and brine would be the greatest and thus fluid exchange the most vigorous, might be an agent for the widely-observed brecciation. Bacterial communities would thrive on released methane and oxidize it to carbonate as they do today in localized cold-water seeps on passive and active margins. As salinities continued to rise, bottom waters would be replaced by denser and denser brine sinking from the surface in regions of the strongest evaporation where the brine surface is the warmest. Haline-driven circulation replaces theromohaline circulation. Warming bottom waters would propagate a thermal pulse into the subsurface across the span of several thousand years and accelerate the disassociation of subsurface gas hydrates. Then even more methane would be released. The one million year interval of anoxia during the formation of the thick Late Tortonian and Early Messinian euxinic sediment ensures abundant organic carbon burial and its subsequent microbial fermentation to methane. It seems reasonable that the diatomaceous and bituminous sediments could have held a sizable hydrate reservoir. Although originally attributed to the calcitization of calcium sulphate (McKenzie et al., 1979), the negative carbon isotopic composition of the Calcare di Base might also be the consequence of carbon derived from methane.

Pierre *et al.* (2002) and Pierre & Rouchy (2004) have described dolomitic nodules in Tortonian marls from South-east Spain and Morocco that they relate to the past occurrence of gas hydrates. Clari *et al.* (1994) and Taviani (1994) report methane-derived carbonates and chemosymbiotic cold vent communities in Miocene sediments of Piedmont and the Apennines. Destabilization on a sufficiently large scale to deliver isotopically light carbon to the basal limestone of the MSC is speculative. Potential triggers for methane release are the heat from warm saline bottom waters as brine stratifies and, alternatively, a drop in confining pressure accompanying drawdown. Even minor sea-surface fall, limited to the elevation of the Suez Sill, could have had a significant impact for triggering methane release.

CONCLUSIONS

It took three decades to advance from the discussions, disagreements and limited concessions at the Utrecht colloquium to a scheme for the Messinian Salinity Crisis (MSC) that integrates the margins of the Mediterranean with its abyss. In comparing shallow-water versus deep-water models, Selli (1973) showed foresight when stating: "both models, even in the same area or basin, can be readily justified".

The floor of Mediterranean basins lay several kilometres below the surface of the Atlantic, before, during and after the MSC. The sills that separated the basins in the west from those in the centre and east were of sufficient height that only a thick layer of concentrated brine could transport the necessary volume of solutes from the Atlantic to the distal interior and on to the Red Sea. During the time required to further concentrate the stratified brine to saturation for halite, the lesser saline surface layer set the stage for the growth of selenite banks of rhythmic succession all around the margins, while the deep remained stagnant and lifeless. Once the input from the Atlantic no longer could overcome the amount of water evaporated, the surface of this vast and pre-concentrated brine sea began to fall, its shorelines shrank and substrates that had been underwater became emerged. The drawdown immediately destabilized the slope. Retrogressive erosion denuded the Gulf of Lions and the Nile Delta. Gypsum banks disintegrated under the attack of waves and spring sapping. As the brine volume shrank, halite accumulated rapidly upon the eroded detritus by a process of 'evaporative concentration'.

The process of evaporative concentration was not necessarily continuous. It may have been interrupted by one or more precession cycles during which the regional climate swung from dry to wet and back again to dry. Major drawdown and eventual isolation from Atlantic sources began first in the eastern interior beyond the sill through the Palaeo-Apennine Arc. Drawdown occurred later in the west as the Atlantic spillway continued its closure. The Lago-Mare fauna appeared when the marine input diminished to a trickle or ceased altogether. The term 'Lago-Mare' more aptly is applied to fresh and brackish water environments than to a Late Messinian chronozone. An extensive erosion surface of Pontian age in the Black Sea correlates with base-level fall there as Paratethys water either found an exit along with its fauna into the partially empty Eastern Mediterranean, or evaporated under its own arid climate. In the terminal phase of the MSC, the Lago-Mare lakes expanded to submerge the crest of the Mediterranean Ridge. yet still left the flanks and summit of the Eratosthenes Plateau exposed. An episode of severe evaporation shrunk the lakes to produce the youngest erosion surface. This lowstand is captured in the stream-valley incisions and deltas of the Abu Madi and Afiq Formations and in the reflection profiles across the Valencia Trough. The Zanclean flood was geologically instantaneous. However, it took a few million years for sedimentation in the Mediterranean to build back its slopes and shelves to the modern and pre-MSC configurations, as a consequence of the extensive removal of former margin sediment as well as by the void created from the downward flexure of the regional lithosphere because of the weight of the salt on the basin floors and the weight of the new water added by the flood.

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