CIESM Workshop on

THE MESSINIAN SALINITY CRISIS FROM MEGA-DEPOSITS TO MICROBIOLOGY – A CONSENSUS REPORT

(Almeria, Spain, 7–10 November 2007)

EXECUTIVE SUMMARY

This synthesis, outlined during the meeting, is based on inputs and written material received thereafter from all the workshop participants [1]*. A special mention is due to Marco Roveri who assumed the responsibility of assembling these different elements and structuring them into the first complete draft with great skills. Frédéric Briand reviewed and edited the entire volume, assisted by Valérie Gollino for the physical production process.*

Note from the Editor: the workshop was held in the historic town center of Almeria from 7 to 10 November 2007. Fifteen scientists from eight countries did participate at the invitation of CIESM. In opening the meeting the Director General of CIESM, Prof. Frédéric Briand, together with the Chair of the CIESM Committee on Marine Geosciences, Prof. Gert De Lange, warmly welcomed the participants. While presenting the genesis and objectives of the seminar, they expressed the hope that the workshop exploratory nature and convivial format would help progress on a theme that had been for very long a matter of fierce scientific debate. If this CIESM brainstorming meeting, after so many years of controversies, could honestly attempt to identify clear areas of agreement, if any, along with unresolved problems, this would be already a success.

The rich, substantial synthesis which follows was written collectively. It highlights the fact that the participants were able to achieve much more than that. Leaving some of their strong convictions behind after a few days of frank, intense discussions, they moved significantly ahead, adjusting and reconciling their views on a number of key points, and considered in earnest a new possible MSC scenario that should be tested. We are grateful to the participants for having made this remarkable step forward, a significant testimony of their openness of mind.

1. INTRODUCTION

1.1 The controversy

As soon as the deep Mediterranean evaporites were discovered (DSDP Leg 13), an intense debate arose about the most appropriate scenario for their formation ("deep desiccated basin" model: Hsü and Cita, 1973; "shallow water desiccated basin" model: Nesteroff, 1973; "deep non-desiccated basin" model: Selli, 1973). Discussing discrepancies between the various scenarios took up most of the following fifteen years while significant progress was achieved on the biostratigraphic definition of the Messinian Stage (Colalongo *et al*., 1979), the impact of fluvial erosion (Clauzon, 1973, 1978; Chumakov, 1973a) and the origin of evaporites (Rouchy, 1982). In the early nineties, a serious effort was made to provide a chronology of the events that occurred during the Messinian Stage, first in the Atlantic area (Benson *et al*., 1991), then in the Mediterranean itself (Gautier *et al*., 1994),

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leading to the long expected magnetostratigraphy of the Messinian Salinity Crisis. The first climate reconstruction of the Sicilian Tortonian to Zanclean series was also published at that time (Suc and Bessais, 1990). These advances favoured the emergence of new scenarios: most of them (Butler *et al*., 1995; Clauzon *et al*., 1996; Riding *et al*., 1998; Krijgsman *et al*., 1999a; Rouchy and Caruso, 2006) aimed to reduce certain contradictions of the "deep desiccated basin" model (Hsü and Cita, 1973); others (Manzi *et al*., 2005) continued to cast doubts about the total desiccation of the Mediterranean basin.

1.2 The Messinian Salinity Crisis of the Mediterranean area: unravelling the mechanisms of environmental changes

About 6 million years ago the Mediterranean Sea was transformed into a giant saline basin, one of the largest in the Earth's history and surely the youngest one. This event, soon referred to as the Messinian Salinity Crisis (MSC), changed the chemistry of the ocean and had a permanent impact on both the terrestrial and marine ecosystems of the Mediterranean area (see Clauzon *et al*., this volume). Its actual magnitude was not realized, nor could it be predicted, from the relatively small and scattered outcrops of Upper Miocene gypsum and halite deposits of perimediterranean areas. This became fully appreciated only at the beginning of the '70s, when Deep Sea Drilling Project (DSDP) cores recovered evaporite rocks from the M reflector (Hsü and Cita, 1973), a seismic feature recognized below the deep Mediterranean basin floors since the pioneering seismic surveys of the '50s. It soon became clear that a salt layer varying in thickness from 1,500 m to more than 3,000 m for a total estimated volume of 1 million km^3 had been laid down throughout the whole Mediterranean basin at the end of the Miocene. The DSDP drilling Leg 13 recovered gypsiferous strata in the upper few meters of the basinal sequences, but the full Messinian succession could not be drilled at that time.

The first, fascinating and successful MSC scenario proposed by Hsü and Cita (1973) envisaged an almost desiccated deep Mediterranean basin with a dramatic 1,500 m evaporative drop of sea-level, the incision of deep canyons by rivers to adjust to the lowered base level and a final catastrophic flooding event when the connections with the Atlantic ocean were re-established at the base of the Pliocene, 5.33 Ma ago. In the 35 years since Leg 13 was completed, over 1,000 papers have been published on the Messinian Salinity Crisis. Outcrop studies based on the record of marginal basins clarified that this event occurred in a relatively short time window of ca. 600,000 years and that it was caused by the temporary reduction of the marine connections between the Mediterranean and the Atlantic Ocean.

In spite of all this research activity, one fact remains: we have no complete calibration of the stratigraphy of the MSC record, because no scientific drilling has yet ventured into deepwater to drill through the thickest succession of the deep basin. In fact, of all the major stratigraphically propelled discoveries of modern geoscience, the MSC stands alone as being underpinned by an outrageously undersampled stratigraphic record. It is estimated that 95% of the total volume of the Messinian evaporites is now preserved in the deep basins (Figure 1), and our lack of knowledge of the deep basinal stratigraphy and facies association strongly limits our understanding of this dramatic event.

For more than 30 years the Messinian Salinity Crisis has represented one of the most important and controversial topics of scientific debate, stimulating interdisciplinary research projects that aim to understand the multiple mechanisms involved in this event, from its timing, the inferred geographic upheavals, the relationships between external forcing and physical systems response, to the implications for the biological activity.

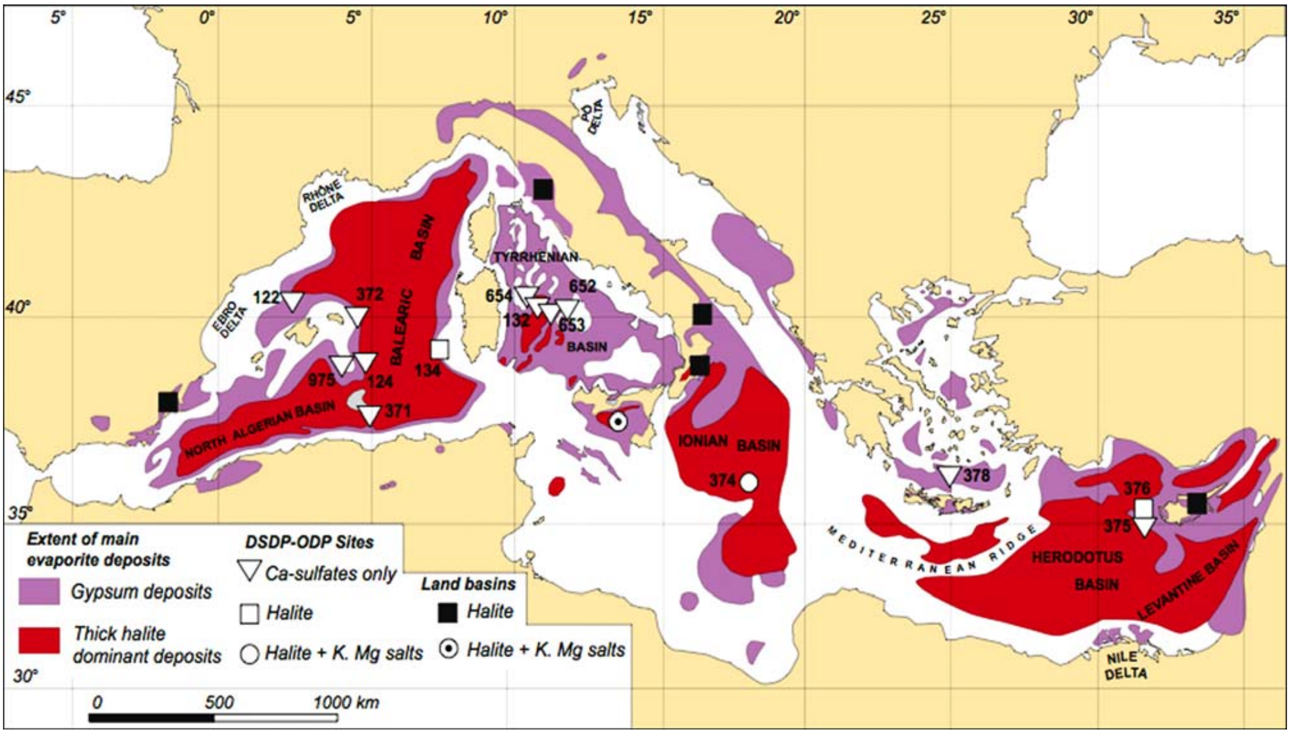

Figure 1. Distribution of Messinian evaporites (modified from Rouchy and Caruso, 2006).

1.3 MSC implications

The interest in basinal Mediterranean evaporites is not restricted to the region. It is generally accepted that a salt giant, i.e. a tabular salt layer of some 1 million km^3 in volume and up to several kilometers in thickness, has a significant impact on the evolution of the hosting basin. Owing to its special rheology, salt is capable of decoupling deep-rooted tectonics from the supra-salt response. In addition, salt tectonics controls the formation of complex traps for hydrocarbon or metals. Lateral salt flow may cause subaerial or submarine slides. Salt intrusive bodies (diapirs) are potential waste repositories. The interaction of fluids and salt may cause suberosion and subsequent surface collapses with a potential impact on civil infrastructures. The impermeability of evaporites controls fluid dynamics and hydrocarbon distribution. However, there is a significant lack of knowledge about the early evolution of juvenile salt giants and their controlling factors. Consequently, a thorough understanding of salt tectonics and fluid dynamics is fundamental in frontier basin research. It is crucial to develop ways to optimize exploitation and risk assessment. The deep basins of the Mediterranean Sea are world class sites for studying the early evolution of such a salt giant, since the mobile unit (MU; i.e. the unit made of salt and able to flow) of the Messinian evaporites is comparatively young, the sediment load varies along the basin margins, and the geometry of most of the basins and of the overburden is well-defined.

1.4 MSC and the biology of extreme environments

Further, Messinian evaporites offer a great opportunity for opening a window on ancient microbial life in shallow and deep salt-saturated environments. The palaeoenvironmental characteristics of Messinian evaporitic basins are only barely known and the study of modern analogues can provide an important improvement in our understanding of this through a careful analysis and interpretation of biomarkers related to microbial activity in such extreme environments.

2. PAST RESEARCH

2.1 Evaporite facies and MSC scenarios

The discovery in the early ‘70s of giant saline bodies in the deepest Mediterranean basins immediately below Plio-Pleistocene units and the impossibility, up to this day, to get direct data of the seismically-imaged deep basin evaporite units, prompted the scientific community to look for possible analogues from Upper Miocene outcrop successions in the perimediterranean area. In this respect, the key role of Sicily for the understanding of MSC events was immediately recognized both because of the striking stratigraphic similarities with deep Mediterranean basins and because of its central position in the Mediterranean which is critical for the understanding of the relationships between western and eastern deep basins. The current MSC paradigm (except for Clauzon *et al.*, 1996) is based on the correlation of the Upper Messinian stratigraphy of the Sicilian Caltanissetta Basin to the deep Western Mediterranean trilogy (Lower Evaporites, Salt and Upper Evaporites) proposed by Decima and Wezel (1971). Lower Evaporites are often identified with the massive selenite gypsum bodies cropping out in Sicily (Gessi di Cattolica), Northern Apennines (Vena del Gesso) and Spain (Yesares Member, Sorbas Basin).

The interest in Messinian events has shed new light on evaporite deposits which until recently were mostly considered as “geochemical events”, devoid of any sedimentological and biological significance. New extensive studies on commercial solar works have been the basis for understanding the sedimentology, petrology and geochemistry of evaporite facies and their relationships with biological activity. A comprehensive facies model for Messinian primary gypsum deposits has been proposed by Vai and Ricci Lucchi (1977) based on Apennine examples. Salt deposits are essentially known from the Sicilian salt mines, showing a mainly halitic composition with minor K and Mg salts intercalations in the middle part. The Upper Evaporites have been described from outcrops in Sicily (Schreiber, 1997) and are present also in the Ionian Islands and Cyprus. The corresponding time interval is recorded by mainly clastic deposits with highly variable thicknesses in the other basins (Apennines, Sorbas). The strong lateral differences in lithology, thicknesses and paleontologic assemblages of the uppermost Messinian deposits have consolidated the idea of a parallel development of several disconnected Mediterranean sub-basins with different base levels that were much lower than the global ocean.

Different interpretations of the palaeogeographic position of the Messinian Sicilian basin and more generally of the synchronous versus diachronous onset of MSC in marginal and deep basins have led to a number of controversial MSC scenarios, summarized (see Figure 2) by Rouchy and Caruso (2006).

Clauzon *et al.* (1996), by refining the deep-basin desiccation model, proposed a two-step development of the MSC (Figure 2): the first step with primary evaporite precipitation only in peripheral basins; the second, following a sea-level fall of more than 1,500 m, characterized by shallow-water evaporite deposition (mainly halite) in the deepest Mediterranean depressions. In this model the correlative conformity of the Messinian Erosional Surface (MES) is traced at the base of the deep Lower Unit (Lofi *et al.*, 2005). In outcrops of uplifted deep-basin Messinian successions such as in the Apennine foredeep, the MES can be traced into a correlative conformity at the base of a clastic evaporite complex that was emplaced through gravity flows in fully subaqueous and relatively deep depositional settings (Roveri *et al.*, 2001, 2003, 2004; Manzi *et al.*, 2005, 2007). This hypothesis, which argued at a larger scale for the true evaporitic nature of the basinal sediments, was also suggested by Lofi *et al.* (2005) for the origin of the Lower Unit of the Gulf of Lions. Based on seismic data, during the initial sea-level fall fully subaqueous processes could have transferred huge volumes of mixed, siliciclastic and evaporitic, sediments to the basin.

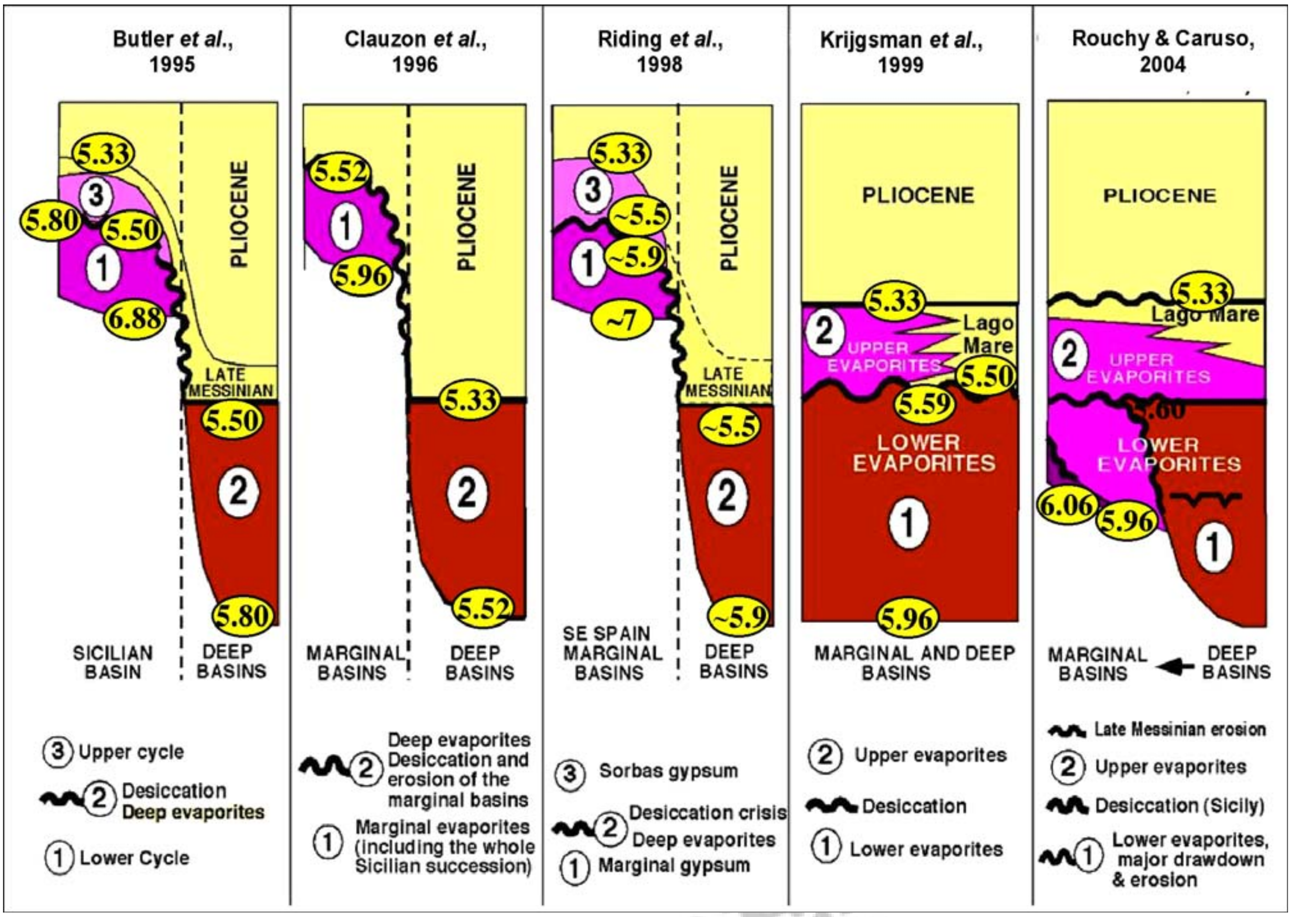

Figure 2. Different MSC scenarios (from Rouchy and Caruso, 2006).

However, a shallow water, primary-precipitated nature of deepest basin Lower Evaporites has been usually envisaged as well as their diachronous development with respect to the marginal ones. Figure 2 contrasts various scenarios. According to the scenarios proposed by Clauzon *et al.* (1996, 2005), Rouchy and Caruso (2006) and Butler *et al.* (1995), the marginal Lower Evaporites formed earlier than their deep basinal counterparts, whereas a post-desiccation age has been claimed for the Yesares gypsum of the Sorbas Basin (Riding *et al.*, 1998; Braga *et al.*, 2006). Only Krijgsman *et al.* (1999a) proposed the synchronous character of the onset of all the Mediterranean evaporites, thus implying the possibly deep-water primary nature of the basinal successions.

2.2 An astrochronology for the Messinian Salinity Crisis

Progress in our understanding of the Messinian Salinity Crisis has long been hampered by the absence of an accurate time frame. Magnetostratigraphic and biostratigraphic results on the pre-evaporitic marls provided the first reliable dating of the onset of evaporite deposition in the marginal basins (Gautier *et al.*, 1994; Sierro *et al.*, 1999; Krijgsman *et al.*, 1999a). However, these techniques are not useful for dating intra-MSC sequences, because these successions are confined to a single (reversed) magnetic chron (C3r; Gautier *et al.*, 1994) and lack age diagnostic planktic foraminifera. The construction of an astronomical time scale for the Messinian (Hilgen *et al.*, 1995; Krijgsman *et al.*, 1999a, 2001) was a major step forward in the understanding of the depositional and paleoenvironmental processes leading to the crisis and solved many of the ongoing chronological controversies.

Cyclostratigraphic correlations between Messinian pre-evaporite sections are rather straightforward and were confirmed by high-resolution planktonic foraminiferal biostratigraphy (Krijgsman *et al.*, 1999a). Astronomical tuning generally shows a good to excellent fit between the characteristic sedimentary cycle patterns and the astronomical target curve (Hilgen and Krijgsman, 1999; Sierro *et al.*, 2001; see also Figure 3), establishing that no sedimentary cycles are missing and that alternative correlations can be excluded. The tuning of the complete pre-evaporite Messinian resulted in an age of 7.25 Ma for the base of the Messinian and of 5.96 Ma for the onset of evaporite formation and, hence, the Messinian Salinity Crisis (Krijgsman *et al.*, 1999a); these ages are now generally accepted.

The tuning of the evaporites themselves proved more problematical, however, even though these evaporites are arranged in a cyclic fashion as well. The pre-evaporitic marl-sapropel cycles are replaced by gypsum-marl cycles of the Lower Gypsum units, indicating that the evaporite cycles are also related to precession controlled oscillations in (circum) Mediterranean climate. The total numbers of evaporite (gypsum) cycles in the Lower Gypsum of Spain (17 cycles) and Italy (16 cycles) are in good agreement (e.g. Krijgsman *et al.*, 2001; Figure 3) and imply a total duration of approximately 350-370 kyr for this unit. The Upper Evaporite units and lateral equivalents of the Mediterranean latest Messinian also display a marked cyclicity, comprising in general seven to eight sedimentary cycles (Decima and Wezel, 1971; Vai, 1997; Fortuin and Krijgsman, 2003; Roveri *et al.*, this volume). The total number of sedimentary cycles agrees well with the total number of precession peaks (Figure 3) suggesting that the Upper Evaporites were deposited in approximately 175 kyr, but slight revision of these correlations may be foreseen (see Roveri *et al.*, this volume) . Tentatively calibrating the post-evaporite cycles to the insolation curve leaves only a small "Messinian gap" (between 5.59 and 5.50 Ma) during which the desiccation of the Mediterranean, deposition of halite, and the accompanying isostatic rebound processes (tectonic tilting and erosion) must have occurred.

2.3 Correlation with oxygen isotope records

Although it was initially tempting to link the onset of evaporite formation to peak glacial stages TG20 and 22 as suggested by Hodell *et al.* (1994), improved age control showed that this was not correct (Hodell *et al.*, 2001). In fact the onset of the MSC evaporites at 5.96 Ma coincides with the glacio-eustatic sealevel rise following glacial stage TG32 and can be related to the influence of the 400-kyr eccentricity cycle on regional climate and, hence, to the Mediterranean water budget, which occurs superimposed on the ongoing trend in tectonic isolation of the basin (Krijgsman *et al.*, 2004; Van der Laan, 2005; Hilgen *et al.*, 2007).

Furthermore astronomical tuning suggested that the base of the Upper Evaporites is intimately linked to the first step of the deglaciation between 5.55 and 5.52 Ma (van der Laan *et al.*, 2006; Figure 3). This leaves the option that the hiatus, or so-called Messinian gap, between the Lower and Upper Evaporites observed in marginal basins is linked to the last two peak glacials TG12-14 of the Messinian glacial interval (Hilgen *et al.*, 2007). The exact duration of the deep Mediterranean halite deposits is still unclear, but the stratigraphic similarity with the Sicilian sequence suggests it was deposited within this gap (see also Roveri *et al.*, this volume). The resulting duration for the halite unit is consequently estimated to be less than 90 kyr.

Clearly, it was also tempting to link the Pliocene reflooding of the Mediterranean to a significant sea-level rise resulting from deglaciation. Increased time constraints, however, revealed that the Miocene/Pliocene (M/P) boundary was significantly younger. Close inspection of the benthic isotope record of the Loulja section (Bou Regreg area) tuned to precession (Figure 3) shows that the M/P boundary (as currently formally defined in the Mediterranean) does not coincide with any major deglaciation (van der Laan *et al.*, 2006; Hilgen *et al.*, 2007).

Accurate age calibrations suggest that both the onset and the end of the MSC were not triggered by glacio-eustatic causes (van der Laan *et al.*, 2006), which is in contradiction with data from dinoflagellate cysts (Warny *et al.*, 2003), a very sensitive group of marine organisms. While tectonic factors are envisaged by most to explain the reduction of the Atlantic connections, the proposition that tectonics also accounts for their reestablishment, via vertical movements of the Gibraltar area during the Messinian (Duggen *et al.*, 2003; see Sierro *et al.*, this volume), is more contested. A more plausible factor for the reflooding of the Mediterranean Sea would be retrogressive erosion in the Gibraltar strait (Loget and Van Den Driessche, 2006).

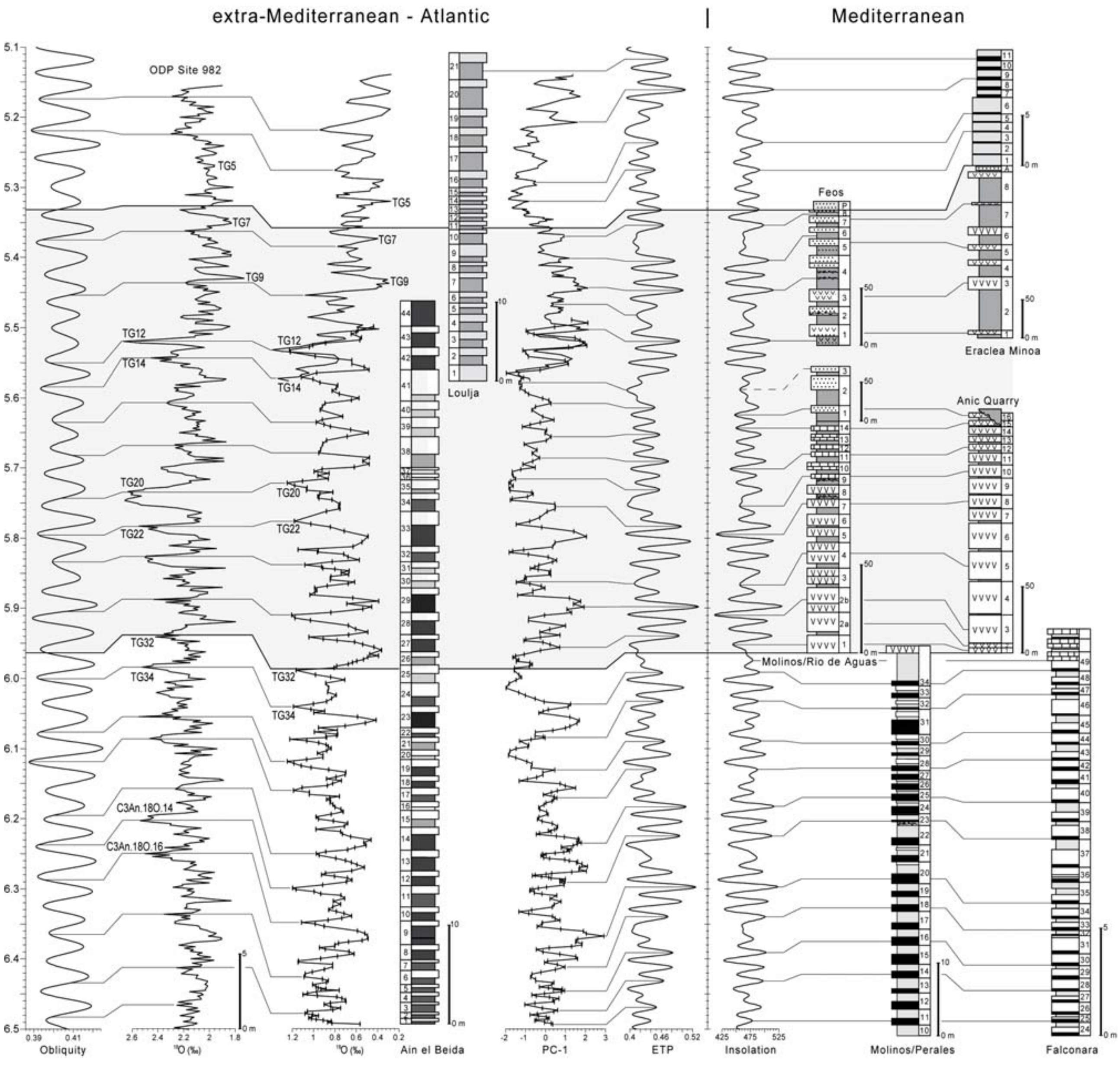

Figure 3. Astronomical tuning of Messinian key sections located in the Mediterranean or in the adjacent Atlantic (after Fortuin and Krijgsman, 2003; Hilgen and Krijgsman, 1999; Sierro *et al.*, 2001; Krijgsman *et al.*, 2001; Van der Laan *et al.*, 2005, 2006; Hodell *et al.*, 2001). Also shown is the astrochronology of benthic oxygen isotope and geochemical records of Ain el Beida, Loulja and ODP site 982. Marked glacial and interglacial stages have been indicated in the isotope records. Shading marks the interval of the Messinian Salinity Crisis (after Hilgen *et al.*, 2007).

2.4 Stepwise restriction of the Mediterranean

It is now well-established that restricted environmental conditions started well before the MSC, as long known from deposition of diatomites and black shales and from associated faunal and isotopic changes in the early Messinian (e.g. Kouwenhoven *et al.*, 2003, 2006 and references therein). The role of basin configuration, connections with surrounding (oceanic) basins and astronomical forcing has also long been recognized, although the relative importance of these is still discussed. Restriction of the basin proceeded with discrete steps, which is shown in many locations in the Mediterranean (e.g. Kouwenhoven *et al.*, 2006; Van Assen *et al.*, 2006). These basin-wide changes have a different expression at deep-water sites where benthic foraminifera disappeared at 7.16 Ma or shortly afterwards, and intermediate-water locations where benthic foraminifera remained present. Stagnancy of bottom waters has preceded a restricted circulation in the surface waters, which developed later. Gradual restriction of the basin was punctuated by rather well defined transitions to a more adverse state around 6.7 and 6.4 Ma. Evidence for increasing surface-water salinity preceding the MSC is apparent as early as 6.7 Ma. It is inferred that rapidly changing surface-water paleoenvironments, leading to oligotypic assemblages, scarcity of calcareous nannofossils and eventually to the a-planktonic zones in the foraminiferal record may in part be explained by periodically enhanced salinity (Kouwenhoven *et al.*, 2006). The restricted configuration of the Mediterranean during the Messinian will have caused an amplification of environmental changes. Causal mechanisms in the restriction history of the Mediterranean were tectonic movements in the Rif Corridor, the effects of which were possibly enhanced by astronomically induced sea level fluctuations concentrating around 400 ky eccentricity maxima.

2.5 Outcrop and offshore perspectives

At the peak of the Messinian Salinity Crisis, the drawdown gave a new configuration to the Mediterranean basin and created a series of morphological and sedimentological changes. A major contrast exists between the margins and the deep basins: the margins have been largely eroded whereas the deep basins accumulated thick evaporitic and detritic units. From a geophysical point of view, the key seismic markers of the MSC in the offshore domain are thus erosion surfaces and depositional units. Until now, no stratigraphic or sedimentological correspondence could be established between the depositional units offshore and those outcropping onshore because of a total geographical and geometrical disconnection. It should be noted that our understanding of the deep basin evaporites is mainly based on seismic data interpretation. Due to the nature of the seismic method the vertical resolution is quite limited. Thus a 50 Hz seismic wavelet has a wavelength of about 40 m in the Pliocene-Quaternary sediments and about 80 m in Halite layers. Therefore vertical resolution is limited to some 10 m. Consequently, all conclusions drawn from seismic interpretation have to be considered in the light of this limitation.

In the western Mediterranean deep basin, three distinct seismic units (the Messinian "trilogy") have been identified (Montadert *et al.*, 1970). This trilogy is observed above the abyssal plains and laterally onlap the margins. This geometry is interpreted as a progressive infill of the abyssal plains when subsidence apparently did not compensate the high sedimentation rates. For a long time, the three members of the trilogy have been called respectively Lower Evaporites, Salt, and Upper Evaporites. To avoid confusing these terms with onshore outcropping units (see Lofi *et al.*, this volume, we refer to them as the Lower Unit at the base (LU, at least partly turbidites), the Mobile Unit in the middle (MU, Halite with plastic deformation) and the Upper Unit at the top (UU, marls and evaporites, interpreted as deposited under oscillating lowered sea-level).

Several erosional surfaces have been described from seismic data in the deep or intermediate basins (e.g. Escutia and Maldonado, 1992; Guennoc *et al.*, 2000; Maillard *et al.*, 2006a), in association with Messinian units. These surfaces merge together upslope into a single one, usually referred to as the Messinian Erosional Surface (MES). In order to eliminate the inherent ambiguity of this term, a new classification of the Messinian erosional surfaces has been suggested (see Lofi *et al.*, this volume) based on their position within the basin and on their stratigraphic relationships with the evaporite units. In agreement with deep dive observations (Savoye and Piper, 1991) the MES which is only observed on the shelves and slopes, is thought to be subaerial. This supports the idea of a substantial drop in sea level during the MSC. One part of the products of the erosion of the margin is regularly imaged in the downstream part of the main Messinian valleys. The internal and geographical spatial and temporal variability of these deposits is important and the deposition of the entire detrital sequence appears to be a non-synchronous event.

A major difference exists between the Western and Eastern Mediterranean basins. While a clear deep basin trilogy is observed in the Western Basin, only a Mobile Unit, eroded at the top, is imaged on seismic data in the Eastern Basin.

In the Nile Delta (Ottes *et al.*, this volume) MU consists of three evaporitic mega cycles dated from the Middle Tortonian to the Late Messinian. However, biostratigraphic information supporting this interpretation is lacking. A major incised valley (the Abu Madi canyon) with fluvial and shallow-marine deposits in an overall evaporitic environment characterizes this period. Recent regional geological work, carried out by the oil industry, and based on an extensive seismic grid, has tied three unconformities, which are easily recognized in the canyon, to their correlative conformities basinward, associated with thick halite. The presence of these three evaporitic cycles has been proven by recent well results; however detailed biostratigraphic dating has not been published yet. Halite is mainly present in the oldest two sequences. The deepest halite is represented by a more chaotic seismic sequence and possibly consists of redeposited evaporites, mixed with some clastics. The middle sequence is represented by a "clean" halite, which has undergone only minor deformation. Based on seismic correlation these halite units are likely to be time equivalent with the condensed, anhydrite-rich sections in the shelfal area. Well results and production testing in the deep basin have demonstrated the presence of an excellent sandstone reservoir in the upper and middle sequences. Interpretation of core data is ambiguous: sedimentological data point towards a deepwater slope channel turbidite setting, but biostratigraphic data indicate a more shallow marine environment (see Ottes *et al.*, this volume).

In the Levantine Basin (Hübscher, this volume) only the Mobile Unit (MU) is visible on the seismic data. MU is up to 2 km thick and deposited in a basin which was already ~2 km deep at the beginning of the Messinian (Tibor and Ben-Avraham, 2005). The Oligocene to Middle Miocene strata beneath the MU have been partly eroded. In the deep basin there is no seismic evidence for so called lower or upper units as reported for the western Mediterranean. The MU itself comprises six evaporite sequences. Two sequences are seismically transparent and are characterized by interval velocities of up to 4.5 km/s, which is typical of halite. The other sequences reveal subparallel internal reflections and interval velocities beneath 4 km/s, which suggests either vertical evaporite facies changes, intercalated clastics or trapped fluids. Prior to deposition of the Pliocene-Quaternary overburden, the evaporite sequences have been strongly deformed by compressional folds and faults, corresponding to a first salt tectonics phase. The top of the MU has been eroded or subroded. A second and still active salt tectonics phase started contemporaneously with significant mass wasting off Israel. The sediment load of the more than 3 km thick Nile Cone squeezes the MU in a north-east direction through the bottle-neck between the Eratosthenes Seamount and the Levantine margin. The sediment prism off Israel has only a slight impact on the lateral salt tectonics. Vertical fluid migration through the MU or escape from the MU is well documented by seismic data. A tectonic overprint of the MU by strike-slip tectonic cannot be excluded; this plate-tectonic activity is related to the Dead Sea transform fault.

In the Black Sea, a widespread Messinian erosional surface is also observed on geophysical data. It correlates downslope to a Upper Miocene unit (coarse clastic pebbly breccia and stromatolitic dolomite) drilled at the foot of the slope offshore the Bosporus (DSDP leg 42B, Ross and Neprochnov, 1978) and considered as deposited in a very shallow water environment (Stoffers and Müller, 1979). This erosional surface is interpreted a the result of a drastic lowering of water-level linked to the MSC (see Gillet *et al.*, 2007).

2.6 Mediterranean hydrologic budget and MSC modelling

The early history of research into the MSC includes some simple but powerful "back of the envelope" calculations. The best known of these is the estimation that 6% of the world ocean's salt was extracted and precipitated in the Mediterranean during the MSC (see Hsü *et al.*, 1977 for details). Recently, more sophisticated numerical modelling techniques have been applied to the study of the Mediterranean and MSC scenarios. These include box modelling, General circulation models, subsidence analysis, etc. These techniques provide powerful mechanisms for testing hypotheses constructed to explain the MSC assuming that quantitative data are available. The following paragraph summarises the insights that can be gained from using numerical approaches. A later section (4.9) indicates the nature of the quantitative information that is required to enhance our understanding of the MSC through the use of numerical models.

Box-modelling has been used to examine the relative importance of palaeogeography, stratification, salinity change, the control of strait geometry, sea level variability and the rates of desiccation and refilling (Blanc, 2000; Blanc, 2002; Blanc, 2006; Gargani and Rigollet, 2007; Meijer, 2006; Meijer and Krijgsman, 2005; Meijer *et al.*, 2004). These models typically use simplified basin geometries and modern hydrologic budget information to run experiments, the tests for which are commonly simple quantitative measures such as the thickness of evaporites as interpreted from seismic sections of the East and West Mediterranean basins. Simple numerical models developed to utilise the relatively substantial Sr isotopic data collected from MSC samples have been used to illustrate the balance of fresh-ocean water in the Mediterranean at different times during the Late Miocene (Flecker *et al.*, 2002; Flecker and Ellam, 2006) and to identify the nature and degree of connectivity between different basins (Çağatay *et al.*, 2006; Flecker and Ellam, 2006). To date most of the General circulation models have focused on the Late Miocene Mediterranean climate (Gladstone *et al.*, 2007; Steppuhn *et al.*, 2006), using atmosphere-only models rather than more sophisticated coupled atmosphere-ocean models. Some of the reasons for this are explored in Flecker (this volume). There is little subsidence analysis research that explores the lithospheric implications of desiccation and evaporite accumulation published in the peer reviewed literature. However, new work presented at recent conferences (Govers *et al.*, 2006a,b; Govers *et al.*, 2007) suggests that this is a productive line of enquiry that should yield useful quantitative results in the near future.

2.7 Salt tectonics

The massive salt layer deposited during the Messinian Salinity Crisis in the deepest parts of the Mediterranean creates a huge Plio-Quaternary thin-skinned tectonics, dominated by gravity gliding and spreading (see Gaullier *et al.* and Hübscher *et al.*, this volume and references therein). The regional seismic studies carried out around the Mediterranean basin now allow to properly image the 2-D (i.e. from upslope to downslope) structural style, with proximal extension, mid-slope translation, and distal shortening. More recently, the 3-D style has been investigated and most of the examples studied show that local characteristics, especially the structural framework, mainly result from interferences between sedimentation, salt tectonics and crustal tectonics, "active" (neotectonics) or “passive” (structural inheritance). Salt tectonics is a helpful tool to better constrain the Messinian paleotopography and paleobathymetry and especially the distribution of the detrital units.

2.8 Indirect observations for deep-basin underlying evaporites

Beyond seismic evidence, the occurrence and potential composition of underlying evaporites in the Mediterranean deep basin can be assessed using pore water deep brine basin data. In particular the ODP pore-water data are useful but scarce. Although some of the elements in pore fluids may have undergone (early) diagenetic changes under enhanced temperature and pressure regimes, these effects are thought to be relatively limited for most Mediterranean settings. The most important findings (see De Lange *et al.*, this volume; De Lange *et al.*, 1990; Van Santvoort and De Lange, 1996; De Lange and Brumsack, 1998; Vengosh *et al.*, 1998; Wallmann *et al.*, 1997) are that:

1. There is no evaporite underlying the Anaximander area and at Erathostenes seamount.
2. Halite is the predominant phase found in most of the eastern Mediterranean settings.
3. Gypsum/anhydrite is a minor contribution, with only one site (Nile fan, approximately 1,200 m present-day waterdepth) where the gypsum contribution seems more important than halite.
4. Mg, Cl salts are also a minor but rather variable contribution for the deep sites alone. In particular, the Discovery Brine basin in the mid-Ionian Sea, consisting of almost pure bisschofite ($MgCl_2$.x H_2O), is an extreme case. The general trend observed in ODP pore-water is that the contribution from Mg,Cl salts increases going from the Ionian into the Levante Basin. This may however be related in part to relative sedimentation rates in these cores.

2.9 Deep and shallow salt biosphere

Shallow hypersaline environments are widespread over the Earth’s surface. Such environments include natural salt lakes like the Dead Sea in Israel, Great Salt Lake in Utah (USA), or the African soda Lakes, as well as artificial systems like the solar salterns used for the commercial production of salt. Among solar salterns, the most intensively studied are the so-called multi-pond solar salterns that consist of a series of shallow ponds connected in a sequence of increasingly saline brines. During evaporation of sea water, sequential precipitation of calcium carbonate, calcium sulfate and halite occurs. This change in salt composition and concentration is accompanied by a change in the microbiota from marine to obligate extremely halophilic microorganisms (see Antón *et al.*, this volume). There are no modern-day analogues for deep, uniformly hypersaline environments. However, there are several examples of deep-sea brine lakes that are anoxic and almost saturated with salt (see McGenity *et al.* and De Lange *et al.*, this volume). Deep-sea hypersaline anoxic brines, formed by dissolution of ancient evaporites, are globally distributed, e.g. in the Red Sea, Orcas Basin, and Mediterranean. The chemocline between the NaCl-rich hypersaline brine lakes and overlying Mediterranean seawater is very narrow (~ 2 m), and supports an abundance of well characterised microbes that are largely distinct from those found in shallow hypersaline brines. Therefore unique biomarkers could provide information about depositional settings of the Messinian evaporites.

3. DISCUSSING A NEW MSC SCENARIO

The physical disconnection between the on-land outcropping Messinian successions and those buried below the Mediterranean seafloor and the lack of deep-Mediterranean core data have hampered the definition of a comprehensive MSC scenario. The MSC has been studied from two distinct perspectives, with obvious difficulties for outcrop and seismic specialists in integrating their data and interpretations, due to the different stratigraphic approaches and resolution.

In this respect, a significant step forward has been achieved during this workshop based on the possible correlation of Sicily deposits with the western Mediterranean seismic trilogy.

The revision of primary and resedimented evaporitic facies models (see Lugli *et al.*, this volume), combined with a new stratigraphic model for the Sicilian basin (see Roveri *et al.*, this volume) and its integration with the Northern Apennines and Calabrian Arc data, offer an opportunity to resolve many long-lived controversies and define, from an outcrop perspective, a possible scenario – remaining to be tested – for correlating shallow and deep-water settings. Such a new interpretation of the Sicilian basin as an example of local deep basin has also strong implications for the geophysical community who studies the MSC offshore. Indeed, interpretations of the Messinian seismic markers are limited by the lack of lithological and stratigraphical calibrations. In the absence of full recovery from deep boreholes, our knowledge of the Mobile and Lower Units (and of most of the Upper Unit) is weak. Hence, the nature, age and depositional environments of the deep basin Messinian deposits can only be derived indirectly (seismic facies, geometries and architecture of the depositional units, stacking patterns, internal seismic velocities, brine chemistry). Outcrops in Sicily and in the Apennines would provide an onshore analogue for the deep-water records located in the present day deep Mediterranean basins, thus allowing their direct comparison. This approach may lead to a possible temporal and lithological calibration of deep basins markers.

However, there is at present no biostratigraphic argument in favour of this newly proposed hypothesis and the only paleontological data from the Sicilian Salt Body (Bertini *et al.*, 1998) tend to support an older age for the Sicilian Lower Evaporites. Further, the recently evidenced erosional surface at Eraclea Minoa between the Lago Mare and Arenazzolo formations (Popescu *et al.*, in press) suggests that the marginal status proposed for Sicily by Clauzon *et al.* (1996) cannot be easily discarded. In the same way, the proposal by Clauzon *et al.* (1997, 2005) that the Apennine foredeep may have persisted as a suspended lacustrine isolated basin during the peak of the Salinity Crisis, as supported by the absence of marine fauna in the pev$_1$b and lower pev$_2$ formations (Carloni *et al.*, 1974; Popescu *et al.*, 2007) and by the migration to the North of subdesertic plants (Bertini, 2006; Fauquette *et al.*, 2006; Popescu *et al.*, 2007) constitutes contrary arguments to the new proposed scenario.

The new Sicilian basin model moves away from the Decima and Wezel's (1971) stratigraphy which does not fully describe the relationships between shallow and deep-water settings. This is crucial for the correct definition of the so called 'Lower Evaporites' unit, a term actually indicating both primary and resedimented gypsum bodies. These sulphate bodies are considered to have formed in different sub-basins at different times and are separated by an erosional unconformity (Messinian Erosional Surface – MES) traceable from shallow to deep-water settings. The MES is a prominent stratigraphic feature well imaged by seismic data throughout the Mediterranean margins where it has been suggested to pass downslope into a correlative conformity flooring the Messinian trilogy (Lofi *et al.*, 2005). It follows that the recognition in outcropping successions of the MES relationships with the evaporite units can be a fundamental key for interpreting the deep basinal stratigraphy.

Based on such considerations, the workshop's participants seriously considered a new MSC scenario which, starting from a new view of Sicilian stratigraphy (Roveri *et al.*, this volume), would combine the two-step model of Clauzon *et al.* (1996) and the chronology of Messinian events established by Krijgsman *et al.* (1999a). This possible scenario comprises three main evolutionary stages that are illustrated in Figure 4 and described below.

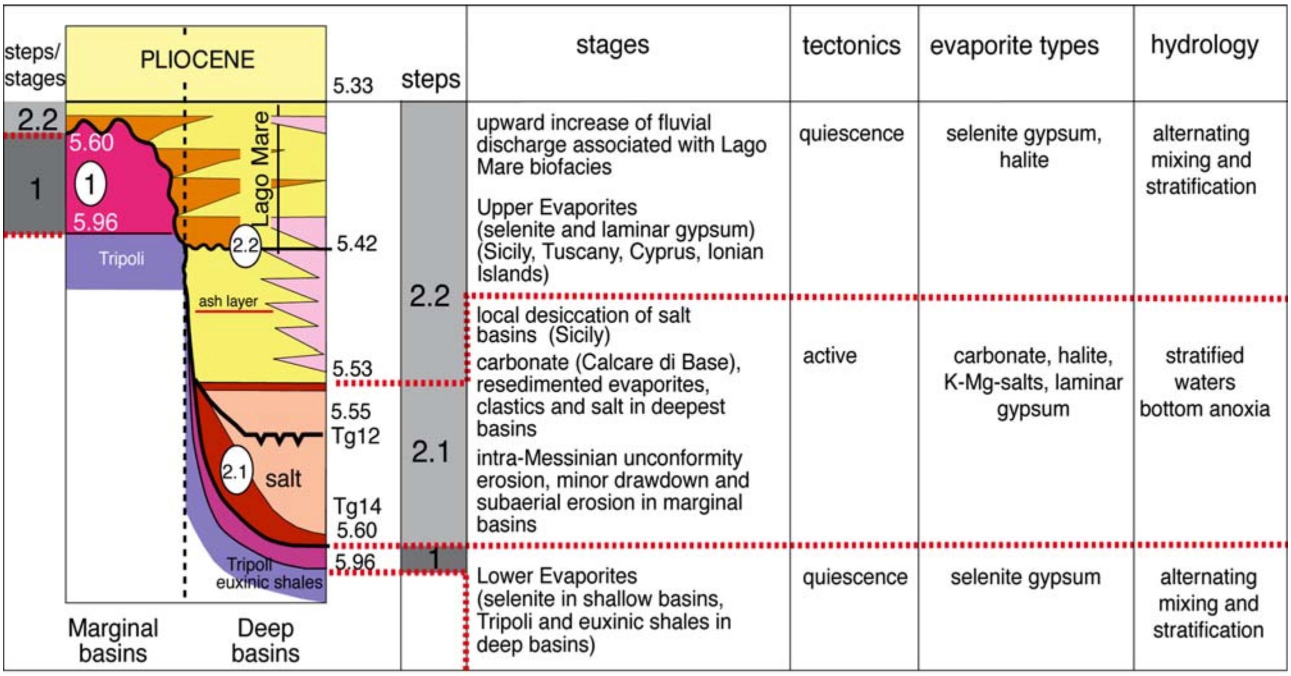

Figure 4. A new MSC scenario.

3.1 A possible chronology

3.1.1 Step 1: 5.96 – 5.6 Ma - MSC onset and first evaporitic stage

During the early Messinian the Mediterranean Basin underwent a progressive restriction of the deep-water circulation as evidenced by the generalized, cyclical development of sapropels (dark-coloured, organic-rich shales indicating reduced oxygen conditions in the bottom waters). Data from both deep and shallow-water records suggest that salinity did not rise significantly before 5.96 Ma. The hydrology and circulation pattern of the Mediterranean Basin rapidly changed at around 5.96 ±0.02 Ma as recorded by the deposition of the first Messinian evaporites (Krijgsman *et al.*, 1999a). At Capodarso (Sicily), detailed micropaleontological and palynological analyses showed that brackish coastal conditions existed in the Caltanissetta Basin at the time of deposition of Calcare di Base (Suc *et al*., 1995). It is here concluded that the MSC onset was a synchronous event throughout the whole Mediterranean Basin even if its expression in the sedimentary record was different in shallow or deep-water settings. The relatively shallow (~200m) Sorbas Basin shows a transition to primary gypsum deposits of the Yesares member, while the deeper (~1,000 m) Caltanissetta and Gavdos Basins show a transition to evaporitic carbonates (Krijgsman *et al.*, 1999a). In this context, the Sicilian section of Falconara (Caltanissetta Basin) is crucial for the astronomical dating of the deep-basin sequences. It has been reported from Falconara that the tripartite pre-evaporite cycles of the Tripoli Formation are replaced by carbonate cycles of the Calcare di Base in the top part of the section at 5.98 Ma (Hilgen and Krijgsman, 1999). We stress here that Roveri *et al.* (this volume) label these basal evaporitic carbonates of Falconara as "dolostones" and do not consider them to be part of the Calcare di Base. According to outcrop data from the Apennines, primary gypsum (selenite) accumulated during this stage only in relatively shallow (maximum 200 m depth; similar to Sicily and Spain), silled and/or semiclosed sub-basins, while in deeper and/or more open settings only organic-rich shales with interbedded dolostones and diatomaceous beds were deposited (Manzi *et al*., 2007). Primary gypsum of this first stage, which is not associated with halite or massive carbonates, is here indicated with the acronym PLG (Primary Lower Gypsum). The coeval deep-water unit is barren (with the exception of pollen) and is usually characterized by a higher organic matter content with respect to the underlying deposits. Stratification of the water column and hyperhaline conditions are suggested by the abundance of specific biomarkers (gammacerane) within the barren interval (Manzi *et al.*, 2007), as well as in the shale intercalations into the gypsum of the Lower Evaporites (Monte Tondo quarry, Vena del Gesso; Sinninghe Damsté *et al.*, 1995a,b). The PLG unit has an average thickness of 150 m, with local differences mainly due to thickness variations of the shale intercalations. The corresponding deep-water unit is highly variable in thickness, ranging between less than 10 m up to 60 m. This is in part due to erosion on top. The lithology of the deep water unit is not strikingly different from the underlying pre-evaporitic deposits; as a consequence, due to both the limited thickness and the very weak impedance contrast with underlying deposit, we suggest here that this unit may be barely detectable on conventional seismic data from deep basinal settings.

The silled character of evaporitic basins of this stage becomes evident when reconstructing the regional geologic evolution, as they formed in strongly articulated basins related to both compressional and extensional tectonic regimes. Data from the Apennines and Sicily suggest that basin articulation due to tectonic processes started in the Late Tortonian.

Up to 16-17 gypsum cycles are recognized within PLG, given by the rhythmic alternation of gypsum and shale beds, testifying to periodic changes in salinity. This cyclicity has been related to precession-driven climatic changes (Krijgsman *et al.*, 1999a), thus allowing the top of the unit to be dated at around 5.6 Ma. The new facies model for PLG (Lugli *et al.*, 2006a; see Lugli *et al.*, this volume) points out impressive similarities in terms of facies, thickness and overall trend which allow bed by bed basin-wide correlation (Apennines, Sicily, Sorbas). The new model also highlights the absence of any evidence of subaerial exposure and of significant clastic deposition within individual cycles. As a consequence PLG is considered here as a fully subaqueous deposit with no evidence of a substantial sea-level fall at the base of the PLG unit and an overall aggradational stacking pattern indicative of the continuous creation and/or availability of accommodation space during gypsum deposition. However, the overall facies trend may indicate a generalized shallowing-upward related to progressive basin fill and space consumption. A maximum 200 m paleobathymetry with periodically oxygenated bottom waters can be inferred from the presence of cyanobacterial mats within gypsum. The absence of gypsum in coeval deeper water settings could be related to less concentrated brines and/or to anoxic, i.e. reduced sulphate content, bottom conditions preventing gypsum formation. During this stage deep basins and abyssal plains were probably fed by deep marine marls and turbidites.

3.1.2 Step 2

- **Stage 2.1: 5.6 – 5.55 Ma - MSC acme**

Erosional surface(s) and products - This stage is characterized by evidence for a substantial relative sea-level drop in the Mediterranean with subaerial exposure, erosion of evaporitic basins (PLG) formed during the previous step (5.96-5.6 Ma), deposition of primary evaporites (mainly halite and potash salts) and constriction and/or restriction of previously deep basins. The clearest evidence of these important modifications come from the shallow basins of the Apennines and Sicily with the subaerial exposure of PLG attested by deep erosion and paleokarstic features. The Mediterranean continental margins show the development of a high-relief erosional surface (MES) indicating that a substantial rejuvenation of the fluvial network took place in the Late Miocene during the MSC peak, when deep canyons were cut on shelves and slopes by the largest rivers (Nile, Rhone – see Chumakov, 1973a; Clauzon, 1973). The products of erosion were transferred downslope toward the deep basins (Lofi *et al.*, this volume). According to Roveri *et al.* (this volume) and to earlier works by Roveri *et al.* (2001), Lofi *et al.* (2005) and Manzi *et al.* (2005), the onset of this erosional phase of the Mediterranean marginal areas is recorded in deep basins of the Apennines and Sicily by the abrupt activation of turbidite systems comprising a complete suite of gravity-driven subaqueous deposits ranging from giant submarine slides, to chaotic bodies, debris flows, high to low-density turbidite flows. These deposits form a unit that has been generally overlooked in the MSC debate and/or considered a time equivalent of PLG ('Lower Evaporites' of Selli, 1960; Decima and Wezel, 1971). To clarify the terminology we hereafter refer to these units as Resedimented Lower Gypsum (RLG) and consider these the best candidates for a possible equivalent of the deep Mediterranean basin's 'Lower Evaporites' unit, (i.e. Lower Unit, LU).

In the Western Basin the seismic facies, the geometrical configuration and the possible lithology of the Lower Unit (LU) are compatible with the gypsum/detrital turbidites of the Apennines. Thus, strong analogies support a possible correlation between outcropping and offshore pre-halitic turbiditic units (Lofi *et al.*, this volume). In the Eastern Basin however such a lower unit is not observed beneath the halite, either because it is absent or because it is too thin to be imaged on the seismic profiles (Hübscher *et al.*, this volume). This points to a potential discrepancy between the Eastern and Western Mediterranean basins, that we still need to explain.

While the composition and thickness of resedimented deposits can vary highly as a function of local basin floor topography and drainage characteristics, they are often characterized by the presence of clastic gypsum deriving from the dismantling of first stage PLG. The thickness of this unit can reach up to 300 m (Northern and Central Apennines); in Sicily this unit is up to 200 m-thick in the main depocenters. In many peripheral basins (Apennines, Sicily, Betic Cordillera, Cyprus), this phase of basin margin instability and the huge transfer of sediments to deep basin settings is clearly associated with ongoing tectonic deformation. In Sicily this stage is recorded in the main foredeep depocenter succession (Caltanissetta Basin) by a heterogeneous unit formed by resedimented gypsum, limestones ("Calcare di Base" – CdB) and salt bodies (halite + K salts). According to Roveri *et al.* (this volume) this unit is bounded by two erosional surfaces merging upslope into the MES. The lower surface can be traced at the base of the CdB and of the RLG and locally has an erosional character related to subaqueous processes which may partially erode the underlying deposits. The upper erosional surface has a subaerial origin and is best developed on the basin margins or on intrabasinal highs where it is associated to a clear angular discordance.

Salt unit - In Sicily, carbonate and gypsum clastic deposits are associated with halite and potash salt bodies which may reach up to 1,000 m in thickness. The lateral relationship between halite and clastic deposits is not visible in the field but geological reconstructions and mine data clearly indicate that salt is exclusively found within the clastic unit. The halite bodies, according to observations in the Realmonte and Racalmuto mines, show a shallowing-upward trend with cumulitic deposits at the base and very shallow-water deposits in the upper half; K and Mg salt are only found below a desiccation surface which has been recognized in the upper half of the unit (Lugli *et al.*, 1999). The characteristics of this surface suggest a very short exposure (possibly a few years) after which shallow-water halite started to be deposited again; the transition to overlying deposits ('Upper Evaporites') is not visible either in outcrops or in mines. In outcrop sections however, a gypsum cumulate bed showing early diagenetic features that may represent the lateral equivalent of halite has been observed between the RLG and the overlying Upper Evaporites. The new age calibration of the overlying unit suggested by Roveri *et al.* (this volume) leads to an age of 5.55 Ma for the top of stage 2. This means that the huge halite unit could have been deposited in 50 ka or even less. This is in good agreement with the results of modelling (Meijer and Krijgsman, 2005) and with other considerations about the cyclicity of the halite unit. No clear evidence for precession-related cyclicity has been observed within salt; this deposit is characterized by a rhythmic layering comprising alternations of thin to very thin halite/ anhydrite/shale beds; this layering could be related to annual cycles, with salt deposited during summer and shale during the winter. Considering a 10-15 cm average thickness of these cycles, a minimum duration of less than 10 ka could be estimated for the whole halite unit; these values are in good agreement with modern solar works where halite precipitation rate is 100 m/ka (Schreiber and Hsü, 1980). An 11 years periodicity, related to sunspot cycles, has also been suggested (Bertini *et al.*, 1998), which would expand the duration of salt deposition to 70-100 ka. In this case, however, a more evident effect of precessional cyclicity would be expected. If these considerations are correct, then the role of very quickly aggrading salt has to be taken into consideration when evaluating the relative sea-level fall during this stage. Such accumulation rates cannot be compensated by any lithospheric subsidence mechanism, thus leading to rapid basin fill and possibly to subaerial exposure independently from sea-level variations.

The high sedimentation rates suggested for Sicilian halite are compatible with the geophysical observations in the Western Mediterranean deep basin where the Mobile Unit (MU) is imaged as infilling the deepest areas of the basins. MU also displays plastic deformation with a transparent and homogeneous seismic facies suggesting "clean" halite. Such a seismic facies may be the result of very high sedimentation rates (small amount of clastics intercalated in the halite) and/or of a deposition under relatively high sea level (minor erosion on the margin). In any case, sea-level was probably lowered so that inflow was continuous at the Atlantic gate, but outflow ceased. In the western Mediterranean the depth of the erosion surface (thought to be subaerial) cannot be found thus there is no way to constrain the maximum water depth during halite deposition. There is currently no evidence that the Western Mediterranean desiccated entirely. The amplitude of sea-level lowering at the beginning of halite precipitation in this basin still needs to be determined. At first view, a possible correlation exists between outcropping halite in Sicily and offshore halite in the Western Mediterranean.

Once again a major difference appears with the observations in the Eastern Mediterranean basin. Whereas MU is transparent in the Western basin, it contains internal reflectors in the Eastern basin. Up to six evaporite sequences are distinguished in the Nile and Levant areas which terminate against the top of the Mobile Unit off the southern Levant margin (Hübscher *et al.*, this volume). In the Levant Basin some of the layers within the halite have lower velocities than expected from pure halite and show internal deformation. This might be due to the presence of Mg and K salts, such as kainite, carnallite and possibly bischofite that are even more mobile than halite. There is evidence as well that significant amounts of fluids flow through or out of the MU. Such a difference in seismic facies between the Eastern and Western Mediterranean basins needs to be understood. In addition, studies carried out by the oil industry in the Nile area suggest that the deepest halitic sequence may be Tortonian in age. Such an age, pre-dating the onset of the MSC, raises important questions concerning the depositional models in the Eastern Mediterranean basin. At first sight, direct correlation between halite outcrops in Sicily and offshore halitic sequences in the Eastern basin is not evident.

Desiccation evidence in Sicilian halite may indicate really low sea level for a very short time. Even if only very rare evidence is observed for complete desiccation towards the top of the halite, this has strong implication for the calibration of the lowering amplitude in the deep basins. However, at the present time, there is no evidence on the seismic data for erosion at the top of the Mobile Unit in the western domain (absence of erosion surface or seismic resolution not high enough to image such a surface). Erosion at the top of the Mobile Unit is however clearly evidenced on the eastern domain, but its origin still needs to be clarified.

Tectonic vs eustatic forcing - Summarizing, this very short MSC stage with its extremely strong stratigraphic signature could have been derived from a positive feedback loop between concurrent climatic, tectonic and sedimentary dynamic factors. This time interval in fact comprises two successive glacial stages (TG14 and TG12). These climatic events coincide with tectonic activity, related to an important phase of reorganization of the Africa-Eurasia plate boundary in the Mediterranean area characterized by active thrusting, foredeep depocenter migration and differential subsidence in the Apennine and Sicily-Maghrebian orogens, by the opening of the Tyrrhenian Sea and by differential subsidence in the Betic Cordillera Basins and the concomitant uplift of the Gibraltar area (Duggen *et al.*, 2003; see Sierro *et al.*, this volume). The combination of tectonics and climate changes could have provoked a strong reduction in the Atlantic connections and in particular the short-lived blockage of the Mediterranean outflow (see Krijgsman *et al.*, this volume) thus triggering the evaporative sea-level drop of the Mediterranean basin and halite precipitation.

- **Stage 2.2: 5.55 – 5.33 Ma - Upper Evaporites and Lago Mare event(s)**

During this period, usually referred to as 'Upper Evaporites', a generalized and rapid transition to environments characterized by periodic water salinity changes occurred throughout the Mediterranean basin, as recorded by alternating evaporites and clastic deposits containing brackish to fresh water faunas (Orszag-Sperber, 2006). The Zanclean base marks the synchronous return at 5.33 Ma to fully marine conditions and thus the end of the MSC. Its base can be defined on cyclostratigraphic ground at around 5.55 Ma (9-10 cycles in the Eraclea Minoa section; see Roveri *et al.*, this volume). A commonly observed vertical organization allows to subdivide the uppermost Messinian successions into two units (p-ev$_1$ and p-ev$_2$ of Roveri *et al.*, 1998, 2001).

The lower unit is characterized by the cyclical alternation of gypsum and shale beds and is more developed in the southern and eastern Mediterranean (Sicily, Ionian Islands, Crete, Cyprus, Nile Delta area). Gypsum facies differ from the PLG and suggest formation in very shallow waters (see Lugli *et al.*, this volume; Manzi *et al.*, 2007); Sr isotope values are lower than PLG indicating a substantial freshwater input as well as the intervening shale interval which contain rare and scattered brackish water assemblages (mollusks and ostracods) (Flecker and Ellam, 2006). As for the PLG, the rhythmic alternation of gypsum and shale suggests cyclic salinity fluctuations likely driven by precession. In the Apennine and Sorbas/Nijar Basins this unit mainly consists of shallow- to deep-water clastic deposits. Thicknesses range from a few tens of meters (Sicily) up to 1 km in the Apennine foredeep basin depocenters.

The upper unit has an overall stronger freshwater signature, as testified by sedimentary facies (showing a generalized fluvial rejuvenation and/or change in the precipitation regime) and faunal and floral assemblages which are characterized by a significant increase of Paratethyan taxa (*Loxocorniculina djafarovi*, *Galeacysta etrusca*) (Bertini, 2006; Gliozzi *et al.*, 2006; Londeix *et al.*, 2007). This unit as a whole records the so called Lago Mare event. However, according to Clauzon *et al.* (2005), several discrete Lago Mare events can be recognized within this interval instead of a general condition or trend. The constant number of 4/5 cycles (mainly given by conglomerate or sandstone/shale alternations related to the periodic activation of flood-dominated fluvio-deltaic systems and of their genetically-related deeper-water turbidite systems) observed in different basins allows to trace the lower boundary of the upper unit at around 5.42 Ma. In some basins (Sicily, Tuscany) gypsum beds are observed in the uppermost cycle, which corresponds to a higher amplitude precessional cycle occurring within the TG 7 isotope stage. Abundance and diversity of Paratethyan biota show a maximum in the uppermost cycle as testified in Sicily by the Arenazzolo unit and underlying shale unit (Londeix *et al.*, 2007). Thicknesses of the upper unit are variable and range between a few tens of meters (Sicily) up to 400 m in the Apennine Basin.

Both units have an aggradational stacking pattern better developed in shallow water depositional settings, which suggests a phase of renewed accommodation space creation following the relative sea-level fall of stage 2. This could indicate a generalized increase of subsidence rate related to a phase of tectonic quiescence following the stage 2 peak. However, the delayed effect of salt lithospheric loading cannot be excluded; these two factors could have concurred to change sills configurations within the Mediterranean, particularly in the Atlantic and Paratethys gateway areas, thus allowing to change the hydrologic budget. The upper unit in particular shows a more clearly developed transgressive trend as it drapes the previously subaerially exposed and eroded areas. This overall trend peaks with the Zanclean marine flooding and continues in the basal Pliocene. This means that, according to the position along the depositional profile, a variable thickness (decreasing landward) of latest Messinian or even Zanclean deposits can be found directly above the MES. Geometry, facies characteristics and relationships with the MES therefore suggest that the Mediterranean refill started before the Pliocene base with the progressive enlargement of a substantially non-marine or highly diluted water body. However, in such a general trend a progressive increase in the connectivity of Mediterranean sub-basins with the Atlantic and the Paratethys can be envisaged, thus explaining the apparent paradox offered by the concurrent presence of stenohaline fishes (Carnevale *et al.*, 2006, 2008), freshwater Paratethyan ostracods (Çağatay *et al.*, 2006) and dinocysts.

Correlation of outcrop successions of this interval with the offshore domain is not clear. In the western deep basin, from a seismic facies point of view, the thick Upper Unit (UU) observed above MU may correlate with the gypsum/clastic alternations in Sicily, whereas the offshore equivalent of the Arenazzolo is not clear and is perhaps too thin to be detected. In the Cyprus arc area, an increase in reflectors towards the top of MU is observed on the seismic profiles. This might reflect a transition to an Upper Unit, but from a seismic point of view it must still contain halite (with more clastics or possibly gypsum within it?). Lago Mare and Upper Evaporites are observed onland in Cyprus, but they are thin so these deposits may not be visible on the seismic data in the basin. However, ODP data document the presence of a thin Lago Mare unit at the top of salt (Iaccarino and Bossio, 1999; Orszag-Sperber, 2006). For these reasons, correlation with the more bedded upper part of the MU is not evident. On the seismic profiles, there is no Upper Unit in the Eastern basin (Levant and Nile), once again illustrating the singular status of this area. Correlation between the different Eastern basins (Nile and Levant, Herodotus Basin) needs to be clarified. A correlation between outcroping Upper Evaporites (UE) in Sicily and offshore Upper Unit (UU) in the Western Mediterranean can be envisaged (at least partly) but is far from being evident. Correlations with the Eastern basin are even more complex.

At 5.33 Ma, a simple flooding is observed on the margins. Thus, at the beginning of the Lower Pliocene, sediments were essentially trapped in the head parts of the Messinian canyons that became suddenly the Zanclean rias, while basinward a condensed layer of clays recovered the Margin Erosion Surface and the Messinian deposits (Lofi *et al.*, 2003).

3.2 MSC in the Paratethys

The palaeogeographic evolution of the Paratethys region during the Messinian Salinity Crisis is still controversial, mainly for lack of a reliable time frame for its sedimentary sequences. Ages and duration of the Late Miocene stages varied in the order of several millions of years according to the different time scales suggested (see Vasiliev *et al.*, 2004 and references therein). Consequently, the exact relation of the palaeoenvironmental events recorded in the Paratethys region with the Mediterranean MSC events could not be established or remained highly speculative (e.g. Hsü and Giovanelli, 1979).

Recently, two different approaches have been used to establish correlations with the Mediterranean Messinian:

1. The search for marine calcareous coccoliths and foraminifera, which allow a direct correlation to the Global Time Scale (Clauzon *et al.*, 2005; Snel *et al.*, 2006; Clauzon *et al.*, recent, unpublished data). The discovery of Mediterranean calcareous coccoliths both within the Dacic (Mărunţeanu and Papaianopol, 1995, 1998; Drivaliari *et al.*, 1999) and Euxinic (Semenenko and Olejnik, 1995) basins allowed improvement of the regional stratigraphy. These advances permitted direct relationships of Paratethyan deposits with the Global Time Scale, even if the marine markers are discontinuously recorded. Mărunţeanu and Papaianopol (1995, 1998) describe three short influxes of coccoliths at the Meotian/Pontian boundary interval, within the local Portaferrian substage and at the Pontain/Dacian boundary interval, repectively.

2. Integration of magnetostratigraphy and biostratigraphy of endemic organisms from Paratethys (mainly molluscs and ostracods) or palynology, often resulting in an astrochronostratigraphy (Van Vugt *et al.*, 2001; Popescu, 2001; Vasiliev *et al.*, 2004; Popescu *et al.*, 2006a,b). Reliable magnetostratigraphic time scales have especially been constructed for the long sedimentary sequences of the eastern and southern Carpathian foredeep (Van Vugt *et al.*, 2001; Vasiliev *et al.*, 2004, 2005). These time scales can be coupled to regional biostratigraphic data on ostracods and molluscs (e.g. Stoica *et al.*, 2007), resulting in high-resolution chronologies for the Meotian to Romanian (7–3 Ma) sediments of the Focsani Basin (Eastern Carpathians) and the Getic Depression (Southern Carpathians). The main conclusion is that the ages of the main stage boundaries are roughly synchronous in the entire Carpathian foredeep of Romania and that the observed environmental changes are at least of regional importance. The onset of the Messinian Salinity Crisis roughly corresponds to the Meotian/Pontian boundary, which is magnetostratigraphically dated at ~6 Ma. The Pontian and Dacian mollusc assemblages of the Getic Depression indicate that a hiatus – comprising the Early Pontian – is present in the stratigraphic successions of the south Carpathian foredeep, which could be related to a base level drop of the Paratethys water column that is coupled to the MSC, similar to that observed in the Turnu Severin region by Clauzon *et al.* (2005). The 1,000 m thick sequences from the Rimnicu Saeat River section seem continuous without significant breaks in accumulation and await high-resolution biostratigraphic analyses to allow direct comparison of the Paratethys (sub)stages and the paleoenvironmental evolution of the Dacic and Euxinic basins in relation to the Messinian Salinity Crisis of the Mediterranean. Furthermore a gradual transition is observed at the Pontian/Dacian boundary, which is magnetostratigraphically dated at ~4.9 Ma, significantly later (by more than 400,000 years) than the Mio-Pliocene boundary in the Mediterranean sequences.

One important issue is the source of fresh- to brackish-water input during the deposition of the Lago-Mare facies usually located in the final phase of the MSC just before the Zanclean transgression. The proposed hypotheses include a rapid input from the Parathethys (Hsü and Cita, 1973; Cita *et al.*, 1978), increased fresh water inflow from the Mediterranean catchment (Krijgsman *et al.*, 2001; Rouchy *et al.*, 2001; Orszag-Sperber *et al.*, 2006), and exchange of water between the marine Mediterranean and the brackish Paratethys during highstands (Clauzon *et al.*, 2005).

3.3 The microbial perspective of MSC

There are three possible scenarios during the MSC: shallow oxic, deep stratified and deep non-stratified hypersaline basins. For the first two we could have modern-day analogues in the man-made salinas and in the deep-sea hypersaline brines, respectively (see chapters by Antón *et al.* and McGenity *et al.*, this volume). However, there is no known modern analogue for deep non-stratified hypersaline brines. The main types of microbes found in modern-day hypersaline environments would have existed in the Messinian. The environmental conditions however would have had a big impact on the microbial composition. For example, in surface hypersaline environments haloarchaea dominate whereas they form only a minor component of the deep-sea hypersaline anoxic basins. Therefore, the modelling of the microbial populations during the MSC would require information about the following issues: salinity and sequence of precipitation, depth of the basins, light penetration, oxygen and nutrient availability. Changes in these parameters would be accompanied by a succession of microbes, as observed today in salinas. Previous research on the microbiology of hypersaline environments could also provide information on the influence of microorganisms on crystallization rates and crystal morphology (see Antón *et al.*; McGenity *et al.* and Lugli *et al.*, this volume).

4. OPEN PROBLEMS

4.1 MSC chronology and shallow to deep-water correlations

A huge amount of descriptive and analytical work has been carried out on the successions preserved in marginal basins, and much effort has been spent on elaborate, often conflicting correlation schemes aimed at a pan-Mediterranean synthesis of these marginal stratigraphies. However, we still have a poor understanding of how the marginal basins were connected to the main deep basinal areas of the Mediterranean. The stratigraphic models of Sicily and Apennines (see paper by Roveri *et al.*, this volume) offer a possible key to address this problem and their implications should be tested in other areas.

Two crucial points deserve emphasis in this respect:

1. The full chronologic and palaeoenvironmental characterization at a regional scale of the deposits representing the deep-water counterpart of the primary Lower Evaporites (PLG of Roveri *et al.*, this volume), recording the first stage of the MSC in onland basins. Open questions to be addressed in future investigations concern the recognition and thorough characterization (mineralogy, organic matter, paleontology and sedimentology) of such deep-water non-evaporitic deposits in other outcropping basins.
2. The accurate chronologic definition of the events in the 5.6-5-5 Ma interval. Field data and observations suggest that halite units could have formed in a very short window within this interval, and this is also supported by modelling. Any effort should be made to test this hypothesis by studying the high-frequency cyclicity of halite deposits.

These points are fundamental to assess a better time and generic characterization of the main physical surfaces bounding Messinian sedimentary units, and to obtain new clues for the interpretation and correlation of the seismic markers in the offshore domain, and particularly of the Messinian Erosional Surface and its correlative conformity. The definition of a reliable scenario of the MSC onset in the different depositional settings is of course crucial to assess the basic physical and chemical parameters of the Mediterranean water column during this phase and provide a more reliable scenario for hydrological budget modelling.

4.2 Location, timing and geometry of the Atlantic gateways

Before the Messinian Salinity Crisis the Mediterranean was connected with the Atlantic through the north Betic and south Rifian corridors in Southern Spain and northern Morocco. Marine sediments and benthic microfaunas indicate that both foredeep basins allowed deep water exchange with the Atlantic during the Serravallian and probably Early Tortonian (Geel *et al.*, 1992; Sierro *et al.*, 1996; Krijgsman *et al.*, 1999b; Sierro *et al.*, this volume). However, during the Tortonian tectonic uplift of the eastern part of the North Betic Gateway strongly restricted this eastern connection, though a narrow corridor remained through the Guadix Basin, that was finally closed near the Tortonian-Messinian Boundary (Soria *et al.*, 1999; Betzler *et al.*, 2006). The Betic Gateway was further narrowed and shallowed when huge olistostromic masses were emplaced from the southern margin inmediately after the Tortonian-Messinian boundary (Sierro *et al.*, 1996; Sierro *et al.*, this volume). During the Early Messinian the western part of the north Betic corridor was still open to the Mediterranean through the Guadalhorce Gateway that extends from the Guadalquivir Basin to the Alboran Sea, near Malaga; this connection was finally closed at around 6.3 myr well before the deposition of the Lower Evaporites (Martin *et al.*, 2001).

In the Rifian corridor (Northern Morocco) Late Miocene marine sediments extended from the Atlantic margin near Rabat to the Taza-Guercif and Melilla basins in the Mediterranean margin; the central part of this seaway also underwent an important tectonic uplift near the Tortonian-Messinian boundary but total disconnection did not occur until 6.0 Ma, nearly at the onset of deposition of the lower evaporates (Krijgsman *et al.*, 1999b). Since an ocean inflow is needed to explain the deposition of the lower evaporites all over the Mediterranean margins, a connection with the global ocean ought to have existed, but little is known about its possible location, although an Atlantic-Mediterranean connection through the Strait of Gibraltar may have existed before the Pliocene inundation.

4.3 Water depth at the beginning/end of halite deposition

This question, which ultimately concerns the amplitude of the sea-level drop(s) during the second MSC step is usually estimated at around 1,500 m (Ryan, 1976; Maillard *et al.*, 2006a), requires the assessment of other related items, i.e. the fully subaerial/partly subaqueous origin of the MES, the origin of the erosional surfaces within and at the top of UU and the water depth implications of the Messinian canyons.

4.4 Eastern vs Western Basin

In the offshore domain, the integrated study of the Messinian seismic markers clearly evidence some major differences at the scale of the Mediterranean Sea:

1. presence/absence of a Lower Unit;
2. unique/multiple sequences in the Mobile Unit;
3. presence/absence of an erosional surface at the top of MU;
4. presence/absence of an Upper Unit.

Such differences in the seismic markers between the Eastern and Western Mediterranean basins need to be explained. A prerequisite for correlation and chronology of the two basins is the definition of the origin of the erosional surfaces at the bottom and top of MU in the Eastern basin and of its sub-units.

The presence of one (or several) sills between the majorbasins (and certain sub-basins) may be envisaged to explain the observed differences. The location of the Sicily strait (north or south of Sicily) also needs to be clarified. The impact of local climate and river run-off must also be taken in consideration. The fact that the lowest halite unit in the Nile canyon is given as Tortonian in age (but this hypothesis needs biostratigraphic support and documentation) has also strong implications on our understanding of the MSC at the scale of the basin. Further work is thus needed to complete our understanding of the depositional models and temporal relationship between deep basin Messinian units at a global scale.

4.5 Paratethys-Mediterranean connections

Paratethys-Mediterranean connections require gateways (Rögl and Steininger, 1983; Popov *et al.*, 2004). Two possible gateways have been suggested in the eastern Mediterranean: one is the Marmara Sea connecting the Eastern Paratethys with the Aegean Sea (Görür *et al.*, 2000; Çağatay *et al.*, 2006); the other is the north Aegean region-Thrace region connecting the Dacic Basin (Central Paratethys) with the Aegean Sea (Clauzon *et al.*, 2005). The Marmara Sea region in NW Turkey is characterized by the widespread occurrence of the Messinian-lowest Zanclean rocks with a brackish- to fresh-water fauna of Paratethyan affinity similar to Lago-Mare facies of Messinian to earliest Zanclean age (NN11b-NN12b Nannofloral Zones, Melinte-Dobrinescu, pers. comm.; Görür *et al.*, 2000; Çağatay *et al.*, 2006; Çağatay *et al.*, this volume). This facies extends further west and south covering large areas in the Aegean Sea regions (Papp *et al.*, 1978; Papp and Steininger, 1979; Sakınç and Yaltırak, 2005). This distribution suggests at least one-way ouflow of the Paratethyan waters into the Aegean via the Marmara Sea region during the Messinian to earliest Zanclean. However, the timing and nature (one-way vs. two-way flow and outflow vs. inflow) of the connections are still a matter of debate and require detailed Sr-isotope studies on stratigraphically dated sections in the Marmara region (Flecker and Ellam, 2006).

The relatively flat area of Istanbul and the Marmara region were both classically considered as the best candidate for a corridor (Rögl and Steininger, 1983; Marinescu, 1992; Çağatay *et al.*, 2006; Popov *et al.*, 2006; Esu, 2007; Faranda *et al.*, 2007; Gliozzi *et al.*, 2007; Stoica *et al.*, 2007). The presence of Paratethyan fossils in the Sea of Marmara region does not contradict this view, which considers at least a one-way outflow from the Paratethys (Görür *et al.*, 2000; Çağatay *et al.*, 2006). For their part Clauzon *et al.* (2005; and new unpublished data) reject the view of a two-way water exchange between the Paratethys and Mediterranean through the Sea of Marmara because Mediterranean microfossils (diatoms, nannoplankton, dinoflagellates, foraminifers) have been recorded in the earliest Zanclean sediments of the Dacic Basin but not in coeval sediments from the southwestern Black Sea (DSDP Site 380). They support instead a passage in the Balkans region at Skopje (already proposed by Marinescu, 1992) (Clauzon *et al.*, 2005; Popescu *et al.*, in press), that considerably mortgages the concepts on regional geodynamics.

4.6 Evaporite facies

The problems faced by scientists in the interpretation of the Messinian evaporite sequences in the Mediterranean are multiple.

First, as all thick and extensive deposits of the past (saline giants) appear to lack a modern equivalent, only non-actualistic models may be proposed for their interpretation. Secondly, most evaporite facies studies have been conducted on land because deep Mediterranean deposits are known only for a few samples coming from the uppermost part of the sequence. The studies on land were concentrated mostly on "classical" sections, ignoring the lateral variations of evaporite facies (see Lugli *et al.*, this volume). An important problem concerns the response of very shallow-water, coastal and continental environments to the first stage of the MSC. In other words we do not have a clear picture yet of what happened in such depositional settings during the intervals characterized by primary gypsum deposition in relatively shallow but fully subaqueous environments. The records of these depositional settings are likely to have been eroded during the relative sea-level fall of the subsequent stage but it is possible that in some areas they have been preserved. Third, studies on the biological activity during evaporite deposition are just at their initial stage (Rouchy and Monty, 2000; Panieri *et al.*, in press).

A last, but very important aspect is that evaporite sediments are among the most elusive for facies reconstruction and correlation. A reliable stratigraphic framework, not yet available, is imperative to attempt correct interpretations.

4.7 Salt tectonics

The salt tectonics observed locally, contemporaneously to the precipitation of the basinal evaporites, is not understood. The vertical succession of evaporites in the Levantine Basin obviously causes a layered rheology and detachment layers, which allows creeping of individual layers during the precipitation phase even without external forcing. The layering obviously strongly influences the structural evolution of salt giants.

The initiation of salt tectonics after the precipitation also requires further investigation. The interaction between the sediment onlaod on the MU, the initiation of gravity gliding, and the subsidence of the underlying crust remains unclear. Furthermore, the lateral creep of the MU is known as a possible trigger mechanism for submarine land slides, which potentially cause tsunamis. No risk assessment has been carried out so far. In order to understand those processes the mechanical behaviour of layered salt bodies needs to be understood.

4.8. Fluids

Several seismic studies provided strong evidence that fluids are able to flow across and out of the MU (Gradmann *et al.*, 2005; Netzeband *et al.*, 2006b; Bertoni and Cartwright, 2006). This surprising observation contradicts the general assumption that massive salt layers represent a stratigraphic seal. The fluids are able to cause circular dissolution structures, salt cones atop the MU, and mud volcanos on the seafloor. The origin and the transport processes are unknown. Water within the MU may result from Gypsum-Anhydrate conversion. The answer may have a major impact on future waste disposal sites in salt diapirs. Generally, as fluid migration is associated with nutrition transport, these fluids should have a significant, but yet unexplored impact on the deep biosphere.

4.9 Microbiology

The deep biosphere in basinal evaporites has been never investigated. In order to establish a model of how the microbial populations changed during the MSC we need information about such environmental parameters as salinity and sequence of precipitation, depth of the basins, light penetration, oxygen and nutrient availability. On the other hand, we do not know to what extent the dynamics of crystal formation in the water column would affect the redistribution of microbes (e.g. from surface to bottom of the brine) and therefore how useful biomarkers inside fluid inclusions would be. Moreover, it seems that above a given salinity, there are no available biomarkers. It would be useful to find biomarkers indicative of shallow-deep, oxic-anoxic, light-dark environments and covering a range of salinities.

It is important to recognise that large numbers of halophilic microbes become trapped inside fluid inclusions of precipitating halite and other minerals. They can also remain viable and active for many years post-crystallisation, and some microbes survive for millions of years (see McGenity *et al.*, this volume). Therefore, in addition to studying the microbes in present-day hypersaline brines we need to investigate the microbial communities inside crystals of halite, in order to learn which microbes preferentially survive entombment, how they grow and what changes in geochemistry they cause. In turn, it should be recognised that this will affect the interpretation of data on the geochemistry of, and biomarkers from, Messinian evaporites. Further investigations into the geology of the salt (from tectonics to fluid-inclusion chemistry) will help us to understand the extent to which Messinian evaporites are a repository or habitat for microbes.

4.10 MSC modelling

Much of the information that has been gleaned from the study of the Messinian Salinity Crisis over the last 30-40 years is largely qualitative. For models to be useful in exploring the processes active during the MSC and provide a powerful mechanism for testing hypotheses, quantitative information and an assessment of the associated errors is required. Some of these data have been available for many years and are extensively used in modelling. For example, the thickness of evaporites across the Mediterranean is relatively well constrained by both marginal basin exposure and seismic evidence from the deep basins. These data provide only a minimum indication of the evaporite precipitation that occurred in the Mediterranean since they do not account for the evaporites that were dissolved during recharge of the basin. The salinity implications of both faunal assemblages such as the Lago Mare faunas (De Decker *et al.*, 1988) and evaporite minerals are also well constrained although large error bars are typically associated.

The high resolution chronology that results from astronomical tuning of Late Miocene Mediterranean sections (Krijgsman *et al.*, 2002; Krijgsman *et al.*, 1999a; Hilgen *et al.*, 2007) has also provided a very valuable constraint on the rate at which processes occur, although tuning issues with regard to the evaporite-bearing successions themselves and the chronostratigraphic significance of particular horizons still leave considerable uncertainties (see paper by Roveri *et al.*, this volume). Further data used in numerical modelling have been provided by isotopes, and particularly by Sr, S and $\delta^{18}O$ isotopic systems. Unfortunately considerable uncertainties remain associated with each of these datasets; in addition the distribution of the samples is highly concentrated around the margins of the Mediterranean. In the absence of suitable sample material recovered from the deep basins, it is currently not possible to demonstrate that these marginal data also reflect the basinal history.

A related issue is the reconstruction of the basin configuration and the palaeogeography of the region before, during and after the MSC. Although Meijer *et al.* (2004) show that palaeogeography had only limited control on Mediterranean circulation, fundamental and contentious issues such as the basinal or marginal nature of the Sicily successions directly impact on how these data can be compared with model results. Another dataset that remains highly controversial is the sea level record determined from canyon depth imaged on seismic data. The degree to which this information can be relied upon is discussed elsewhere in this chapter.

Other quantitative datasets are challenging to construct and may not yet exist in a form that can be easily utilised by the numerical modelling community. For example, as hydrologic budget information for the Late Miocene is largely absent, modern fluxes have to be used instead (see Flecker, this volume for details). Ultimately it should be possible to derive good estimates of this information from General circulation models (GCM) of the Late Miocene, but this prospect is still some way off. One route for model testing is through the quantitative reconstruction of the climate from pollen analyses (Fauquette and Bertini, 2003; Fauquette *et al.*, 2006). However, this information is currently extremely limited and its location rarely ideal for testing the validity of GCM simulations. An alternative approach is to evaluate river discharge through the resulting sedimentary signature, as explored in a qualitative way for North African rivers by Griffin (1999, 2002 and 2006). Further potential quantitative insights could be gained by incorporating the influence of microbiological activity on rate of evaporite precipitation.

5. STRATEGY AND RECOMMENDATIONS FOR FUTURE RESEARCH

The Workshop participants recommend focusing future research activities, in the context of international, interdisciplinary programs, on the following key questions:

1. Where were the gateways between the eastern and western basins during the MSC?
2. What was the paleo-depth of the sills before, during and after the MSC?
3. What was the location, the timing and the nature (one-way vs. two-way flow, and outflow vs. inflow) of the Parathethys-Mediterranean connections?
4. What is the temporal and structural relationship between the basinal evaporites in the western and eastern Mediterranean?
5. What can we learn from Messinian outcrops regarding geology, geochemistry and biosphere?
6. What can we learn from geochemical analysis (e.g. at mud volcanoes and deep brine basins) about deep biosphere and evaporitic facies?
7. What are the characteristics of the Messinian evaporites in the unexplored basins (Tyrrhenian, Ionian and Herodotus Basin)?
8. How can the abundant qualitative information available on the MSC be translated into quantitative datasets suitable for the testing of a variety of different numerical models?

Besides these fundamental questions, the Workshop participants wish to highlight additional paths for future activity:

Ultradeep drillings – Recovering cores from deep Mediterranean basins Messinian evaporite sequences is an urgent need for the scientific community. Such a drill program would greatly advance our understanding of the MSC, the evolution of the Mediterranean salt giant, and of geologically much older counterparts elsewhere. A single and continuous drill core through the complete Messinian evaporite sequence would allow us to unravel the evolution of a salt giant which would shed important new light on fundamental aspects of the Earth system. The opportunities offered by deep drilling are powerful, provided that suitable sites are carefully chosen. To this end, great effort must be made to identify drillsites that intersect the most complete evaporite sequences and those that retain their sedimentological characteristics, i.e. avoiding successions that have been strongly modified by salt flow.

Outcrop-offshore interactions – The probable timescale for ultradeep drilling is relatively long, e.g. ~ a decade. During this period closer interaction between outcrop and subsurface specialists is required to define more comprehensive MSC scenarios and thereby help solve scale and correlation problems. The groups working on Messinian outcrops could advantageously focus on reconstructing and providing the subsurface specialists with regional-scale stratigraphic and depositional models to be translated into seismic-stratigraphic units. The most promising areas for this are Sicily and Northern Apennines for which outcrop-based stratigraphic models are already available. Cyprus and Ionian Islands should be revised to help constrain the interpretion of the Messinian seismic units of the Levantine Basin.

Evaporite-related processes, products and life - Many of the problems associated with evaporite interpretation may be successfully addressed by considering the following issues:

1. New significant data on the various environments of evaporite deposition may be obtained by studying the biological content of evaporite minerals, especially halite that has not been investigated yet.
2. Study of the present-day life in evaporite deposits. This can be approached with a range of molecular and microbiological techniques. An improved understanding of the activities of microbes in evaporite deposits would allow a more rational interpretation of biogeochemical data used to address issues such as palaeoenvironmental depositional settings.
3. Further efforts must be made to investigate in detail the lateral facies variation of evaporite sequences, especially for those areas, such as Sicily, thought to represent on-land equivalents of the deep Mediterranean sequences (see Roveri *et al.*, this volume); the same approach should be attempted for Cyprus and the Ionian Islands where the correlation with the abyssal plains evaporite sequences is even more problematic.
4. The geochemical dataset of the various evaporite facies must be expanded and placed in a reliable stratigraphic framework.