C I E S M W o r k s h o p M o n o g r a p h s

The Messinian Salinity Crisis from mega-deposits to microbiology - A consensus report

Almeria, 7-10 November 2007

CIESM Workshop Monographs ◊ 33.

To be cited as: CIESM, 2008. The Messinian Salinity Crisis from mega-deposits to microbiology - A consensus report. N° 33 in *CIESM Workshop Monographs* [F. Briand, Ed.], 168 pages, Monaco.

This collection offers a broad range of titles in the marine sciences, with a particular focus on emerging issues. The Monographs do not aim to present state-of-the-art reviews; they reflect the latest thinking of researchers gathered at CIESM invitation to assess existing knowledge, confront their hypotheses and perspectives, and to identify the most interesting paths for future action.

A collection founded and edited by Frédéric Briand.
Publisher: CIESM, 16 bd de Suisse, MC-98000, Monaco.

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This synthesis, outlined during the meeting, is based on inputs and written material received thereafter from all the workshop participants. 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), 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.

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.

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).

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.

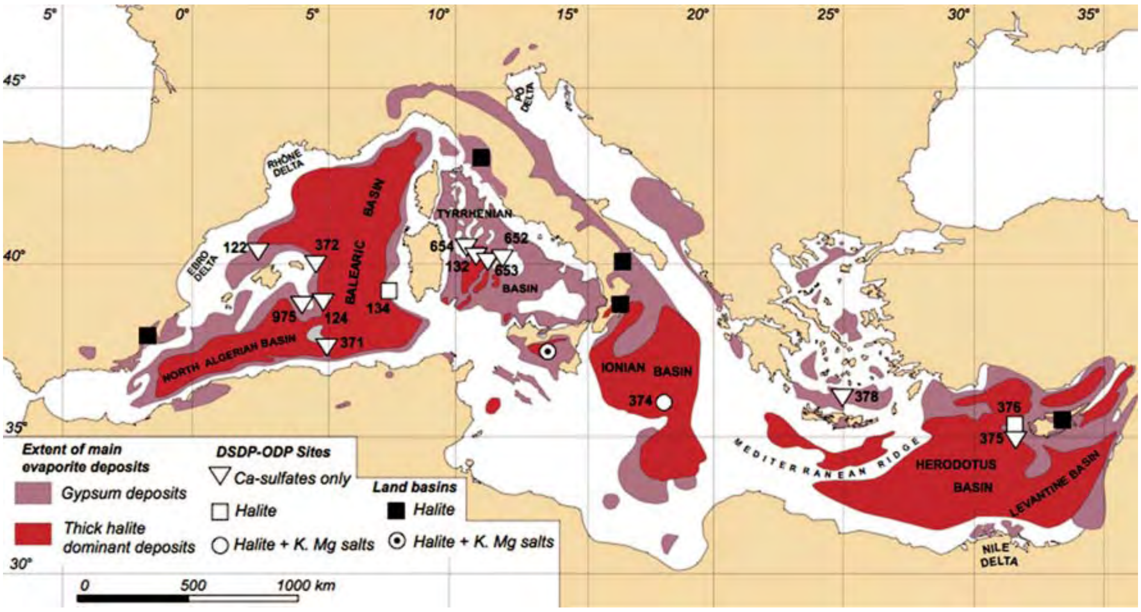


Fig. 1. Distribution of Messinian evaporites (modified from Rouchy and Caruso, 2006).

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

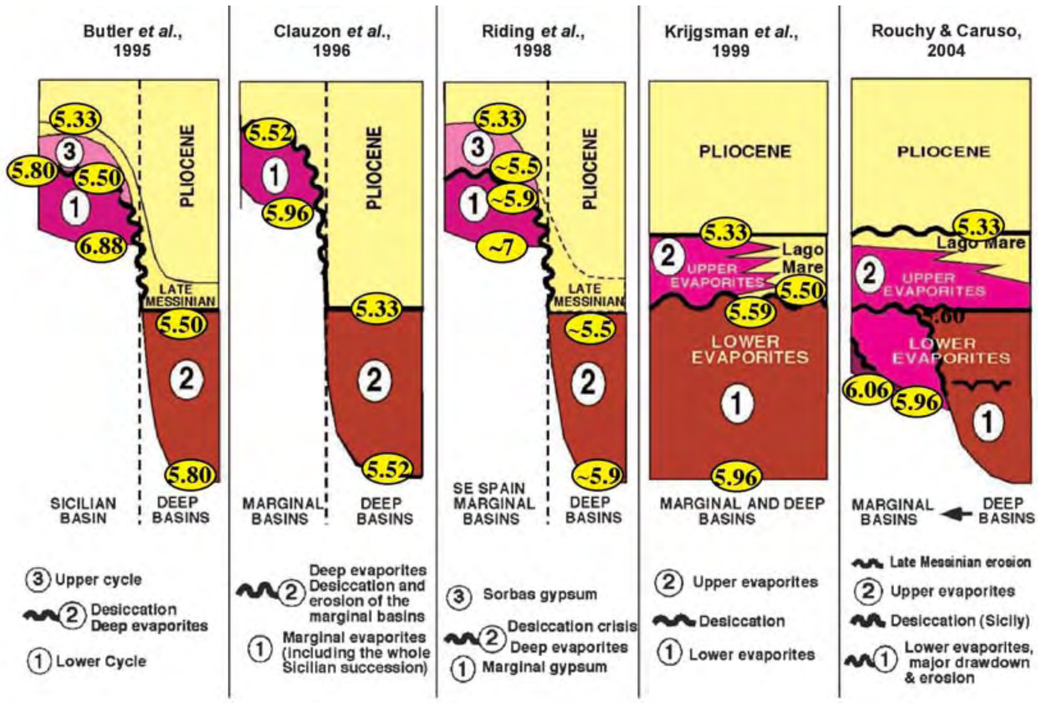


Fig. 2. Different MSC scenarios (from Rouchy and Caruso, 2006).

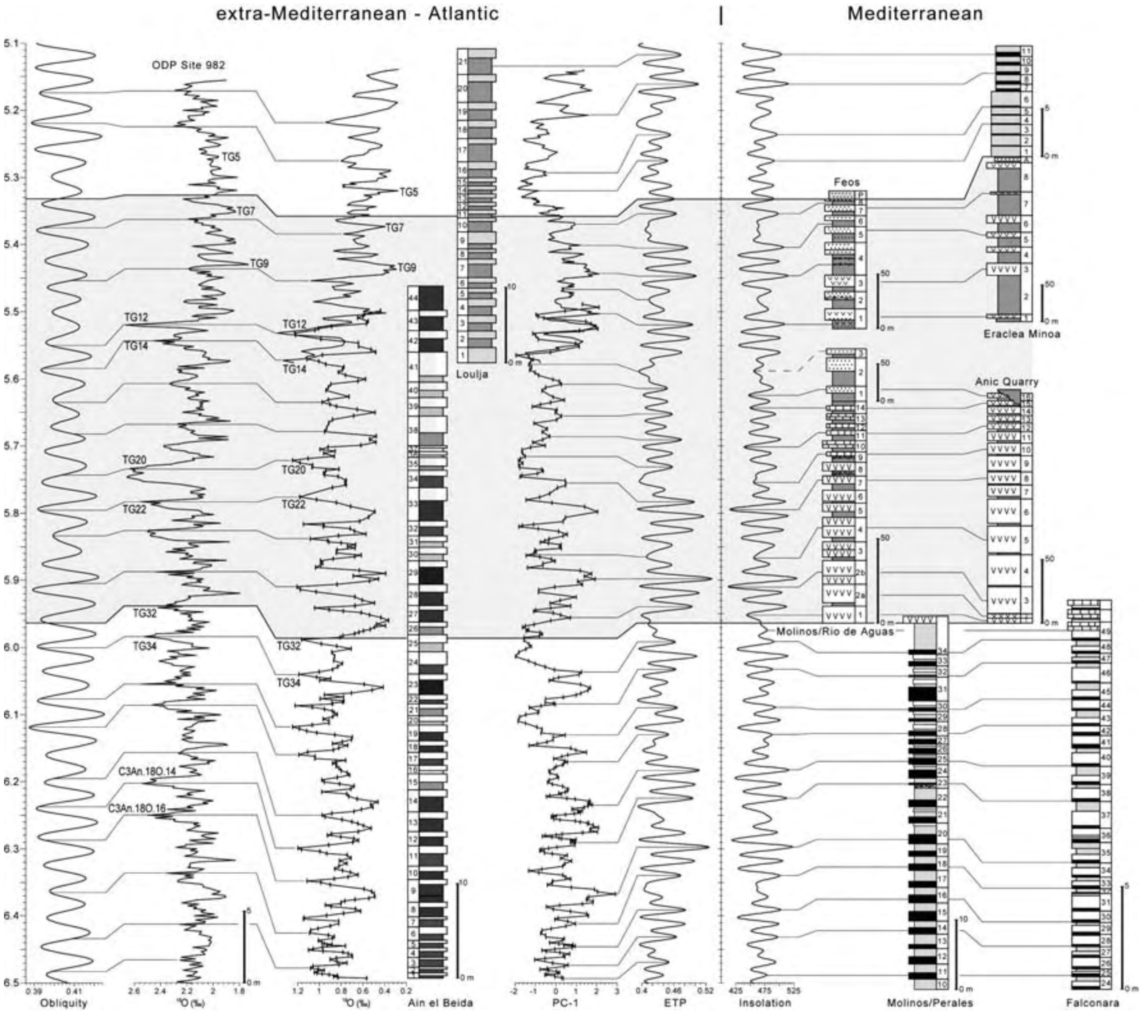


Fig. 3. Astronomical tuning of Messinian key sections located in the Mediterranean or in the adjacent Atlantic (after Fortuin and Krijgsman, 2003; Hilgen and Krijgsman, 1999; Sierro *et al.,* 2001; Krijgsman *et al.,* 2001; Van der Laan *et al.,* 2005, 2006; Hodell *et al.,* 2001). Also shown is the 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).

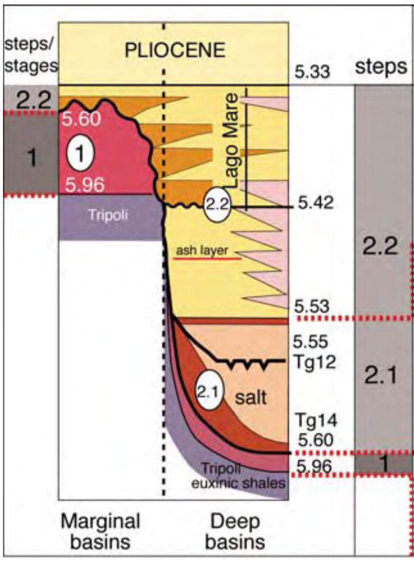
of most of the Upper Unit) is weak. Hence, the nature, age and depositional environments of the deep basin Messinian deposits can only be derived indirectly (seismic facies, geometries and architecture of the depositional units, stacking patterns, internal seismic velocities, brine chemistry). Outcrops 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.



stages	tectonics	evaporite types	hydrology
upward increase of fluvial discharge associated with Lago Mare biofacies Upper Evaporites (selenite and laminar gypsum) (Sicily, Tuscany, Cyprus, Ionian Islands)	quiescence	selenite gypsum, halite	alternating mixing and stratification
local desiccation of salt basins (Sicily) carbonate (Calcare di Base), resedimented evaporites, clastics and salt in deepest basins intra-Messinian unconformity erosion, minor drawdown and subaerial erosion in marginal basins	active	carbonate, halite, K-Mg-salts, laminar gypsum	stratified waters bottom anoxia
Lower Evaporites (selenite in shallow basins, Tripoli and euxinic shales in deep basins)	quiescence	selenite gypsum	alternating mixing and stratification

Fig. 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 Roveri *et al*., this volume). Much uncertainty also remains, unfortunately, with data sets provided by Sr, S and $\delta^{18}O$ isotopic systems. Further the distribution of the samples is 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.

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.

II - Workshop Communications

Chronology of the Messinian events and paleogeography of the Mediterranean region *s.l.*

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Abstract

After an intense effort in chronology (magnetostratigraphy, biostratigraphy), the effects of the Messinian Salinity Crisis have been explored all around the Mediterranean Sea and its appendix, the Eastern Paratethys. The respective influence of regional tectonics and global climate has been estimated, the role of the latter cannot be neglected. The Messinian Erosional Surface cuts everywhere the marginal evaporites and correlates to the halite in the central deep basins, an observation that led to the two-step scenario of the crisis (Clauzon *et al.*, 1996). The Lago Mare biofacies results from various paleogeographic conditions, reproduced several times: Mediterranean–Paratethys exchanges during high sea-levels, dilution by river input at the end of the evaporitic phase. Henceforth, Lago Mare cannot have a chronostratigraphic value. This dense

study results in a detailed chronology of the Messinian Salinity Crisis and in the paleogeographic reconstruction of the region, showing that the crisis cannot be reduced to a simplistic scenario.

Introduction

Since Gautier *et al*. (1994) first published a magnetostratigraphy of deposits encompassing the Messinian Salinity Crisis, systematic biostratigraphic studies (nannoplankton and planktonic foraminifers) carried out around the Mediterranean and adjacent basins (Eastern Paratethys) have enabled the development of a detailed succession of Messinian events and associated paleogeographic changes.

These aspects are discussed below along the following development: climate, erosion, and "Lago Mare" events as a basis of the two-step scenario (Clauzon *et al*., 1996), followed by a discussion of chronology and paleogeography.

1. Climate

Pollen records have established that drastic climatic change was not the cause of the desiccation of the Mediterranean Sea (Suc and Bessais, 1990; Fauquette *et al*., 2006). However, the influence of cooling cannot be discarded as done by Krijgsman *et al*. (this volume). It may have caused, in conjunction with the tectonic narrowing of the Rifian Corridor (Figure 1; Warny *et al*., 2003; see also Drinia *et al*., 2007), a context of minor sea-level fall in the Mediterranean, which was prevalent in the marginal basins because of their relative isolation by sills. At Bou Regreg (i.e. the Atlantic outlet of the Rifian Corridor), the large fluctuations in abundance of *Operculodinium israelianum*, a neritic dinoflagellate cyst, indicate that glacio-eustatic variations mostly controlled the water-depth changes in the Rifian Corridor before and after the Antarctic glacials TG 22 and TG 20. These conditions continued up to 5.6 Ma, i.e. during the narrowing of the corridor, indicated not only by increasing neritic conditions according to dinocysts but also by the transition from distal to coastal conditions according to a severe decrease of *Pinus* in the pollen record (Figure 1; Warny *et al*., 2003).

The newly exposed coastal regions around the Mediterranean Sea probably experienced very dry conditions, as expressed by the migration of subdesertic plants from Sicily, which is 4° to the

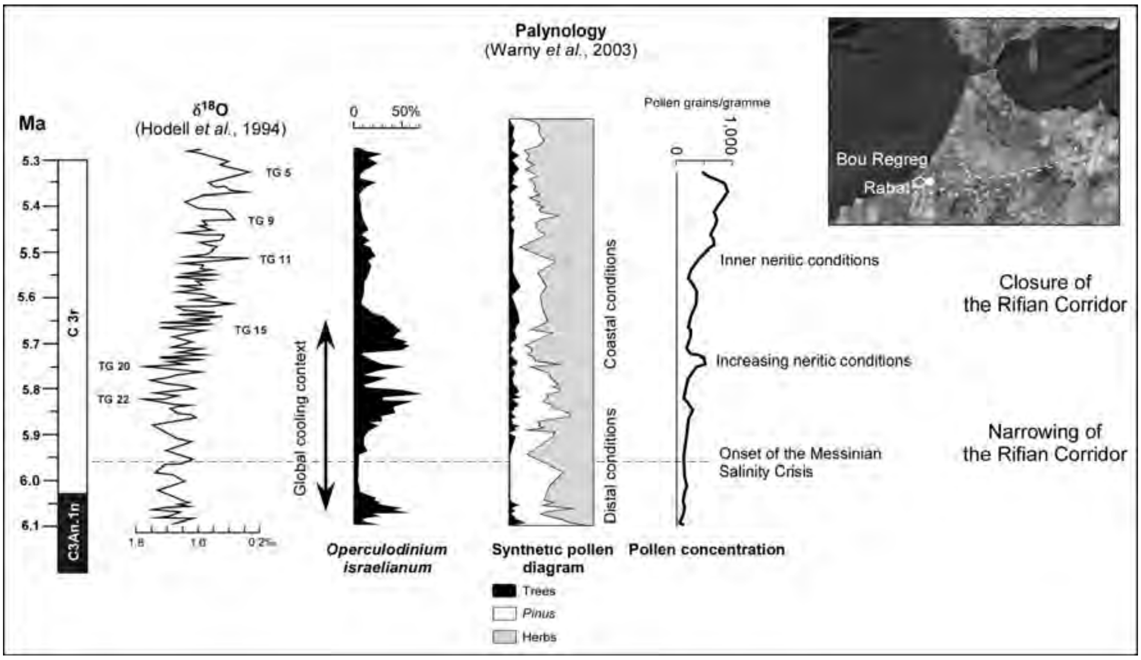

Fig. 1. Palynology at Bou Regreg (Morocco) documents the global and local conditions during the narrowing of the Rifian Corridor leading to its closure.

Palynological data and $\delta^{18}O$ from foraminifers are taken from the same samples.

The Rifian Corridor is indicated by a doted line on the map.

south (Fauquette *et al*., 2006; Popescu *et al*., 2007). Steppic elements are also shown to increase in pollen records from the earliest Zanclean of the Black Sea (Popescu, 2006).

2. EROSION

Only the erosional surface which cuts the uppermost marginal evaporites (Figure 2) is the Messinian Erosional Surface overlain by Zanclean deposits and corresponds to the peak of the Salinity Crisis, i.e. deposition of evaporites in the almost desiccated central basins (Clauzon *et al*., 1996; see also Lofi *et al*., this volume). This feature has been observed everywhere around the Mediterranean (for example: Clauzon, 1973; Chumakov, 1973a; Delrieu *et al*., 1993; Poisson *et al*., 2003) and also in the Eastern Paratethys (Dacic Basin: Clauzon, pers. comm.; Black Sea: Gillet *et al*., 2003, 2007). In Sicily, an erosional phase is intercalated between the Lower and Upper Evaporites and is often considered as the Messinian Erosional Surface (Butler *et al*., 1995; Krijgsman *et al*., 1999c). As this erosion is expressed at the foot of the Nebrodi Mountains, in a

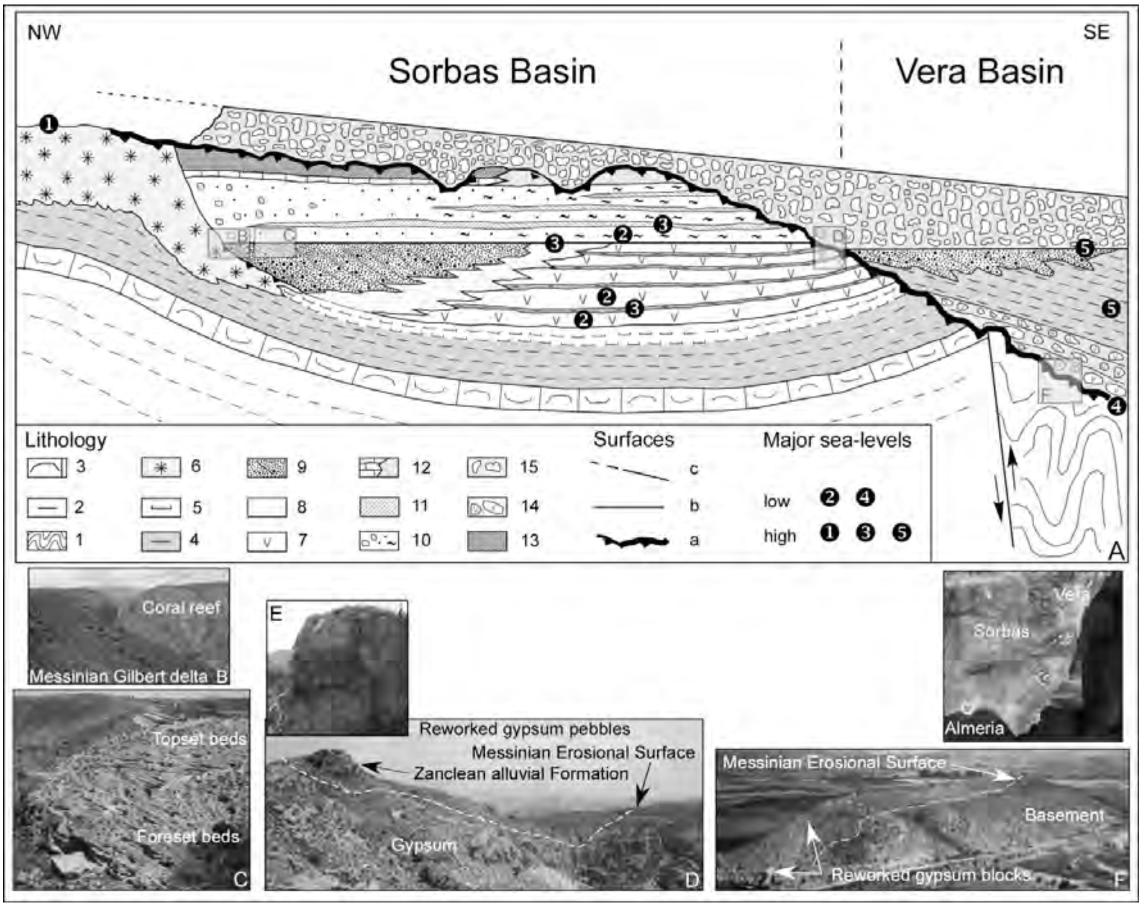

Fig. 2. Restituted Sorbas and Vera basins (Spain).

A: Synthetic cross-section.

Sorbas: **B:** Messinian Gilbert delta overlying coral reef with erosional contact; **C:** Marine-continental transition of Messinian Gilbert delta; **D**: Late Messinian valley infilled by Zanclean alluvial deposits; **E:** Detail of Zanclean alluvial deposits including reworked gypsum pebbles.

Vera: **F:** Block formation including reworked gypsum overlying the Messinian Erosional Surface.

Lithology: **1:** Betic basement; **2:** Tortonian clays; **3:** Earliest Messinian (=M) calcarenite; **4**: Messinian and Zanclean (=Z) clays; **5:** Diatomites (M); **6**: Carbonated constructions (coral reefs, Terminal Complex: M); **7**: Gypsum (M); **8**: Silts with gypsum (M); **9**: Fluvial conglomerates Gilbert deltas (M, Z); **10**: Red continental pebbles (M); **11**: White clays (M) with marine fossils; **12**: Continental clays and limestones (M); **13**: Paleosoils; **14**: Subaerial formation with reworked gypsum blocks; **15**: Continental pebbles. Surfaces: **a**: Erosional surface; **b**: Marine-continental transition within Gilbert deltas; **c**: Pliocene abandonment surface.

Major sea-levels: **1**: Ante-crisis coastline; **2**: Cyclic low sea-levels during the first step of the crisis (deposition of marginal evaporites); **3**: Cyclic high sea-levels during the first step of the crisis; **4**: Sea-level drop of the second step of the crisis (deposition of evaporites in the central basins); **5**: Zanclean high sea-level.

similar relief context as in Tunisia (El Euch – El Koundi *et al*., in press) where it is overlain by the Messinian Erosional Surface itself, we consider that it has been caused by tectonic uplift and has only a local significance. Some marginal localities simulate an apparent continuity between Messinian and Zanclean deposits but show in fact a clear discontinuity caused by a weak erosion in an interfluvial context: Cava Serredi in the Livorno region and Eraclea Minoa in Sicily (Popescu *et al*., in press), Intepe in the Dardanelles Strait (Melinte-Dobrinescu, pers. comm.; see also Çağatay *et al*., this volume).

In many places (Sorbas: Figure 2; Vera, Dardanelles Strait, Orb Valley), an older erosional surface coeval with the marginal evaporites is evident, and this surface corresponds to the first step of the crisis (Clauzon *et al*., 1996). Contrary to the assumption defended by Krijgsman *et al*. (this volume) the marginal evaporites significantly preceded the central deep basin ones.

3. "Lago Mare" events

Two "Lago Mare" events correspond to exchanges between the Mediterranean and Eastern Paratethys during high sea-level episodes just preceding and following the peak of the Salinity Crisis, respectively (Clauzon *et al*., 2005): Paratethyan congeria, ostracods and dinoflagellates invaded the Mediterranean, while Mediterranean calcareous coccoliths, foraminifers and dinoflagellates entered the Eastern Paratethys (Figure 3).

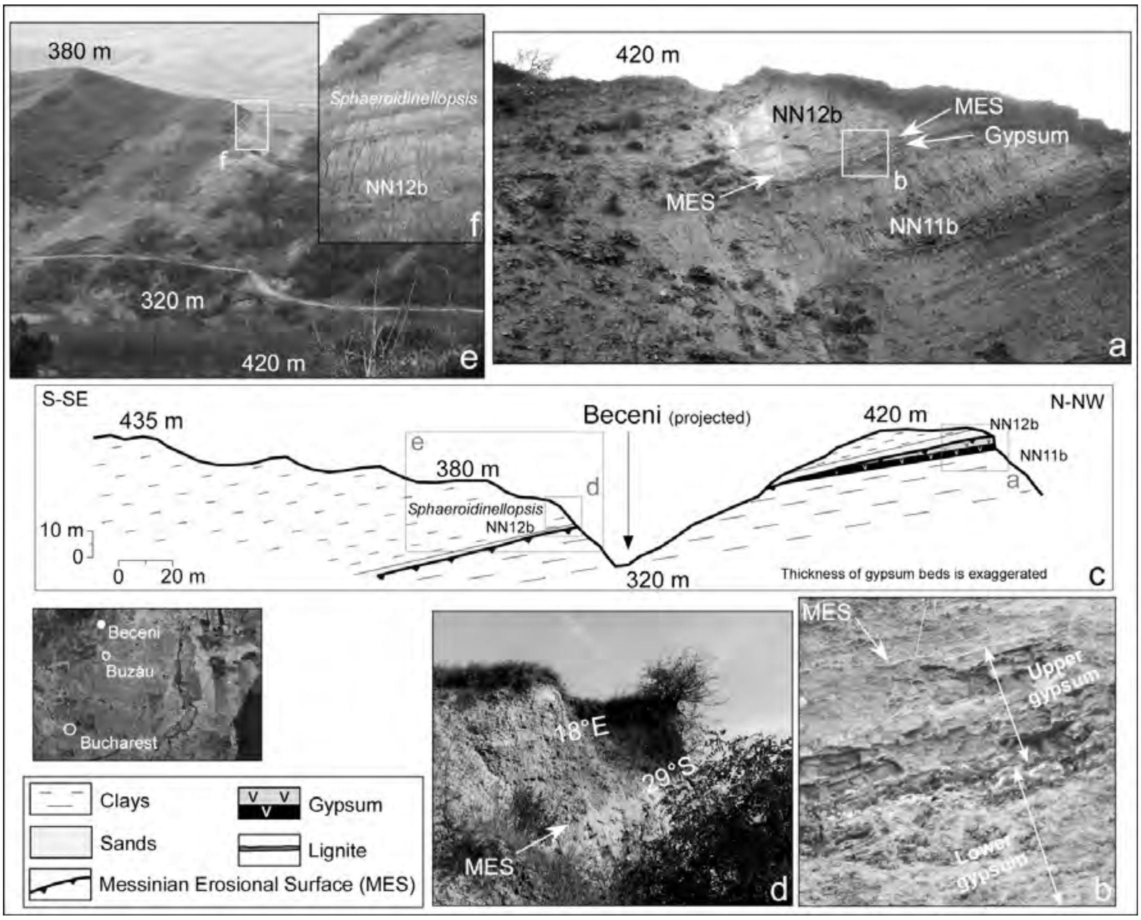

Fig. 3. The Messinian–Zanclean succession at Beceni (Romania, Eastern Paratethys).

a: General view of the Messinian gypsum layers overlying clays, truncated by the Messinian Erosional Surface; **b**: Detail of the gypsum; **c**: Cross-section in the Beceni area; **d**: Messinian Erosional Surface overlain by Zanclean clays; **e**: Zanclean deposits channelled within the Messinian ones; **f**: Detail of the earliest Zanclean clays.

Note the two successive influxes of Mediterranean marine waters below and above the Messinian Erosional Surface indicated by nannoplankton and foraminifers, and corresponding to the two high sea-level "Lago Mare" events in the Mediterranean.

For example, on both sides of the Tyrrhenian Sea, the "Lago Mare" of Aleria (Corsica) belongs to Zanclean while that of Cava Serredi (Livorno, Italy) belongs to Messinian. In the Adriatic perched area, the Colombacci Formation (a "Lago Mare" biofacies) and the immediately underlying sediments are earliest Zanclean in age (Popescu *et al.*, 2007). At Eraclea Minoa (Sicily), the Lago Mare Formation belongs to Messinian but the overlying Arenazzolo Formation (separated by the Messinian Erosional Surface) shows a "Lago Mare" biofacies which is attributed to the earliest Zanclean (Londeix *et al.*, 2007; Popescu *et al.*, in press).

Another "Lago Mare" event marked by ostracods only was exclusive of the almost desiccated central Mediterranean basins, probably corresponding to freshwater inputs (Rouchy *et al.*, 2001) maybe caused by stream piracy of rivers with a large drainage basin at the end of the crisis peak, the Ebro (Babault *et al.*, 2006) and Sahabi rivers (Griffin, 2002).

4. Chronology

The resulting detailed chronology is given in Figure 4. In many places (Marches: Popescu *et al.*, 2007; Sicily: Popescu *et al.*, in press; northern Morocco: Cornée *et al.*, 2005; Dacic Basin: Clauzon, pers. comm.; Dardanelles Strait: Melinte-Dobrinescu, unpublish. data), the Zanclean reflooding precedes the "official" base of Zanclean. This is also supported by two superposed "foreset-topset bed" sequences in some Gilbert deltas (Roussillon, Skopje). Zanclean reflooding seems to have occurred in two steps (collapse of the Gibraltar Strait at 5.480 Ma, widening of the Gibraltar Strait at 5.330 Ma; Figure 4).

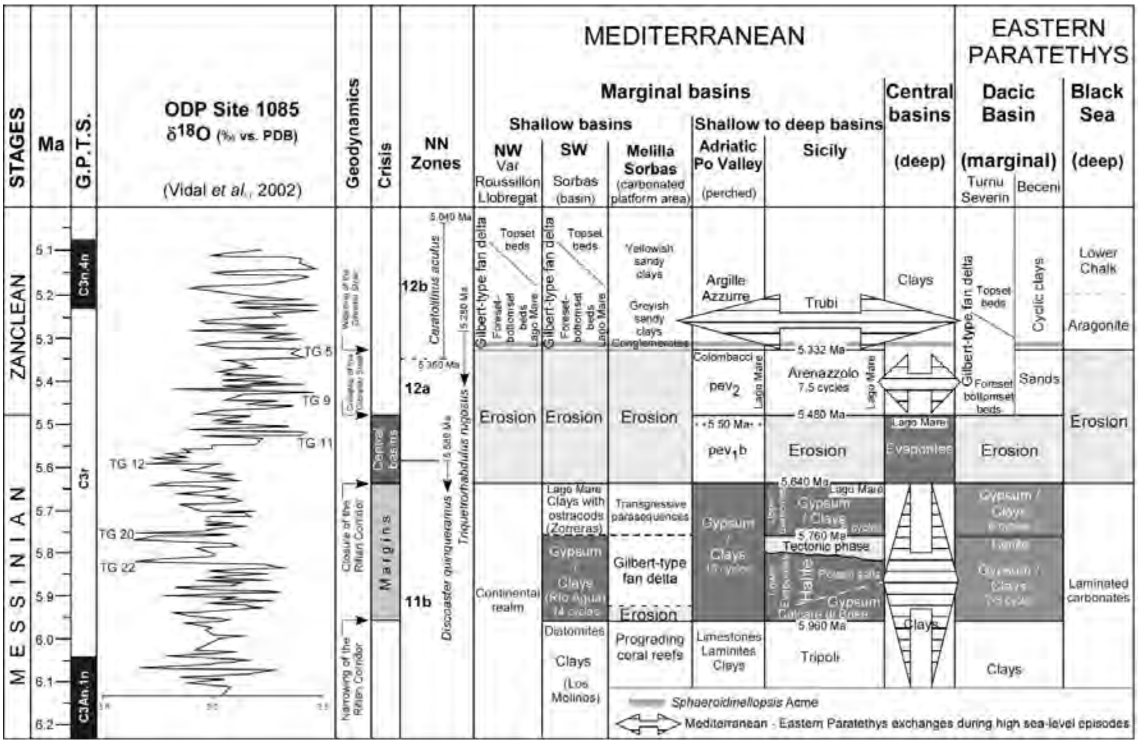

Fig. 4. Chronology of the Messinian–Zanclean events in the Mediterranean and Eastern Paratethys.

5. Paleogeography

A continuous paleogeographical development is shown on Figure 5, which focuses on five critical periods. Among the most important new evidences one notes:

- the pre-crisis activity of the corridor between the Aegean Sea and the Dacic Basin which connected these basins during high sea-level episodes up to the Early Pliocene, and its western branch as a link with the Panonian Basin which was active before the crisis (Popescu *et al.*, in press);

- the absence of direct connection between the Aegean Sea and the Black Sea through the Marmara Sea area and the resulting Messinian canyon in the Dardanelles Strait area, the cutting of which provides a fine time-control to the passage of the North Anatolian Fault (Armijo *et al.*, 1999);
- the continuous passage of Atlantic waters through the Gibraltar Strait before its collapse caused by regressive erosion (Blanc, 2002; Loget *et al.*, 2005);
- the persistence of some perched freshwater (Adriatic-Po: Roveri and Manzi, 2006; Popescu *et al.*, 2007; Dacic: Clauzon *et al.*, 2005) basins with an almost continuous sedimentation during the peak of the crisis.

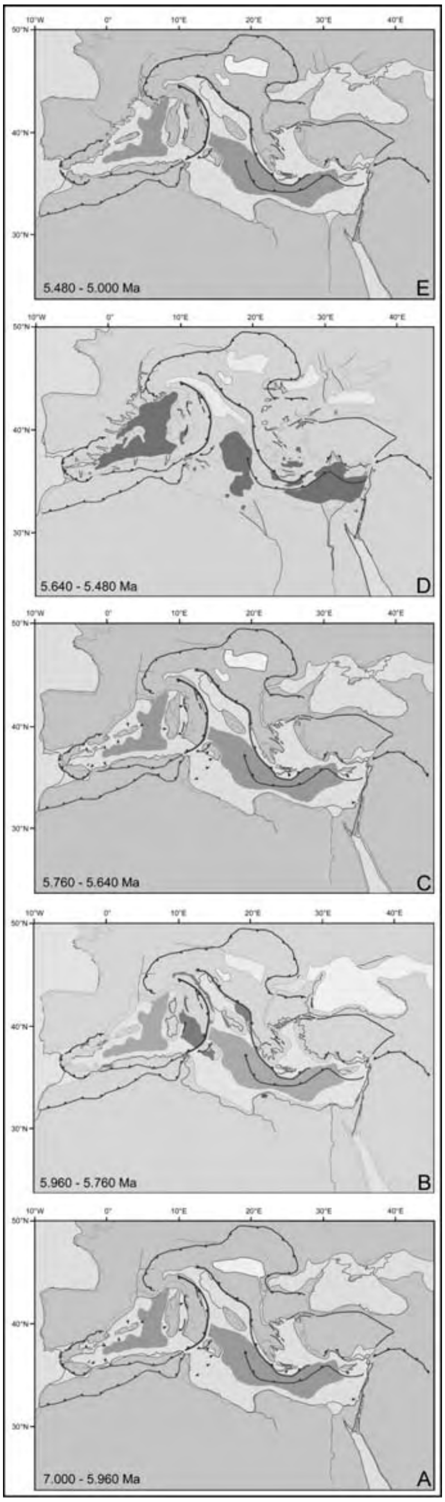

Figure 5. Palaeogeography of the Mediterranean *s.l.* region between 7 and 5 Ma.

Some of the modern sills (Gibraltar, Otrante, Sicily) were extant between 7 and 5 Ma. Marginal shallow basins are in light grey, central deep basins in dark grey, brackish to freshwater ones in very light grey. The architectural relief frame is indicated in black. Evaporitic rocks are in very dark grey, carbonated platforms in doted areas indicated by arrows.

A: 7.000–5.960 Ma, Ante-crisis situation; **B**: 5.960–5.760 Ma, First (marginal) step of the crisis; **C**: 5.760–5.640 Ma, High sea-level interval between the two evaporitic steps; **D**: 5.640–5.480 Ma, Second step (almost complete desiccation of the Mediterranean and Black seas; **E**: Zanclean “Deluge”.

Such a succession of major geographic changes strongly affected the fauna (fishes, molluscs, echinoids, bryozoans, crustaceans, foraminifers) and flora (dinoflagellates, calcareous coccoliths, diatoms) from marine and continental (rivers, lakes, groundwaters, lagoons) aquatic habitats. Processes which resulted in restoring the Mediterranean biota after the Messinian Salinity Crisis are still unknown. Isolation of basins followed by their re-connection, catchment of rivers, huge variations in salinity, etc. have drastically affected organisms, the marks of which could be still present in the present-day biodiversity. To study how much the crisis influenced modern biodiversity is an exciting challenge both for paleontologists and biologists.

CONCLUSION

The Mediterranean region *s.l.* was marked by severe upheavals during the 6-5 Ma time-interval which encompasses the Messinian Salinity Crisis, forced both by tectonics and sea-level changes. Their deciphering depends on a finer chronological evaluation and more detailed paleogeographic reconstructions. To core the central basin evaporites is also an absolutely necessary target. In addition to these questions, a problem is to be answered: was the Black Sea almost completely desiccated too? The pre-existing connection with the Mediterranean is able to explain the beginning of the process up to the desiccation of the sill of the Skopje Corridor. And then? It could be considered that the desiccation of the Mediterranean caused a severe aridity in the nearby regions as suggested by pollen records (Popescu, 2006) that extended the process.

Chronological constraints and consequences for the Messinian Salinity Crisis

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Abstract

The Messinian Salinity Crisis of the Mediterranean resulted from a complex interplay between tectonic gateway closure and climate evolution. Recent astrochronological constraints show that 1) the onset of Lower Gypsum at 5.96 Ma is not related to glacio-eustatic sealevel lowering but its timing can best be attributed to the influence of the 400-kyr eccentricity cycle on regional climate superimposed on a tectonic trend; 2) the evaporite cycles are controlled by precession induced regional climate changes rather than by obliquity forced glacio-eustatic sealevel change; 3) the main desiccation phase between the Lower and Upper Evaporites coincides with the twin peak glacials TG12-14 suggesting a glacio-eustatic control; 4) the Pliocene flooding of the Mediterranean is not related to a glacio-eustatic sealevel rise. Simple quantitative analyses were used to evaluate controversial water level scenarios for the Mediterranean "Lower Evaporites". The results indicate that a shallow-water scenario for the Lower Gypsum units would imply unrealistic salt thicknesses on the order of 3 km. Some outflow to the open ocean must have persisted, implying that the Mediterranean was a deep-water basin during Lower Gypsum formation. Potential precipitation of gypsum in the deep-Mediterranean basins will critically depend on the availability of oxygen and thus on the stratification of the water column. The model results furthermore indicate that the deep Mediterranean halite units could have been deposited under shallow conditions, assuming that they correspond to the ~80 kyr time interval between the onset of glacial TG12 and the termination of TG14, when Mediterranean outflow to the Atlantic was blocked.

Introduction

The Messinian Salinity Crisis is recognized as one of the key events in Earth's history attracting a great deal of scientific interest and fueling imagination with huge waterfalls during the reflooding of the Mediterranean following desiccation. During the crisis vast amounts of evaporites were deposited when the Mediterranean became progressively isolated from the world ocean; these evaporites are locally sandwiched in between deep marine sediments of Tortonian and Zanclean (Pliocene) age. Scientific debate focused on whether the isolation of the Mediterranean was caused by a (dominant) tectonic or glacio-eustatic control and on the depositional environment of the evaporites (e.g. Clauzon *et al*., 1996; Hsü *et al*., 1977; Rouchy and Caruso, 2006; Roveri and Manzi, 2006). Controversies exist concerning the presence of deep versus shallow basins in the pre-Messinian Mediterranean and on deep versus shallow water during Messinian evaporite deposition. Geophysical observations of oceanic crust beneath the western Mediterranean, benthic foraminiferal data showing deep-water species and geographical studies showing canyon formation at the margins have confirmed the deep basin hypothesis for the pre-Messinian setting. By contrast, the controversies on the depositional environment of the so-called "Lower Evaporites" units have yet not been resolved. It became increasingly clear that only a high-resolution age model based on astronomical tuning would provide the necessary means to unravel the intricate and fascinating history of the Messinian Salinity Crisis (Hilgen *et al.*, 2007; Sierro *et al.*, this volume).

Chronology for the Messinian in the Mediterranean Basin

The classic Messinian sequence in the Mediterranean as described from Sicily (Decima and Wezel, 1973; see Roveri *et al.*, this volume) starts with cyclic alternations of open marine marls and sapropels, passes via diatomites into the Lower Evaporites (gypsum, evaporitic limestone and halite), and ends, above an erosional surface and sometimes angular unconformity, with the Upper Evaporites (gypsum, marls) and fresh to brackish water deposits of Lago Mare facies. Here we define the MSC as the interval of evaporite deposition and Lago Mare sedimentation in the Mediterranean.

Messinian pre-evaporite sequences

Continuous pre-evaporite sequences from all over the Mediterranean were subjected to integrated high-resolution stratigraphic studies in order to obtain a cyclostratigraphic framework and develop an astronomical age model that would allow accurate dating of the onset of the MSC. The first preliminary attempts were based on simple cycle counts in the successive lithostratigraphic units of the Mediterranean Messinian (Hilgen *et al.*, 1995; Vai, 1997). 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 salinity crisis proper (Hilgen and Krijgsman, 1999; Krijgsman *et al.*, 1999a); these ages are now generally accepted. Cyclostratigraphic correlations between the Mediterranean sections are rather straightforward and were confirmed by high-resolution planktonic foraminiferal biostratigraphy (Figure 1). Astronomical tuning of Messinian pre-evaporite cycles to successive insolation peaks generally shows a good to excellent fit between the characteristic sedimentary cycle patterns and the astronomical target curve, including precession/obliquity interference patterns in the insolation curve (Hilgen and Krijgsman, 1999; Sierro *et al.*, 2001). Alternating thick/thin beds consistently correlate with high/low amplitude variations in insolation, proving that no sedimentary cycles are missing and that alternative correlations can be excluded. Additional paleoclimatic studies revealed that the sedimentary cycles of the Messinian pre-evaporites reflect - precession induced - changes in (circum) Mediterranean climate (e.g. Sierro *et al.*, 1999; and this volume).

The "Lower Evaporite" units

The resultant astrochronology shows that the transition to the evaporites occurs at exactly the same sedimentary cycle (Krijgsman *et al.*, 1999a). It proves that the MSC is a synchronous event over the entire Mediterranean, the onset of which is dated astronomically at 5.96 ± 0.02 Ma. Cyclostratigraphically, the pre-evaporitic marl-sapropel cycles are replaced by gypsum-marl cycles of the Lower Gypsum, indicating that the evaporite cyclicity is related to precession controlled oscillations in (circum) Mediterranean climate as well. As a consequence, gypsum beds correspond to precession maxima (insolation minima) and relatively dry climate (Krijgsman *et al.*, 2001). The tuning of the evaporites themselves, proved to be more problematical, even though they are arranged in a cyclic fashion as well. This tuning, which is based on cycle counts rather than on cycle patterns, hinted at the presence of an hiatus of ~60-90 kyr in marginal basins during which sealevel was significantly lowered in the Mediterranean (Krijgsman *et al.*, 2001). The total amount of cycles in the Lower and Upper Evaporites also exclude an obliquity control and, hence, that glacio-eustatic sealevel changes are responsible for the evaporite cyclicity. The total number of evaporite (gypsum) cycles in the Lower Evaporites of Spain (17 cycles) and Italy (16 cycles) is in good agreement and implies a total duration of approximately 350-370 kyr. Deposition of the Lower Gypsum is thus independent of the paleogeographic and geodynamic setting of the individual basins. Moreover they require a continuously marine environment (see Lugli *et al.*, this volume), excluding a relative sea level fall exceeding the paleodepth of the marginal basins (i.e. < 200 m). It should be noted here that all the information on the Lower Evaporite units comes

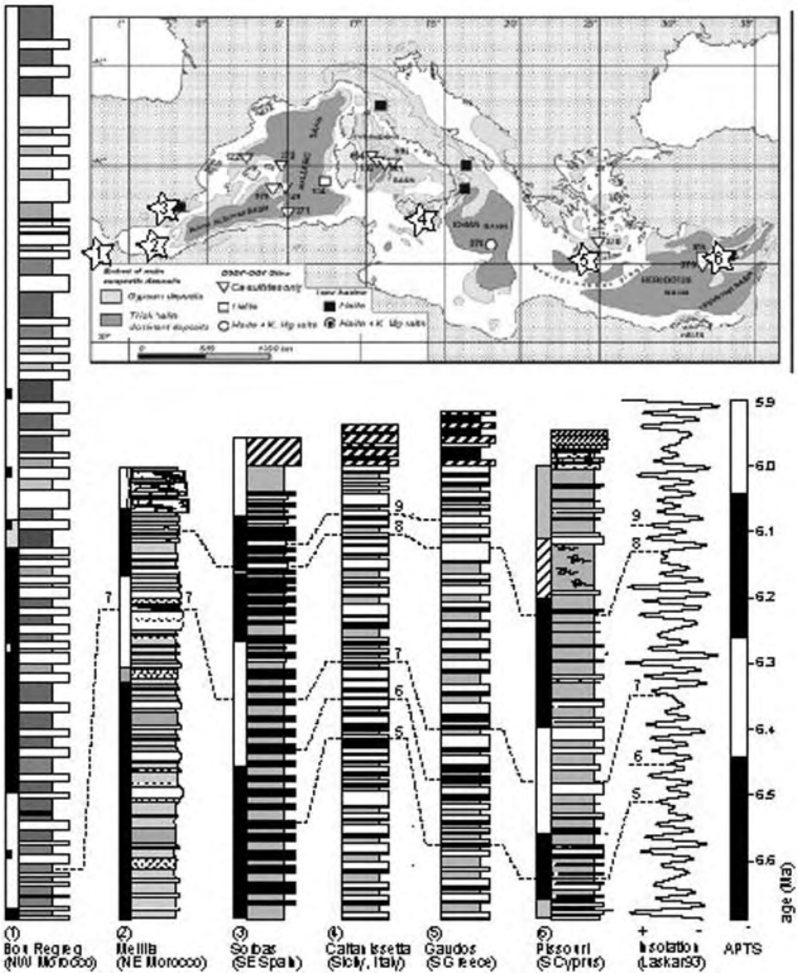

Fig. 1. Cyclostratigraphic correlation of the Messinian pre-evaporite sections of the Atlantic and Mediterranean on a W-E transect, and confirmed by biostratigraphic data (numbers correspond to biostratigraphic levels according to Krijgsman *et al.,* 1999a; 5=last occurrence (LO) G. conomiozea group, 6=first common occurrence (FCO) Turborotalita multiloba, 7=sinistral/dextral coiling change Neogloboquadrina acostaensis, 8=first influx sinistral neogloboquadrinids (90%), 9=second influx sinistral neogloboquadrinids (40%)). Inset map shows the locations of key sections used to construct the astrochronological framework for the Messinian: 1) Bou Regreg; 2) Melilla; 3) Sorbas; 4) Sicily; 5) Gavdos; 6) Cyprus. It also shows the distribution and extent of the Messinian evaporites in the Mediterranean with location of the DSDP-ODP sites that recovered evaporitic deposits (modified after Rouchy and Caruso, 2006).

from basins indicative of a marginal setting during the Messinian. Researchers have traditionally assigned the “N” reflectors (below the salt) as the deep basin equivalents of the marginal Lower Evaporites (Lofi *et al*., 2005; and this volume), but there is thus far no direct evidence of repetitive gypsum/marl cycles in the very deep basins (e.g. Roveri and Manzi, 2006).

The “Upper Evaporite” units

Complete isolation and possible desiccation was only established after deposition of the Lower Gypsum, when the Mediterranean water level dropped more than 1,000 m as evidenced by incised canyons of the Rhone, Ebro, Po and Nile rivers in the Mediterranean margins. Deposition of the Upper Evaporite unit, overlying erosional surfaces, took place in a non-marine, deep Mediterranean basin forming a large Lago Mare. The post-evaporite units of the Mediterranean latest Messinian also display a marked cyclicity, comprising in general seven to eight sedimentary cycles. The total number of sedimentary cycles is in good agreement with the total number of precession peaks, whereas there is clearly not enough time for a 40 kyr obliquity control, thus excluding glacioeustasy. As the average periodicity for precession in Neogene times is 21.7 kyr, the Upper Evaporite units have a duration of approximately 175 kyr.

Unfortunately, the tuning of the Upper Evaporites is not fully certain because it is based on counting and tuning the number of supposedly precession related Upper Evaporite cycles from the Miocene-Pliocene boundary downward which itself is well tuned. Only the Upper Evaporites at Eraclea Minoa reveal a pattern that can be recognized in the astronomical target curve. 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 (Hilgen *et al.*, 2007).

Recent studies in northern Italy indicate that the Colombaccio Formation with its characteristic limestone beds that were initially listed as being the full equivalent of the Upper Evaporites, covers only a significantly reduced time span. It is now suggested that it corresponds to the younger part of the Upper Evaporites only (Roveri and Manzi, 2006). The older part of the Upper Evaporites is contained in part by the underlying Formazione di Tetto. This unit has been deposited in a deep basin equivalent of the marginal rimmed basins in which the Lower Evaporites were deposited. The older part of the post-evaporite sequences consists of reworked evaporites and supposedly covers the Messinian gap inferred from marginal basins, suggesting that the deep basins in Northern Italy did not experience any desiccation event (Roveri and Manzi, 2006).

Consequences for the Messinian Salinity Crisis scenarios

No glacio-eustatic control for the onset of the MSC

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 is not the case (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, Mediterranean water budget, which occurs superimposed on the ongoing trend in tectonic isolation of the basin. The isotope records in particular portrayed a late Messinian interval marked by heavy values and high-frequency fluctuations, the latter reflecting dominantly obliquity-controlled glacial cyclicity. The glacial series reveals two prominent peak glacials TG20 and 22 in the lower reversed Gilbert, with astronomical ages of 5.75 and 5.79 Ma. This interval corresponds to the *Globorotalia margaritae* acme in the Bou Regreg area (Krijgsman *et al.*, 2004). The glacial interval ends with two more distinct obliquity steered glacials TG12 and 14 (with astronomical ages of 5.548 and 5.582 Ma), followed by the marked stepwise deglaciation from TG12 to TG 9 (5.445 Ma) recognized in all oceanic basins. This deglaciation is associated with an overall glacio-eustatic sealevel rise; it is marked by invasions of the warm water planktonic foraminiferal species *Globorotalia menardii* and *Neogloboquadrina dutertrei* in the Bou Regreg area on the Atlantic side of Morocco and signifies a key event in Messinian paleoceanographic history (van der Laan *et al.*, 2006).

Depositional environment of the Lower Evaporites

Knowing the chronology of the MSC events, we can quantitatively investigate by means of budget calculations the influence of the Mediterranean-Atlantic water connection on the depositional environment of the "Lower Evaporites" (see also Flecker, this volume). Since the Mediterranean is characterised by an excess of evaporation over precipitation and river input, complete disconnection from the Atlantic Ocean will lead to desiccation and evaporite deposition. Quantitative analysis of complete disconnection shows that, without inflow from the Atlantic Ocean, the sea level of the Mediterranean drops fast and will reach a level of –2,500 before 10 kyr (Meijer and Krijgsman, 2005). In addition, stable intermediate water levels would require a very specific and constant balance between inflow, precipitation, and evaporation. We can estimate the thickness of the deposit that would accumulate in the time span represented by the Lower Gypsum (i.e., at least 360 kyr) in a configuration of continuous inflow and fully blocked outflow. This scenario results in a fast initial rise of average salinity until halite saturation is reached (Figure 2). The blocked-outflow scenario is in conflict with data on the Lower Gypsum in several ways: (1)

halite formation is only slightly (<20 kyr) delayed with respect to gypsum accumulation, (2) the calculation predicts most of the sequence to consist of halite, and (3) the total model-predicted thickness of the evaporites is much larger than the 500-700 m estimated from seismic profiles (Lofi *et al*., this volume). It follows that the deep-basin, shallow-water scenario can be regarded as unrealistic. The results of these calculation hint that it is likely that Mediterranean water was continuously able to flow back to the Atlantic, suggesting that no (major) sea level lowering took place at the onset of the Messinian Salinity Crisis and that the "Lower Evaporites" were consequently deposited in a deep-water Mediterranean basin. This scenario would require the Atlantic connection to become modified to such extent that inflow would still be able to continuously compensate for the net water loss in the Mediterranean, but that outflow of Mediterranean water (and salt) into the Atlantic becomes restricted. In that case, the amount of salt precipitation in the Mediterranean would critically depend on, amongst other factors, the amount of outflow, which is probably a direct consequence of the configuration of the Strait geometry, and on the amount of stratification in the Mediterranean (Meijer, 2006). In addition, the role of precession-induced changes in the freshwater budget must be addressed. Imagine we start from a Mediterranean basin in which the efficiency of transport through the Atlantic gateway has been reduced to such extent that the average basin salinity has reached a level halfway the middle of the gypsum saturation range (130-160 g/l). It can then be shown that a reduction of the freshwater loss to about 0.75 × the starting value (which we take to be the present-day value) would bring salinity below the range of gypsum saturation.

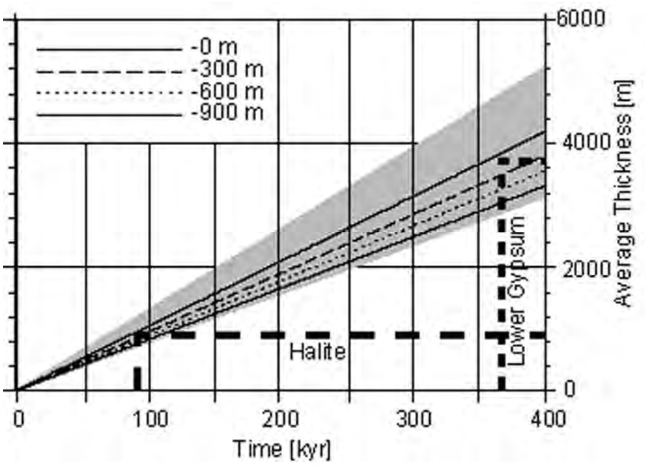

Fig. 2. Evaporite thickness as a function of time, calculated for the case of fully blocked outflow. The calculation has been done for a range of values for Mediterranean sea level. The solid line corresponds to sea level at the present-day position, the dashed lines to a sea level 300, 600 and 900 m lower. The shaded band comprises results for all intermediate positions of sea level. Estimated model thickness for Lower Gypsum and halite is according to our astrochronological ages.

A glacio-eustatic cause for the Mediterranean desiccation phase

Increased time control suggested that the base of the Upper Evaporites is intimately linked with the beginning of the major stepwise deglaciation between TG12 and TG9 from 5.55 to 5.45 Ma, or more correctly to the first step of the deglaciation between 5.55 and 5.52 Ma (van der Laan *et al*., 2006). 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. The reason why glacio-eustatic sealevel lowering associated with twinned glacials TG14-12 resulted in the final desiccation of the Mediterranean rather than the even more prominent peak glacials TG22-20 is explained by the additional influence of the ongoing trend in tectonically driven/induced isolation. This scenario suggests a strong link between Messinian glacial history and associated glacio-eustatic sealevel change and the final desiccation/drawdown of the Mediterranean and the subsequent refill at the base of the Upper Evaporites and Lago Mare. If our correlation holds, it may explain why repetitive (marginal) marine influxes are reported from the Lago Mare (Carnevale *et al*., 2006), although indications exist that the dominant environmental conditions were not fully marine but dominantly hyposaline. In this way it may even be argued that the "Pliocene" flooding already started at the base of the Upper Evaporites. The exact duration of the deep Mediterranean halite deposits is still unclear, but the stratigraphic similarity with the Sicilian sequence suggests it is deposited between the "Lower" and "Upper Evaporites". The resulting duration for the halite unit is consequently estimated at ~80 kyr which indicates a total thickness of ~1,000 m in the box model scenario (Figure 2). This is a rather realistic figure which indicates that Mediterranean-Atlantic return flow may have become cut off at the beginning of the Messinian halite deposits in the deep Mediterranean basins.

End of the MSC: Pliocene flooding of the Mediterranean

The Messinian glacial history and closing stages of the MSC made it tempting to link the Pliocene reflooding of the Mediterranean to a significant sea-level rise resulting from deglaciation. Hodell *et al*. (1994) incorrectly linked the main flooding event to the TG12-9 transition through linear extrapolation of the sedimentation rate in the Salé drill hole. However increased time constraints revealed that the M/P boundary was significantly younger. Suc *et al*. (1997) therefore attributed the Pliocene flooding to the abrupt deglaciation associated with TG5 which occurs in the M/P boundary interval and is particularly evident in the record from ODP site 846 (Shackleton *et al*., 1995b). Close inspection of the benthic isotope record of the Loulja section (Bou Regreg area) tuned to precession revealed 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). This outcome renders credibility to alternative scenarios such as the headward erosion of fluvial incisions in the Gibraltar area (Blanc, 2002; Loget *et al*., 2006). It is also consistent with indications for marine influences in the Lower Evaporites.

Acknowledgements

Special thanks to the CIESM organisation, and especially to Frédéric Briand, Valérie Gollino and Laura Giuliano, for bringing us together in a highly successful workshop environment. Gert de Lange must be complimented for structuring and steering the meeting in such a productive manner that it spectacularly ended in a large-scale agreement (see the Executive Summary of this volume).

Astrobiochronology of Late Neogene deposits near the Strait of Gibraltar (SW Spain). Implications for the tectonic control of the Messinian Salinity Crisis.

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INTRODUCTION

The Messinian Salinity Crisis was the result of total isolation or strong restriction in the Atlantic-Mediterranean water exchange during the Late Messinian. This isolation could be driven by global sea level changes or tectonic processes affecting the Atlantic-Mediterranean gateways. Tuning of rythmic sedimentary records and/or oxygen isotope records to astronomical solutions allowed in the last decades to establish a reliable time framework for the late Neogene, including the Messinian (Hilgen and Langereis, 1993; Hilgen *et al*., 1995, 2000; Hilgen and Krijgsman, 1999; Krijgsman *et al*., 1999a,b; Lourens *et al*., 1996; 2004; Sierro *et al*., 2001). This allowed for the first time the cycle to cycle correlation of Mediterranean and open ocean sections with a resolution higher than a precession cycle (Hodell *et al*., 2001; Vidal *et al*., 2002; Krijgsman *et al*., 2004; Van der Laan *et al*., 2005, 2006; Tiedemann *et al*., 2006). Although some global events can be related to particular events in the Mediterranean, these studies suggest that there is no significant drop in global sea level at around the onset of evaporite deposition in the Mediterranean, neither a major sea level rise near the Pliocene inundation. This strongly argues in favour of tectonic changes along the Gateways as the main cause for the Mediterranean isolation during the Messinian and the early Pliocene flooding.

The Guadalquivir-Gulf of Cadiz basin in Southern Spain is a foreland basin that was originated north of the Betic orogen during the Miocene and Pliocene, north of the Strait of Gibraltar. This basin was always open to the Atlantic and during the Middle to late Miocene it was one of the main gateways that connected the Atlantic and Mediterranean.

Fig. 1. Map of south Spain, showing the Guadalquivir basin and the location of boreholes and seismic line mentioned in the text.

The main objective of this work is to explore the Guadalquivir basin and the Gulf of Cadiz to obtain continuous sediment records for the interval of the Messinian Salinity Crisis on the Atlantic side of the Iberian peninsula so as to analyse the possible paleoenvironmental, tectonic or paleoclimatic changes in a region which was only a few kms away from the Mediterranean coasts during this time period.

CLOSURE OF THE NORTH BETIC ATLANTIC-MEDITERRANEAN GATEWAY

During the middle Miocene the North Betic Gateway was a deep forebasin extending from the Atlantic margin in the Gulf of Cadiz to the Mediterranean Sea. It was a foreland basin that was originated between the Betic orogen to the South and the Iberian Foreland to the North. Marine deposits throughout the basin evidence a deep water connection between the Atlantic and Mediterranean at that time (Geel *et al*., 1992). However, rapid emergence of the Prebetics during the Tortonian blocked this connection to the East, which left a relatively narrow Atlantic Mediterranean connection through the Guadix basin to the southeast (Soria *et al*., 1999; Betzler *et al*., 2006). Marine deposits of Middle to Late Tortonian age are present in the eastern part of the Guadalquivir basin that extend towards the Guadix basin (Sierro *et al*., 1996; Soria *et al*., 1999; Betzler *et al*., 2006) and the Mediterranean. Near the Tortonian-Messinian boundary, however, a change from marine to continental deposits marks the end of the Atlantic-Mediterranean connection through the Guadix basin (Soria *et al*., 1999; Betzler *et al*., 2006). This cannot be tested in the eastern Guadalquivir basin because deposits of this age were probably eroded (Sierro *et al*., 1996).

Since its eastern closure, the Guadalquivir basin was progressivelly filled with sediments that prograded from west to east. Emplacement of huge olistostromic masses from the south (Martínez del Olmo, 1984; Suárez *et al*., 1989; Martínez del Olmo *et al*., 1996; Riaza and Martínez del Olmo, 1996; Sierro *et al*., 1996) rapidly filled up the Gualquivir basin, causing a significant shallowing and narrowing of the Betic Gateway. This event occurred in the western part of the basin near the Tortonian-Messinian boundary (Sierro *et al*., 1996).

The last Atlantic-Mediterranean connection through the North Betic corridor seems to occur through the Guadalhorce Gateway that connects the Alboran Sea, the Guadalquivir basin and the Atlantic margin (Martin *et al*., 2001). Records of sediments formed under active bottom Mediterranean outflow currents were formed until 6.3 myr (Martin *et al*., 2001), well before the onset of the Messinian evaporates. This seems to be the date of final closure of the North Betic Gateway.

ORIGIN OF THE MESSINIAN SUBMARINE CANYON OF THE GUADALQUIVIR BASIN

Infilling sediments of the Guadalquivir-Gulf of Cadiz basin mainly consist of hemipelagic homogeneous clays that were deposited from the Late Serravallian to the Quaternary, recording normal marine conditions (Martínez del Olmo, 1984; Suárez *et al*., 1989; Martínez del Olmo *et al*., 1996; Riaza and Martínez del Olmo, 1996; Sierro *et al*., 1996). Biostratigraphic studies allowed us to identify planktonic foraminifer events of regional significance that were later calibrated to the Astronomical Polarity Time Scale (APTS) (Sierro *et al*., 1993; 1996; 2001). Some events, such as the sinistral to dextral coiling change in *Neogloboquadrina acostaensis* and the First abundant occurrence of *Globorotalia margaritae* predate the onset of the Messinian evaporites in the Mediterranean (Sierro *et al*., 1996), but no significant event was recognized at the Miocene-Pliocene boundary. In fact, the time interval of the Messinian Salinity Crisis can only be constrained between the First abundant occurrence of *Globorotalia margaritae*, which is approximately synchronous with the base of the evaporites and the First occurrence of *Globorotalia puncticulata* that occurred well into the Pliocene (Ledesma, 2000).

Numerous boreholes were drilled for gas exploration over the last 50 years, especially in the western part of the basin and offshore in the Gulf of Cadiz. Tuning of sonic and gamma-ray logs to the 65ºN summer insolation record has allowed to accurately correlate Atlantic and Mediterranean records during the Pliocene (Sierro *et al*., 2000). The use of biostratigraphic events together with the cyclical analysis of the well logs and the seismic profiles allowed us to precisely reconstruct the geometry of the sedimentary filling (Ledesma, 2000).

During the Messinian a significant tectonic elevation, especially in the eastern and southern margins of the basin, caused a profound incision that can be easily recognized in the seismic profiles (Martínez del Olmo *et al*., 1996). This canyon is narrow and deeply erosive in the central part of the basin and relatively flat and conformable towards the west (Martinez del Olmo *et al*., 1996). Filling of this canyon led to rapid SE to NW progradation accompanied by deposition of turbidite lobes that develop along the axial part of the basin in front of the slope (Martínez del Olmo *et al*., 1996; Ledesma, 2000). Although we still have not dated it with precision, this event was contemporaneous with the evaporite deposition in the Mediterranean. We suggest that this tectonic uplift recorded in the Guadalquivir basin could be the expression of a more general tectonic elevation occurring in the Strait of Gibraltar area and, in consequence, responsible for the progressive restriction of the Atlantic-Mediterranean water exchange. Alternatively, part of this tectonic uplift and canyon incision in the Guadalquivir basin could be originated by the Messinian isostatic rebound caused by water removal from the Mediterranean after dessication because this basin is not far away from the Mediterranean coast.

The Miocene-Pliocene boundary in the Guadalquivir-Gulf of Cadiz basin

Near the Miocene-Pliocene boundary turbidite deposition in the basin ceased and was replaced by hemipelagic sediments both in the Gulf of Cadiz and the Guadalquivir basin (Ledesma, 2000). Throughout the basin an important change in the sedimentary filling occurred. Uplift during the Late Messinian changed to subsidence all along the basin, especially in the southern margin towards the Strait of Gibraltar. As a result, the dominant northwestward progradation during the Late Messinian changed to a general southwestward progradation during the Early Pliocene, indicating subsidence was high in the southern part (Ledesma, 2000). This change is especially evident in seismic profiles from the Gulf of Cadiz (Figure 2).

The lack of a reliable stratigraphic framework prevented to accurately date this tectonic event in the past, however, tuning of cyclical changes in physical properties to astronomical solutions indicates that subsidence was synchronous with the reopening of the Atlantic-Mediterranean connection, marking the end of the Messinian Salinity Crisis.

Correlation between sonic and gamma-ray logs from the Gulf of Cadiz and sedimentary cycles from Capo Rossello sections in Italy is very straightforward from insolation cycle 502 to insolation

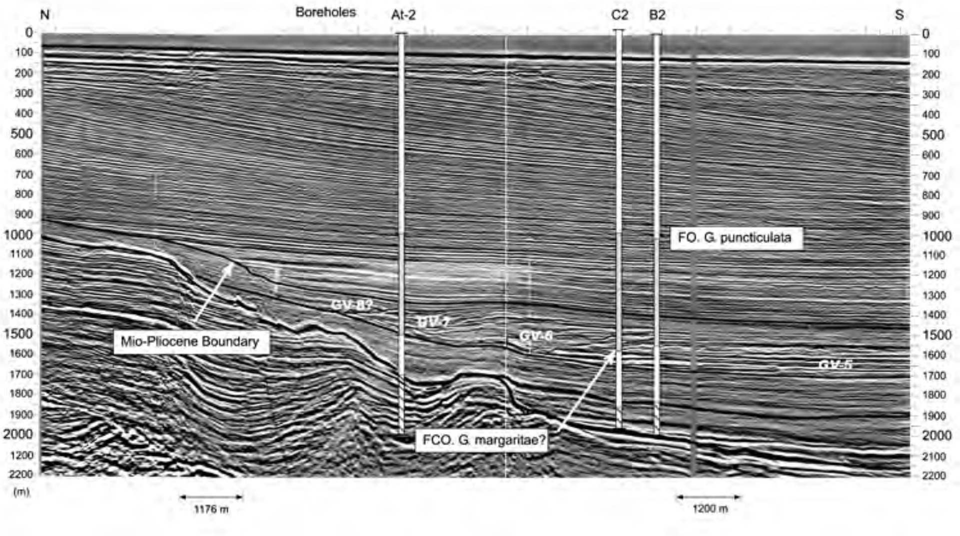

Fig. 2. Seismic line showing the Late Neogene sedimentary filling in the Gulf of Cadiz and the location of three boreholes drilled for gas exploration. Modified from Ledesma 2000 . Various turbidite bodies (Gv 6 to Gv8?) were deposited during the Late Messinian between the First abundant occurrence of *G. margaritae* and the Miocene-Pliocene boundary. At the Miocene-Pliocene boundary a major change in sedimentation from turbidite to hemipelagic deposition took place. Log astrobiochronology (Sierro *et al.,* 2000) allowed to precisely locate the Miocene-Pliocene boundary (see Figure 3). Location of the seismic profile is shown in Figure 1.

cycle 250 a (astronomical cycles as defined by Lourens *et al*., 1996). The change from turbidite to hemipelagic sedimentation in the Gulf of Cadiz seems to be the result of an important relative sea level rise in the Guadalquivir basin probably caused by the initiation of tectonic subsidence. This important sedimentary change was recorded in various holes a few meters below insolation cycle 502 which can be correlated with cycle 5 in Capo Rossello and consequently very close to the Miocene-Pliocene boundary (Figure 3).

In outcrops from the northwestern margin of the Guadalquivir basin a glauconite-rich layer can be traced for more than 100 km between Sevilla and Huelva. Apart from glauconite grains, this layer is characterized by abundant biogenic and authigenic grains, in particular foraminifer and mollusk shells as well as shark teeth and other bones. It was interpreted as a condensed deposit that was probably originated during this relative sea level rise at the Miocene-Pliocene boundary, although the lack of accurate datings does not allow to fully confirm this hypothesis (Sierro *et al*., 1996).

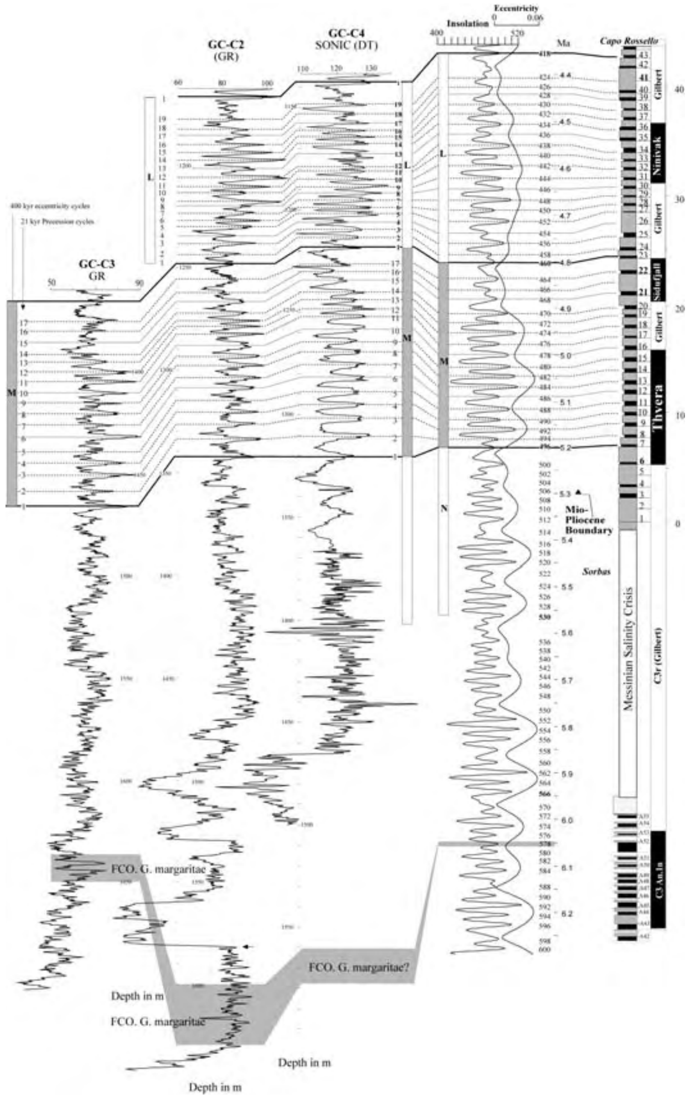

Fig. 3. Gamma ray (GR) and sonic (DT) logs for boreholes GC-C2, GC-C3 and GC-C4 drilled in the Gulf of Cadiz. Modified from Ledesma, 2000. Analysis of cycle patterns allowed the astrochronological correlation of these logs with the 65ºN summer insolation record (Laskar *et al.,* 1990) and Capo Rossello section (after Hilgen, 1991; Langereis and Hilgen, 1991; Lourens *et al.,* 1996) in the Mediterranean (see Sierro *et al.,* 2000; Ledesma, 2000). For reference, rythmic sections from the Sorbas basin are shown (Sierro *et al.,* 2001; Krijgsman *et al.,* 2001). Astronomical cycles are clearly recorded in the logs from nearly the base of the Pliocene. The Miocene-Pliocene transition is marked by a change in physical properties as recorded in the logs. Letters L, M, N mark the 400 kyr cycles as recognized in Sierro *et al.,* 2000 and in Ledesma, 2000).

Messinian in Northwest Turkey: implications for paleogeographic evolution and water mass exchange between Paratethys and Mediterranean

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Abstract

The widely distributed rocks of Messinian-Early Zanclean age in NW Turkey with a fauna of Paratethyan affinity suggest that the Marmara Sea region was a gateway for the input of the fresh-brackish Paratethyan waters into the Mediterranean during this period. The presence of calcareous nannoplanktons (coccoliths) belonging to NN11b-NN12b zones in these rocks suggests also the Mediterranean influence in this passage area. There was erosional episode in the Late Messinian, which probably also resulted in the carving of the Çanakkale Strait's channel. This was followed by widespread deltaic deposition in the region during the Early Zanclean flooding. Although the present data strongly suggest at least one-way ouflow of the Paratethyan waters via the Marmara region during the Messinian to Early Zanclean, the timing and nature of the connection(s) are still matters of debate, and require detailed Sr-isotope studies on the biostratigraphically dated sections in the region.

Introduction

One of the key scientific questions regarding the Messinian Salinity Crisis (MSC) is the source of fresh- to brackish-water during the deposition of the Lago-Mare facies just before and after the Zanclean flooding. The suggested sources include the Paratethys (Hsü *et al*., 1973; Cita *et al*., 1978) and increased fresh water runoff from the Mediterranean catchment areas (Krijgsman *et al*., 1999a; Rouchy *et al*., 2001; Orszag-Sperber *et al*., 2006). Another suggested mechanism for the freshwater input is the exchange of waters between Paratethys and Mediterranean during marine highstands (Clauzon *et al*., 2005).

One of the favoured gateways between the Paratethys and Mediterranean during the Neogene is the Marmara region in NW Turkey (Rögl and Steininger, 1983; Görür *et al*., 2000; Popov *et al*., 2004; Çağatay *et al*., 2006), where the Messinian rocks with a brackish- to fresh-water fauna of

Paratethyan affinity similar to Lago-Mare facies widely exists (Figure 1). 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).

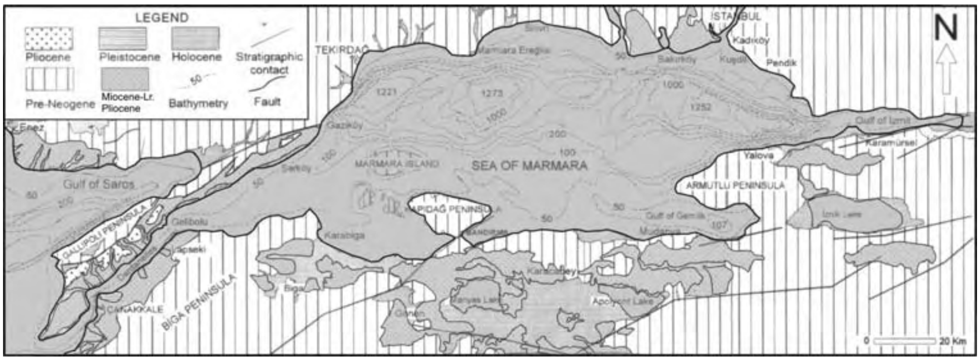

Fig. 1. Map showing the distribution of Neogene rocks around the Sea of Marmara (Çağatay *et al.,* 2006).

The Sea of Marmara and NE Aegean regions in NW Turkey are therefore strategically located for constraining the timing and nature of water-mass exchanges between the two realms (Figure 1), and testing the hypothesis on the sources of fresh water for the Lago-Mare facies in the Mediterranean Messinian sequence. NW Turkey is also tectonically active, being influenced by the dextral North Anatolian Fault (NAF) and N-S extentional regime of the Aegean since the Neogene (Figure 2; McKenzie, 1972; Dewey and Şengör, 1979; Le Pichon and Angelier, 1981; Çağatay *et al.*, 1999; Görür *et al.*, 1997; Yılmaz *et al.*, 2000; Şengör *et al.*, 2005). The Neogene stratigraphic and paleogeographic evolution of NW Turkey is thus also important for timing the tectonic events in the region in general, and the evolution of the NAF in particular.

In this paper we first describe the Neogene sequence in the northern Gulf of Saros and the Gelibolu and Biga peninsulas on the basis of new field studies and calcareous nannofossil analysis. We then discuss the paleogeographic and paleoceanographic evolution in NW Turkey, based on the stratigraphy. The new biostratigraphic data based on nannoplankton assemblages, together with new field studies, indicate the presence of marine Messinian sedimentary rocks on both sides of the Çanakkale Strait (Dardanelles) and the widespread existence of the Lower Zanclean deltaic sedimentary rocks. These results further imply significant modification in the Neogene paleogeographic evolution of the region.

STRATIGRAPHIC FRAMEWORK

Neogene rocks are widely distributed in the NE Aegean and the around the Sea of Marmara (Figure 1). The Neogene succession in NW Turkey starts with fluvio-lacustrine sedimentary rocks of the Gazhanedere Formation above a pre-Early Miocene unconformity (Figures 2 and 3). In the Biga Peninsula in the western Marmara region, the first stratigraphic unit above the unconformity consists of a fan conglomerate. In the Gelibolu Peninsula, the northern margin of the Gulf of Saros and Gaziköy-Şarköy areas, the Gazhanedere Formation is composed of vari-colored (green, gray, red and purple) sandstone and mudstone with some rare conglomerate interbeds, coal seams and marl. The marls and mudstone beds contain the fresh water bivalve, *Unio* sp. The Gazhanedere Formation is about 400-m thick in the Gaziköy-Şarköy area, with micro-mammal fauna indicating a late Orleanean age (equivalent to early Serravallian in Mediterranean chronostratigraphy; Ünay and de Bruijn, 1984) and an Astaracian age (early Burdigalian to late Serravallian) in the Gelibolu Peninsula (Sümengen *et al.*, 1987). It is conformably overlain by the Upper Serravallian to Tortonian siliciclastic shoreline sedimentary rocks of the Kirazlı Formation, which is in turn conformably followed upwards by mudstones, marls and bioclastic carbonates of the Messinian (Pontian) to Lower Zanclean Alçıtepe Formation (Figure 3; Gillet *et al.*, 1978; Görür *et al.*, 1997, 2000; Sakınç *et al.*, 1999; Sümengen *et al.*, 1987; Siyako *et al.*, 1989; Sakınç and Yaltırak, 2005).

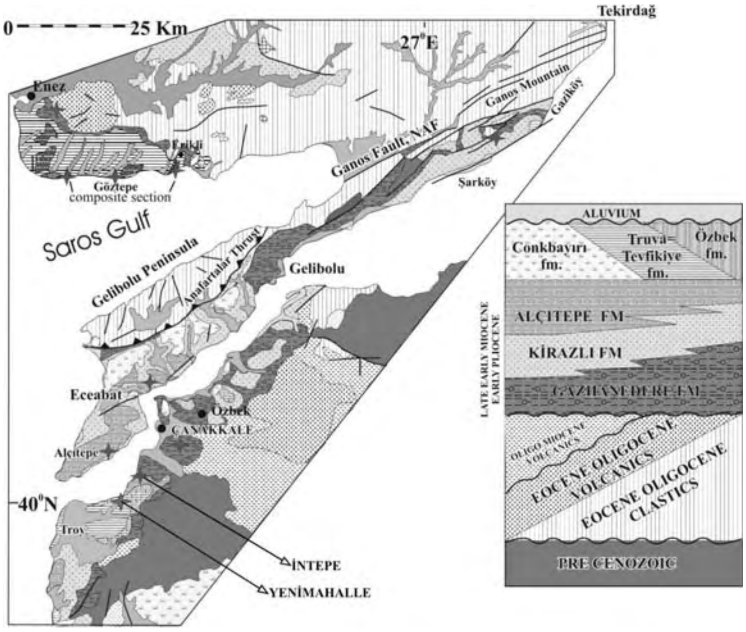

Fig. 2. Geological map of the area around the Gulf of Saros and Çanakkale Strait (Dardanelles) showing the location of the study sites. Note that the Alçıtepe Formation outcrops on the map also includes Pliocene sedimentary rocks according to new nannoplankton data. (Geology after Sümengen *et al.,* 1987; Siyako *et al.,* 1989; Sakınç *et al.,* 1999; Çağatay *et al.,* 1999, 2006).

Alçıtepe Formation contains brackish-water mollusks and ostracods of Paratethyan affinities, and is overlain by the fluvio-lacustrine sedimentary rocks of the Kimmerian Truva Formation. The bioclastic carbonates of the Alçıtepe Formation with an endemic Paratethyan fauna are widely distributed in the Gelibolu and Biga peninsulas and along the northern coast of the Gulf of Saros (Figure 2). These rocks extend further south, covering wide regions in the Aegean regions (Papp *et al*., 1978; Papp and Steininger, 1979).

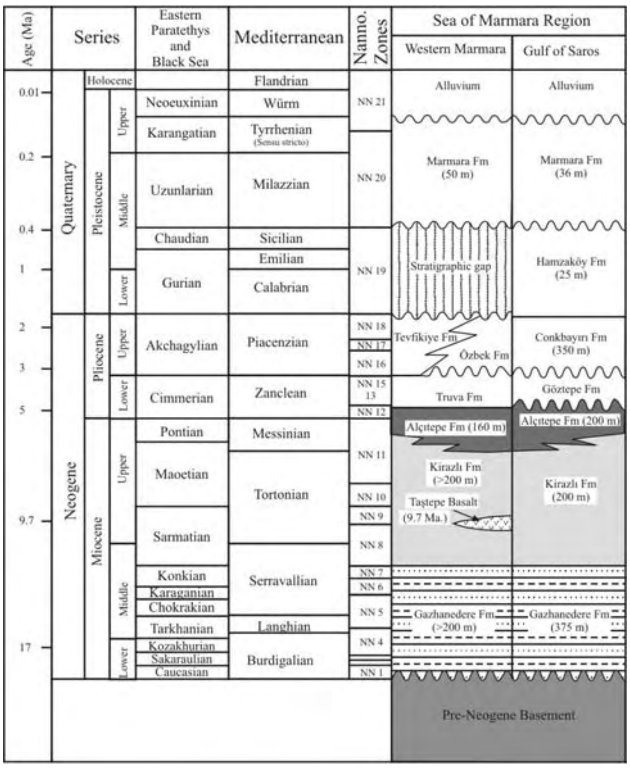

Fig. 3. Stratigraphy of the Neogene sections in NW Turkey (modified from Çağatay *et al.,* 2006).

Our new qualitative and semi-quantitative nannofossil analysis in NW Turkey indicate the presence of NN11b, NN12a and NN12b nannoplankton Zones in the Alçıtepe Formation, which represents the Late Messinian-Early Zanclean interval. The presence of NN12 nannoplankton Zone in the upper part of the Alçıtepe Formation makes the Lower Pliocene deposits more widespread in the region than previously thought. The erosional unconformity between the Upper Miocene and Lower Pliocene sediments is clearly visible in the northern coastal area of the Gulf of Saros and İntepe (south of Çanakkale Strait).

In this study we follow the Atlantic nannoplankton chrono- and biostratigraphy of Iaccarino (pers. comm.), which places NN12b Zone in the earliest Zanclean in the Mediterranean Sea. Although NN12b Zone begins in the latest Messinian in the global biostratigraphy (Lourens *et al*., 2004), the basis of this practice is debatable because of the nature of connections of the Mediterranean with the Atlantic during this time.

Gulf of Saros and Enez

Along the northern coastal belt of the Gulf of Saros, the Messinian (Pontian) Alçıtepe formation consists of *Mactra*-bearing bioclastic and cross-bedded limestones, interbedded with *Cardium*-bearing sandstones and *Ostrea* banks (Figure 4) (Ternek, 1949; Sakınç *et al*., 1999). The formation is overlain with an erosional unconformity by the Göztepe Formation of Early Zanclean age (NN12 Zone), consisting of deltaic bottomset beds overlain by marine siltstone and sandstone with *Ostrea* banks and mollusc-rich (mainly *Cardium* and gastropods and brackish foraminifera, *Ammonia becarii*, *Elphidium* sp.) sandy interbeds with diatomites towards the top (Çağatay *et al*., 1999,

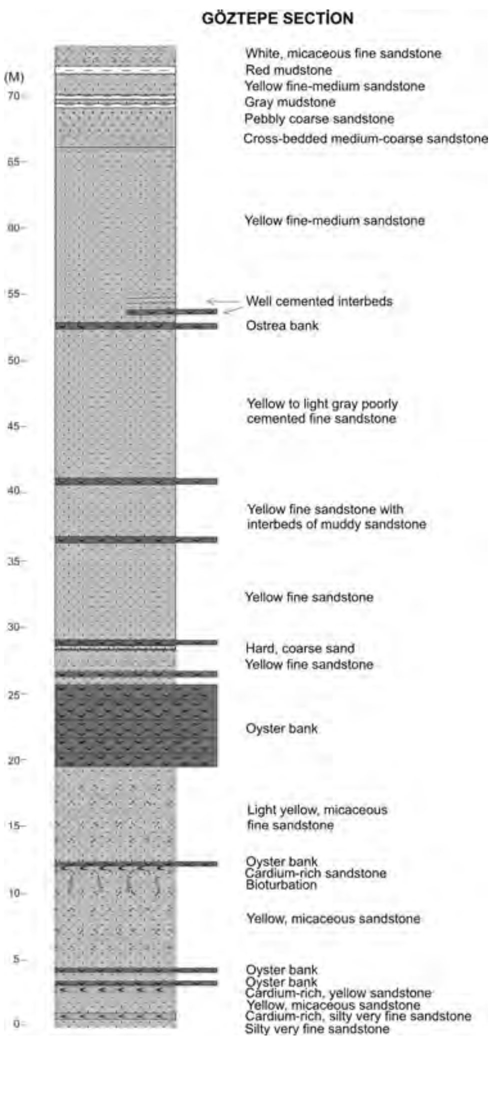

Fig. 4. Stratigraphy of the Neogene rocks in the northern coastal area of the Gulf of Saros.

2006). The frequent alternations of the *Ostrea* beds and *Cardium*-bearing sandstones indicate changing salinity conditions in a likely lagoonal setting. In Yaylaköy beach, the blue muddy fine sandstone bottomset beds with NN12 Zone nannoplankton assemblage are nested in the bioclastic limestones of the Alçıtepe Formation. The nannoplankton assemblage includes *Ceratolithus acutus, Triquetrorhabdulus rugosus, Thoracosphaera* sp., *Reticulofenestra pseudoumbilicus, Sphenolithus moriformis, S. abies, Braarudosphaera bigelowii, Florisphaera profunda, Amaurolithus delicatus, Coccolithus pelagicus* and *Calcidiscus leptoporus*.

In Enez, near the border of Turkey with Greece (Figure 2), the Alçıtepe Formation consists of 23-m thick *Mactra*- bearing limestones that crop out from beneath the widespread late Quaternary delta of the Meriç River (Figure 5). It contains a rich bivalve fauna (*Paradacna abichi sinz*, *Dreissena* sp.). In the upper part of the section, the limestone unit contains *Cardium* sp., *C. edulis*, and *Paradacna*, and is ovarlain by an *Ostrea*-bank unit.

In the Enez area, the Early Zanclean blue mudstone bottomset beds crop out below the Holocene delta of the Meriç River (Figures 2 and 6). These beds, previously mapped by Göçmen (1977) as the late Quaternary marine terrace deposits below the Late Pleistocene-Holocene deltaic sediments, contain bivalves (*Corbula gibba*) and a nannoplankton similar to the one in Yaylaköy, indicating NN12 Zone (Early Zanclean). The late Pleistocene-Holocene age of the delta is also not supported by the AMS radiocarbon analysis of a *Corbula gibba* shell from the bottomset beds, which produced an age greater than the upper age limit of the method (i.e., ca. 50 kyr) (Çağatay, unpublished data). The bottomset beds are overlain by 15-20 m thick Early Pliocene topset sandstone beds in this area (Figure 6). The topset deltaic sandstone sequence was previously mapped by Sümengen *et al*. (1987) and Şentürk and Karaköse (1998) as the Middle to Late Miocene Çanakkale Formation (equivalent of the Kirazlı Formation).

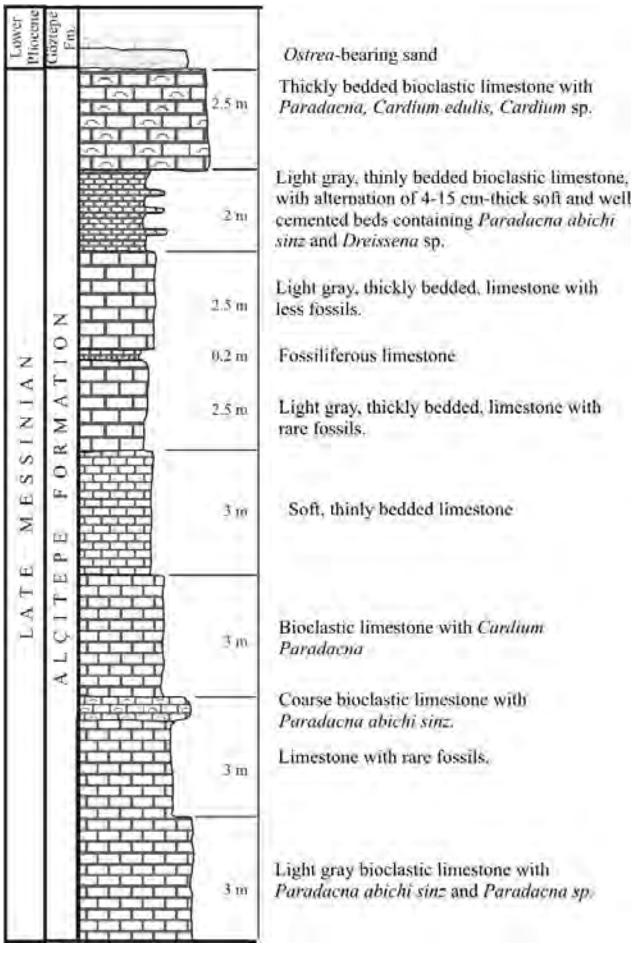

Fig. 5. Stratigraphic section of the Alçıtepe Formation in Enez. See map in Figure 2 for location.

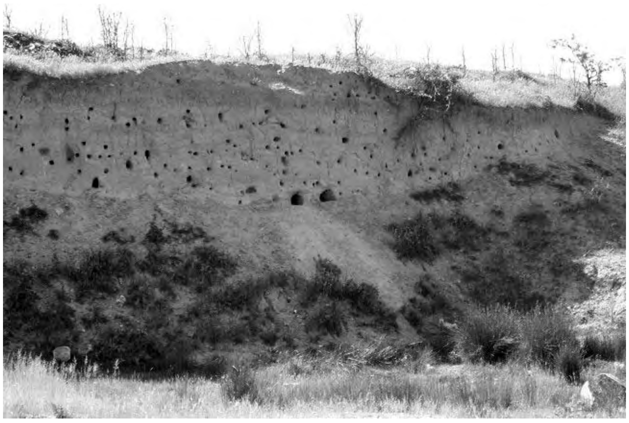

Fig. 6. Photograph showing the Lower Zanclean deltaic bottomset mudstone beds overlain by the topset sandstone beds.

Gelibolu and Biga Peninsulas

Gelibolu and Biga peninsulas north and south of the Çanakkale Strait include widespread exposures of Neogene rocks (Figure 2). The Alçıtepe Formation consists of mudstone and marl in the lower part and bioclastic and oolitic limestones with marl, mudstone, and sandstone intercalations in the upper part (Figures 3, 7 and 8). It conformably overlies the cross-bedded sandstones of the Kirazlı Formation. The Alçıtepe Formation in the Gelibolu and Biga peninsulas has rich brackish-water bivalve (*Mactra* sp., gastropods) and ostracod (*Cyprideis pannonica, Cyprideis torosa, Candona neglecta, C. Candida, Loxoconcha* sp.*, Heterocypris salina salina*) faunas endemic to Paratethys (Çağatay *et al*., 2006). Our new biostratigraphic studies indicate that the lower part of the Alçıtepe Formation, consisting predominantly of mudstones and sandstones, commonly contains a rich nannoplankton assemblage of *Amaurolithus amplificus, Calcidiscus leptoporus, Coccolithus pelagicus, Sphenolithus moriformis, Sphenolithus abies, Reticulofenestra minuta, R. pseudoumbilicus, Syracosphaera pulchra, Rhabdosphaera clavigera, Helicosphaera carteri* var. *wallichi, Helicosphaera intermedia, H. stalis,Thoracosphaera* spp.*, Braarudosphaera bigelowii, Triquetrorhabdulus rugosus* (also Clauzon *et al*., this volume). This assemblage indicates a Messinian age (NN11b Zone) (Figure 7).

The upper levels of the Alçıtepe Formation belong to NN12 (Earliest Zanclean) (Figure 7). The Lower Zanclean rocks consisting of mudstones, sandstones and bioclastic carbonates disconformably overlay the Alçıtepe Formation, although this stratigraphic relationship is not obvious everywhere. The Lower Zanclean rocks mapped as part of the Messinian (Pontian) Alçıtepe Formation form extensive outcrops in the Gelibolu and Biga Peninsulas (Figure 2). In the southwestern coast of the Gelibolu Peninsula overlooking the Gulf of Saros, these rocks show 20-30º foreset dips towards the southwest. In the western part of the Gelibolu Peninsula close to a flower structure formed by the NAF, the Lower Zanclean and older rocks are strongly deformed with steep dips.

In the Intepe area, south of the Çanakkale Strait (Biga Peninsula), a 170 m-thick sedimentary package is exposed in the new road cut. The Messinian Alçıtepe Formation in this section conformably overlies the Kirazlı sandstones, and consists of mudstone and sandstone at the base and predominantly fossiliferous and bioclastic limestones interbedded with mudstone towards the top (Figure 7). Its upper boundary is defined by a 5-20 cm-thick lignite bed. The 1.8 m-thick mudstone and marl part below the lignite bed is cyclicly banded and finely laminated. The nannoplankton of the Alçıtepe Formation below the lignite bed consists of *Triquetrorhabdulus rugosa, Reticulofenestra rotaria, Amaurolithus primus* and *A. delicatus* that belong to NN11b nannoplankton Zone (Figures 3 and 7). The earliest Zanclean starts with a 2 cm-thick sandstone bed over the lignite, and is followed upward by a 20 cm-thick highly fossiliferous limestone, fossiliferous mudstone, sandsone, and cross-bedded, pebbly, fossiliferous limestone beds. The foreset beds in the bioclastic carbonates and sandstones dip at 10-20º northward. Nannoplankton assemblage of the underlying clays includes the first occurrence of *Ceratolithus acutus* and, then, the extinction of *Triquetrorhabdulus rugosus*, indicating the presence of NN12b Zone (Figure 7).

The Yenimahalle section, about 8 km south of the İntepe along the Çanakkale-İzmir road, is about 50 m-thick. Here, the Alçıtepe Formation is about 30-m thick and consists of beige and white *Mactra*-bearing marl and limestone interbedded with green, grey and less commonly red mudstones and sandstones (Figure 8) (Çağatay *et al*., 2006). The sandstones and mudrocks are more abundant in the lower part of the section, which also contains a few finely-laminated diatomite beds. Oolitic limestone units are more common in the top 2.5 m of the formation. The thickness of individual marl and limestone units vary from 0.2 to 2.5 m.

The Alçıtepe Formation at Yenimahalle is devoid of any nannofossils and foraminifera. Instead, these deposits contain a molluscan and ostracod fauna that are endemic to Paratethys (Çağatay *et al*., 2006). The fauna indicates deposition in a shallow, brackish- to fresh-water environment. Faunal and paleomagnetic analyses of a section of the Alçıtepe Formation at Yenimahalle (Çanakkale) indicate that the formation is of Pontian age and represents chron C3r (6.04-5.24 Ma) (Çağatay *et al*., 2006). Considering the few degrees of general westward dip of the strata in the İntepe-Yenimahalle area, the Yenimahalle section probably corresponds to the upper part of the İntepe section, and was probably deposited in the later part of the chron C3r (i.e. in the earliest Zanclean).

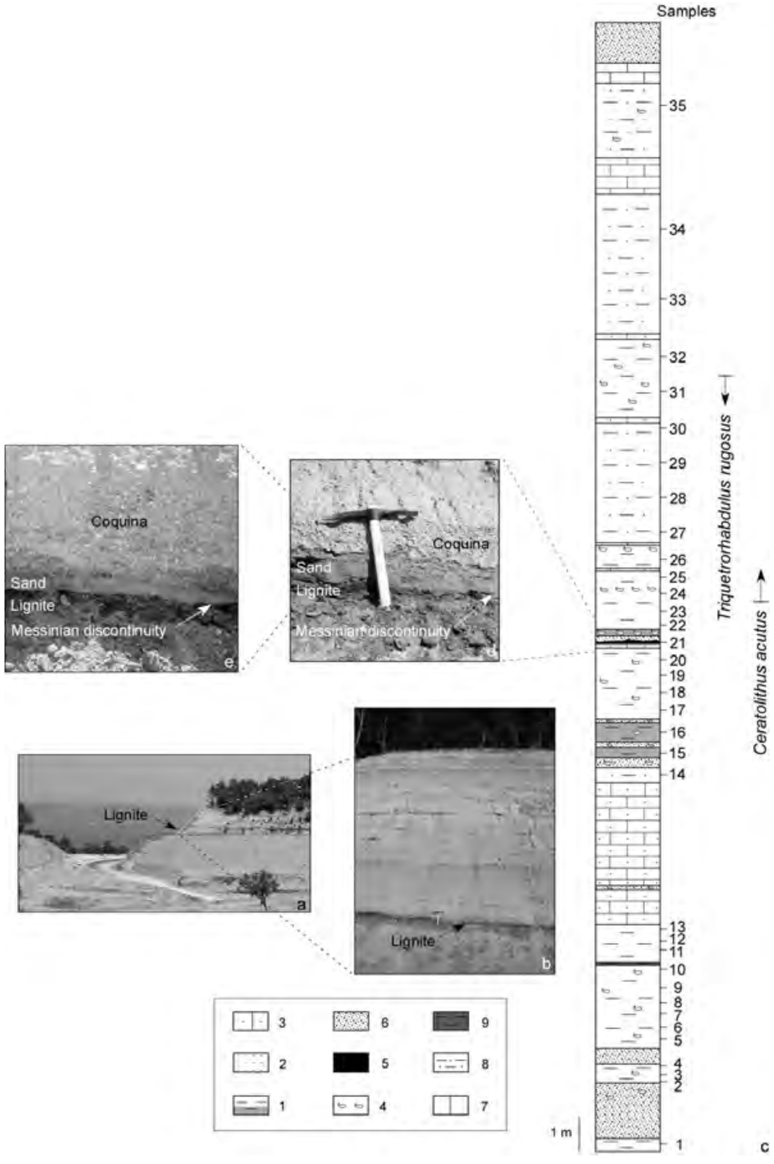

Fig. 7. İntepe Neogene section, south of Çanakkale. The lignite devides the section into two nannoplankton zones: NN11b (Messinian) and NN12 Zone (Lower Zanclean) in the Alçıtepe Formation.

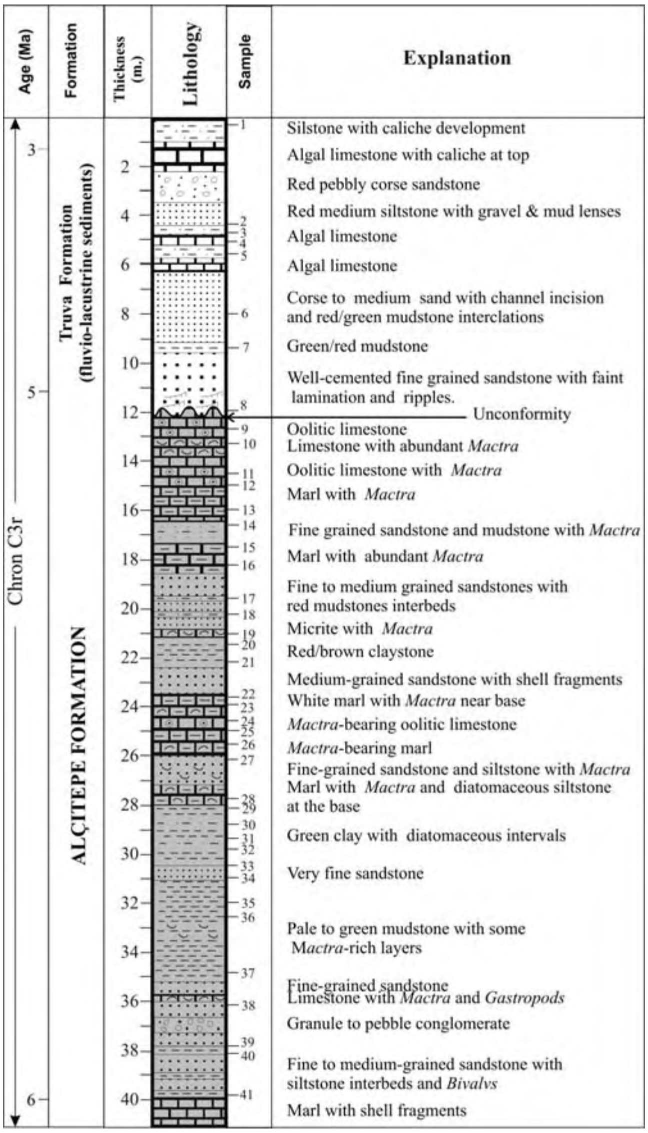

Fig. 8. Stratigraphic section at Yenimahalle south of Çanakkale (Çağatay *et al.,* 2006).

DISCUSSION: PALAEOGEOGRAPHIC EVOLUTION AND WATER-MASS EXCHANGE BETWEEN PARATETHYS AND MEDITERRANEAN

The widespread occurrence of the Alçıtepe Formation around the Marmara and North Aegean regions in NW Turkey, together with its brackish-fresh water bivalve and ostracod fauna of Paratethyan affinities, indicate that fresh-brackish water lacustrine conditions similar to Paratethys existed in these regions during most of the Messinian-earliest Zanclean (Görür *et al*., 1997, 2000; Sakınç and Yaltırak, 2005; Çağatay *et al*., 2006). These data also suggest a connection between the Paratethys and Mediterranean during this time period. Indeed, the distribution of the similar facies in the Aegean regions suggest that Paratethys extended far into south and west, and caused the deposition of the fresh- to brackish-water facies coeval with the Lago Mare sequence in the Mediterranean (Papp *et al*., 1978; Papp and Steininger, 1979; Sakınç and Yaltırak, 2005).

The distribution of *Mactra*-bearing bioclastic limestones in the south of Istanbul (the Bakırköy Formation, equivalent of Alçıtepe Formation; Figure 1), suggests that the strait connecting the Paratethys with Mediterranean was probably close to the present Istanbul Strait (Bosphorus), or just to the west of it in the Büyük Çekmece-Terkos area (Figure 9). A patchy occurrence of the fresh-brackish Paratethyan facies in these areas is mainly due to the Late Pliocene uplift and peneplanation of the area (Erol, 1981; Emre *et al*., 1998).

The new nannoplankton data from NW Turkey constrain the age of the Alçıtepe Formation between the Messinian and Early Zanclean (NN11b-NN12b Zones), rather than the Middle to Late Miocene (Sarmatian-Pontian) (Önem, 1974; Gillét *et al.*, 1978; Sümengen *et al.*, 1987; Kaya, 1989; Siyako *et al.*, 1989). The coexistence of brackish water bivalve and Ostracod fauna and nannoplankton flora in NW Turkey further suggests that the predominantly brackish water environment of this region was influenced by the Mediterranean during this time (Figure 9). The faunal and floral data from the different sections in the region (e.g., Gulf of Saros, Yenimahalle and Intepe sections) suggest that locally variable depositional conditions prevailed in NW Turkey during the Messinian. As indicated by its *Ostrea*- and foraminifera-bearing facies, the North Aegean (Gulf of Saros) region was more open to Mediterranean waters during the MSC than the Gelibolu and Biga Peninsulas which were relatively isolated from the Mediterranean, because of the presence of sills activated by the splays of the NAF.

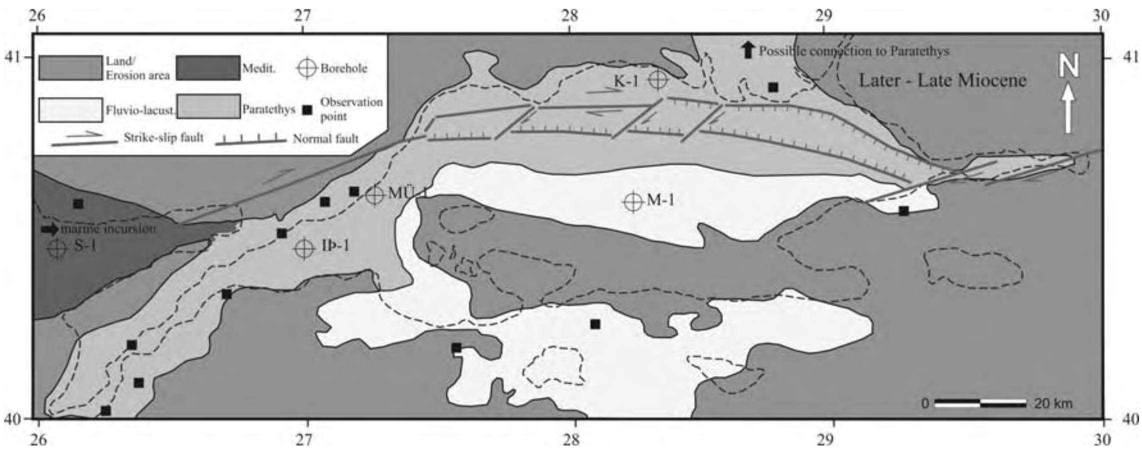

Fig. 9. Late Messinian palaeogeographic map of the Marmara Sea region. Note that the basin covering the Marmara region as a Paratethyan realm also shows Mediterranean influence, as indicated by the presence of nannoplanktons (modified from Çağatay *et al.,* 2006).

After the sea-level lowering during the Late Messinian, there was an erosional period which is especially well recorded in the northern coastal area of the Gulf of Saros and the Gelibolu Peninsula. This period was followed by deltaic sedimentation with the onset of the marine transgression during the Early Zanclean. The foreset beds dip at 20-30º towards the Çanakkale Strait. This, together with the distribution of the erosional surfaces and the overlaying Zanclean deltaic deposits, suggests that the Çanakkale (Dardanelles) Strait's channel was cut during the MSC sea-level lowering (Clauzon *et al.*, this volume). In Enez and the NW coastal area of the Gulf of Saros, there are extensive Zanclean deltaic deposits that are nested in the Messinian Alçıtepe Formation. The Late Pleistocene-Holocene delta of the Meriç River, located on the border between Turkey and Greece, is in turn embedded over the Zanclean Gilbert-type Delta.

Although the present data strongly suggest at least a one-way connection between Paratethys and Mediterranean during the Messinian-Early Zanclean, the exact timing of the connection(s) between the Paratethys and Mediterranean are still unknown (see also Popescu, 2006). The fresh-brackish water conditions in NW Turkey may have continued after an initial input of freshwaters from the Paratethys, and the Paratethyan species may have continued to live as an endemic fauna in the isolated basin covering the Marmara Sea regions. Moreover, the nature of connection(s), as to one-way flow from the Paratethys versus two-way flow mode similar today, is also debatable. To resolve these problems related to timing and nature of connections between the Paratethys and Mediterranean, detailed Sr-isotope studies on the biostratigraphically dated sections in the Marmara region are needed (see Flecker and Ellam, 2006; Flecker, this volume).

The important use of the Sr-isotope studies has already been demonstrated in the Yenimahalle section of the Biga Peninsula. Here, the faunal and Sr-isotope evidence indicate that the continental (lacustrine) conditions prevailed during the Late Messinian-Early Zanclean (Çağatay *et al*., 2006). The Sr-isotope data from the Yenimahalle Section further suggest that during the deposition of the sequence, the exchange with the Mediterranean was reduced or terminated and that this area was dominated by local river water discharge. The salinity increase indicated by the Ostracod fauna in the upper part of the section was controlled by the dominance of the evaporation flux. The faunal and isotopic results in Yenimahalle and faunal evidence in İntepe further support the presence of locally variable depositional conditions in NW Turkey during the MSC.

Isotopic and modelling constraints on the hydrologic budget of the Mediterranean during the Messinian Salinity Crisis

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Summary

During the Messinian Salinity Crisis (MSC) the saltiness of Mediterranean seawater varied from near fresh to ~10 times more saline than today. The causes of these salinity fluctuations are controversial and attempts to discriminate between hypotheses have been hampered by an inability to constrain hydrologic fluxes in the past e.g. river run-off, precipitation, evaporation, Atlantic inflow and Mediterranean outflow. This paper summarises the work that has been done to quantify these fluxes during the MSC, previews work that is likely to be carried out soon and highlights areas in which information is still woefully inadequate.

Introduction

The salinity of marginal marine basins is controlled by the hydrologic budget. In the Mediterranean case, this relates specifically to the salinity and magnitude of four hydrologic fluxes (Figure 1):

- inflow from the ocean ($F_{O \rightarrow Med}$);
- outflow to the ocean ($F_{Med \rightarrow O}$) +/- outflow to Paratethys ($F_{Med \rightarrow T}$);
- the amount of non-oceanic (e.g. rivers, F_R +/- Paratethyan, $F_{T \rightarrow Med}$) water feeding the basin; and
- the balance of evaporation and precipitation ($F_{E\text{-}P}$).

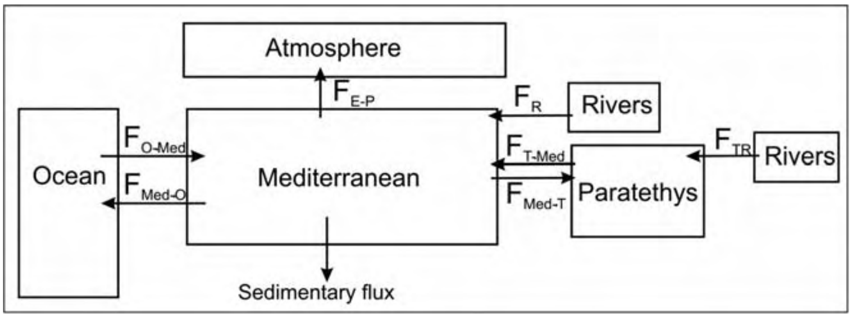

Fig. 1. Schematic representation of the flux controls on Mediterranean salinity.

Typically, the hydrologic fluxes in marginal basin systems are controlled partly by climate (e.g. rainfall, river runoff and evaporation) and partly by tectonics (e.g. the scale of exchange at the gateways). Marginal basins at mid-latitudes, like the Mediterranean where evaporation exceeds precipitation (Figure 2, Peixoto and Kettani, 1973) are particularly sensitive to relatively small-scale changes in climatic forcing (Flecker and Ellam, 2006). The development of precession-driven cyclicity in the last ten million years of the Mediterranean's sedimentary record (Krijgsman *et al.*, 1999a) and its associated minor fluctuations in salinity (e.g. Emeis *et al.*, 2000) is a well documented example of this sensitivity. The extreme salinity variations that characterise several Miocene mid-latitude marginal basins e.g. the Mediterranean Messinian Salinity Crisis, Red Sea (Elanbaawy *et al.*, 1992; Rouchy, 1986) and Gulf of California (Nava-Sanchez *et al.*, 2001) are clearly part of this phenomenon. All these basins contain successions which indicate periods of hypersaline, fresh or brackish water and normal marine conditions and, while the general picture is well known, detailed understanding of how and why individual salinity transitions occurred remains very poorly constrained. In the Mediterranean, the result of this gap in our knowledge is that despite considerable consensus about the geology of the MSC (see introduction to this volume) multiple contrasting hypotheses for the controls on the salinity changes have persisted in the literature untested for 30 years or more and our understanding of their causes therefore remains frustratingly limited.

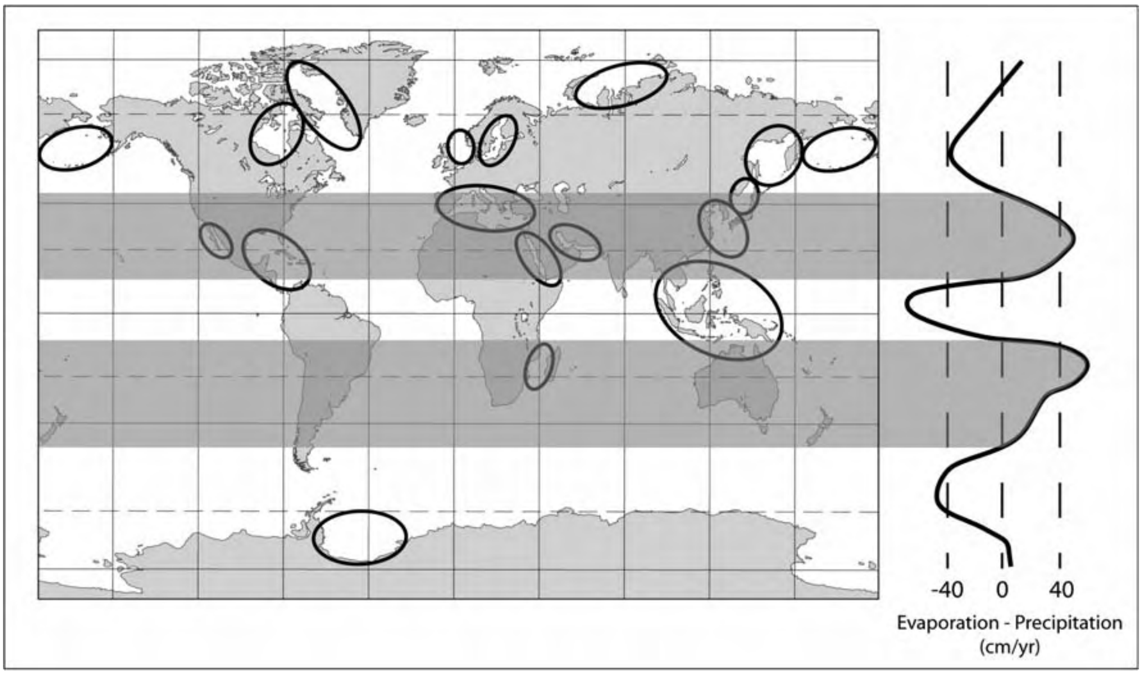

Fig. 2. Map indicating the global distribution of marginal marine systems. The shaded bands indicate latitudes where evaporation exceeds precipitation. Basins at these latitudes are particularly prone to fluctuating salinity conditions.

Testing hypotheses for salinity transitions during the MSC

The Messinian Salinity Crisis encompasses five major salinity changes.

1. The transition from marine (35-38g/l) to hypersaline (130-160g/l) conditions with the onset of gypsum precipitation at the base of the First Evaporite Unit.

2. An oscillation between hypersaline and marine conditions during deposition of gypsum-clastic/pelitic cycles.

3. The transition to a higher salinity state (>350g/l) suitable for halite precipitation.

4. The change from hypersaline to brackish water (~5-20g/l) conditions during the Evaporite-Lago-Mare transition.

5. The return to marine conditions at or just before the base of the Pliocene following the Lago-Mare.

Hypotheses to explain each of these transitions exist and each can be described in terms of the different hydrologic scenarios they describe (Table 1).

Table 1. Summary of hypotheses for the five major salinity transitions that characterise the MSC with their associated hydrologic fluxes.

Transition	Hypothesis	Hydrologic fluxes involved
1. Onset of gypsum precipitation	Reduction or closure of Atlantic-Mediterranean gateway(s) (e.g. Hsü *et al.*, 1973; Krijgsman *et al.*, 1999b) and associated regression and sea level fall (e.g. Barber, 1981; Clauzon, 1973; Clauzon, 1982; Stampfli and Hocker, 1989)	Outflow and inflow reduced or terminated, evaporation constant or increased.
	Atlantic transgression impacting to an already highly restricted marginal basin (Flecker *et al.*, 2002; Flecker and Ellam, 2006)	Outflow limited, evaporation dominant, sudden increase of salty water (Atlantic inflow)
2. Gypsum-clastic cycles	Oscillations in salinity resulting from precession driven changes in climate (Krijgsman *et al.*, 1999a). The clastic intervals have been correlated with insolation minima (Krijgsman *et al.*, 2001)	Fluctuations in freshwater fluxes e.g. river runoff, rain fall and/or evaporation
	In the Sorbas Basin these oscillations in salinity have been thought to results from periodic restriction of the oceanic connection (Dronkert, 1985)	Outflow and inflow reduced or terminated, evaporation constant or increased.
3. Transition to and sustaining of halite precipitation	Isolation and substantial draw-down (Clauzon, 1973) if not dessication (Hsü *et al.*, 1973) possibly on multiple occasions	Permanent cessation of outflow; permanent/episodic cessation of Atlantic inflow; evaporation constant or increased.
4. Hyper- to hypo- saline transition	Changing climatic conditions either on a precessional scale (Abdul Aziz *et al.*, 2000; Krijgsman *et al.*, 1997; Krijgsman *et al.*, 2001) or on the scale of the sequence (Rouchy *et al.*, 2001)	Increased river run-off and precipitation
	Paratethyan inundation (Archambault-Guezou, 1976; Hsü *et al.*, 1973)	Sudden influx of fresh to brackish Paratethyan water
5. Return to marine conditions	Tectonic and/or eustatic driven relative sea level rise; the Zanclean deluge (Cita, 1975; Di Stefano *et al.*, 1999; Hsü and Cita, 1973; Hsü *et al.*, 1978; Iaccarino and Bossio, 1999; Krijgsman *et al.*, 1999a; McKenzie *et al.*, 1988)	Increased Mediterranean-Atlantic exchange increasing both oceanic inflow and outflow and lessening the dominance of evaporation
	Episodic marine influxes (Carnevale *et al.*, 2006; Carnevale *et al.*, in press)	Periodic influx of Atlantic water

Recently, progress in testing the various hypotheses for each salinity transition has been made through efforts to model the hydrologic behaviour that characterised the Mediterranean during the Messinian Salinity Crisis (Blanc, 2000; Blanc, 2006; Flecker *et al*., 2002; Gargani and Rigollet, 2007; Meijer, 2006; Meijer and Krijgsman, 2005). These simple numerical models allow us to explore the implications of the different scenarios and consider the relative likelihood of each one in a quantitative context. This powerful approach is hampered by the lack of quantitative information about past hydrologic fluxes. As a result, all published models to date have been run with at least some modern hydrologic fluxes which today produce normal marine salinities in the Mediterranean. This limitation means that full testing and disproval of individual hypotheses is still difficult because of the lack of realism in the input parameters used to model them. The purpose of this paper is to indicate where quantitative MSC flux data exist, the uncertainties associated with this information and which fluxes need to be the focus of future work.

Constraints on past hydrologic fluxes

i) Sr isotope constraints on inflow fluxes

The balance of oceanic and non-oceanic water that fed the Mediterranean in the past can be reconstructed by analysing the Sr isotope composition of fossil shells and authigenic minerals such as gypsum and halite. This method is predicated on the fact that the Sr isotope ratio of marginal basin water is the product of mixing between ocean and non-ocean water and is preserved in shell and minerals that precipitated in that water mass (Ingram and Sloan, 1992; Reinhardt *et al.*, 1998). Although this method does not produce absolute figures for river runoff or Atlantic inflow, it does indicate the proportion of each. Results from the pre-Messinian successions suggest that although the proportion of ocean water reaching the basin was already significantly reduced ~3 million years before the onset of gypsum precipitation, this varied considerably (from >50% ocean water to as little as 6%; Flecker *et al.*, 2002). The Sr results also suggest that the trigger for the MSC was an influx of Atlantic water rather than a regression, since the isotopic record shows a sudden return to oceanic Sr values coincident with early gypsum mineralization (Flecker *et al.*, 2002; Flecker and Ellam, 2006). This approach can be applied to other salinity transitions where authigenic and/or biogenic material incorporating Sr from Mediterranean water exists. One ongoing area of study is the gypsum-clastic alternations that characterise exposures such as Ereclea Minoa on Sicily. The presence of foraminifera and fish fossils (e.g. De la Chapelle and Gaudant, 1987) in the interbedded clastics and pelitic carbonates suggests that the salinity of the water between episodes of evaporite precipitation must have been much lower; compatible with the salinity requirements of this fauna. However, establishing that the foraminifera are *in situ* and not reworked remains challenging. Should this be resolved, then Sr isotopes do offer an opportunity to discriminate between relatively small-scale fluctuations above and below the lower gypsum saturation boundary (~130 g/L) caused by climatic oscillations (see Krijgsman *et al.*, this volume) and more substantial changes to the hydrologic budget which involve changes in Mediterranean-Atlantic exchange.

ii) GCM constraints on precipitation, run-off and evaporation

State of the art fully coupled ocean-atmosphere General Circulation Models are inadequate for the study of the Mediterranean Messinian Salinity Crisis in a number of ways. Firstly the scale of the grid boxes is large so that the Mediterranean is typically represented by at most two or three (Bigg *et al.*, 2003). This is clearly insufficient to capture the complexity of the bathymetry and geometry of the system. The gateway(s) are also too small to be represented effectively and if Mediterranean-Atlantic exchange is included at all, the gateway(s) are either modelled as a tunnel, presenting problems associated with the depth at which this is placed, or an extra salt flux that is released from the Atlantic side of Gibraltar, resulting in a lack of response in the Mediterranean itself.

The third issue is the tension between the complexity of the model and the computer time it takes to run a simulation. Clearly, high resolution models are required to capture even some of the important geographic features of relatively small basins like the Mediterranean. However, the more complex the model, the longer it takes to run a simulation and the more expensive that simulation is. As a result, high resolution climate simulations are typically only run for a few tens to hundreds of years and provide equilibrium snap-shots of past climate states rather than an evolving image of climate through time. In terms of investigating the MSC, a model able to provide a transient simulation spanning this ~700kyr period would be preferable, but despite the obvious draw-backs, the snap-shot simulations do play an important role in constraining past hydrologic fluxes. They are, for example, currently the only mechanism for constraining that key flux, evaporation over the Mediterranean region, although locally and on a small-scale, quantification of pollen information is also beginning to elucidate this (Fauquette and Bertini, 2003; Fauquette *et al.*, 2006). They also provide some quantitative basis for river run-off and precipitation, which can feed into, and help constrain the absolute volumes involved in Sr analysis and numerical box modelling studies. Prompted by the recent publication of the Gladstone *et al.* (2007) study, this cross-fertilization has just started (Gargani, pers. comm.; Krijgsman, pers. comm.; Topper, 2007). Initial results suggest that one of the most problematic issues is likely to be the orbital setting chosen for the simulation. In Gladstone *et al.* (2007) we opted to use the present-day orbital configuration. This produced a much wetter Mediterranean with most of the increase in fresh water being sourced from North Africa down rivers that no longer flow today (Griffin, 1999; Griffin, 2002; Griffin, 2006). It also produced a net hydrologic flux very close to zero. This results in problems generating evaporite conditions particularly of the volume required, but does provide an explanation for the fluctuations in salinity seen in the Mediterranean record. Future simulations need to explore the variability in evaporation, precipitation and run-off that result from the orbital configurations and extreme insolation states that are associated, in the Mediterranean, with systematic changes in lithology (see for example paper by Krijgsman *et al.*, this volume).

iii) Mediterranean outflow

Of all the hydrologic fluxes, arguably the most important and certainly the least well constrained is Mediterranean outflow. Quantitative information about this flux is clearly essential for modelling purposes, since outflow from the Mediterranean is the main mechanism for removing salty water from the system. However, even fundamental qualitative information about outflow during the MSC is missing. For example, at present we do not know if outflow ceased at any time during the salinity crisis and if so for how long a period. This is clearly essential for testing many of the hypotheses for different salinity transitions (Table 1), but it also has much wider implications for global climate.

Reduced exchange between semi-enclosed marine basins, like the Mediterranean, and the ocean, results in an amplified response to changes in the hydrologic balance of the marginal marine system (Thunell *et al.*, 1988). For example, limited exchange through the Strait of Gibraltar today leads to ~2g/l higher salinity in the Mediterranean than the Atlantic as a result of net evaporation (Bryden and Stommel, 1984). This salinity response, although not large enough to impact faunal assemblages or sediment type, results in high salinity outflow from the Mediterranean which contributes to the pattern and vigour of North Atlantic thermohaline circulation (Bethoux *et al.*, 1999; Johnson, 1997; Reid, 1979; Van Aken and Becker, 1996). Understanding the cause of extreme Late Miocene salinity fluctuations is therefore critical both in assessing Mediterranean impact on Late Miocene thermohaline circulation in the Atlantic and in anticipating the effect of changing the degree of connection on future climate.

One potential route to reconstructing Mediterranean Outflow during the MSC uses another isotopic tracer, Neodymium (Nd). Nd isotopes in marine precipitates such as ferromanganese (Fe-Mn) crusts can be used to track past ocean water masses (Dickson and Brown, 1994) and have been shown to record faithfully the Nd isotopic composition of the bottom water in which they are bathed (Frank, 2002). Today, Mediterranean Outflow Water (MOW) spreads across the Atlantic at intermediate levels to form a prominent, high salinity plume, easily recognized in oceanographic databases (Conkright *et al.*, 2002). MOW's Nd isotopic composition is also distinctive in being considerably more radiogenic than ambient intermediate Atlantic water (Wüst, 1961). As a result several attempts have been made to discern the nature of Mediterranean Outflow during the salinity crisis (e.g., Abouchami *et al.*, 1999). Results have been inconclusive however because the temporal resolution at which slow-growing Fe-Mn crusts (typically 1-10mm/million years) were sampled was too low. For example, the highest resolution study published to date that is able to demonstrate the influence of MOW was only able to provide two data points within the MSC period (Abouchami *et al.*, 1999). Advances in mass spectrometry and laser ablation protocols have recently enabled this obstacle to be overcome (Foster and Vance, 2006). A project to harness this new technique to perform high-resolution Nd analysis (e.g. sample periodicity less than or equal to 20kyr) on a high growth rate Fe-Mn crust that records MOW at the present-day (Abouchami *et al.*, 1999) has just begun in collaboration with colleagues at Bristol University, Scottish Universities Environmental Research Centre and the Max Plank Institute in Mainz. The aim is to reconstruct and quantify Mediterranean Outflow during the MSC at as high a resolution as possible.

New facies interpretation of the Messinian evaporites in the Mediterranean

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INTRODUCTION

The study of the Messinian Salinity Crisis (MSC) in the Mediterranean has generated a controversy with a long-term discussion on many aspects. One of the problem faced by scientists is that the interpretation of evaporite sediments can be very complicated. Evaporite sediments are among the most elusive for facies reconstruction and correlation and most data in the literature were not correctly placed in a stratigraphic framework. Some examples of these difficulties are the following:

a) deposits traditionally included in the Lower Evaporites are actually clastic sediments that derive from the dismantlement of autochthonous Lower Evaporites (Manzi *et al*., 2005; Roveri *et al*., 2006);
b) many of the Lower Evaporites outcrops in Italy are actually large-scale blocks emplaced by extensive mass-waste movements (Roveri *et al*., 2003; Roveri *et al*., 2006); some of these chaotic complexes were interpreted as collapse deposits due to halite dissolution (Caruso and Rouchy, 2006);
c) some Lower Evaporites outcrops were commonly considered Upper Evaporites and vice-versa;
d) laminated clastic sulphate sediments were commonly mistaken for primary cumulate deposits and vice-versa;
e) the significance of halite deposition, which actually bears the only unequivocal sign of exposure found within the Messinian evaporites, has been overlooked;
f) the Calcare di Base carbonates commonly show evidence of resedimentation;
g) the Calcare di Base is never found at the base of the Lower Evaporites primary *in situ* selenites;
h) lateral transitions between carbonate, gypsum or halite primary evaporites cannot be directly observed and must be considered speculation.

For these reasons we devoted our efforts to provide a detailed stratigraphic and facies analyses of all the Messinian evaporites and criteria for distinguishing the Lower from the Upper Evaporites. The main aim was to discuss new possible stratigraphic markers to correlate the elusive evaporite sediments across the Mediterranean during the MSC and to correctly place the Messinian units into a reliable stratigraphic framework.

Finally, as the peculiar and restricted setting of evaporite deposition makes the use of geochemical data problematic, we need to integrate the geochemical data in a detailed stratigraphic and facies framework. This because many of the available isotope data are scattered and commonly obtained from sections whose stratigraphy is not well constrained in the regional framework. An extensive study of the literature showed that the majority of the geochemical data were provided without a reliable record even for the *local* stratigraphy.

This presentation illustrates our studies on a new evaporite facies interpretation that may be useful for large-scale correlations. The effort is to provide a new reliable facies, isotope and stratigraphic framework for the understanding of the Salinity Crisis in the Mediterranean.

LOWER EVAPORITES

Primary Lower Gypsum (PLG)

The only available facies model for the Messinian Lower Evaporites in the Mediterranean is the "ideal cycle" of Vai and Ricci Lucchi (1977) for the Vena del Gesso basin. A revision of these sulfates and a comparison with other basins (Tuscany, Sicily, Calabria, Spain and Crete) and elsewhere (Babel, 2004) suggest a new facies model for their deposition.

The Vena del Gesso consists of 16 gypsum cycles separated by thin euxinic shale layers. The basal portion is made of thick beds of vertical massive selenite grading into banded selenite (F3 and F4 facies of Vai and Ricci Lucchi, 1977). The upper part of the section (from the 6th to the 15th bed) consists of thinner beds showing a basal massive and banded selenite, followed by nodular and lenticular selenite (F5). This nodular and lenticular selenite was considered as a clastic deposit that developed sabkha features by subaerial exposure (anhydrite nodules). The study of this facies shows no such features, but reveals that clusters of selenite crystals grew laterally, grouped in branches projecting outward from a nucleation zone into a gypsiferous carbonate-marly matrix. We interpret this facies as an extreme evolution of subacqueous selenite supercone structures described by Dronkert (1985) in the Sorbas basin (Spain). Because no obvious conical shape may be recognized, we proposed the use of the term "branching selenite" for the F5 facies.

Moreover, the chaotic selenite (F6 facies of Vai and Ricci Lucchi, 1977) present in the upper portion of some evaporite beds has been re-interpreted as a early diagenetic feature related to the displacive growth of large gypsum crystal within the shale deposits.

According to this revisitation of the "ideal cycle" for the Lower Evaporites, no evidence of subaerial exposure or evaporite resedimentation can be found inside this evaporitic succession.

The resulting facies sequence records a phase of concentration and subsequent dilution of the mater mass, and describes a complete small-scale cycle made up of regressive and transgressive phases. The depositional cycles can be described as follows:

1. Initial evaporite precipitation at relatively low salinity produced the vertical massive selenite in a relatively deep setting (falling stage, F3);

2. Continuous evaporation and drawdown produced relatively higher salinity conditions with an oscillating brine level and variable saturation conditions (lowstand, banded selenite, F4);

3. A general brine level rise and dilution introduced significant carbonate material in the system; selenite crystals formed large supercones with peripheral branches spreading laterally (transgression, branching selenite, F5); growth of cones and branches was controlled by brine level, spacing of cones and amount and composition of matrix surrounding the cones (fine-grained gypsum, carbonate and/or marls);

4. Flooding by undersaturated water during humid periods stopped gypsum precipitation with the deposition of organic-rich shales (highstand, F1).

The comparison (see Figure 1) of Sicily PLG with the Northern Apennines and Spain (Sorbas, Nijar) equivalent units, documents an impressive similarity of the massive selenite unit, in term of number of cycles, facies and stacking pattern, allowing bed by bed Mediterranean-scale correlations (Lugli *et al.*, 2006a). These similarities indicate that no episode of subaerial erosion within individual cycles occurred and that the general very shallow setting of selenite deposition (<10 m; Babel, 2004) should be reconsidered.

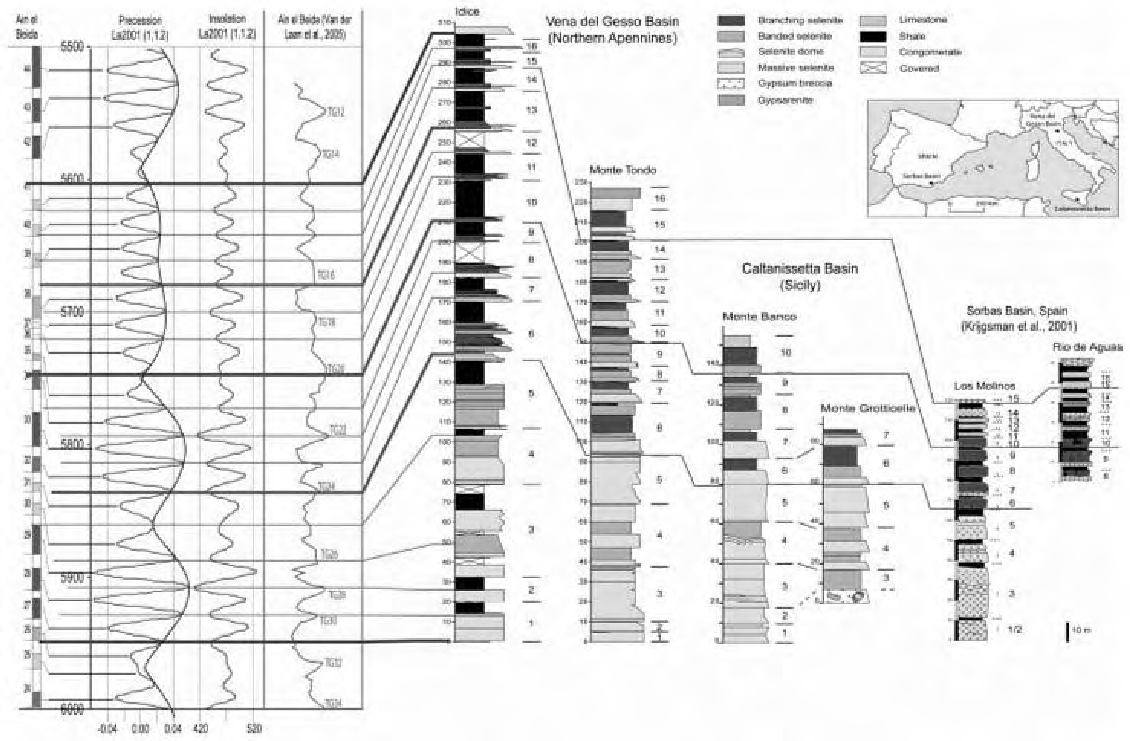

Fig. 1. Astronomical tuning and correlation of Lower Gypsum sections across the Mediterranean. Note the impressive similarity in stacking pattern and facies association for sections located hundreds of km apart.

Isotope data

Strontium isotope ratios indicate that the F5 facies appears in correspondence of major oceanic influxes in a general setting dominated by solutions modified by continental waters in the Vena del Gesso (Lugli *et al*., 2007a,b). In Sicily the influence of continental water is far less important than in the Northern Apennines, possibly as a consequence of the more distal position of such basin from the mainland. A few data from the Sorbas basin suggest a situation similar to that of Sicily.

Resedimented Lower Gypsum (RLG)

Recent studies have stressed the importance of resedimented evaporites in the northern Apennines Messinian deposits (Manzi *et al*., 2005 and references therein). An integration of a siliciclastic-approach to field recognition, microscope analysis and geochemical determinations allowed us to provide an interpretation of the large variety of resedimented evaporites in the Apennine Foredeep and in Sicily.

When the grain-size of resedimented evaporites cannot be directly observed, e.g. when crystal pseudomorphs or terrigenous clasts are not visible due to diagenetic obliteration, the sedimentary properties have been derived from the preserved sedimentary structures, adopting a siliciclastic perspective.

The clastic gypsum facies have been grouped in three main interpretative facies associations ranging from the coarser-grained to the finer-grained:

i) chaotic deposits, representing the "proximal" poorly evolved gypsum-shale flow deposit, mainly consist of chaotic complexes including primary evaporite slabs, boulders and blocks (facies R0), debris flow and hyper-concentrated flow deposits (facies R1, R2 and R3).

ii) lobe deposits representing the product of high to lows density gravity flows, are made up of medium to fine-grained gypsarenites, silt and shales (facies R4, R5 and R6) forming tabular or lenticular bodies interbedded with thin-bedded fine-grained gypsarenites; these deposits are commonly called "balatino gypsum".

iii) drape deposits representing the ultimate products of the flow evolution, consist of thin parallel gypsum laminae interbedded with bituminous shales (facies R7). Due to the lack of obvious transport evidence, as cross-laminations or convolutions, these deposits were traditionally considered primary deep-water evaporites ("balatino" gypsum; Parea and Ricci Lucchi, 1972).

Most of the evaporite succession cropping out between the eastern edge of the Vena del Gesso and the Laga Basin have a clastic origin. Almost all the laminar ("balatino") gypsum exposed in the northern Apennines, previously considered as a deep-water primary gypsum deposit, has been re-interpreted as the fine-grained product of high to low-density gravitational flows (Manzi *et al.*, 2005).

A complete transition from higher to lower density gravity-driven deposits has been recognized with the reconstruction of the history of the primary evaporites dismantlement from shallower thrust-top basins and their subsequent resedimentation to deeper and more subsident areas. The accumulation of such a wide spectrum of gravity-driven deposits, witnessed by the presence of slides, slumps and gravity-flow deposits, was probably related to the formation of large submarine collapse and glide structures triggered by tectonically-induced gravitational instability.

The resedimented Lower Gypsum of the Sicilian basins consists as well of deep-water resedimented gypsum deposits, emplaced by a great variety of gravity-flows high to low-density turbidity currents, debris flows, slumps, olistostromes containing up to mountain-sized slabs of massive selenite (Roveri *et al.*, 2006).

Although the resedimentation of the evaporites occurred within a fragmented minor-basin foredeep in both, the Apennine Foredeep and the Sicilian Basins, their wide, transitional distribution and depositional character suggest the absence of a basinal desiccation event during their emplacement.

Isotope data

Gypsum samples collected in the Apennine foredeep show values of $^{87}Sr/^{86}Sr$ ranging from 0.708887 to 0.708950. These values fall within the range of both the Lower Evaporites in the Mediterranean (0.708838 - 0.709034, Müller and Mueller, 1991; and 0.70892 - 0.70900, Keogh and Butler, 1999) and in the Vena del Gesso Basin (0.708890 - 0.709024, Vena del Gesso section; Lugli *et al.*, 2007a,b). These data are compatible with a source area for the evaporite resedimentation located in the Vena del Gesso Basin or in equivalent topset, shallow-water sites, which were completely eroded away.

CALCARE DI BASE (CDB)

The "Calcare di Base" (CdB; Ogniben, 1957) of the Caltanissetta basin is considered a calcareous evaporitic and microbialitic deposit belonging to the Lower Evaporites (LE; Decima and Wezel, 1971; Decima *et al.*, 1988) laterally equivalent of the primary selenite (Gessi di Cattolica; Selli, 1960) that for some authors, in turn, is lateral equivalent of halite (Garcia-Veigas *et al.*, 1995; Rouchy and Caruso, 2006). It was interpreted as an *in situ* collapse breccia produced by halite dissolution (autobreccia; Pedley and Grasso, 1993), due to the local presence of halite and gypsum moulds.

The Calcare di Base is a composite unit of carbonate (variously calcite or aragonite; Decima *et al.*, 1998), marls and locally gypsum. The most common facies is represented by a breccia made of carbonate mudstone forming m-thick beds.

Our studies revealed that, beside brecciated deposits indicating *in situ* collapes and/or very limited transport, most of the carbonate beds show very widespread sedimentary features like bed gradation, erosional bases, load structures and clay chips, suggesting a clastic origin and moderate distance transport through high- to low-density gravity flows. CdB is never associated with massive selenites but more often with clastic and laminated gypsum. The latter may occur as isolate beds, or more commonly, gypsum and carbonate may be present within the same graded bed in different positions (e.g. gypsarenite on top of carbonate breccia or massive limestone topping gypsrudite beds); in the latter case a clastic origin seems reasonable and deposition from mixed gravity flows can be envisaged. Individual carbonate beds commonly show low lateral persistency and are commonly characterised by pinch-out terminations. Coarsening and thickening upward trends are also common features of the CdB unit.

HALITE

One of the less-known product of the Messinian Salinity Crisis in the Mediterranean is salt. The facies association, age and stratigraphic position of the halite deposits are not well constrained, with a few exceptions (Lugli *et al*., 1999; Roveri *et al*., 2006; Lugli *et al*., 2007a,b).

Our new data on the Racalmuto deposit suggest common sedimentary facies for the Sicilian salt. The Racalmuto deposit is one of the several halite bodies present in the sub-surface of the Caltanissetta basin. The salt deposit reaches a maximum apparent thickness of more than 1000 m (commonly overestimated because of halokinesis) and can be divided into two main parts: 1) a lower halite unit with minor kainite and carnallite layers, and 2) an upper halite unit. These two units are separated by several mud/halite cycles with a maximum thickness of ~10 m.

The kainite zone of the lower unit consists of halite plate cumulate. These salt layers show no evidence of current structures, dissolution and/or truncation surfaces and bottom overgrowth of the halite crystals. These characteristics indicate that evaporite precipitation took place in a stratified water body, a feature that suggests the existence of a relatively deep basin (below wave base).

Going upsection the halite rocks consist of cube and inverted pyramid cumulates with variable presence of large rafts. These features suggest a shallowing upward trend for the halite sequence.

The halite layer immediately below the mud/halite layer separating the two main evaporite units is strongly modified by closely spaced dissolution pipes, filled by clear halite cement and black mud to such an extent that it appears extremely difficult to reconstruct the original facies. This piped zone can be interpreted by the effect of meteoric dissolution on subaerially exposed salt layers.

A similar zone has been described in the halite of Realmonte mine (some 22 km apart) where the piped salt layers are commonly upturned to form tepee structures and are cut by spectacular vertical fissures interpreted as the bordering surfaces of giant contraction polygons, which developed by the effect of annual temperature fluctuations on exposed salt layers (Lugli *et al*., 1999).

The exposure of the basin was interrupted by several floods which deposited argillaceous layers intercalated by newly formed halite.

The upper halite unit consists of cumulates of halite skeletal hoppers showing further vertical overgrowth (chevron) that occurred at the bottom of the basin after initial growth at the brine surface. This halite shows dissolution pipes and irregular truncation of the halite crystal terminations, indicating precipitation from a non-stratified, relatively shallow water body, characteristics very similar to the upper halite unit of the Realmonte mine, immediately above the cracked surface.

The study of the Racalmuto deposit suggests that the salt facies and the basin evolution are similar to those of the Realmonte mine. Both salt deposits are characterized by a marked drawdown of a relatively deep basin culminating with complete desiccation, probably caused by the very high sedimentation rate of such sediments (Schreiber and Hsü, 1980). After the subaerial exposure and the flooding of the basin, a new halite phase developed in a shallow water setting.

The original stratigraphic position of salt cannot be investigated in outcrop. A detailed facies analysis revealed that deposition of halite in the depocenters may be correlated to a gypsum cumulite horizon which underwent dehydration. This horizon is located between carbonate/gypsum clastic deposit traditionally ascribed to the Calcare di Base and the Upper Evaporites.

UPPER EVAPORITES

The existence of two distinct selenite units in Sicily was first pointed out by Selli (1960). They were considered as equivalent of the evaporitic units buried below the floor of the Mediterranean and were defined respectively "Gessi di Cattolica" (LE) and "Gessi di Pasquasia" (UE). Unfortunately, clear criteria to distinguish these units were not available till now.

The studies carried out in the last years on the primary evaporites of Sicily, suggest unequivocal sedimentological, physical stratigraphical and geochemical criteria to differentiate the two evaporitic units.

Like the LE, UE show a well-developed cyclic pattern. The ideal cycle of the UE (modified after Schreiber, 1997) starts with thin, laminated gypsum cumulates and gypsarenites developed on top of an alternation of fluvio-deltaic sandstone and shelfal shales. Upward the clastic component is gradually replaced by primary selenitic gypsum locally forming large domal structures. UE beds do not show branching selenite which is common in the LE (Lugli *et al*., 2006a); they are composed only of massive selenite in thinner beds with smaller crystals compared to the LE. Banded selenite have been recognised only in the lowermost cycle. Carbonatic stromatolites have never been found associated with these primary deposits. On the other hand, laminated gypsum, which always is present in the lower part of UE cycles, is not present in the LE (Lugli *et al*., 2006a).

The UE overall thickness is commonly less than the LE, and each gypsum bed does not exceed ten meters in thickness. The UE unit is characterized by a thinner basal bed of banded selenite, overlain by a cluster of 5 thicker gypsum beds. A 7th bed, just below the "Arenazzolo" unit, is usually separated from this cluster by an argillaceous interval, locally more than 50 m thick and containing up two sandstone horizons.

The UE unit shows its maximum thickness in the western Caltanissetta basin where the gypsum beds are separated by dam-thick argillaceous intervals. The terrigenous component decreases eastward and the gypsum beds tend to become more tightly packed.

The rhythmic alternation of shales with gypsum or sandstone bodies led us to recognize 9-10 lithological cycles in the UE of Sicily, thus allowing a more precise astronomical calibration of the MSC.

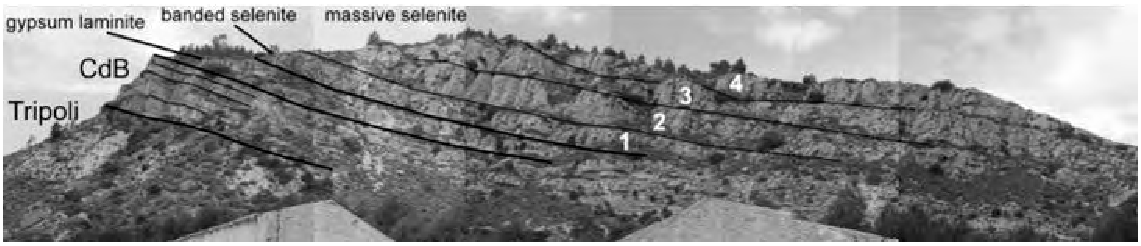

Fig. 2. Tripoli, Calcare di Base (CdB) and Upper Evaporites at Monte Gibliscemi (Sicily). No Lower Evaporites are present in this section. We interpret the gypsum laminite located between the CdB and the Upper Evaporites as the lateral equivalent of halite.

Sr isotope data

Our efforts in producing a reliable stratigraphic framework deriving from a new facies study of the salinity crisis products is here coupled with a revisitation of all available Sr isotope data in the literature and with the addition of a large amount of new data coming from sections whose stratigraphy we have studied in detail.

In this reinterpretation we have not considered literature data for which no unequivocal stratigraphic position was provided. This particularly to avoid the common problem of erroneous attribution of the Lower Evaporites to the Upper Evaporites and vice-versa. The remaining data were placed in a time-scale fitting our new stratigraphic interpretation of the salinity crisis.

Our new data confirm that the Lower Evaporites have a marine origin, although modified by continental water at various proportions, whereas the Upper Evaporites were deposited in an environment dominated by continental waters (Flecker and Ellam; 2006).

The shallow- to deep-water record of the Messinian Salinity Crisis: new insights from Sicily, Calabria and Apennine basins

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Abstract

Regional-scale physical-stratigraphic reconstruction of Sicilian basin geological evolution during the Messinian and its comparison with Calabria and Apennines basins, show that the 'Lower Gypsum' unit actually comprises *in situ* and resedimented facies separated in both space and time by the intra-Messinian unconformity. Halite bodies are associated with resedimented gypsum and Calcare di Base in Sicily and Calabria; these deposits are suggested to fully postdate *in situ* massive selenite deposition which occurred only in small and silled wedge-top and foreland ramp basins of Sicily and Apennine foreland systems while in Calabria they were not preserved. New data from the Upper Evaporites of Sicily allow cyclostratigraphic considerations suggesting that the unit comprising resedimented gypsum, carbonate and halite formed between 5.6 and 5.55 Ma. This unit records the acme of the Messinian Salinity Crisis occurred during a pan-Mediterranean tectonic phase coupled with glacio-eustatic sea-level falls at isotope stages TG14-TG12. This revised stratigraphic framework overcomes the long-lived controversies about the peripheral *vs* deep basin character of Sicilian basin, thus offering a concrete opportunity for the interpretation of the deep western Mediterranean evaporite trilogy and, more generally, for correlating shallow and deep water records of the Messinian Salinity Crisis. A Messinian scenario is envisaged with three stages characterized by different primary evaporite associations: mainly gypsum selenite in the first and third stages, carbonate, halite and potash salt in the second one associated with hybrid resedimented evaporites. Evaporite precipitation took place only in shallow basins during the first stage and in deep to shallow basins in the second and third stages. Our reconstructions suggest that the Ocean connections, even reduced during the second and third stages, likely persisted throughout the Messinian Salinity Crisis (MSC), leaving a residual marine water body whose upper part underwent periodical dilution due to a progressively larger input of meteoric waters, especially during the final MSC phase. This scenario could explain the paradox of the concomitant occurrence of marine and freshwater faunal assemblages characterizing the so called 'Lago Mare event' which shortly precedes the Zanclean marine flooding.

Introduction

The quantitative modelling of the Messinian Salinity Crisis (Meijer and Krijgsman, 2005) requires a reliable high-resolution stratigraphic framework based on regional-scale reconstruction of the geological evolution of peri-Mediterranean basins and their correlation. A well-known problem is establishing genetic and stratigraphic relationships between late Messinian shallow and deep basin successions, which explains the large number of MSC scenarios so far proposed (Gautier *et al.*, 1994; Butler *et al.*, 1995; Clauzon *et al.*, 1996; 2005; Krijgsman *et al.*, 1999a; Riding *et al.*, 1998; Rouchy and Caruso, 2006; Hilgen *et al.*, 2007). This is mainly related to the still ambiguous true nature and age of the deep Mediterranean basins evaporites (Hardie and Lowenstein, 2004) and in particular of the Lower Evaporites, a unit which should record the onset of the MSC in deep basinal settings (see Krijgsman *et al.*, this volume). Due to the lack of bio- and magnetostratigraphic constraints for the late Messinian successions, even the cyclostratigraphic approach can lead to ambiguous results if the studied sections are not well framed within their regional geologic context reconstructed through the application of physical-stratigraphic concepts and careful facies analysis. Clastic gypsum deposits, as well as the stratigraphic signature of Messinian pan-Mediterranean tectonics and its related important palaeogeographic changes, have been systematically ignored in the current models, which usually envisage a 'static' Mediterranean basin throughout the MSC.

Field studies carried out in the last years in the Sicilian basin, usually considered the best analogue for the deep Mediterranean basin evaporite succession, show that the classic stratigraphic models for this complex geologic event (Ogniben, 1957; Decima and Wezel, 1971; Decima *et al.*, 1988; Garcia-Veigas *et al.*, 1995; Butler *et al.*, 1995; Rouchy and Caruso, 2006) need to be reconsidered. Our findings in Sicily are in good agreement with the results of the studies carried out in the Apennine foredeep basin (Roveri *et al.*, 1998, 2001, 2003, 2004, 2005, 2006; Roveri and Manzi, 2006; Manzi *et al.*, 2005, 2007) and, more recently, to field observations and analysis in the Crotone Basin (Calabrian Arc; Costa pers. comm.).

SICILIAN BASIN

Some inconsistencies are apparent in the Sicilian Messinian stratigraphy, probably due to the fact that the classic stratigraphic model of Decima and Wezel (1971), subsequently modified by Garcia Veigas *et al.* (1995), Butler *et al.* (1995) and Rouchy and Caruso (2006), derives from the Caltanissetta Basin (CB), the largest depozone of the Sicilian-Maghrebian foredeep basin system, while the other basins on the wedge top (Calatafimi, Ciminna and Belice in northwestern Sicily) and the foreland ramp (Licodia Eubea) have been largely ignored. The Decima and Wezel's model describes the Messinian succession as composed by two main sedimentary cycles separated by an angular discordance recording a intra-Messinian tectonic phase. The lower cycle overlies the Tripoli Fm. and comprises the Calcare di Base (CdB), the Lower Gypsum (LG; usually referring to massive selenite of the Gessi di Cattolica Fm.) and the Halite and potash salt assemblage. The upper cycle consists of the Upper Gypsum unit (UG; interbedded gypsum laminite and selenite beds and marls of the Gessi di Pasquasia Fm.; Selli, 1960) overlain by the siliciclastic Arenazzolo Fm., in turn covered by the Pliocene, normal marine, Trubi Fm.

The stratigraphic scenarios proposed by Krijgsman *et al.* (1999a) and Rouchy and Caruso (2006) imply a single evaporite suite deposited in both marginal and deep Mediterranean basins, envisaging respectively a synchronous or a slightly diachronous onset of the MSC. The lower cycle is correlated with the deep Mediterranean Lower Evaporites (LE) and Salt, the upper cycle with the Upper Evaporites (UE). The intra-Messinian unconformity corresponds to the Messinian erosional surface (MES). According to Clauzon *et al.* (2005 and this volume) the Sicilian evaporite suite would fully predate the deep Mediterranean one. The MES, developed during the final sea-level drop and desiccation of deep basins, is placed at the base of the Arenazzolo Fm. Butler *et al.* (1995) envisaged a fully diachronous development of the Sicilian evaporitic suite across an array of sub-basins formed at different depth above the orogenic wedge controlled by the gradual evaporative sea-level fall culminating with the desiccation of deepest basins and the successive refill up to the Zanclean flooding.

LOWER CYCLE (LOWER EVAPORITES + SALT UNIT)

As the term *'Lower Gypsum'* is quite ambiguous because it is indifferently used to indicate both primary and clastic resedimented gypsum bodies formed in different sub-basins of the Sicily-Maghrebian foreland system and never showing lateral transitions, we rather prefer to introduce the terms ***Primary Lower Gypsum*** **(PLG)** and ***Resedimented Lower Gypsum*** **(RLG).**

Primary massive selenites of the PLG (Gessi di Cattolica Fm.; Selli, 1960) are present in their original position only in the innermost wedge-top basins (Calatafimi, Ciminna and Belice p.p.) and in the Hyblean foreland ramp basins (Licodia Eubea); they conformably overlie shelf to deltaic lower Messinian deposits and are *never* found associated with Halite or Calcare di Base; they are unconformably overlain by uppermost Messinian clastic deposits or by lower Pliocene Trubi and show clear evidence of subaerial exposure only at the top with important paleokarstic features, filled by upper Messinian continental deposits (Grasso, pers. comm.), in the Hyblean foreland ramp. PLG of Sicily are very similar to the equivalent units cropping out in the Northern Apennines (Vena del Gesso) and Spain (Sorbas and Nijar) basins. Individual gypsum cycles can thus be correlated basinwide throughout the Mediterranean basin (Lugli *et al.*, 2006a) suggesting deposition within the same water mass. All these primary evaporite successions lack evidence of subaerial exposure.

The RLG of the Belice basin and of the inner Caltanissetta Basin (Casteltermini, Cattolica Eraclea, Racalmuto) mainly consist of relatively deep-water resedimented gypsum deposits, emplaced by several types of gravity-flows ranging from low-density turbidity currents to giant submarine slides involving huge slabs of massive selenite (Roveri *et al.*, 2006), and are strictly associated with CdB and Salt. At a regional scale this unit thins out toward the outer Caltanissetta basin (*i.e.* southeastward) where it is also characterized by finer-grained facies dominated by gypsarenites and gypsum laminites. Rapid lateral facies and thickness changes within individual sub-basins suggest a strong topographic control and a possibly syntectonic deposition. In particular, the evidence of huge mass-wasting involving the PLG massive selenite unit points to large-scale collapses of primary evaporitic basins, probably favoured by the strong mechanical contrast between gypsum beds and intervening and/or underlying euxinic shales and marls as also documented in the Apennine foredeep basin (Roveri *et al.*, 2003; Manzi *et al.*, 2005). Deformation involving massive selenite unit has been usually related to dissolution of salt originally interbedded with gypsum (Rouchy and Caruso, 2006); one of the most famous examples described to support this hypothesis is the lower portion of the Eraclea Minoa section. In our interpretation this section corresponds to a single megabed composed of a basal chaotic division made of disarticulated blocks of massive selenite followed upward by a graded gypsrudite to gypsiltite (Roveri *et al.*, 2006). This bipartite bed bears strong similarities with the Eocene megaturbidites of the Hecho Group (Pyrenees, Spain), which can reach thicknesses up to 200 m and are the product of catastrophic gravitational collapse of carbonate platforms.

Calcare di base. The Calcare di Base (CdB; Ogniben, 1957) is a generic term that has been used to indicate several carbonate rocks with different origin and not genetically linked. The most common facies, which we refer to as the true CdB is represented by a micritic limestone (calcite or aragonite; Decima *et al.*, 1988) of evaporative and/or bacterial origin (Decima *et al.*, 1988; Guido *et al.*, 2007) but often found as brecciated deposit, usually related to the dissolution of intervening salt or gypsum also due to the local presence of halite and gypsum moulds. Our observations reveal that, beside brecciated deposits indicating *in situ* collapse and/or very limited transport, most of the carbonate beds show very widespread sedimentary features like bed gradation, erosional bases, load structures and clay chips, suggesting a clastic origin and moderate distance transport through high- to low-density gravity flows. CdB is never associated with massive selenite but more often with clastic and laminated gypsum. Within the CdB are often included deposits consisting of interbedded dolostone, euxinic shales and diatomites, and sulfur-bearing limestones deriving from the bacterial reduction of gypsum. We believe that such rocks should be set apart from the CdB as their palaeoenvironmental, genetic and chronostratigraphic meaning are likely different and should be better defined by future research.

The Calcare di Base is commonly present above structural culminations (intrabasinal topographic highs) and passes downslope to laminar gypsum deposits as documented by Pedley and Grasso (1993). Commonly observed coarsening upward sequences could witness the progressive uplift and rapid erosion of shallow-water carbonate factories. The CdB is here interpreted, in agreement with Butler *et al.* (1995), Pedley and Grasso (1993) and Suc *et al.* (1995), as the syntectonic product of penecontemporaneous dismantling through dissolution, autobrecciation and/or gravitational processes of small carbonate platforms developed in very restricted waters above actively growing structural highs within or at the borders of the main foredeep basin. Continuous uplift caused the progressive narrowing and exposure of these platform tops and the steepening of the frontal slope, promoting increasingly active destructive processes over constructional ones up to the deactivation of carbonate factories.

The CdB is considered a lateral equivalent of the PLG selenite and, accordingly, is supposed to record the onset of the MSC (Krijgsman *et al*., 1999a). However, the common occurrence of CdB at the base, within or even on top of the RLG deposits, casts many doubts about its true age.

Salt. The Salt unit, comprising halite and potash salt horizons, occurs in the core of relatively narrow synclines in the inner and central Caltanissetta basin. It rarely crops out and it is best known from mine walls. This unit shows a shallowing upward trend with deeper water cumulates at the base and a gradual upward transition to very shallow water facies with at least one subaerial exposure surface in the upper part (Lugli *et al*., 1999) related to a desiccation event which has no known equivalents within the selenite unit. This surface, first discovered in the Realmonte mine, has been recently observed also at Racalmuto (Lugli *et al*., 2006b). The salt shows a pervasive small-scale cyclicity given by cm- to dm-thick halite-clay and or anhydrite couplets. The Salt bodies do not show the precessional cyclicity characterizing all the PLG bodies of Mediterranean basins, with cyclic dilution phases recorded by euxinic shales.

UPPER CYCLE (UPPER EVAPORITES)

Based on sedimentological, physical stratigraphical and geochemical criteria the primary gypsum facies of the 'Upper Gypsum' unit can be easily differentiated from the Lower Gypsum ones. (Lugli *et al*., 2006a; also Lugli *et al*., this volume).

The UE overall thickness is commonly lower than the LE, and each gypsum bed does not exceed ten meters in thickness. The UE unit is characterized by a basal thinner bed of banded selenite, overlain by a cluster of five thicker gypsum beds. A 7th bed, just below the Arenazzolo Fm. unit, is usually separated from this cluster by a shale interval, locally more than 50 m thick and containing up to two sandstone horizons.

The UE unit shows its maximum thickness in the western Caltanissetta basin where the gypsum beds are separated by dam-thick shale intervals. The terrigenous portion decreases eastward and the gypsum beds tend to become more tightly packed. The UE lie conformably on RLG in basin depocenters while clear onlap terminations against the main structural highs can be observed. In the first case the transition is marked by a few m-thick laminar cumulite gypsum horizon, while in the second an angular discordance with the underlying CdB is often observed. This cumulite gypsum horizon shows early diagenetic features suggesting the deposition within a iperhaline water mass.

Detailed field work at regional scale led us to recognize nine to ten lithological cycles formed by the rhythmic alternation of shales with gypsum and/or sandstone beds; the 2/3 additional cycles with respect to the 7/8 evaporite cycles usually envisaged (see van der Laan *et al*., 2006) come from the thick fine-grained interval between the 6th and 7th gypsum bed. This interval contains laterally persistent sandstone horizons recording the cyclic activation of fluvio-deltaic systems, as for the sandstone facies just below the thickest gypsum beds in the Eraclea Minoa section. This observation allows us to astronomically calibrate the base of this unit very close to the TG12 glacial stage.

CROTONE BASIN (CALABRIA)

A fairly thick Messinian succession crops out in the Crotone basin. It consists of a basal unit made of resedimented gypsum and carbonate breccia layers overlying Tripoli-like deposits; the surface separating the two units is clearly erosional as evidenced by spectacular onlap terminations of clastic carbonate and gypsum beds against the eroded Tripoli (Figure 1a) whose uppermost part is characterized by a barren horizon currently under study. The resedimented gypsum unit in turn is overlain by hybrid (gypsum, carbonate and terrigenous) clastic deposits encasing halite lenses which in some cases are still in their original stratigraphic position (Figure 1b) while in this area the salt usually occurs as diapir emplaced within the Lower Pliocene deposits (Cavalieri marls). The uppermost Messinian deposits are represented by the Carvane conglomerate, a fluvio-deltaic deposit associated with Lagomare deposits witnessing a sharp change in the fluvial drainage and in the precipitation regime, similarly to what happens in the Northern Apennines and in the Betic Cordillera basins where coeval units are respectively the Colombacci and Feos-Zorreras Fms.

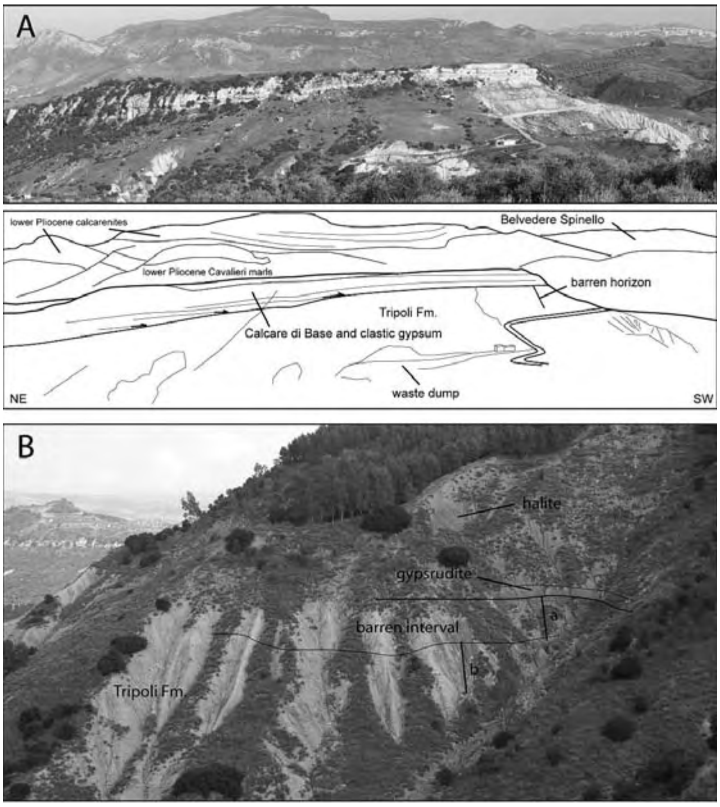

Fig. 1. The ‘Lower Evaporites’ of the Crotone Basin (Calabrian Arc). A, the onlap of Calcare di Base carbonate breccia against the intra-Messinian unconformity cutting Tripoli Fm. diatomites and euxinic shales; B, T. Lepre section: a residual halite lense in its original stratigraphic position above gypsarenites sealing the intra-Messinian unconformity.

Apennine foredeep basin

The clear differentiation between primary and resedimented gypsum bodies accumulated in different sub-basins and likely in different times has long been recognized (Roveri *et al.*, 1998, 2001, 2003, 2004; Manzi *et al.*, 2005). More recently this hypothesis has been confirmed by the recognition of a euxinic shale unit coeval of PLG below resedimented gypsum in deep basinal settings (Manzi *et al.*, 2007). No halite formed in the Apennine basins and the RLG is overlain by a very thick (up to 1,500 m) siliciclastic ‘post-evaporitic’ unit showing in its uppermost part a transition from skizohaline to ipohaline conditions (the Lago Mare event). Detailed studies allowed to establish a high-resolution stratigraphic framework for this interval which has been subdivided into two units (p-ev_1 and p-ev_2) separated by a regional unconformity aged at 5.42 Ma based on the astronomical tuning of the well-developed sedimentary cyclicity of the upper unit (Roveri *et al.*, 1998; 2004; Roveri and Manzi, 2006). Based on this stratigraphic framework, the onset of the Lagomare event occurs in the uppermost part of the p-ev_1 unit and is best approximated by the p-ev_1/p-ev_2 boundary.

A new stratigraphic model for the Sicilian basin

Like in the Apennine foredeep basin, the Messinian succession of the Sicilian-Maghrebian foreland system cannot be summarized into a single comprehensive stratigraphic colums. Two end-member stratigraphic successions can be defined corresponding to different depositional and structural settings at the onset of the MSC (Figure 2). The first corresponds to the more elevated and shallower basins developed in the innermost portion of the orogenic wedge and in the outermost foreland area; here the MSC is recorded only by PLG overlying shallow-water deposits and cut on top by a subaerial unconformity sealed by uppermost Messinian to (more frequently) Zanclean marine deposits. The second corresponds to the main foredeep (Caltanissetta basin) which was surely a deeper and more subsiding even if articulated basin during the MSC onset. Here a complex unit formed by resedimented gypsum, halite and Calcare di Base overlies the Tripoli Fm.; the lateral relationships between the three deposits suggest a articulated topography with intrabasinal highs characterized by the development of peculiar carbonate platforms separating deeps where resedimented gypsum and carbonates and halite accumulated. This unit is overlain by the second cycle Upper Gypsum; the contact is unconformable and with angular discordance on structural highs and conformable in the depocenters.

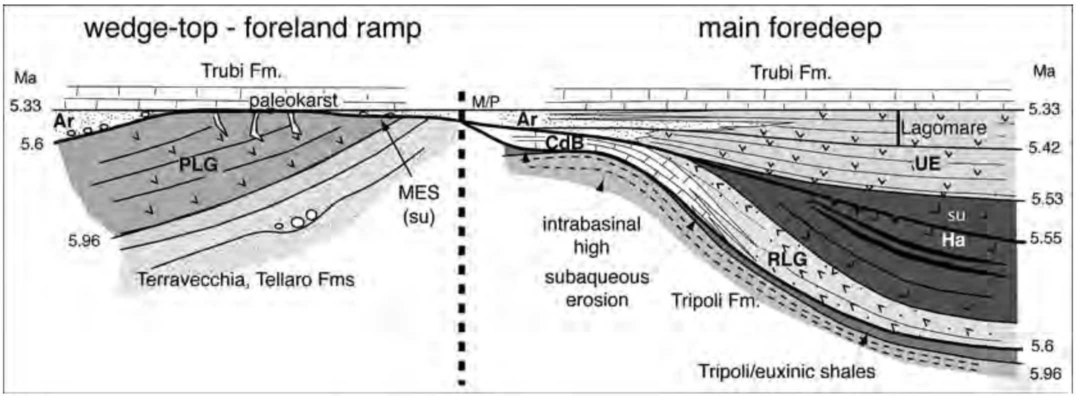

Fig. 2. Correlation of Messinian successions of Sicily across the different morphostructural settings. Abbreviations: Ar, Arenazzolo Fm.; CdB, Calcare di Base; PLG, Primary Lower Gypsum (Gessi di Cattolica Fm.); UE, Upper Evaporites (Gessi di Pasquasia Fm.); Ha, halite; RLG, Resedimented Lower Gypsum; su, subaerial unconformity; MES, Messinian erosional surface; M/P, Miocene-Pliocene boundary.

These two end-member stratigraphic successions are always separated by tectonic structures so their correlation needs a physical-stratigraphic approach. A common feature is the intra-Messinian unconformity bounding on top the PLG and the Lower Cycle of the Caltanissetta basin. This does not necessarily mean that the two units were coeval. The abundance of clastic gypsum in deeper basins comprising slided slabs of PLG suggests that these deposits postdate the PLG, also considering that no trace of emersion and/or erosion and detritus production is found within the primary massive selenite unit other than the intra-Messinian unconformity on top.

In our opinion the intra-Messinian unconformity developed diachronously across the basin and the onset of the erosion in shallower areas was recorded in deeper settings by the sudden arrival of gypsum clastic deposits. As a consequence we consider the CdB-Salt-RLG unit as formed during a phase of relative sea-level fall driven by both tectonic and eustatic-evaporative factors, thus corresponding to a large part of the hiatus observed in shallower areas.

In sequence-stratigraphic terms such a unit would correspond to a falling-stage systems tract (FSST), that is to say a linkage of genetically-related depositional systems developed during the relative sea-level fall, from its onset up to its lowest peak. This correlation between shallow and deep depositional settings provides new chronostratigraphic constraints to the evolution of Sicilian basin during the MSC (Figure 3). According to Krijgsman *et al.* (1999a) the onset of the intra-Messinian unconformity is aged at 5.59 Ma; the 9 to 10 precessional cycles recognized within the Upper Evaporites in depocentral areas allow to assess an age of about 5.53 Ma for its base (Figure 4). Our reconstruction implies that the CdB-RLG-Salt unit would have deposited in a very limited time span during a short but strong tectonic pulse, probably coupled with a moderate to high-amplitude sea-level fall. This syntectonic unit accumulated only in the main foredeep while the

PLG underwent subaerial exposure and erosion; the unit records the acme of the MSC, when the connections with the Atlantic Ocean were severely reduced, leading to the accumulation of huge volumes of evaporites in deep Mediterranean basins. Besides tectonics, the MSC paroxysmal phase was likely triggered by sea-level lowerings associated to the TG12 and TG14 isotopic stages. This reconstruction is in good agreement with the Apennine foredeep data as in that case the top of RLG is time constrained by the 5.51 ± 0.05 Ma (Odin *et al.*, 1997) age of a ash layer occurring in the lower half of the overlying siliciclastic unit.

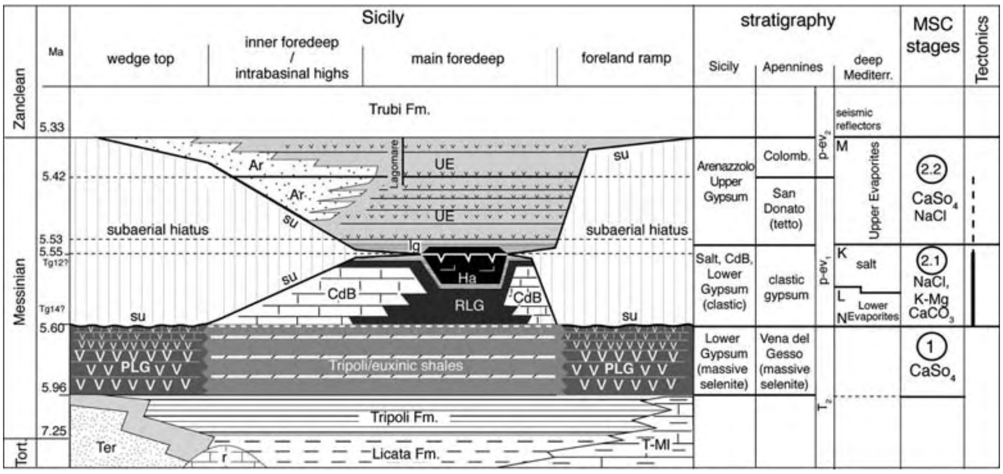

Fig. 3. Stratigraphic model for the Messinian of Sicily and correlation with the Apennines and the deep Mediterranean basins. Abbreviations: Ar, Arenazzolo Fm.; CdB, Calcare di Base; PLG, Primary Lower Gypsum (Gessi di Cattolica Fm.); UE, Upper Evaporites (Gessi di Pasquasia Fm.); Ha, halite; lg, gypsum laminite; r, pre-evaporitic reefs; RLG, Resedimented Lower Gypsum; su, subaerial unconformity; Ter, Terravecchia Fm.; T-Ml, Tellaro Fm-Marly limestones.

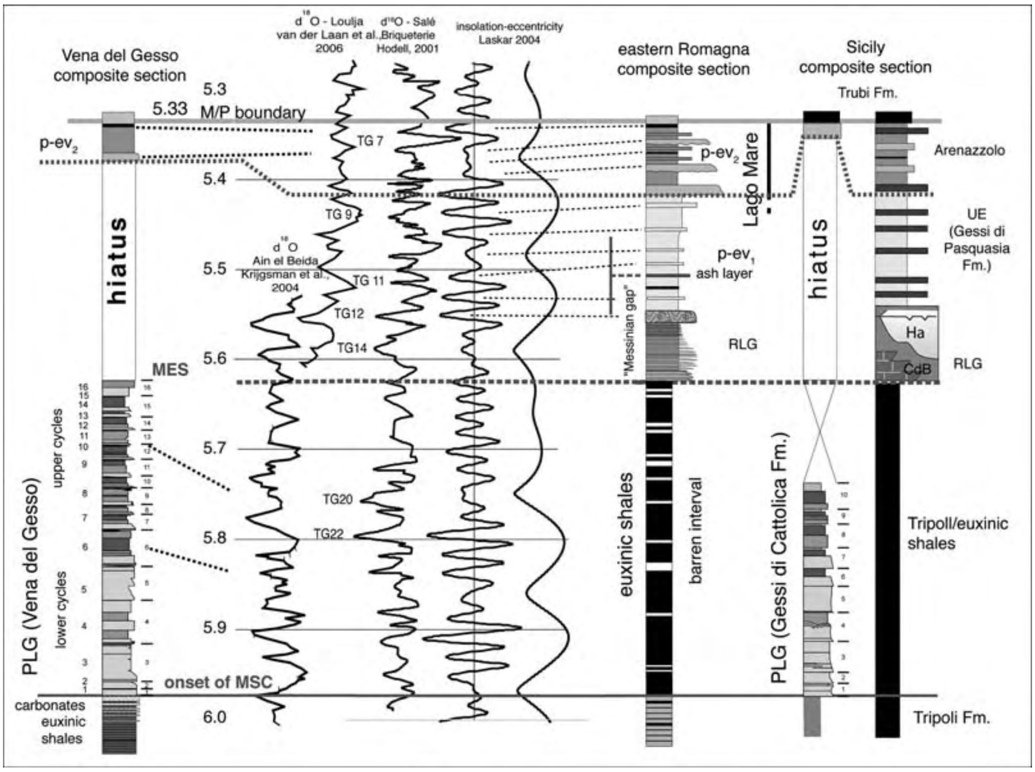

Fig. 4. Chronostratigraphic scheme of Messinian deposits and events from the Apennine and Sicily basins. Abbreviations: CdB, Calcare di Base; PLG, Primary Lower Gypsum; UE, Upper Evaporites; Ha, halite; RLG, Resedimented Lower Gypsum; MES, Messinian erosional surface.

HOT TOPICS

Massive selenite paleodepth. This point has always been greatly debated as paleodepths ranging from 200 to 1,000 m have been reported from different basins based on data from underlying deposits. Actually this unit formed in a fully subaqueous environment at moderate depths (no deeper than 200 m) within the photic zone. In fact, light and oxygen are necessary for selenite crystal growth and particularly for the cyanobacterial mats developed above crystals and are commonly preserved within them; these subaqueous conditions persisted during all PLG deposition. As a consequence the paleodepth values of underlying deposits could suggest a relative base-level fall associated with the MSC onset. However, as pointed out in Roveri *et al.* (2003), in many cases the PLG units are not in their original position (see the Vena del Gesso example) as they were involved in large-scale gliding processes favoured by the development of a highly efficient detachment horizon on top of the underlying organic-rich deposits. Moreover, the low-oxygen conditions usually characterizing the topmost pre-evaporitic phase do not allow reliable paleodepth reconstructions based on benthic foraminifera. In our opinion, the available data make it more plausible that massive selenite deposition occurred in relatively shallow and silled basins developed in different geodynamic settings and was not necessarily triggered by relative sea-level falls. Good examples of PLG developed above carbonate and/or siliciclastic shelfal deposits come from wedge-top and foreland ramp basins of Sicily (Ciminna, Calatafimi, Licodia Eubea), from the Sorbas basin, from the innermost wedge-top basins of the Northern Apennines and from Tuscany basins. Nevertheless, PLG have never been preceded by subaerial exposures.

Resedimented gypsum. Albeit systemically neglected in the MSC debate, this unit is of paramount significance in many tectonically active basins where it has a clear chronostratigraphic value as it is strictly associated to the progressive development of the intra-Messinian unconformity. Based on seismic data, the presence of clastic submarine fans within the LE has been also proposed for the Western Mediterranean (Lofi *et al*., 2005; also Lofi *et al*., this volume) and the Levant basins (Bertoni and Cartwright, 2007a,b). A common objection to such an interpretation would consider the volume of deep basin Lower Evaporites too large and that it would better applies to tectonically-active basins like the Sicilian, Calabria and Apennine ones. However, a growing body of evidence indicates that a strong tectonic pulse affected the whole Mediterranean area during the Messinian. A large volume of sediment below the MES was removed and deposited below or laterally to Salt (Lofi *et al*., 2005). The clastic evaporites that are present in the outcropping areas are characterized by a clear hybrid composition and by large amounts of shales recycled from older deposits. If this is true also for the LE in the Mediterranean lows as recently suggested (Lofi *et al*., 2005; and Lofi *et al*., this volume), then it would considerably reduce their volume estimated on the basis of seismic velocities; part of them could derive from the dismantling of first stage primary evaporites, whose original distribution is unknown, because, due to intense erosion, they are now preserved in place only in few, small basins.

Salt stratigraphic position. Decima and Wezel (1971) placed the Salt above the Lower Gypsum selenite separated by a gypsum turbidite horizon. Garcia-Veigas *et al*. (1995) and Rouchy and Caruso (2006) envisaged instead lateral transitions between these deposits, a setting that, however, has not been unequivocally documented so far. In these models, the presence of gypsum turbidites below the Salt, as well as the mine data showing that salt bodies are encased within clastic, commonly chaotic gypsum deposits (Ogniben, 1957; Selli, 1960; Decima and Wezel, 1971) has been ignored. The synchronous deposition of massive selenite and salt is not supported by field evidence and can be ruled out considering the absence of periodic dissolutions related to the precessional cyclicity well developed in PLG deposits.

The pervasive small-scale (dm-thick) cyclicity characterizing the salt bodies could be related to an annual or even pluriannual periodicity; at observed depositional rates (Schreiber and Hsü, 1980) it follows that a 1 km-thick salt body would form in less than 20 ka, *i.e.* within a single precessional cycle, thus explaining the lack of evidence for precessional cyclicity and confirming the possibility that it could have formed in a very short time interval. Salt accumulated during an acme of the tectonic pulse possibly coupled with the glacial(s)? TG14 or, more likely, TG12 (~5.55 Ma). Basin narrowing, higher brine concentration, severe water stratification and bottom anoxia characterized this selenite-free phase; the ongoing tectonic deformation and the positive balance between fast salt aggradation and subsidence accounted for rapid basin fill leading to local subaerial exposure and desiccation. The gypsum cumulite horizon observed in the flanks of salt-bearing synclines just below the conformable base of the UG, is here interpreted as the lateral equivalent of salt.

CdB age. The Calcare di Base most commonly overlies Tripoli or, locally, gypsarenites or laminar gypsum, thus implying that its deposition, at least in some areas, postdates the clastic evaporites and thus also the primary ones. The CdB is considered a lateral equivalent of the PLG and, accordingly, is supposed to record the onset of the MSC (Krijgsman *et al*., 1999a). Unfortunately, CdB has never been found associated with PLG. On the contrary, CdB is commonly present at the base or within resedimented gypsum deposits, thus casting many doubts about its true age. It occurs only in the Caltanissetta basin and the variable age obtained for its base has been interpreted as indicative of a diachronous onset of the MSC (Butler *et al*., 1995; Rouchy and Caruso, 2006), whereas its possibly unconformable character has never been taken into consideration. The claimed cyclicity of this unit has been interpreted as precession-related. We suggest that due to the mainly clastic origin of these deposits, the calibration of the CdB cyclical lithology with the astronomical parameters could be incorrect. In our reconstruction its base does not correspond to the MSC onset and the different ages of underlying deposits suggest its unconformable nature, probably related to local subaqueous erosional processes related to slope failures and or gravity flows favoured by the combination of tectonic uplift and sea-level fall.

Deep-water equivalents of PLG. According to our reconstruction the interval corresponding to the PLG unit (5.96-5.61 Ma) should be recorded in deeper-water settings by deposits underlying the CdB-RLG-Salt unit, i.e. the top of the Tripoli Fm or equivalent units. This situation has been recognized in the Northern Apennine basins (Manzi *et al*., 2007) where the uppermost part of the euxinic shales unit in deeper basins shows a barren unit correlatable to the PLG of the Vena del Gesso. Preliminary micropaleontologic and magnetostratigraphic analysis carried out on several sections in Sicily and Calabria (Gennari, pers. comm.) and the reassessment of data from the literature (Manzi *et al*., 2007; Bellanca *et al*., 2001) suggest that a similar barren unit, showing strongly variable thicknesses, also occurs in the uppermost part of the Tripoli Fm. or above it, usually referred to as Calcare di Base Fm. for the occurrence of carbonate beds (see the Capodarso, Falconara, Serra Pirciata, Marianopoli and T. Vaccarizzo sections). As previously discussed, we believe that such deposits, consisting of cyclically interbedded dolostones, euxinic shales and diatomites, have no genetic relationships with the mainly resedimented micritic limestones of the true CdB which usually unconformably overlies them as suggested by the abrupt vertical facies change and local erosional features.

The Lago Mare event. The Upper Evaporites unit and its equivalents show a similar palaeoenvironmental evolution with evidence of increasing dilution of surface waters toward the top. This is well constrained by change of faunal assemblages and by sedimentary facies which show a ubiquitous more or less abrupt upward transition to deposits which indicate a change in the drainage patterns and in the precipitation regime, possibly related to the activation of the Asian Monsoon (Griffin, 2002) and to the deglacial phase following the TG12 isotope stage (van der Laan *et al*., 2006), with the development of fluvio-deltaic systems dominated by catastrophic fluvial floods. This change occurred at around 5.42 Ma and can be observed, besides the Apennines and Calabria basins, also in Spain, Ionian Islands (Pierre *et al*., 2006), Cyprus and Eastern Mediterranean. In Sicily, the revisitation of the Eraclea Minoa section led us to similar conclusions as the uppermost part of the Gessi di Pasquasia is characterized by the development of fluvio-deltaic deposits. This climate change toward more humid conditions is in good agreement with the shift of the Strontium isotope ratio toward more depleted values suggesting a non marine origin for the Upper Evaporites (Flecker and Ellam, 1999; 2006). – This factor, together with the reduced connections with the Atlantic, may have hampered the income of surface oceanic water causing the generalized development within the Mediterranean basin of shallow-water environments not suitable or with highly stressed conditions for normal marine faunal assemblages, both benthic and planktonic. The hydrology of individual sub-basins could have been controlled by local precipitation regime and climatic latitudinal gradients. However, admitting the persistence of a residual marine water body connected with the Atlantic ocean could explain the episodic occurrence of opportunistic taxa as witnessed by the recovery of stenohaline to euryhaline fishes (Carnevale *et al*., 2006; in press).

MEDITERRANEAN-SCALE IMPLICATIONS

The classic Messinian trilogy of deep western Mediterranean basin (Lower Evaporites, Salt and Upper Evaporites) is mirrored by the Sicilian basin stratigraphy, usually considered to be their best outcrop analog. If this is true, then our reconstruction may have important implications on the age and nature of the deep western Mediterranean LE, as their possible Sicilian equivalents postdate the first stage evaporites and mainly consist of deep-water clastic gypsum. This possibility, first suggested by Roveri *et al.* (2001) and Manzi *et al.* (2005), has been documented in the Apennine foredeep (Manzi *et al.*, 2007) and could perfectly agree with the reconstruction of deep western Mediterranean basins sedimentary evolution envisaged by Lofi *et al.* (2005; see also Lofi *et al.*, this volume). The stratigraphic model for the Sicilian basin may offer important insights for the general problem of correlating shallow and deep basinal settings and comparing outcrop and seismic-imaged Messinian successions, thus allowing to better assess the genetic and stratigraphic relationships between the western and eastern Mediterranean deep basins, the latter lacking the typical evaporite trilogy (see Hübscher, this volume).

The scenario emerging from these considerations supports a three stage evolution of the Messinian Salinity Crisis, characterized by different evaporite associations reflecting long-term modifications in the Mediterranean hydrology and palaeogeography and includes (Figure 3):
- **a first $CaSO_4$ stage** (5.96-5.6 Ma) with the precipitation of massive selenite in small and moderately deep (< 200 m), periodically oxygenated basins, and deposition of organic-rich, barren shales in larger, deeper and oxygen depleted basins. Evaporite facies and isotope characteristics suggest precipitation from a relatively homogenous Atlantic-fed water body with a partially reduced outflow;
- **a second $CaCO_3$-NaCl-K stage** (5.6-~5.55 Ma) marking the MSC acme, was triggered by a combination of pan-Mediterranean tectonic and climatic factors which caused important palaeogeographic changes with drastic reduction of the Atlantic connections and a possible short-lived blockage of the Mediterranean outflow, leading to salt and evaporitic carbonate precipitation during the TG14-TG12 interval. Active tectonics and the combination of loading due to rapid salt deposition and unloading of the margins related to partial drawdown likely resulted in strong differential vertical movements of basin edges and basin floors, thus causing changes of drainage pattern and promoting large-scale mass-wasting processes on the Mediterranean slopes, leading to the accumulation of huge volumes of resedimented evaporites and clastic deposits Based on the vertical facies trend of Sicilian salt, we believe that the usually envisaged high-amplitude sea-level fall (up to 1,500 m) should be drastically reduced and that many areas did not undergo total desiccation. The subaerial erosional surface(s) in the upper part or at the top of salt could have developed diachronously in the different basins according to the local balance of subsidence and salt aggradation rate but a major desiccation event at the TG12 glacial peak is likely; in some cases a dissolution surface could have developed on top of salt following the hydrological change marking the transition to the following stage;
- **a third $CaSO_4$-NaCl stage** (~5.55-5.33 Ma), characterized again in shallow-water basins by mainly massive selenite deposition and anhydrite-halite precipitation in deeper basins (Western and Eastern Mediterranean). Evaporite precipitation likely occurred from a large stratified water body only partially connected with the Atlantic characterized by residual denser and more concentrated deep waters (hyperhaline?) capped by surface waters undergoing a progressive dilution due to a change in the precipitation regime - possibly related to the transition to a long-term deglacial phase (van der Laan *et al.*, 2006) and to the activation of the Asian Monsoon (Griffin, 2002) - and intermittent inflow of evaporated continental waters. Tectonic quiescence and generalized subsidence, especially in the Gibraltar area (Sierro *et al.*, this volume), also comprising the delayed effects of salt loading, together with the attenuation of the Asian Monsoon were possibly responsible for the progressive reestablishment of full connections with the Atlantic and the final Zanclean flooding.

Alternative scenarios envisaging the primary, shallow to deep-water evaporitic nature of the deep Mediterranean Lower Evaporites, as well as their deposition during the first stage, is of course fully suitable. In this case the role of the Sicilian basin as on land analog of deep Mediterranean basins should be reconsidered.

The Messinian Salinity Crisis in the offshore domain: an overview of our knowledge through seismic profile interpretation and multi-site approach

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Abstract

Most studies dealing with the Messinian Salinity Crisis (MSC) are based on outcrops located in peripheral Mediterranean basins (Morocco, Cyprus, Spain, etc.). These basins contain incomplete Messinian successions, making a full interpretation of this event a difficult challenge. Seismic profiles allow the exploration of the deep domain, which, contrary to the peripheral basins, registered the entire MSC event. We present here new results based on a comparative study of 13 areas located offshore, in the Mediterranean and Black Seas. The key seismic markers of the offshore MSC are erosion surfaces and depositional units. This work provides an overview of these markers and illustrates the potential of the multi-site seismic approach in increasing our understanding of the MSC. We also propose a new global and coherent terminology for MSC markers in the entire offshore Mediterranean area.

Following the workshops' conclusions, it appears that outcrops in Sicily and the Apennines may offer for the first time an onland analogue deep basins markers.

1. Introduction

Due to limitations in funding and data accessibility, most studies of the Messinian Salinity Crisis (MSC) are based on outcrops located onland (Morocco, Cyprus, Spain, Italy, etc.). A near-consensus now exists around an adaptation of the deep-desiccated basin model (Hsü and Cita, 1973), but several key points are still debated, including the detailed modalities of the crisis, the timing, duration and amplitude of the sea falls, and the significance, nature and relative relationships of Messinian deposits and erosion surfaces. This is essentially because the peripheral basins (where most detailed field observations come from) only contain incomplete Messinian successions, making a full interpretation of this event a difficult challenge. In addition, the observations from the offshore domain are only partly used in scenarii of the MSC because of scale integration problems and ambiguous labelling, leading to frequent ambiguities and misunderstandings (e.g. onshore and offshore "lower evaporitic unit"). Offshore studies have thus been less numerous than works onshore. However, the increasing quality of the geophysical seismic reflection data offers the advantage to image the Messinian markers much better than previously. It is now possible to study the spatio-temporal organisation of these markers from the inner shelf down to the abyssal plain. Seismic profiles thus allow exploring the deep domain, which, conversely to the peripheral basins, has registered the entire MSC event.

Since 2004, work on the MSC has been undertaken as part of the ECLIPSE French research programme, aiming to produce a seismic atlas illustrating the MSC markers in the Mediterranean offshore domain. Several study areas are considered, from the western Mediterranean to the Black Sea (Figure 1). We present here for the first time results based on a comparative study of these areas and highlight the potential of the offshore multi-site seismic approach in increasing our understanding of the MSC. Comparative study and multi-site approach allow analysing the impact of the MSC on margin segments and basins that have various structural, geodynamical and geological backgrounds.

During the crisis, while the margins were largely eroded, deep basins accumulated sediments under the form of thick evaporitic and detritic units. At the contact of both, in an area of highly variable extent, detritals are supposed to emplace and were until recently either missing or impossible to identify. The key seismic markers of the MSC in the offshore domain are thus erosion surfaces and depositional units.

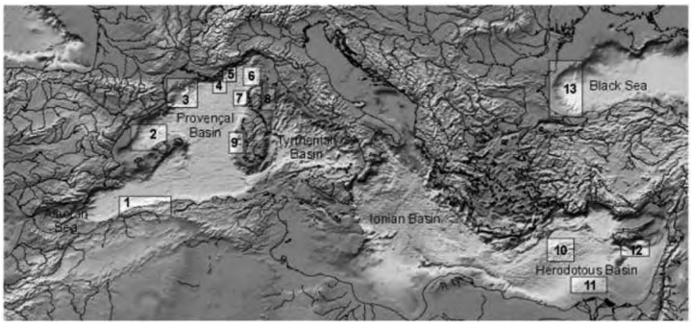

Fig. 1. Map showing the location of the 13 study areas used for the comparative study at the scale of the Mediterranean and Black Seas. The multi-site approach allows analysing the impact of the MSC on margin segments and basins that have various structural, geodynamical and geological backgrounds. Intermediate basins: Valencia Through (1) and Eastern Corsica (8); Narrow and steep margins: Provençal (4) and Ligurian (5) margins, Western Corsica (7), Western Sardinia (9); Large thick margins: Gulf of Lions (3), Nile (11), Romanian margin (13); Active areas: Algerian Margin (1), Florence ridge (10), Cyprus arc (12).

2. Messinian units in the offshore domain

2.1 Deep basin evaporites and deep basin trilogy

Messinian evaporites occupy most of the present-day Mediterranean domain. Two groups can be distinguished. The first concerns thick evaporites deposited in the large and deep/intermediate basins (mostly present-day deepest areas of the Mediterranean). The second refers to thinner evaporites accumulated in the peripheral basins (now located onshore and generally isolated from the deep basins). No stratigraphic or sedimentologic correspondences can be established between those two groups of evaporites because they are totally disconnected from a geographical and geometrical point of view.

The deep basin evaporites are generally evidenced on the seismic profiles, thanks to the transparent facies and the plastic deformation of the Messinian salt, creating listric faults and diapirs (Gaullier *et al.*, this volume). Seismic reflection studies report thicknesses up to 2,500 m in the oriental basin and up to 1,600 m in the occidental basin.

In the western Mediterranean deep basin, three distinct seismic units (Messinian trilogy) have been identified (Montadert *et al*., 1970). For a long time, they have been called Lower Evaporites, Salt, and Upper Evaporites. However, in order to avoid misleading use of these terms, we refer to them as the Lower Unit (LU) at the base, the mobile unit (MU) in the middle and the Upper Unit at the top (UU). In the eastern Mediterranean basin, the Messinian seismic trilogy (UU, MU, LU) has not been identified on the seismic profiles. In our data a thick Mobile unit is visible, but not bracketed by any LU and UU.

In the central part of the western Mediterranean basin, the "trilogy" is concordant at the base and at the top with the Miocene and the Plio-Pleistocene sequences, respectively. The absence of erosion surface in this sequence testifies to the permanent immersion of the deepest part of the abyssal plain during the "desiccation" phase. Therefore, the deep western basin has never been emerged and appears as a continuous recorder of the entire MSC. In more proximal areas, the deep basin trilogy is observed as a lateral onlap on margin foots. This peripheral onlap shows that, unlike the more distal areas, the registration of the MSC is incomplete. This onlap possibly reflects the progressive infilling of the abyssal plain by the Messinian deposits, as the subsidence apparently did not compensate the extremely high sedimentation rate in the basin (> 1,600 m in less than 300,000 years).

Only a very small part of the deep MSC sequence has been sampled during the ODP and DSDP legs (Hsü and Cita, 1973). The deep sea drilling holes failed to penetrate into the mobile unit. The halite and potash salts encountered in Holes 134, 374 and 376 all belong to top deposits. The greatest part of the Messinian evaporites (around 90%) is thus still unknown (Rouchy, 2004) and the lithology, stratigraphy and depositional environments can only be studied indirectly. Seismic profiles allow clarifying the internal structure of the deep MSC sequence.

2.1.1 Upper Unit (UU)

UU is the upper and most recent deep basin unit. It is generally 500-800 m thick in the occidental basin and is indicated by a group of parallel and relatively continuous reflectors. UU is aggrading and onlaps the margin foots. The top of this unit has been sampled during DSDP Leg XIII (Hsü and Cita, 1973) with the discover of the "pillar of Atlantis", made with dolomitic marls and anhydrite in layers. Stromatolites characterizing arid and shallow marine depositional environments (Sabkha) have also been observed, interbedded with marly levels rich in deep marine fauna, locally non salty. The top of UU has been labelled TES in this study. It is overlain by Plio-Pleistocene deposits.

UU has been evidenced in many areas all around the Northwestern-Mediterranean, where it is continuous, from the Gulf of Lions, to the Valencia Trough, Alboran and Algerian basins. However, this UU layer has not been seismically observed in the deep eastern Mediterranean (Levantine domain, Cyprus or Florence arcs of the Mediterranean Ridge). Only the thick salt unit (MU) is clearly visible on the seismic profiles, and we lack evidences for both UU and LU. In the Nile, the Rosetta Anhydrite Formation (Barber, 1981) is interpreted as the landward equivalent of the deep basin UU sampled during DSDP legs. Gypsum has been drilled in the Cretan basin and Florence rise. These deposits are either too thin (compared to the western basin) to be clearly evidenced on the seismic profiles or have been subsequently eroded by a late phase of erosion during the last stage of deposition in the eastern basin (Bertoni and Cartwrigth, 2007a).

2.1.2 Mobile Unit (MU)

This unit corresponds to the Messinian Salt and is evidenced by a characteristic transparent acoustic facies displaying plastic deformation. The reflection-free seismic facies has been interpreted as consisting dominantly of halite (Nely, 1994). MU is 600-1,000 m thick in the western basin and 1,500 m at least in the eastern one (e.g. Levantin Basin). Several internal discontinuous reflector packages are observed in the Eastern Mediterranean, separating several evaporitic sequences (Netzeband *et al*., 2006b; Bertoni and Cartwright, 2006; Hubscher *et al*., this volume; Ottes *et al*., this volume) possibly related to lithological and/or diagenetic differences. A strong erosion on top and on bottom of this unit has been observed in the Levantine Basin (Bertoni and Cartwright, 2006 and 2007a; Tahchi *et al*., 2004).

MU onlaps the Miocene margins. Listric faults linked to post MSC salt tectonics are currently observed passing progressively downslope to salt anticlines and diapirs in the more distal areas

(Loncke *et al*., 2006; Gaullier *et al*., 2006). Because the two Mediterranean basins are now disconnected, the lateral correlation between the observed MU is not possible and a synchronicity between those two units cannot be demonstrated.

2.1.3 Lower Unit (LU)

LU is 500-700 m thick and corresponds to a group of very continuous high amplitude reflectors. Recent seismic profiles suggest that LU onlaps some Miocene margins (Réhault, pers. comm.; Lofi *et al*., 2005) but this geometrical relationship is generally poorly imaged. This unit has been initially labelled "Lower Evaporites" by analogy with the Lower Evaporites of the Sicilian peripheral basin. However, this analogy is improper as no correlation is possible between those two units. In addition, the age, lithology and depositional environment of LU are still speculative, as it has never been drilled. Some authors propose that LU is entirely evaporitic and coeval from the peripheral lower evaporites (Krijgsman *et al*., 1999a). It would have deposited before 5.6 Ma. Others suggest that LU could contain a large part of clastic sediments accumulated at the beginning of the drawdown, after 5.6 Ma (Lofi *et al*., 2005). Ryan (2004) proposes a combination of those depositional environments.

2.2 Products of erosion

During the crisis, the margins were deeply eroded. Thanks to the increasing quality of the seismic data, one part of the products of this erosion is now regularly imaged in the downstream part of the main Messinian thalwegs. It corresponds to some fan-shaped accumulations labelled CU (Chaotic Unit) and also sometimes BU (bedded Unit).

The products of the margin erosion have been evidenced on many margins: Ligurian and Provencal margins (Savoye and Piper, 1991), Gulf of Lions (Lofi *et al*., 2005), Valencia basin (Maillard *et al*., 2006a), Valencia seamount flanks (Mitchell and Lofi, unpubl. data), Western Sardinia (Sage *et al*., 2006), Provencal margin (Obone Zue Obame *et al*., 2007) and on the Algerian margin (Déverchère *et al*., 2005). The Nile system is however the best documented because of the potential that these deposits represent in terms of reservoir (Rizzini *et al*., 1978; Barber, 1981; Ottes *et al*., this volume).

CU displays a characteristic chaotic seismic facies, more or less transparent. It can reach up to 1,000 m thick locally. CU is not observed on the upper slopes or on the margin shelves. It is essentially evidenced infilling the Messinian thalwegs and downslope at Messinian river mouths. It appears therefore as irregular in terms of lateral extent (and overall thickness). In some cases, CU is replaced by (Ligurian margin) or lays upon (Algerian margin) a bedded unit called BU. Downslope, CU displays a complex relationship with the other Messinian units: either beneath or above MU, and a lateral facies change to UU and/or MU is locally suspected.

Where it has been drilled (on the slopes), CU consists of sands and conglomerates intercalated with marly levels and overlain by early Pliocene deep marine sediments. These are interpreted as Messinian fluviodeltaic deposits (Rizzini *et al*., 1978; Estocade, 1978; Stampfli and Höcker, 1989; Savoye and Piper, 1991). Downslope, in its more distal part, CU may consist of subaqueous gravitary deposits resulting from an early erosion of the margin at the beginning of the drawdown (Lofi *et al*., 2005). The presence of thick resedimented deposits through gravitative processes into relatively deep waters has also been evidenced in the Apennine foredeep (Roveri *et al*., 2001).

3. Erosion in the offshore domain

Evidence for a substantial drop in sea level during the MSC has been collected from numerous records of deep erosional features in offshore areas (Ryan and Hsü, 1973). Several erosion surfaces have been evidenced on seismic data. They are labelled MES, BES, TES, IES. The MES is observed only on the margins and is systematically overlain by the Plio-Pliostocene sequence. The BES, TES and IES are observed only in the deep or intermediate basins, in association with Messinian units. These surfaces merge together upslope into the MES, generally at (or close to) the onlap point of the deep basin Messinian trilogy. The MES is thus only observed on the Miocene margin shelves and slopes.

3.1 Margin erosion surface (MES)

The MES is a widespread erosion surface generally quite well identified on the margins. It is a unique, complex poly-phased and polygenic unconformity, commonly interpreted as the result of subaerial erosion, essentially by river action and retrogressive erosion (Loget and Van Den Driessche, 2006). Onshore, the MES is characterised by the presence of deep narrow incisions ("canyons"), which correspond to the entrenchment of streams in response to the huge fall of sea level (Chumakov, 1973b; Clauzon, 1973). Offshore, numerous investigations have enabled reconstructions of the detailed paleomorphologies of the MES at several margins, revealing the existence of Messinian paleo-fluvial networks: Egyptian margin (Barber, 1981), Gulf of Lions shelf (Guennoc *et al.*, 2000); Ebro margin and Valencia trough (Stampfli and Höcker, 1989). On large margins, subaquatic processes may also have contributed to the shaping of the MES at the beginning of the drawdown (Lofi *et al.*, 2005).

The MES has been correlated with several exploration boreholes in the Mediterranean Sea but its existence has also been confirmed recently in the Black Sea (Gillet *et al.*, 2007). Boreholes located on the shelves revealed only a discordance between Miocene and Pliocene deposits (or extremely incomplete successions). Subaerial erosional features (for instance desiccation cracks and stromatolite layering (DSDP, Leg 42), fossil meanders and fluvial terraces (Stampfli and Höcker, 1989) have been described from margin edges, supporting the interpretation of fluvial erosion.

The MES is overlain by Plio-Pleistocene deposits and extends downslope to the onlap point of the deep basin Messinian trilogy deposits. There it passes laterally to the BES, TES and IES, each of these erosion surfaces being defined based on their relationship to Messinian units downslope.

3.2 Bottom erosion surface (BES)

The BES is the basinward prolongation of the MES. It is an erosion surface separating pre-MSC deposits from MSC deposits. Thus on the Miocene slopes, the BES passes in the Messinian thalweg axis, beneath CU and/or BU (Nile, Gulf of Lions, Valencia Basin, Levantine margin, Ligurian margin, Algerian margin). The BES then extends out beneath the deep basin Messinian trilogy and both UU and MU clearly pinch out against this surface. The BES also possibly extends to the base of LU. It is however difficult to estimate how far this surface extends basinward because it progressively becomes conformable with the underlying strata. Where the BES is clearly erosional, it truncates the underlying reflectors and displays locally small discontinuous gully-type incisions such as in the Valencia and Eastern Corsica basins.

3.3 Intermediate erosion surfaces (IES)

The IES are erosional discordances that are only observed within UU. From a stratigraphical point of view, they were created after the BES and before the TES. Up to now, the IES have only been observed on the Northern Ligurian and Western Sardinia margins and in the Valencia and East Corsica basins. In these basins, MU is absent and UU thus is representative of the entire Messinian deposits between several distinct entrenched sub-units (Maillard *et al.*, 2006b).

3.4 Top Erosion Surface (TES)

The TES consists of an erosion surface observed at the top of Messinian units. It separates the MSC deposits from the Plio-Pleistocene sequence. Thus, on the Miocene slopes, the TES passes in the Messinian thalweg axis, at the top of CU (e.g. Gulf of Lions, Valencia Basin, Nile). The TES extends to the top of the Messinian trilogy (top of UU). Its erosional character is clear in the Valencia basin where it consists of a very flat surface with a sinuous central paleo-valley and its tributaries (Escutia and Maldonado, 1992; Maillard *et al.*, 2006a). These characteristics have also been clearly observed in the eastern Corsica basin at the top of UU (Thinon *et al.*, 2004), on the Northern Ligurian and Western Sardinia margins, and more locally in the Gulf of Lions at the top of the CU and UU and in the Nile at the top of CU (Barber, 1981). It has also been evidenced recently on the Levantine margin, on top of the MU unique Messinian unit where this unconformity is interpreted as a subaerial exposure linked to a regression, occurring during the last stages of deposition of the Messinian unit (Bertoni and Cartwrigh, 2007a).

The TES extends towards the centre of the basins and progressively becomes concordant with the top of UU.

4. Discussion

Offshore, studies of the Messinian markers are limited by the lack of lithological and stratigraphical calibrations. In the absence of fully recovering deep boreholes, our knowledge about the nature and age of the deep evaporite sequence is weak, in particular concerning the Mobile and Lower units. Diving may bring invaluable information (e.g. cirque Marcel on the Ligurian margin, see Savoye and Piper, 1991 but they is limited because of sampling difficulties and because MSC deposits seldom outcrop in the Mediterranean Sea. Industrial boreholes could be very useful but the data are not easily accessible to the scientific community. Thus, considerable progress will be achieved when this sequence is drilled integrally. Until such time, only the seismic approach can be envisaged.

Offshore seismic studies are based on the recognition and interpretation of seismic facies. Because several lithologies can correspond to a unique seismic facies, we suspect that UU displays an important variability (in term of lithology and depositional environment) since it is recovered at river mouths (increased detrital fraction), in the centre of the deep basins (increased evaporitic fraction?) or in an intermediate basin (proportion of lacustrine fraction?). A definitive interpretation of the seismic facies requires direct well calibration.

The architectural complexity, the lateral changes in seismic facies, the deformations related to salt tectonics, volcanism or tectonics are among the factors that make interpretation difficult or equivocal at a local scale. For instance, the Messinian units found on the slope of the Ligurian margin cannot be definitely correlated with the abyssal plain units because of a major listric fault. In the same way, the MSC deposits of the eastern Corsica basin cannot be correlated with the rest of the western Mediterranean because of the presence of a volcanic intrusion at the outlet of the Messinian basin. As a last example, in the Eastern Mediterranean basin, geometry and thickness of MU have been modified by subsequent tectonics and the present day geometry does not reflect the initial deposition.

Correlation at a larger scale is limited essentially by the existence of topographic sills that disconnect the different Mediterranean basins and sub-basins. This is essentially true for the main Mediterranean basins. Although a mobile unit has been evidenced in both basins, their synchronicity is not obvious. Indeed, the principle of the communicating vessels suggests that it may exist a delay between the deposition of the MU eastern and western basins (Blanc, 2000). The knowledge of the paleo-geography of the Mediterranean and Paratethys during the MSC is also essential for restituting the paleo-connections among the basins during higher sea-levels (Clauzon *et al*., this volume).

The multi-site comparative study approach proposed here allows us to remove some of the problems discussed above and to bring new information regarding the MSC and some local and global triggering factors. The multi-site approach thus evidences the crucial impact of the initial geological-morphological context on the registration of the crisis. The response of the margin/basin is thus closely related to local triggering factors (morphology, dimensions and initial bathymetry of the area, lithology, dimension of the drainage basins and of the continental shelf, proximity and height of aerial relieves, tectonic context, subsidence, etc.). These factors will play a key role on the spatial and temporal organisation of the Messinian erosions, the location, the amount and the nature of the sediment eroded and the modalities of sediment transport and sedimentation toward/in the basins. Whatever the study area considered, we evidence a more or less complete association of characteristic seismic markers.

The MSC sea-level drawdown is testified by the erosion surfaces observed all over the Mediterranean and Black Seas. If only one erosion surface (Messinian in age) is observed on the margins, several are observed downslope. These surfaces must be clearly distinguished. We did label them according to our observations. The BES, TES and IES can be identified thanks to their relationship with the Messinian deposits. They all join each other and merge upslope into a single erosion surface, the MES, that can be traced landward. This illustrates the complexity of the MES, which appears as a diachronic and polygenic erosion surface representing the entire time interval of the crisis: Bottom erosion (BES), MSC deposits (LU, MU, UU, CU), and Top erosion events (IES, TES). The MES is also older on the upper parts of the margins than on the lower parts, as the shelves have been emerged before and over a longer period than the margin slopes.

The magnitude of the sea-level drop in the Western Mediterranean Sea can be estimated from the depth of the onlap of UU in the deep basin, corrected for the effects of post-Messinian vertical movements and compaction (Ben-Gai *et al.*, 2005; Steckler *et al.*, 2003; Tibor and Ben-Avraham, 2005). UU sampled south of the Balearic Islands contain stromatolites and anhydrite nodules characteristic of arid shallow-water depositional environments. This suggests that sea-level drop was at least as much as the depth of the depositional onlap of UU. This interpretation is reinforced by the existence of the TES and IES in the Valencia Basin, showing that sea-level changes occurred during a lowstand phase that persisted during deposition of UU. These multiple phases are interpreted as reflecting alternating episodes of the Atlantic advancing into and retreating from the Mediterranean (Escutia and Maldonado, 1992). These multiple phases could nevertheless also reflect small amplitude variations in the base-level due to climatic changes, that influence the different runoff in the basins. The TES may also be related to the so-called “Lago-Mare”, characterised by the presence of brackish shallow-water sediments in the uppermost MSC deposits (Rouchy *et al.*, 2001). This event could also attest that lacustrine settings could have formed at different elevations in the depressions during the end of the MSC.

If a very lowstand or aerial erosion is clearly suspected at the end of the MSC (TES), the subaerial/subaqueous nature (and depth of extension) of the BES beneath the onlap of UU is still a matter of speculation. Here we lack crucial information concerning the nature of LU and the thickness of the water column before, during and after MU deposition (Lugli *et al.*, this volume). This would allow us to assess how far the BES extended more basinward and how it formed in this area. A subaerial origin beneath the onlap of MU is not excluded. It would imply the formation of a subaerial erosion surface before the deposition of the Salt. In other words, the fall in sea level would have reached a maximum (greater than the onlap depth of UU) before salt precipitation in the basin.

The erosional character of the BES, IES and TES is much more visible in the Valencia Basin compared to other areas such as the Gulf of Lions. This illustrates the importance of basin paleo-depth and morphology in the registration of the erosion. In the Valencia basin, erosion is enhanced by the very low gradient of the basin floor that favoured the registration of very slight variations during the low-stand. This is also observed in the intermediate Eastern Corsica basin, which had a relatively gently sloping southward basin floor. Strong geometrical and morphological equivalence exists between those two study areas characterised by thin UU bracketed by the BES and the TES that are extremely well imaged. Only some seismic facies differences are observed, suggesting that climate may have partly controlled the deposition of UU. Their lateral equivalence however cannot be fully demonstrated in the absence of datation. However, because of their intermediate-depth, these basins could be key areas for constraining the precise timing of the Messinian events.

Regarding the erosion products, we find that CU and BU develop generally at river mouths and in the Messinian thalwegs. The internal spatio-temporal variability of CU and BU is important and the deposition of the entire detrital sequence appears as a non-synchronous event. The depositional environments (subaqueous gravitary/subaerial fluvial) may also differ significantly within the deposional unit. Such an internal variability has been evidenced in the Gulf of Lions (Lofi *et al.*, 2005). It is also observed in the Nile where CU is overlain upslope by some marly Pliocene deposits and downslope by a Messinian anhydritic unit (Barber, 1981). In the Algerian margin (west of Algiers), characterized by high reliefs on land, steep slope, tectonic activity, and existence of abundant clastic sediments, CU (and BU, in a lesser extent) is very thick and spread over the margin foot. Because CU and BU often make the transition between the eroded slopes and the deep Messinian trilogy, the fine stratigraphic relationships between these markers on slope and the trilogy in the deep basin are complex. It appears that their spatio-temporal organisation presents a high variability from one margin to another. For instance, in the Gulf of Lions, CU extends beneath MU in its distal section, whereas in some smaller systems (Sardinia, Provence, Algeria), CU is clearly imaged above MU. Such a geometrical and temporal variability possibly results from the initial morphology, lithology and structure of the margin. Large, thick and clastic shelves favouring large-scale submarine instabilities during the drawdown, allow the deposition of one part of CU before MU deposition. On the other hand, narrow margins with thin sedimentary cover or shallow substratum depict much smaller and distributed drainage slopes, and may therefore be eroded more lately, once the maximum drawdown has been reached and river power is maximum. In such a case, CU is deposited after MU.

As a last point, a major difference exists between the western and eastern Mediterranean basins. When a clear deep basin trilogy is observed in the western basin, only the Mobile Unit is recovered on seismic data in the eastern basin (excepted maybe in the Ionian basin). Although an increase of the number of internal reflectors within MU is observed toward the top of the unit, the seismic facies is very different from UU. This suggests that the paleo-environmental changes or triggering factors during the crisis were different in the two basins. This interpretation seems supported by geochemical analyses of the Messinian deposits that reveal basic differences between the eastern, central and western Mediterranean basins during the last stage of the Messinian salinity event. The western and Ionian Basin were characterized by marine brines whereas the eastern basins were rather fed with brines of continental origin (Kushnir, 1982). The synchronicity of MU in both basins is also far from obvious.

5. Conclusion

This study proposes for the first time a global and coherent terminology for MSC markers in the entire offshore Mediterranean area. We also compare several study areas characterised by various structural and geodynamical contexts. This multi-site approach is based on seismic data interpretation. It allows us to document the way the MSC left its imprints in the offshore domain. The sedimentary and morphological response of the margin/basin depends of the local/global triggering factors. Thus it is important to know the evolution of the study areas since the achievement of the MSC and to redefine the initial morphology of the margins and the paleo-topography/bathymetry of the Mediterranean sub-basins (and their connections). This restitution must take into account the quantification of the successive deformations that are very contrasted in the Mediterranean. Whatever the study area considered, we observe a more or less complete association of characteristic seismic markers. Some global triggering factors and superimposed local trends can be discriminated, allowing us to discuss: (1) the existence of several erosion surfaces in the basins merging together upslope, as well as associated detritals; (2) the amplitude of sea-level fall during the crisis and evidence for sea-level oscillations at low-stand; (3) the importance of the initial Miocene geological-morphological context on the organisation of the Messinian markers in the basins.

Implications of Workshop conclusions

The new interpretation of Sicily as a locally deep basin (Roveri *et al.*, this volume) has strong implications for the geophysician community studying the MSC offshore. Indeed, interpretations of the Messinian seismic markers offshore are limited by the lack of lithological and stratigraphical calibrations. Outcrops in Sicily and in the Apennines may thus offer for the first time an onland analogue to the deep-water records located in the present day deep Mediterranean basins, thus allowing direct comparison. This approach may lead to a possible complete/partial temporal and lithological calibration of the deep basins markers.

Following the CIESM Workshop in Almeria, the main new points that we need to take in consideration are as follow: 1) In the Western deep Mediterranean basin, the seismic facies, the geometrical configuration and the possible lithology of the Messinian units presented in this study seem compatible with the interpretation from outcrops in Apennines and Sicily (Roveri *et al.*, this volume). Several analogies support a possible correlation between the Reworked Primary Gypsum and Halite observed onland (Roveri *et al.*, this volume) and the deep basin Lower and Mobile Units respectively. The possible correlation between the Upper Evaporites onland and the Upper Unit offshore needs to be clarified. 2) Ottes *et al.* (this volume) suggest that the lowest halitic sequence of the Mobile unit may be Tortonian in age. This major point must be confirmed from a biostratigraphic point of view. Indeed, such an age, pre-dating the onset of the MSC, would raise important questions concerning the depositional models in the Eastern Mediterranean basin and possible correlations with the Western basin.

Acknowledgements: this work was undertaken as part of the ECLIPSE research programme.

Salt tectonics in the deep Mediterranean: indirect clues for understanding the Messinian Salinity Crisis

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Abstract

The massive salt layer deposited during the Messinian Salinity Crisis in the deepest parts of the Mediterranean creates an huge Plio-Quaternary thin-skinned tectonics, dominated by gravity gliding and spreading. The four regional examples presented here, respectively: 1. The North-Balearic basin (Rhône deep-sea fan); 2. The Provençal margin (offshore the Maures Massif); 3. The Egyptian basin (Nile deep-sea fan) and 4. The Algerian margin (offshore Algiers), display the same 2-D structural style (i.e. from upslope to downslope), with proximal extension, mid-slope translation, and distal shortening. Regional differences in 3-D style, and especially the structural framework mainly result from interferences between sedimentation, salt tectonics and crustal tectonics, "active" (neotectonics) or "passive" (structural inheritance). We also aim in this study at identifying how salt tectonics and salt-related structures can constitute indirect clues for understanding some aspects of the MSC, especially, the Messinian paleotopography and paleobathymetry and the distribution of the detrital units.

1. Introduction

The recent (i.e. Plio-Quaternary) sedimentary architecture in the deep Mediterranean basin is commonly disturbed by vigorous salt tectonics related to the presence of a thick evaporitic Messinian mobile layer deposited during the Messinian Salinity Crisis (MSC), while the margins were also subjected to large fluxes of clastic sediments. Some researchers working on the Messinian Salinity Crisis view salt-related structures (such as diapirs or faults) as annoying perturbations that prevent any clear understanding of the spatial and time evolution of the MSC sedimentary units and surfaces since salt structures affect and perturb the calm seismic sequences observed offshore. Others consider that, conversely, salt tectonics can be of help to better understand the MSC by providing several indirect but reliable clues. In this paper, we first illustrate the main characteristics of salt tectonics in the deep Mediterranean using four geographic examples

(Figure 1): 1. The North-Balearic basin (Rhône deep-sea fan); 2. The Provençal margin (offshore the Maures Massif); 3. The Egyptian basin (Nile deep-sea fan) and 4. The Algerian margin (offshore Algiers). Second, we illustrate how we can use salt tectonics as a guide to better understand some aspects of the MSC in the deep parts of the Mediterranean.

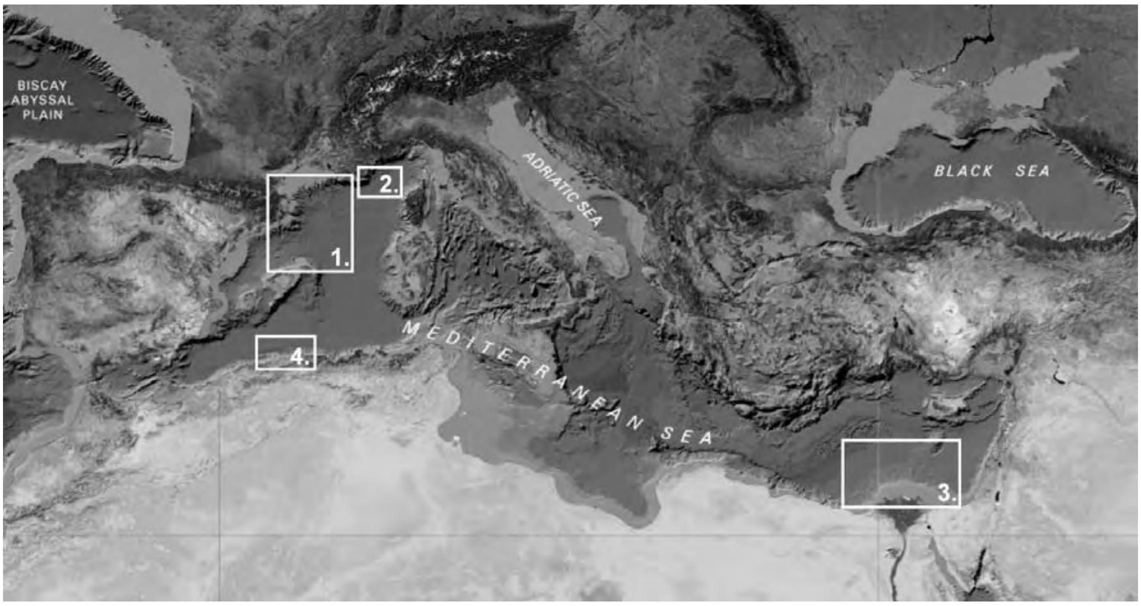

Fig. 1. Location of the study areas described and compared in this work: 1. North-Balearic basin (Rhône deep-sea fan); 2. Provençal margin (offshore the Maures Massif); 3. Egyptian basin (Nile deep-sea fan); 4. Algerian margin (offshore Algiers) (Map modified from <www.ngdc.noaa.gov/mgg/gebco/posters>).

2. Characteristics of salt tectonics in the deep Mediterranean

Plio-Quaternary tectonics in the deep Mediterranean is dominated by gravity gliding and spreading above the thick, mobile Messinian evaporites and is characterized by proximal extension, mid-slope translation, and distal shortening (Figure 2, Vendeville, 2005). The distal region often comprises circular or elongate diapirs, whose rise was driven by combined shortening and sediment loading, rather than by density inversion. We interpreted multibeam bathymetric data and 6-channel seismic profiles from several recent surveys: (1) the PROGRES cruise (2003) in the deep-water North-Balearic Basin, including in, and westward of, the Rhône deep-sea fan, (2) the MARADJA cruise (2003) along the margin and in the deep basin offshore Algeria, (3) the MAURESC cruise (2003) along the Provençal margin and (4) the PRISMED (1998) and FANIL (2001) cruises on the Nile deep-sea fan. These analyses allowed us to (1) identify precisely the geometry and distribution of salt-related structures and (2) investigate the relationships between sedimentation, gravity-driven thin-skinned salt tectonics and thick-skinned crustal tectonics.

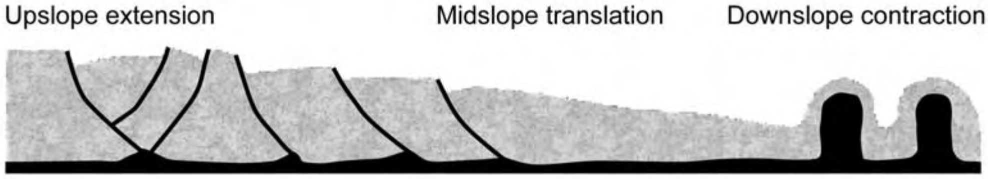

Fig. 2. Structural domains due to gravity spreading above a mobile layer (modified from Vendeville, 2005).

Western Mediterranean examples

In the Western Mediterranean, the morphology of the top of the mobile salt results from a combination of at least three main parameters:

1. For the three areas concerned (North-Balearic basin, Provençal margin and offshore Algeria, Figure 3A), the regional salt top depth distribution and the upslope salt pinch-out reflect the initial morpho-structure of the basin (variations in shape and orientation of the margin) and the basin's late evolution (impact of the Messinian Salinity Crisis and subsidence of the sediments).

2. Local perturbations result from salt tectonics, especially the numerous diapirs in the deepest parts, such as in front of the Rhone deep sea fan (Figure 3A1, Gaullier *et al*., 2006), at the base of the Provençal margin (Figure 3A2, Obone Zue Obame E., 2007) and in the western part of the Algerian area (Figure 3A3, Gaullier *et al*., 2006). The location, orientation and 3-D geometry of the salt anticlines, diapirs and ridges and associated depocenters (minibasins) are controlled mainly by differential sedimentary loading during gravity spreading and gliding of the brittle-ductile series. The 3-D network of salt ridges, as observed in the three areas, suggests that salt-related thin-skinned contraction was multi-directional.

3. The role of thick-skinned tectonics depends on the local geodynamic setting. In the North-Balearic basin, reentrants of the upslope diapir boundary are unmistakably aligned above the Catalan and North-Balearic transfer zones (corresponding to basement steps). This geometry attests that the subsalt basement exerts significant "passive" structural control on salt tectonics (Maillard *et al*., 2003). Conversely, in some places along the Algerian margin, located on the inner Europe-Africa convergent plate boundary, salt is more passively involved in the play of active ramps and flats (Déverchère *et al*., 2005, Domzig *et al*., 2006), and depicts an uplifted eastern area and squeezed salt walls and anticlines outlining the NW-SE crustal compressional stress direction (Gaullier *et al*., 2006).

In the North-Balearic basin, regional thickness changes in the brittle layer are related to the distributary channel-levees system of the Rhone deep-sea fan whereas local variations are directly associated with the salt-related deformation (segmentation in ridges and minibasins, Figure 3B1). In the Algerian basin, the lateral thickness changes correspond, in the west, to the segmentation in ridges and minibasins whereas, in the east, tectonic uplift has created a wedge-shaped basin, where strata thicken upslope (Figure 3B3). In both cases, the influence of the crustal tectonics on salt tectonics is strong whether this influence is active or passive. Conversely, studying the geometry and distribution of the salt structures and the relationship between the depth of the top salt and the brittle cover thickness appears to be a very good way to distinguish between deformation caused by salt tectonics alone and deformation directly controlled by neotectonics or by inherited structures.

Eastern Mediterranean example

In the Nile deep-sea fan, the preexisting subsalt topography and bathymetry also have greatly influenced the pattern of salt structures, but in a different manner than in the western basin (Figures 3B2 and 3C, Gaullier *et al*., 2000; Loncke *et al*., 2006). Sedimentary loading of Messinian evaporites triggered gravity gliding-spreading, causing proximal extension, mid-slope translation, and distal contraction. Minibasins first formed during progradation. These are found only in a narrow deformation corridor and are bounded by two main families of salt ridges. At the present time, the NE-SW ridges are widening and rising, whereas the NW-SE ridges are being shortened and reactivated as strike-slip faults guiding an overall northwestward escape. This structural fabric results from recent collision of the distal tip of the prograding deep-sea fan against the large Eratosthenes seamount. The mount acted as a distal buttress preventing further northeastward spreading, and causing reactivation of a minibasin network initially similar to that of the Sigsbee area (Gulf of Mexico, Gaullier and Vendeville, 2005) in contractional, extensional and strike-slip regimes. Comparison between the thickness maps of mobile salt (Figure 3C) and brittle sedimentary cover (Figure 3B2) clearly illustrates the role of both sedimentary loading and Messinian palaeotopography.

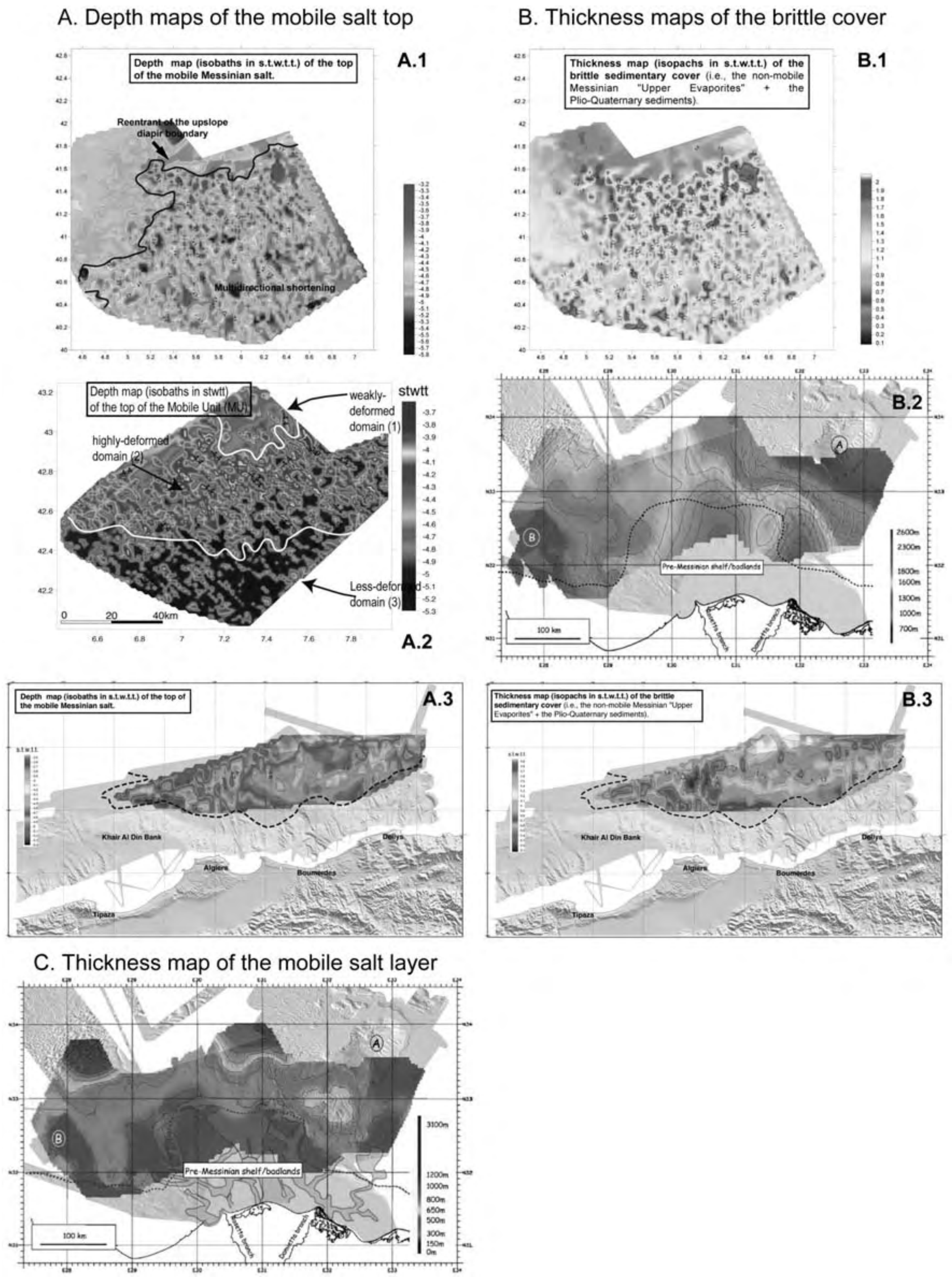

Fig. 3. **A.** Depth maps of the mobile salt top (in s.t.w.t.t.): A1, A2 and A3 respectively correspond to the North-Balearic, Provençal and Algerian areas (see location on Figure 1 and text for references). **B.** Thickness maps of the brittle cover (i.e. non-mobile Messinian layers (Upper Units, see Lofi *et al.,* this volume) + Plio-Quaternary sediments): B1 (in s.t.w.t.t.), B2 (in meters) and B3 (in s.t.w.t.t.) respectively correspond to the North-Balearic, Nile and Algerian areas (see location on Figure 1 and text for references). For B2, Areas A and B are two Messinian bathymetric or topographic highs onto which no salt was deposited. **C.** Thickness map (in meters) of the mobile salt layer of the Nile deep-sea fan (Loncke *et al.,* 2006).

3. Characteristics of the relationships between Messinian Salinity Crisis units

Current studies focus on the relationships between Messinian Salinity Crisis units in the deep-water Mediterranean using for the first time a new common terminology (see Lofi *et al*., this volume) that allows comparing several areas of this domain. In this preliminary work, we aim to identify how salt tectonics and salt-related structures can constitute indirect clues for understanding some aspects of the MSC, especially, the Messinian paleotopography and paleobathymetry and the distribution of the detrital units. We present here the main geometrical characteristics of the relationships between the different MSC units.

Along the Provençal margin, offshore the Maures Massif (Area 2 on Figure 1), salt tectonics appears to be a good tool to better constrain the distribution of detrital sediments and the location of the upslope initial salt pinch-out (Obone Zue Obame *et al*., 2007). For example, the location of the highest fault detaching on salt (Limit 3 on Figure 4) can be used to better reconstitute the geometry of the initial salt pinch-out, before the salt flowed seaward. Another interesting observation is the correlation between the downslope limit of the detrital unit (7 and 8 on Figure 4) and the dense cluster of salt diapirs (5 on Figure 4). A similar correlation also exists in the less-deformed domain (Figure 3A2; corresponding to the UUc location). The detritic overload favours the downslope salt migration and the diapir rise.

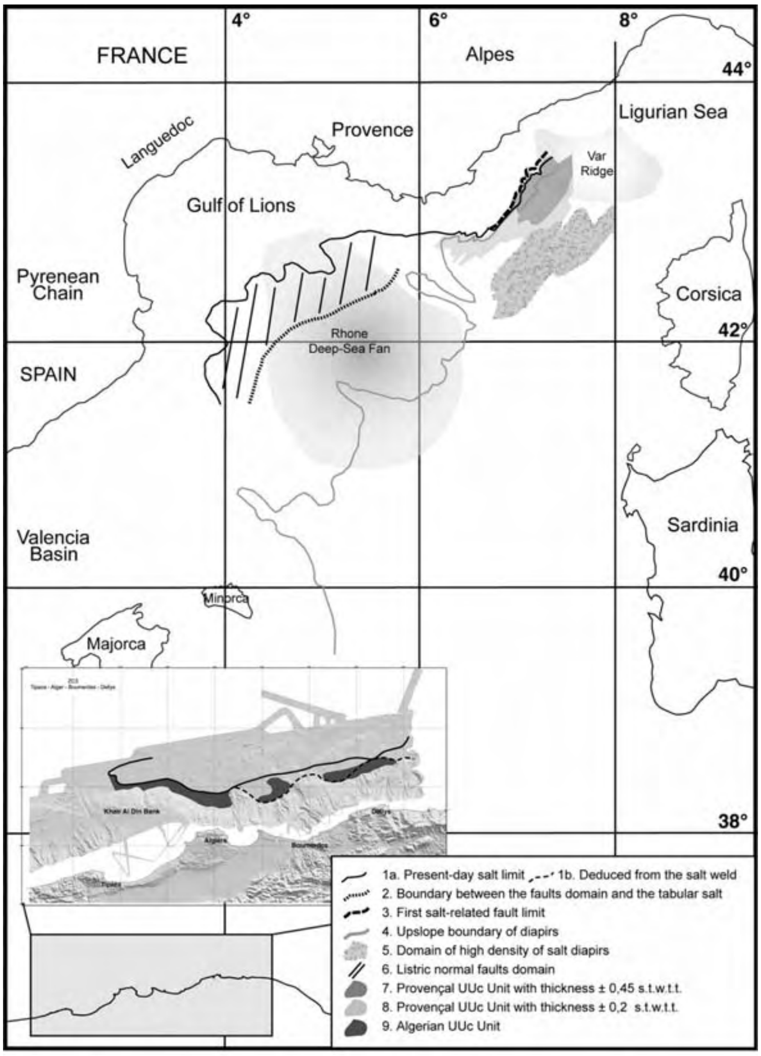

Fig. 4. Schematic map of the relationships between the salt-tectonics markers and the Messinian detritism (modified from Gaullier and Bellaiche, 1996; Gaullier *et al.,* 2006; Maillard *et al.,* 2003; Dos Reis *et al.,* 2005; Obone Zue Obame *et al.,* 2007). See Lofi *et al.,* (this volume) for the labelling of the MSC markers.

In the Nile deep-sea fan (Area 3 on Figure 1), the dotted line on Figure 3C indicates the upslope pinch-out of the mobile salt. The Messinian clastic units are located south of it, as indicated by the network of Messinian canyons (Figure 3C). Because our data set could not image directly the detrital units, we used the indirect clues provided by the salt structures to delineate their limit using a simple approach: where there are no faults or diapirs affecting the Plio-Quaternary cover, the Messinian deposits are not mobile and hence are detritic! Salt thickness salt and salt structures were also useful to better constrain the Messinian paleotopography, for example to identify large positive bathymetric highs where no salt was deposited such as on A (Eratosthenes Seamont) and B on Figure 3C.

Along the Algerian margin, offshore Algiers (Area 4 on Figure 1), salt structures can also be used to locate more precisely the initial upslope salt boundary: in some areas, salt was initially present, but later nearly all the salt flowed away, leaving only a remaining salt weld. However, because salt welds appear as very bright seismic horizons (limit 1b on Figure 4, Gaullier *et al*., 2006), their presence is an excellent clue for paleogeographic reconstruction. Moreover, the variation in salt thickness between the western and eastern domains is marked by a steep north-south limit that could be attributed either to a Messinian bathymetric high or to a recent tectonic boundary (Figure 3A3).

In the Gulf of Lions (Area 1 on Figure 1), Messinian detrital units are found beneath the mobile salt (Lofi *et al*., 2005). Also, the limit of the Upper Unit (Upper Evaporites) matches almost exactly the present-day landward salt pinch-out. Therefore the limits 1, 2 and 4 on Figure 4 correspond directly to the salt tectonics effects but do not provide any major information about the geometric relationships between the MSC units, except for the upslope limit of salt deposition.

4. Conclusions

Our preliminary study aims at using salt-related structures as clues, rather than obstacles, for a better understanding of the Messinian Salinity Crisis. Data from salt tectonics must be carefully analyzed because the observed geometries of the MSC units result *pro parte* from salt movement (for example: salt pinch-out, strata tilting, lateral correlation between similar seismic facies on both compartments of salt-related faults, etc.). Conversely, these data can serve as useful guides to (1) reconstitute the depositional geometry of the Messinian salt basins (upslope salt pinch-out, positive bathymetric or topographic highs having no salt), (2) delineate the distribution of detrital deposits. Furthermore, the bathymetric slope is the primary parameter driving deformation and is controlled mainly by the sediment influx. Therefore, the gravity-driven deformation of the salt and its overburden reflects the regional depositional history and, in the case of the MSC, its analysis can contribute to better constrain the reconstruction models.

Stratigraphy, fluid dynamics and structural evolution of the Messinian Evaporites in the Levantine Basin, Eastern Mediterranean Sea

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Abstract

The mobile unit (MU) of the Messinian evaporites in the Levantine Basin is up to 2 km thick. It was deposited in a basin of 2-3 km water depth. The Oligocene to Middle Miocene strata beneath the MU was partly eroded. 6 evaporite sequences have been identified in the MU. Four of them are seismically transparent and are characterized by interval velocities of up to 4.6 km/s, which is typical for halite. The other two sequences reveal subparallel internal reflections and interval velocities below 4 km/s, which suggests vertical changes in the evaporite facies, intercalated clastics or trapped fluids. Prior to deposition of the Pliocene-Quaternary overburden, the evaporite sequences were strongly deformed by compressional folds and faults and the top of the MU was eroded or subroded. The syn-depositional deformation of the MU may have resulted from subsidence of the deep basin and uplift of the Levantine hinterland due to the onload of the MU. Both processes would have enhanced the dip angle of the basin floor and caused the salt to creep towards the deepest part of the Levantine Basin. A second thin-tectonic phase (gravity gliding) started contemporaneously with significant mass wasting off Israel during Pliocene times. The sediment load of the more than 3 km thick Nile Fan squeezes the MU in a north-east direction through the bottleneck between the Eratosthenes Seamount and the Levantine margin. The onload of the sediment prism off Israel has only a slight impact on the lateral salt tectonics. Vertical fluid migration through the MU and fluid escape out of the MU is well documented by seismic data. A Dead Sea transform fault related plate-tectonic overprint of the MU by strike-slip tectonics is likely.

1. Introduction

It is generally accepted that a salt giant, i.e. a tabular salt layer of some 10,000 km^3 volume and up to some km thickness, has a significant impact on the evolution of the hosting basin. Owing to its viscous rheology, salt is capable of decoupling deep-rooted tectonics from the supra-salt response. Salt tectonics controls the formation of complex traps for hydrocarbon or metals. Lateral salt flow may cause subaerial or submarine land slides. Salt diapirs are potential waste repositories. The interaction of fluids and salt may cause subrosion 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.

The Levantine Basin in the south-eastern Mediterranean Sea is a world class site for studying the early evolution of such a salt giant, since the mobile unit (MU) of the Messinian evaporites in the deep basin is comparatively young, the sediment load varies along the basin margin, the evaporites are little tectonically overprinted, and the geometry of the basin and the overburden is well-defined. On a regional scale, the high interest in the analysis of the MU is based on the fact that the so-called Messinian Salinity Crisis (MSC) represented the most significant environmental change in the Mediterranean realm. The reconstruction models are based on the analysis of evaporites in the marginal basin, which led partly to contradictory models (see Rouchy and Caruso, 2006 and the references therein). Finally, the deep biosphere of such an extreme habitat is absolutely unexplored.

During the last few years, new attempts were made to unravel the structural evolution of the MU in Levantine Basin and associated fluid dynamics. Since 2004 several studies have been published in which the evolution of the Levantine basin is discussed by means of academic seismic data. (Loncke *et al*., 2004; Gradmann *et al*., 2005; Loncke *et al*., 2006; Netzeband *et al*., 2006a, b, Hübscher *et al*., 2007; Hübscher and Netzeband, 2007). The release and subsequent publication of industrial 2D and 3D-seismic data led to a giant step forward in the understanding of salt tectonic related processes (Martinez *et al*., 2005; Bertoni and Cartwright, 2005, 2006, 2007a; Gardosh and Druckmann, 2006).

In this paper we will summarize the recent achievements in understanding salt dynamics in the Levantine Basin and point out the ongoing debates. Since most results are based on seismic interpretation it should be noted that due to the limited band width of the seismic wavelet the vertical resolution is quite limited compared to outcrop studies. For instance a 50 Hz seismic wavelet has a wavelength of about 40 m in the Pliocene-Quaternary sediments and about 80 m in halite layers. It follows that vertical resolution is limited to some 10 m. Consequently, all conclusions drawn from seismic interpretation have to be considered under this limitation.

2. Geological framework

The Levantine Basin in the south-eastern Mediterranean Sea is bounded to the south by the Egyptian and to the east by the Levantine coast (Figure 1). The Eratosthenes Seamount in the north-west of the basin is considered to be a continental fragment of the African plate (Makris *et al*., 1983). Between the Eratosthenes Seamount and the Egyptian coast there is the gateway to the

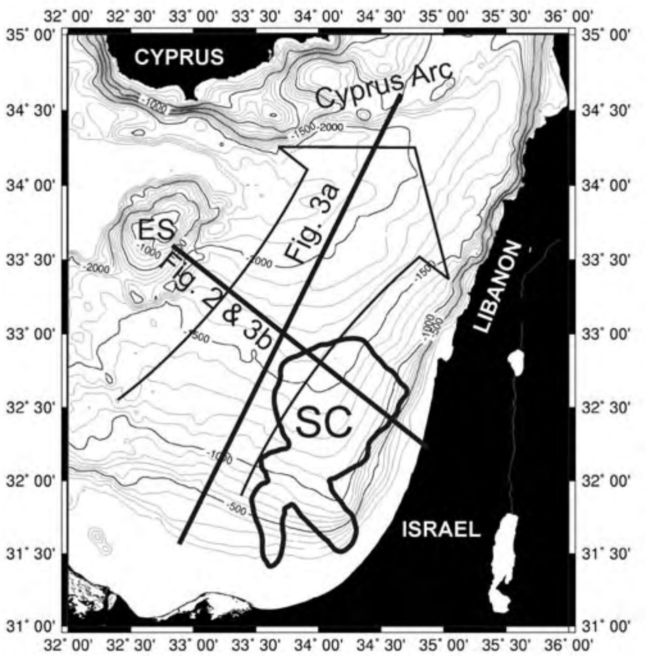

Fig. 1. Map of the Levantine Basin. Black lines show locations of cross-section in Figure 3. The arrow indicates the main gliding direction of the mobile unit (MU) of the Messinian evaporites (after Netzeband *et al.,* 2006a). The MU is squeezed through the bottleneck between Eratosthenes Seamount (ES) and the basin margin to the east. SC: slump complex (after Martinez *et al.,* 2005).

Herodotus Basin to the west. The Levantine Basin includes the northward moving African plate, the postulated Sinai sub-plate (Almagor, 1993; Mascle *et al.*, 2000), the N - NW moving Arabian plate, and the westward moving Anatolian plate. The Cyprus Arc, which results from the collision between the African and Eurasian plate represents the northern boundary (e.g., Robertson *et al.*, 1998; Vidal *et al.*, 2000a).

Recent studies showed that the Levantine Basin is underlain by stretched continental crust (Vidal *et al.*, 2000b; Gardosh and Druckman, 2006; Netzeband *et al.*, 2006b). The basin-fill deposits reach a thickness of 14-16 km (Netzeband *et al.*, 2006b; Gardosh and Druckmann, 2006, Figure 2). The basin is considered to be a relic of the Mesozoic Neo-Tethys Ocean (Robertson and Dixon, 1984; Garfunkel, 2004). The initial rifting occurred in the Middle Triassic in a northwest-southeast direction (Garfunkel, 1998; Robertson, 1998). Inversion and hence contraction pulses started in the Upper Cretaceous and ended in the Miocene. The folding was associated with the closing of the Neo-Tethyan ocean, the so-called Syrian Arc inversion and contraction (Gardosh and Druckmann, 2006). A number of smaller fault zones were interpreted in the Levantine Basin, which were associated with the rifting and contraction phase. Several SW - NE striking shear zones converge towards the north, e.g., the Pelusium Line, the Hinge Line and the Damietta-Latakia Line (Neev, 1975, 1977; Neev *et al.*, 1976; Abdel Aal *et al.*, 2000). There is some evidence that these faults are still active (Gradmann *et al.*, 2005; Netzeband *et al.*, 2006a). However, as shown by Gardosh and Druckmann (2006, Figure 2), these faults do not significantly overprint the Miocene to recent succession in the central basin.

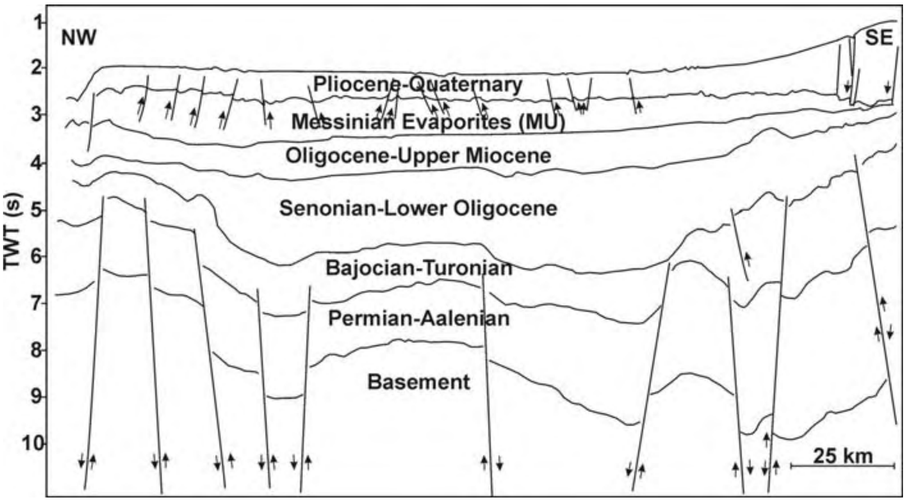

Fig. 2. Line-drawing of a seismic time section between the central Levantine coast and the Eratosthenes seamount (after Gardosh and Druckmann, 2006). See Figure1 for location.

In Late Miocene (5.96 Ma ago) a combination of tectonic uplift, combined with other factors, caused a narrowing of the western connection to the Atlantic Ocean and initiated the Messinian Salinity Crisis (see Executive Summary of this volume). The water shortage and the high evaporation rates in the Mediterranean climate resulted in a sea level drop, an increase in the salt concentration finally lead to precipitation. The first reported increase in salinity took place in Sicily at 6.26 Ma (Blanc-Valleron *et al.*, 2002). According to the chronostratigraphic scheme of Clauzon *et al.* (1996) or Krijgsman *et al.* (1999a) the precipitation of the MU started around 5.6 Ma during the middle of the Messinian Salinity Crisis (MSC). The end of the MU formation and the rapidity with which the Mediterranean basin was refilled at the end of the MSC is debated, the given time intervals varying between a few thousand years (Clauzon *et al.*, 1996) and about 200,000 years (Krijgsman *et al.*, 1999a). Hilgen and Langereis (1993) dated the end of the salinity crisis to 5.33 Ma. The lowered base of erosion during the MSC caused the drainage channels to incise canyons and valleys into the continental shelf (Garfunkel *et al.*, 1979; Almagor and Garfunkel, 1979). According to Maillard *et al.* (2006a) and by analogy with the Western Mediterranean we will use the terms Top Erosion Surface (TES) for the upper boundary of the MU and the term Basinal Erosion Surface (BES) for its base. The Marginal Erosion Surface marks the Messinian erosional unconformity where no MU is present.

The Plio-Quaternary deposits overlie the MU unconformably (Almagor, 1984) and consist mainly of Nile derived sediments (Ross and Uchupi, 1977). South of Haifa the continental shelf and slope are formed by a broad and smooth shelf and the easternmost part of the Nile Fan (Almagor, 1984).

3. Structural evolution of the Messinian evaporites

3.1 Overall structure

The evaporites in the Levantine Basin reach a maximum thickness of about 2 km. According to back-stripping analysis of Netzeband *et al*. (2006b) the initial basin depth prior to MU deposition lay between 2 and 3 km. The underlying strata are partly eroded (Bertoni and Cartwright, 2006).

Two cross-sections elucidate the overall structure of Late Miocene to recent deposits (Figure 3). In the east, a series of anticlines of the Syrian Arc fold belt acted as a structural barrier indirectly governing the overall landward extension of the evaporites (Bertoni and Cartwright, 2006; Gardosh and Druckmann, 2006). The load of the Nile Fan pushes the entire evaporites in a NNE direction and parallel to the bathymetric gradient. In front of the lower Nile Fan, the evaporites are thickened due to forebulging (Figure 3a). In the bottleneck between the Eratosthenes Seamount and the Levantine slope the evaporites are squeezed. In the north, the Cyprus Arc acts as a backstop, where compressional folds strike parallel to the arc as it is revealed in bathymetric data (Benkhelil *et al*., 2005).

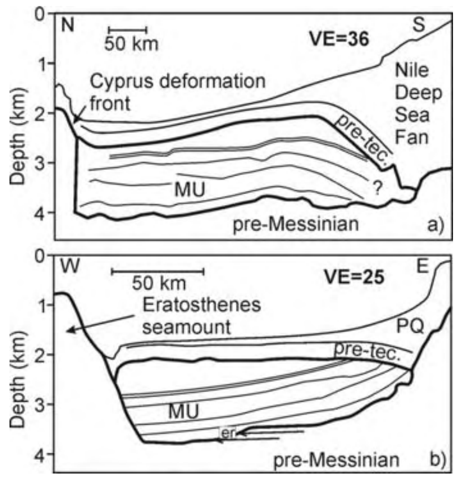

Fig. 3. Simplified line-drawings of pre-stack depth migrated seismic sections showing the mobile unit (MU) of the basinal Messinian evaporites across the entire Levantine Basin (after Netzeband *et al.,* 2006b). The reflections within the MU indicate the geometry and termination, respectively. For location see Figure 1. PQ: Pliocene-Quaternary. Er: Erosion.

The top of the evaporites declines beneath the Nile Fan (Figure 3a) in the south and beneath the sediment prism off the Levantine margin not only because of the lateral displacement (Netzeband *et al*., 2006a). The differential load of the basinward prograding overburden also causes the evaporites to creep towards the basin. The load of the basinward prograding sediment causes differential subsidence which is highest beneath the thickest part of the sediment prism. The resulting down-warping at the basin margins presents rollback folding and thin-skinned extension, respectively, also in areas where no or very little thin-skinned extension occurred.

3.2 Stratigraphy of Messinian evaporites

Six MU sequences labelled ME-I – ME-VI can be traced across the entire Levantine basin (Figures 3, 4) (Hübscher *et al*., 2007). Sequences ME-I, II, IV and VI are seismically transparent and sequences ME-III and ME-V reveal several internal reflections. Since the entire succession of the MU has never been drilled, the interpretation of the sequences has to rely on seismic data. The absence of seismic reflections is typical of salt bodies (Mitchum *et al*., 1977) and so is the interval velocity of up to 4.5 km/s which we recently calculated for ME-VI. Consequently, we suggest to interpret sequences ME-I, II, IV and VI as halite deposits. The interpretation of the layered sequences is more speculative. Some authors consider them as evaporites with intercalated (and presumably overpressurized) clastics (Garfunkel, 1979; Gradmann *et al*., 2005). However, 3D-seismic data analysis proved a high lateral continuity of seismic reflection characters and identified polarity changes which are more indicative of chemical sedimentation processes (Bertoni and Cartwright, 2007a). In this case the acoustic impedance contrasts could result from alternating halite, anhydrite, limestone or potash.

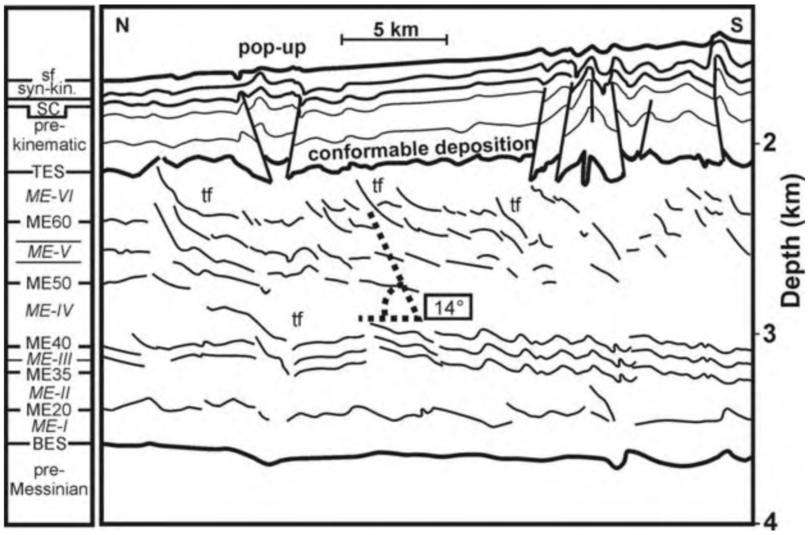

Fig. 4. Line-drawing of pre-stack depth migrated seismic section showing intra-evaporitic sequences labelled ME-I-VI (after Hübscher *et al.,* 2007). Horizon labels ME 20 – 60 according to Bertoni and Cartwrigh (2006, 2007a). BES: Base Erosion Surface. TES: Top Erosion Surface. tf: thrust fault. SC: slump complex.

Chemical depositional processes do not necessarily produce reflection horizons which represent isochrones. For example, a laterally prograding overburden could cause a temporal and lateral increase in overburden thickness and pressure, respectively, which could have resulted in gypsum-anhydrite conversion and, consequently, in acoustic impedance contrasts. In this case internal reflections would represent diachrons and no isochrons.

Submarine canyons represented preferential sites of erosion and deposition of evaporites at the basin margin during the MSC. Seismic geomorphological analysis of 3D seismic data strongly suggests the occurrence of clastic bodies within the basal part of the MU (Bertoni and Cartwright, 2007b). They are composed of two closely spaced channel-mouth lobe deposits and are presumably correlated with a long-lived system of canyons (i.e. the El Arish and Afiq Canyons).

The temporal and stratigraphical relation between marginal and basinal evaporites is still a matter of debate. The same age for the onset of evaporite deposition in the marginal basins and in the deep basin and therefore a correlated stratigraphy is considered by some research groups (Krijgsman *et al*., 1999a, Figure 5a). Other authors assume diachronic deposition (e.g., Clauzon *et al*., 1996; Cornée *et al*., 2002; Butler *et al*., 1995; Riding *et al*., 1998, Figure 5b). Rouchy and Caruso (2006) suggested a progressive but fast deposition of evaporites from the margin to the deep central basin. This question is critical to the understanding of the depositional environment and the reconstruction of the Miocene climatic conditions. It is noteworthy that the vast reconstructions of the Messinian paleo-environment are based on the descriptive and analytical work on the succession preserved in the marginal basins only. The climate archive represented by about 95% of the MU within the deep basins has not been opened yet.

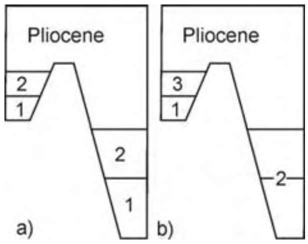

Fig. 5. Endmember models elucidating the ongoing debate regarding the temporal relationship between marginal and basinal evaporite stratigraphy (simplified after Rouchy and Caruso, 2006). Basinal and marginal sequences may have developed contemporaneously (a) or alternating (b).

3.3 Deposition and erosion patterns

Outside the main part of the Nile Fan the internal reflections dip towards northwest. Both the eastern and northern dip component are seen in Figure 3a and b. Different models apply to explain an isochronic deposition of each sequence.

The sequences aggraded within the central basin almost symmetrically if a hinge zone is assumed 40 km west of the eastern termination point (Netzeband *et al*., 2006a, Figure 6). The northwestern tilt of the basin after the deposition of sequence ME-V could have been the consequence of the collision between the Eratosthenes Seamount and Cyprus or, alternatively, of the increasing load due to evaporite deposition. The uplift of the Levantine hinterland results from the flexure of the lithosphere. If no significant tilting and flexural response is assumed, the evaporites in the northwest were deposited in a much deeper water than those in the southeast (Figure 6b). It may be speculated that marine water inflow from the Herodotus basin through the gateway between Eratosthenes Seamount and Cyprus Arc would have caused laterally varying salinity and, consequently, laterally varying deposition rates and facies.

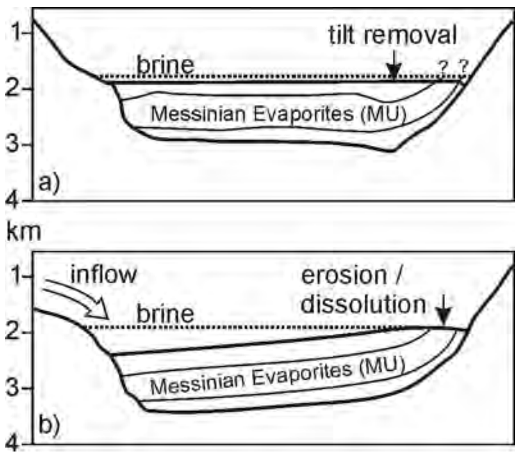

Fig. 6. Endmember models elucidating the growth pattern of the Mobile Unit (MU). a) Evaporites aggradation in an untilted basin. b) Progradation and lateral facies change owing to dipping basin floor and water inflow, which cause a lateral salinity gradient.

Towards the east and south the reflections and sequences, respectively, terminate updip against the TES in different distances to the pinch-out line of the MU (Figure 3a). Thus the termination distance of sequence ME-VI is 40-60 km (Bertoni and Cartwright, 2006). The similar depth levels of the toplap location indicate a simultaneous erosion of the marginal parts of the sequences, likely due to subaerial exposure at the end of the MSC. The abrupt up-dip termination and absence of asymptotic tapering rule out the interpretation of TES as a non-depositional surface. The geometry of the eroded evaporites at the basin margin remains uncertain.

3.4 Syn-depositional deformation

The intra-evaporitic sequences are highly deformed by faults and fault-propagation folds (Figure 4). In many regions, the lower Pliocene deposits overlie the TES concordantly, even if the intra-evaporite sequences are deformed. The time of deformation obviously predates the erosional truncation of the uppermost evaporites. This observation has been published for the first time by Netzeband *et al.* (2006a) who suggested that thin-skinned salt tectonics (compression) already occurred during the deposition phase. Bertoni and Cartwright (2007a) discussed the same process later by analyzing 3D-seismic data. The strongest deformation has been observed for the layered sequences ME-III and ME-V. In Figure 4 the thrust fault planes dip with up to 14°, maximum values of 30° have been observed in the 3D-data.

The most likely driving forces for the syn-depositional deformation are gravity gliding. According to the thin-skinned tectonic concept, the slope of a margin or simply the differential load of a seaward prograding shelf causes the overburden to move basinward, leaving extensional structures such as listric normal faults and rotated blocks along the upper slope. Compression is present at the distal end leading to folds or thrusts. A submarine Nile Fan developed presumably in the Messinian (Barber, 1981; Griffin, 2002). Such a fan squeezing the evaporites basinward during the precipitation phase should interfinger with the MU. The post-Messinian pre-tectonic sequence has a thickness of some 100 meters (see section below), a similar thickness should be assumed for the syn-depositional fan. However, industrial seismic data give no evidence for this (Abdel Aal *et al.*, 2000).

We suggest therefore that the basinward creep and thrusting of the individual evaporitic sequences during the deposition phase were driven by gravity gliding above a tilted subsurface and without significant sediment load. The lateral displacement was presumably comparable to modern salt glaciers, e.g., in Iran. Owing to the onload of the deposited MU the basin-floor tilted towards the basin center which may have acted also as a trigger mechanism (Figure 7). Furthermore, we assume that the internal shear strength of the entire salt body was reduced since sequence boundaries acted as detachment layers.

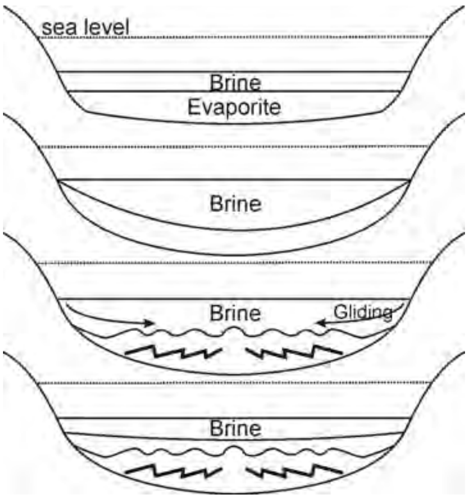

Fig. 7. Model to explain syn-depositional shortening of the MU. The deposition of the evaporites increases the dip angle of the basin margin. The mobile evaporites creep towards the basin center. The subsequent deposited evaporite sequence drapes the folded sequence beneath.

3.5 Post-depositional deformation

There is a clear line of evidence that a second phase of thin-skinned extension started in the later Pliocene (Garfunkel *et al.*, 1979; Almagor, 1984; Gradmann, 2005). Extensional faults in the overburden typically include listric and antithetic growth faults, turtle back structures and crestal grabens (Humphris, 1978; Martin, 1978). Some faults pierce the seafloor proving that this phase is still active (Gradmann *et al*., 2005). Salt rollers developed in the extensional domain (Figure 8). Netzeband *et al*. (2006b) showed that the thin-skinned compression at the Cyprus Arc which acted as a buttress for the generally NE-flowing MU ceased in the Quaternary.

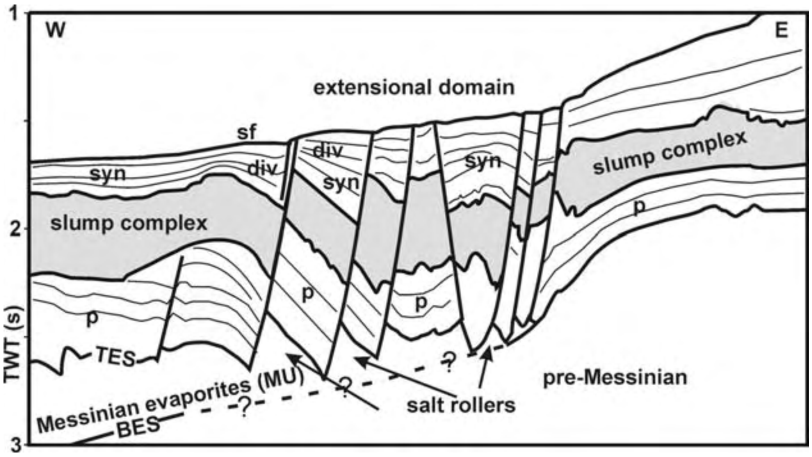

Fig. 8. Thin-skinned salt tectonics in the extensional domain. Pre- and syn-tectonic deposits are separated by a slump complex. p: parallel. div: divergent; syn: syn-tectonic; sf: sea floor. BES: Base Erosion Surface; TES: Top Erosion Surface.

A pre- and syn-tectonic unit can be clearly identified. The pre-tectonic unit is about 300-400 ms TWT or 250-400 m thick and it is characterized by parallel horizons. The syn-tectonic unit includes the sediment prism off the eastern shelf and reveals divergent horizons above the salt rollers. The pre- and syn-tectonic sequences are separated by a late-Pliocene slump complex off the southern Levantine slope (Martinez *et al*., 2005). The slump complex has been mapped by means of 3D-seismic data and the volume was estimated to approx. 1,000 km^3. Several trigger mechanisms are possible, e.g., over-steepening, seismicity, gas migration and initial salt tectonics. A sequence of low seismic reflectivity that is time correlated with the slump can be traced all over the basin separating pre- and syn-tectonic sequences also in the compressional domain (Netzeband *et al*., 2006b).

Near the Eratosthenes Seamount, the situation is different (Netzeband *et al*., 2006a). The BES appears comparatively flat and smooth until it merges into the flank of the seamount, while the TES and the seafloor are strongly distorted (Figure 3b). Hence, the deformation observed there has probably been caused by thin-skinned tectonics. Since there is no significant E–W movement of the evaporites, the E–W contraction observed at the Eratosthenes has probably been caused by the northward creep through the bottleneck between seamount and the Levantine margin. It is remarkable that no salt glaciers or salt tongues escaped from the evaporites into the Nile Scarp.

4. Migration of fluids and volatiles

Fluid escape structures have been reported from the southern and eastern basin margin. Possible fluid resources may be located beneath and within the MU (Figure 9a). Several factors combine to control fluid release locations. E.g., the MU were considered as a sealing sequence and syn-tectonic faults as conduits (Loncke *et al*., 2004, Figure 9b). However, a mud volcano is located at the lower Nile Fan and above almost undisturbed and 1.5 km thick MU without any evidence for lateral fluid flow (Netzeband *et al*., 2006a). A cone-like feature at the top of the MU directly beneath the mud volcano was interpreted as salt that precipitated from fluids escaping out of the MU (Figure 8b). These fluids remobilized sediments within the overburden that feed the mud volcano.

Buried circular collapse structures within the upper MU strata were recorded by 3D-seismic data on the eastern basin margin (Bertoni and Cartwright, 2005). These structures formed during the Pliocene as the buried MU underwent extensive dissolution in a submarine, deep-water setting. The

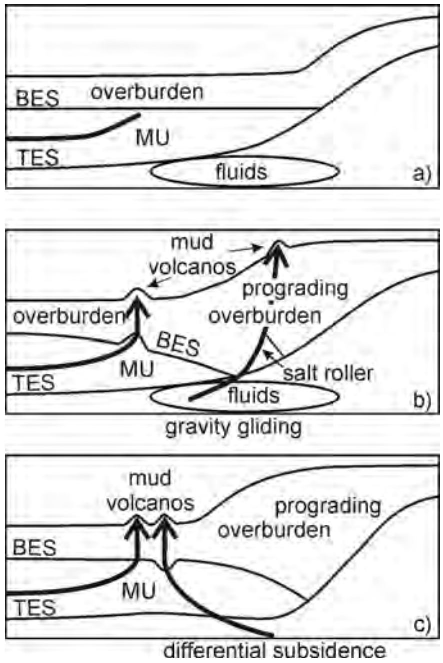

Fig. 9. Endmember models for salt tectonic related fluid dynamics. A) Fluids are present within the evaporites and beneath. B) The differential load of the prograding marginal sequences initiates basinward salt creeping. Extensional faults act as conduits for fluids which migrate upwards where salt has vanished. Fluids escape from the salt and feed mud volcanoes. Precipitated salt form salt cones on top of the main salt body. C) The differential sediment load causes differential subsidence which squeezes fluid through and out of the evaporites.

authors propose that focused vertical fluid flow at the base of the evaporitic series dissolved the more soluble evaporites within the entire MU succession (Figure 9c). Fluid through and outflow from the MU has been also reported. Near vertical faults represent the conduits from the top of the MU to the seafloor, where muddy fluids escape. Possible fluid reservoirs within the MU are intercalated sediments or water that was released from gypsum-anhydrite conversion.

The fluid escape structures at the eastern basin margin are located at the lower slope. This location coincides with the landward termination of the evaporite layer, which is buried under the prograding shelf sediments. Fluids that were trapped within the MU presumably became overpressured, eventually penetrated through the overlying strata and migrated upwards.

The Messinian Salinity Crisis in the Nile Delta: chasing shallow marine reservoirs in a deep-water basin

Willem Ottes, Piet Lambregts and Ahmed El Barkooky

Shell Egypt NV.

Abstract

The Messinian / Upper Miocene sequence in the Nile Delta consists of three evaporitic mega cycles starting in the Middle Tortonian and ending in the Late Messinian. A major incised valley (the Abu Madi canyon) with fluvial and shallow-marine deposits in an overall evaporitic environment characterizes the play with three, easily recognized unconformities. Outside the canyon, basinward, marine-to-evaporitic conditions prevailed. Laterally extensive reservoirs, of likely shallow marine origin are present, separated by halite sequences, and have now been proven by five wells. Initial results of recent drilling have demonstrated good sand development in the Upper Abu Madi sequence, with reservoir thickening and an increase of the net-to-gross towards the centre of the canyon front depocentre.

The Nile Delta is a large Tertiary basin with sediment thicknesses up to at least 7 kilometres. The delta spans about 350 kilometres in West-East and at least as much in a South-North direction.

Hydrocarbon play trends include Pliocene turbidites, Mio-Pliocene shallow marine sediments, Messinian valley fills, and pre-salt deltaic to deepwater sediments; all potentially in structural, stratigraphic or combination traps. The main hydrocarbon phase is gas, both thermal and biogenic. Over 25 Tcf of gas has already been found in the Nile Delta, and yet to find (YTF) volumes are estimated at 64-84 Tcf (Dolson *et al.*, 2000; Dolson and Boucher, 2002) and even up to 100 Tcf (Dolson *et al.*, 2005).

The Nile Delta stratigraphy can be split into three sections:
- Oligo-Miocene (mainly) deepwater sediments, with paleo-coastlines close to the present day one. This section has been under-explored and is the focus of all major operators, with a number of deep, high-pressure wells being drilled at present;
- Upper Miocene Messinian coastal-shallow marine sediments, related to the Messinian Salinity Crisis (Dalla *et al.*, 1997);
- Pliocene-Pleistocene deepwater sediments. These plays are clearly amplitude supported on seismic and have been creamed.

The Messinian / Upper Miocene sequence in the Nile Delta consists of three evaporitic mega cycles starting in the Middle Tortonian and ending in the Late Messinian. A major incised valley (the Abu Madi canyon) with fluvial and shallow-marine deposits in an overall evaporitic environment characterizes the play. Three unconformities that are easily recognized in the canyon translate into their correlative conformities basinward, associated with thick halites (Figures 1 and 2). 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 halites are likely time equivalent with condensed, anhydrite-rich sections in the shelfal area.

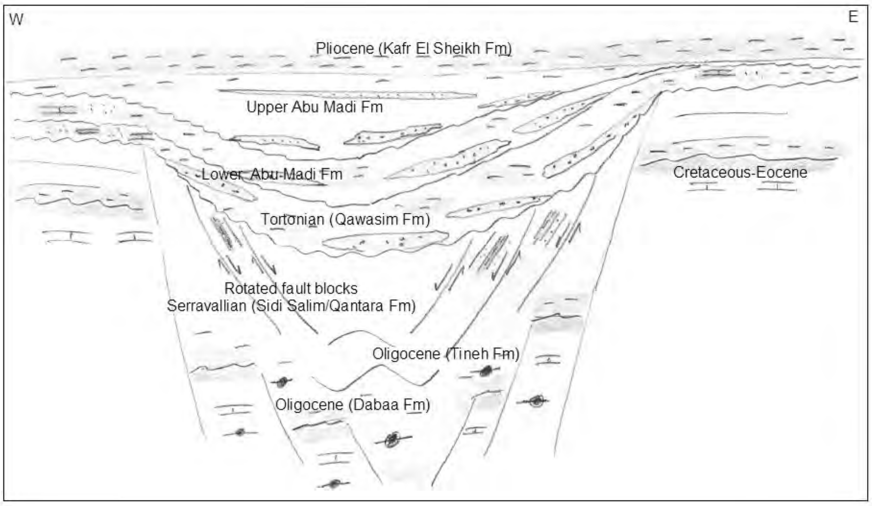

Fig. 1. Schematic cross section: the Messinian-Tortonian canyon in the Nile Delta.

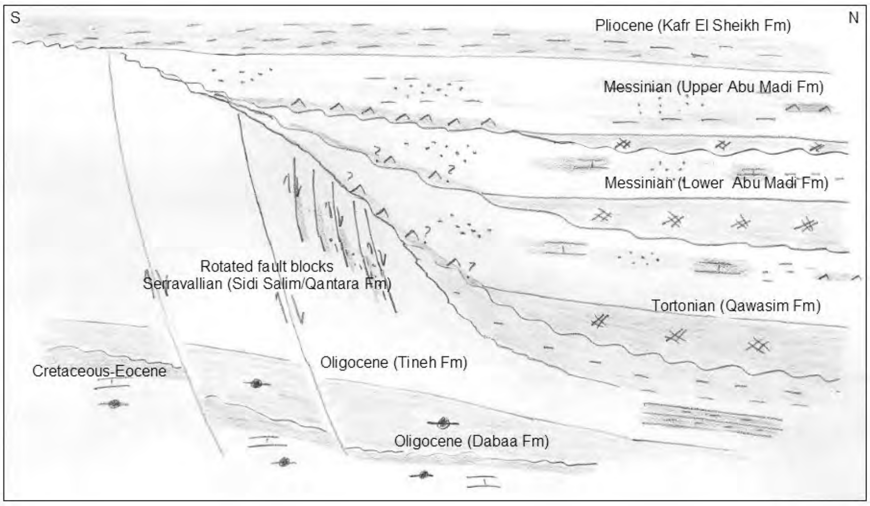

Fig. 2. Schematic cross section: the Messinian in the Nile Delta, from inboard to outboard.

Reservoir is proven for each cycle: the Tortonian Qawasim Formation and the Messinian Lower and Upper Abu Madi Formations. The Kafr El Sheikh Formation, deposited during the major transgression in Early Pliocene, represents the ultimate top seal. The Messinian play is well established, including the Abu Madi field with 3Tcf, the third largest field in the Nile Delta. The play, however, is almost creamed in the inboard Nile Delta.

Outside the canyon, basinward, marine-to-evaporitic conditions prevailed. Laterally extensive reservoirs, of likely shallow marine origin are present, separated by halite sequences, and have now been proven by five wells. Two of them were gas discoveries in the Upper Abu Madi Formation. Both wells also found excellent reservoirs in the Lower Abu Madi Formation. This canyon front area is exclusively present in Shell Egypt's deepwater NEMed concession. Shell is drilling two further play testers in the ongoing 2007 drilling campaign. The first will test the Tortonian Qawasim Formation, and the second will penetrate the full Messinian to test Lower Miocene and Oligocene reservoirs. Furthermore, core has been taken in the Upper Abu Madi in order to determine the depositional environment.

Initial results of the recent drilling have demonstrated good sand development in the Upper Abu Madi sequence, with reservoir thickening and an increase of the net-to-gross towards the centre of the canyon front depocentre. Initial sedimentological interpretation of the cores, taken in this sequence, indicates a depositional environment of slope channel turbidites. Biostrat data, however, are pointing to a shallow marine environment.

A preliminary assessment of the composition of evaporites underlying the eastern Mediterranean seafloor using pore water

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Abstract

Most porewaters of eastern Mediterranean sediments appear to be influenced by diffusion of salt from underlying Messinian evaporites, except most of the Anaximander area, and other sites that were relatively shallow during the Messinian (Erathosthenes, Nile delta above 2 km). These enhanced salinities are predominantly related to halite (NaCl) and Gypsum/anhydrite ($CaSO_4$) contributions. Some sites of limited extension but enhanced advection of evaporite-related salt fluxes have even at short distances rather different composition, ranging from pure halite (Olympi area south of Crete) to pure gypsum (Amon MV, Nile area) or even Bisschofite (Discovery basin).

Salinity gradients are observed in most pore waters of eastern Mediterranean cores, indicating a salt flux from underlying sedimentary units into the bottom water. These salinity gradients were found in DSDP cores (Presley *et al*., 1973; McDuff *et al*., 1978), ODP cores (Emeis *et al*., 1996),

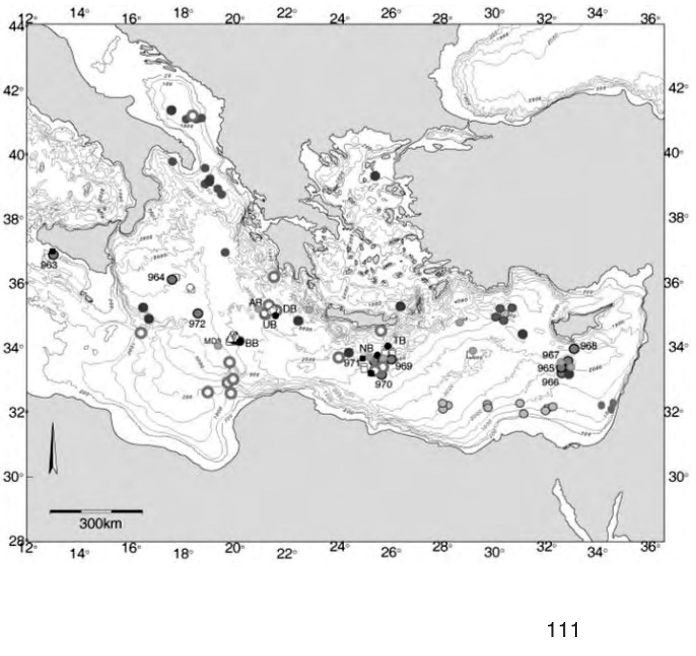

Fig. 1. Eastern Mediterranean. Cores with pore-water data are indicated as well as known brine basins: BB: Bannock basin; AB: Atalante basin; UB: Urania basin; DB: Discovery Basin; TB: Tyro basin; NB: Nadir Basin.

in normal piston cores (Ten Haven *et al*., 1987), and in Marion Dufresne Giant piston cores (Van Santvoort and De Lange, 1996). Interpretation on the basis of the older data is limited due to the low sample resolution or the limited length of the cores.

The high quality long piston cores with high sample resolution and lengths up to 36 m and the ODP Leg 160 coring with reduced resolution but greater sediment depths, together with the careful sample processing procedure and the high precision chloride determinations (De Lange, 1986; 1992; Emeis *et al*., 1996) have permitted a more quantitative study. In addition to the rather moderate increases in normal Mediterranean sediments (Presley *et al*., 1973; McDuff *et al*., 1978; Ten Haven *et al*., 1987), rather dramatic increases of salinity with depth have been reported for exceptional cases (Klinkhammer and Lambert, 1989; De Lange, 1990a,b; Henneke, 1993). All of these increases are thought to relate to the underlying Messinian salt deposits. Compositional and structural differences between the various occurrences (mud diapirs, brine-filled depressions and the various dissolution and collapse structures, such as the cobblestone areas and salt dissolution holes) probably depend on physical (tectonic related) circumstances, on the way of transport from the source areas to the sediment surface and on possible underway-interaction with sediment pore water and/or seawater (Kastens and Spiess, 1984; Camerlenghi and Cita, 1987; De Lange *et al*.,1990a,b; Camerlenghi *et al*., 1992).

Despite the potential interactions for upward diffusing and to a lesser extent for upward advecting fluids, some general conclusions can be drawn on the basis of observed major elemental composition of pore water. There is now a reasonable coverage of cores where porewater has been extracted over the eastern Mediterranean. On the basis of all observations, four different porewater salinity gradients versus depth in the sediment can be distinguished: 1. A rapid decrease with depth, 3. A rapid increase with depth, 2. A gradual but small decrease with depth; and 4. A gradual increase with depth.

The first two are associated with mud diapir related cores with upward advecting fluids of deep origin (usually > 5 km, > 100°C; e.g. Dählmann and De Lange, 2003; Haese *et al*., 2006; Mastalerz *et al*., 2007). The low-salinity fluid of pre-Messinian origin either dissolves Messinian evaporite during its ascend or not, probably partly related to the period of ongoing upward advection, i.e. age of the expulsion structure. Extreme expressions of such upward advection are the deep Mediterranean brine basins (e.g. De Lange and Ten Haven, 1983; Jongsma *et al*., 1983; Scientific Staff Bannock *et al*., 1985; Wallmann *et al*., 1997). A gradual but small – if any – decrease with depth is observed only in very few areas: Erathostenes Seamount, and the Anaximander area, both thought to lack underlying Messinian evaporites. In most of the eastern Mediterranean, however,

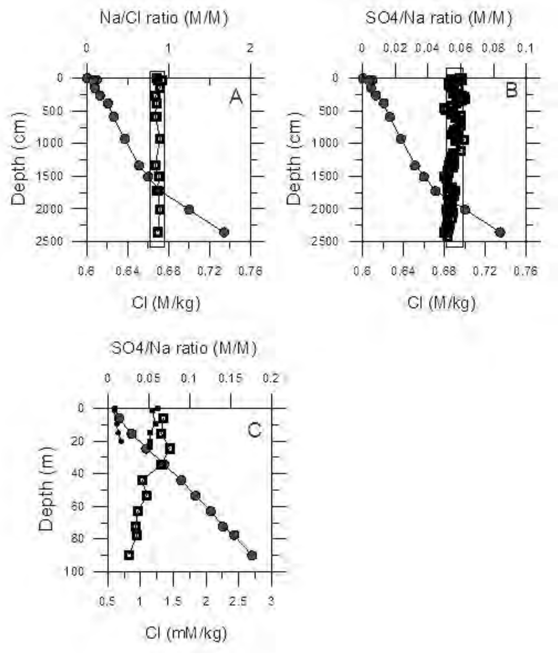

Fig. 2. **A.** Pore-water Cl (M; •), Na/Cl (M/M; ◻), and **B.** Cl (M; •), SO_4/Cl (◻) for Ionian core KCO3 (3,250m waterdepth); lines indicate standard deviation; C. Cl (M •) SO_4/Cl (M/M ◻), for ODP972 and KCO3, both Ionian.

there is a small gradual increase of salinity with depth in the sediment (Figure 2). The gradual salinity increases with depth can be explained by the (partial) dissolution of underlying Messinian evaporites and subsequent upward diffusion (e.g. Ten Haven *et al.*, 1987). Camerlenghi (1988) explains salinity gradients in a different way. The Plio-Quaternary sediments act as a huge membrane with seawater on one side and a brine on top of the evaporites on the other. This causes an osmotic pressure resulting in a flux that is thought to be larger than would be possible by molecular diffusion alone. In this contribution, the focus will be on composition rather than on quantification of fluxes.

Composition of observed pore-waters and brines

The composition of porewater in particular can be influenced by interactions and microbial processes during ascend. If comparing halite (NaCl) versus gypsum/anhydrite ($CaSO_4$) evaporites, it is the first that is relatively unaffected by most interactions, whereas the latter can be influenced by several processes. Carbonate dissolution or recrystallization may result in changes in the pore-water Ca content, whereas microbially mediated sulphate reduction can result in a large reduction in the porewater sulphate content. The potential increase in pore-water sulphate due to sulphide (e.g. pyrite) oxidation is thought to be irrelevant for the case studied here, as there is no oxidant available. If a fluid enhanced in Ca and SO_4 would ascend through carbonate-rich sediments, it will adapt its Ca content while equilibrating with these carbonates, whereas sulphate reduction may decrease the SO_4 content (Boettcher *et al.*, 1998).

For relatively shallow cores, i.e. down to 10 m, the gradual increase of Cl is detectable as well as for Na, whereas deviations of Ca, SO_4 remain analytically undetectable. For deeper sediments such as those recovered by ODP, increases for all four parameters are observed throughout the eastern Mediterranean (Figure 3). The increases remain relatively modest for those sediments with high (ODP963) to moderate (ODP964) sedimentation rates, but are drastic for the other sites with relatively low sedimentation rates thus limited diffusion path lengths. In all cases there is not only evidence for halite but also for gypsum/anhydrite occurrence. The high gypsum contribution is always accompanied by a substantially enhanced pore-water Mg (probably from $MgCl_2$) (Figure 3) but not K, Rb. The consistent profiles for all cores but 972 suggest upward diffusion whereas for the latter an additional advection term may be needed to explain the more advanced concentration versus depth profile.

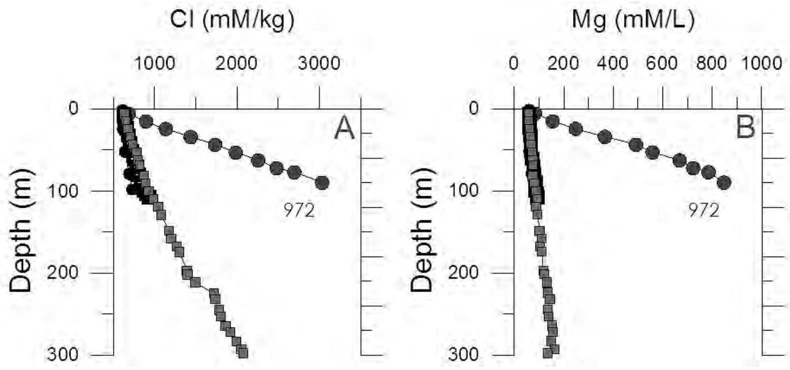

Fig. 3. Porewater data of ODP sites 964-972-969-968 in a West to East transect for **A.** Cl, and **B.** Mg.

Brine basins are a peculiar expression of Messinian evaporite expulsion either directly by relic brine or through dissolution of evaporite (e.g. De Lange *et al.*, 1990a,b; Vengosh *et al.*, 1998). The predominant brine dissolved species are Na,Cl (Tyro, Bannock, Nadir brines), with substantial contributions of SO_4 and Mg, increasing from Tyro-Nadir-Bannock-Urania-Atalante basins from near seawater ~35 to as much as 305 mM /kg brine for SO_4, and from ~11 to 285 mM/kg brine for K. The most extreme brine basin is Discovery having 4,100 mM/kg brine Mg, which is thought to be related to the dissolution of underlying bisschofite ($MgCl_2.xH_2O$) evaporite. It is remarkable that the three brine basins that are most close to each other (Urania, Atalante, Discovery) have the most extreme compositional differences.

Another direct window into deeper units is provided by mud volcanoes, where the expulsion of deep pre-Messinian fluid may entrain and dissolve Messinian evaporites. The mud volcanoes in the Olympi field, just south of Crete, have a predominantly NaCl signature with minor contributions of Mg, K (De Lange and Brumsack, 1998). This is rather comparable to the brine compositions at Tyro (Ten Haven *et al*., 1985) and Nadir basins. For the latter this is not surprising as it is thought to be formed from brine overflow from the nearby Maidstone mud volcano (MV). A different situation exists at the Nile area, where extensive work has been done. In the deep (> 3 km waterdepth) West-delta, high brine salinities were found with Na:Cl ~ 1, and a potential small $CaSO_4$ contribution. In the more shallow sites (~ 500m waterdepth) no evaporite contribution has been detected as expected from Geophysical information (Loncke *et al*., 2006). In the 2 km deep sites in the East delta, at one site (Isis MV) there is no detectable evaporite contribution, whereas at the other (Amon MV), a clear pure gypsum contribution is deduced. For the latter, the Cl and SO_4 concentrations at a few meters depth in the core are 100 and 90 mM/L respectively, thus compared to seawater (560 and 31 mmole/L resp.) having an excessive amount of sulphate. It must be noted that all of these sites are severely influenced not only by the deep low-salinity fluid but also by the relatively high temperature fluid/rock interactions resulting in high B but extremely low K,Mg pore-water contents.

Connectivity between 'ancient' and 'modern' hypersaline environments, and the salinity limits of life

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Abstract

Halophilic microbes, particularly haloarchaea, are consistently cultivated from salt deposits. Based on published metabolic rates in the deep subsurface we show that co-deposited organic matter, consisting mainly of microbial cells, would provide sufficient carbon and energy to allow haloarchaea trapped inside the fluid inclusions of salt crystals to survive over millions of years. In addition, the ingress and/or redistribution of brine in salt deposits may provide new nutrient sources to starved microbes. The continuing post-depositional activities of such microbes must be considered when interpreting geochemical data from salt crystals. Moreover, the return of microbes and their genetic material into the wider environment (as a result of tectonic activity, mining operations and dissolution) after millions of years of separation will have important evolutionary consequences.

Evaporites are heterogeneous and abundant microbial habitats

Although the high osmotic pressure and low water availability of highly saline brines are extremely stressful for most types of cell, halophilic microbes are able to tolerate and in some cases even thrive in such environments. Salt deposits underlie one quarter of the Earth's landmass and are often hundreds of metres thick (Blatt *et al*., 1980; see paper by Hübscher, this volume) which makes them one of the most significant subterranean microbial habitats. Much of Europe was covered by the hypersaline Zechstein Sea in the Permo-Triassic period (Zharkov, 1981), and the Mediterranean Sea was desiccated more recently, with halite precipitation starting between 5.6 and 5.55 million years ago (Hsü *et al*., 1973; see the Executive Summary, this volume). Some salt deposits have been neither deeply buried beneath other geological deposits nor dissolved after their deposition, whereas others have undergone much alteration. Even within the same salt deposit, altered and primary halite can be juxtaposed, as found in the Salar Grande in Chile (Bobst *et al*., 2001; Chong Díaz, *et al*., 1999), and many salt deposits, such as Messinian evaporites in Sicily, contain a heterogeneous array of minerals in addition to halite (see paper by Lugli, this volume). Therefore, exploration of life in salt deposits will provide insight into the impact of different cocktails of ions, as well as the geological histories of evaporite deposits, on the limits of cellular life and the processes that enable microbes to survive over millions of years. In turn, it may reveal information about the role that microbes have played in the formation of evaporites and in post-depositional events.

Salt-saturated brines are biomass-rich but biodiversity-poor

Salinity was found to be the main factor influencing microbial community composition in a recent synthesis of 111 studies (Lozupone and Knight, 2007). Restricted flow of salt-laden water (usually seawater), as may occur in a coastal lagoon, together with a variety of environmental factors such as high temperatures, leads to evaporation of water and formation of salt crystals, which precipitate in a specific sequence: first calcite ($CaCO_3$), then gypsum ($CaSO_4.2H_2O$), and finally halite (NaCl), leaving behind a solution rich in Mg^{2+} and K^+, Cl^- and SO_4^{2-} ions. Environments with a salinity about two to three times higher than seawater, e.g. where gypsum is precipitating, can have a high microbial diversity. This is especially the case where redox and light gradients exist, such as in microbial mats. For example, 42 of the main Bacterial phyla and 15 novel candidate phyla were reported in a microbial mat in Guerrero Negro with a salinity of 8% (Ley *et al.*, 2006), representing an unprecedented level of microbial diversity (Lozupone and Knight, 2007).

The situation is very different in the more homogeneous brines compared with sediments, and especially when the salinity exceeds 15%. More than 2,000 years ago the Chinese observed that reddening of almost salt-saturated ponds encouraged halite precipitation (see Baas-Becking, 1931). We now know that the red colour was caused by high densities of carotenoid-containing microorganisms, which may encourage evaporation by trapping solar radiation and thereby raising the temperature of the brine. Also, the presence of halophilic microbes leads to the formation of larger halite crystals (Lopez-Cortes *et al.*, 1994), with more voluminous fluid inclusions (Norton and Grant, 1988). The high biomass is in part a consequence of evaporative concentration of nutrients, but also due to primary production mainly by the phototrophic eukaryote, *Dunaliella salina*, which converts a significant amount of CO_2 into glycerol, its main compatible solute. Glycerol is released into the brine by leakage and as cells of *D. salina* die, providing an abundant carbon source for heterotrophic microbes (Oren, 1995). The dominant red halophiles in crystalliser ponds (NaCl concentrations between 20 and 32% w/v) are haloarchaea (the Archaeal order Halobacteriales), especially species such as *Haloquadratum walsbyi* (Walsby's square), *Halorubrum* and *Haloarcula* species (Benlloch *et al.*, 1996; Burns *et al.*, 2004; Ochsenreiter *et al.*, 2002; Oren, 2002a). Occasionally, the Bacterium, *Salinibacter ruber* can represent up to a quarter of the community in crystalliser ponds (Antón *et al.*, 2000). NaCl crystalliser ponds are exceptional, not only because most of their microbial inhabitants can be brought into culture (Bolhuis *et al.*, 2004; Burns *et al.*, 2004), but also because a significant proportion have had or are in the process of having their genome sequenced. Haloarchaea are the most extremely halophilic microbes known; their cytoplasm (and that of some Bacteria, like *Salinibacter ruber)* is characterised by high concentrations of salts, predominantly KCl, which balance the external salt concentration, and consequently their macromolecular machinery is adapted to a high-KCl milieu (see paper by Antón, this volume).

Microbes remain viable in halite crystals for an indefinite period, and are consistently cultured from ancient salt

Nearly all haloarchaea tested remain viable for several years inside the fluid inclusions of laboratory-grown halite (Norton and Grant, 1988; see McGenity *et al.*, 2000). Natural salt crystals also contain microbes, such as *Halobacterium salinarum*, that remain viable for many years, often hatching out to cause proteolysis in salt-treated fish, meat, or animal hides. Microbes also grow and/or survive in ancient salt deposits, as demonstrated by numerous, independent isolations of haloarchaea and Bacteria from surface-sterilised, freshly blasted rock salt, and the most likely explanation for their presence is that they are the remnants or descendants of populations trapped when salt crystallised thousands or millions of years ago (see McGenity *et al.*, 2000). Such microbes are not necessarily as old as the geological formation, particularly as there may have been ingress of water resulting in dissolution and recrystallisation of salt.

Nevertheless, various lines of evidence support the possibility that haloarchaea and other microbes can remain viable inside the fluid inclusions of salt crystals over geological time. For example

Halobacterium salinarum was cultivated from a brine inclusion in 97,000 year-old primary halite (Mormile *et al*., 2003), and a strain resembling *Virgibacillus marismortui* was isolated from 250 million-year-old halite (Vreeland *et al*., 2000). Recently, strains of *Halobacterium noricense* were isolated from 121 million-year-old primary halite (Vreeland *et al*., 2007). This is particularly interesting as *Halobacterium noricense*-like strains had been detected independently in, and isolated from, several other subterranean hypersaline environments and rock salt (Norton *et al*., 1993; McGenity *et al*., 2000; Radax *et al*., 2001; Fish *et al*., 2002, Gruber *et al*., 2004). Yet *Halobacterium noricense* has never been detected in surface hypersaline environments which have been studied much more intensively (e.g. Burns *et al*., 2004), thereby suggesting that they have preferentially grown or survived in subsurface salt deposits. A similar argument for subterranean specialisation can be made for *Halococcus salifodinae* that was isolated independently from three presently remote salt deposits or associated brines, connected in the Permian period by the hypersaline Zechstein Sea (Stan-Lotter *et al*., 1999).

What are the mechanisms enabling growth and long-term survival of microbes trapped within ancient salt deposits?

The specific adaptations and mechanisms that enable growth and survival of haloarchaea and other microbes in ancient salt deposits are currently unknown. The importance of retaining a minimum level of metabolism that would allow repair of biological macromolecules, particularly nucleic acids, (termed 'survival energy' by Morita (1997)) has been emphasised (McGenity, 2000). Price and Sowers (2004) compared the metabolic rates of numerous microbial communities from many different environments, e.g. the ocean, ice, deep subsurface, and found a clear relationship between metabolic rate and the temperature of the environment. By using their values for the metabolic rate of microbes in the deep subsurface at 20°C, we calculate that in 100 million years a cell would consume around 50,000 times its own mass in carbon, and in so-doing would obtain sufficient energy to avoid DNA depurination (Price and Sowers, 2004). A crucial question is whether there would be sufficient carbon and nutrient resources in the fluid inclusions of salt crystals. Organic matter of many different types has been found in halite fluid inclusions, including petroleum hydrocarbons; and the importance of dead cells, which have the appropriate balance of nutrients, as a source of carbon and energy in enclosed subterranean environments is often overlooked. Photomicrographic images of laboratory-produced and naturally forming halite crystals show that haloarchaeal cells can be packed inside fluid inclusions at high cell densities (Norton and Grant, 1988; Castanier *et al*., 1999), such that a large cubic fluid inclusion with dimensions of 100 µm could readily accommodate 50,000 haloarchaeal cells that could provide sustenance for one cell over a 100-million-year period.

Such a cannibalistic existence in a closed system raises many issues. For example, those organisms that could effectively utilise a wide variety of cellular components and tolerate/re-use products of metabolism would be at a distinct advantage. The redox potentials of fluid inclusions in halite are generally negative, usually from -10 to -130 mV (summarised by Roedder, 1984), and so will require entombed microbes to function, for the most part, anaerobically. It is noteworthy that the majority of haloarchaea are nutritionally versatile and can function aerobically and anaerobically (see McGenity *et al*., 2000). The metabolic rates needed to repair macromolecules may be much lower in salt-saturated fluid inclusions than in the deep-subsurface environments used in the calculation above, in the same way that lower rates are needed (and found) as the temperature of the environment decreases (Price and Sowers, 2004). In low-salinity, aerobic, surface environments, radiation damage could limit cellular survival to the order of thousands of years (Lindahl, 1993). However, salt deposits provide an environment that is much more conducive to the survival of biological macromolecules and cells. Cosmic radiation is attenuated in the deep subsurface, which is why laboratories have been set up in salt mines to detect rare particles such as WIMPS. Intracellular ions protect biological macromolecules from radiation and free radicals (Marguet and Forterre, 1998; Tehei *et al*., 2002; Nicastro *et al*., 2002). Indeed a whole range of studies have demonstrated that the model haloarchaeon, *Halobacterium salinarum*, which is frequently isolated from salt crystals, is highly tolerant of radiation damage and reactive oxygen by means of many mechanisms including abundant carotenoids, fewer susceptible nucleotides and very efficient repair mechanisms (Zhou *et al*., 2007; DeVeaux *et al*., 2007; Kottemann *et al*., 2005;

McCready and Marcello, 2003). Low redox potentials that are characteristic of fluid inclusions in salt crystals will also minimise oxidative damage. It is therefore clear that extrapolation between systems is not justified, and that experimentation is needed to improve our understanding of the effect of salt concentration, ionic species, entombment and microbial adaptation mechanisms on the attenuation of damage to cellular macromolecules.

Under some circumstances microbes trapped within fluid inclusions in salt deposits may be brought into contact with new sources of carbon and energy. For example, freshwater, seawater, other sub-saturated brines and released water-of-crystallisation from hydrated minerals can all dissolve salt crystals in evaporites at different times after deposition. It has been suggested that geothermal gradients encourage movement of fluid inclusions, but little is known about the rate, and therefore whether this is a potentially important means by which entombed microbes can tap new resources. However, salt deposits can flow, and seismic data indicate that a lot of the Messinian halite has been mobilised (see paper by Gaullier *et al*., this volume), which can promote the expulsion of fluid from within crystals to spaces between crystals.

We do not know exactly where the majority of organisms are located in salt deposits. It is tempting to speculate that most microbes are inside fluid inclusions because that is where they are seen to concentrate when laboratory-made halite crystals are investigated (Norton and Grant, 1988; Adamski *et al*., 2006), and because most studies of ancient salt (often with the aim of demonstrating longevity and hence concerned about possible external contamination) have attempted to isolate microbes from inclusions. However, it is also feasible that many microbes exist between halite and other crystals – indeed there is more organic matter outside of crystals (Pironon *et al*., 1995). Zones where evaporite minerals meet organic-rich shales (as found in Messinian and many other evaporite deposits) are likely to contain large numbers of microbes. Indeed clays could provide a means of slowly releasing organic compounds to microbes (Lünsdorf *et al*., 2000). While entombed microbes may find new sources of carbon and energy when released into the wider environment, the release of brine could stimulate microbes living outside crystals, e.g. clay-rich intercrystalline regions, which may be limited not by a source of carbon and energy but by terminal electron acceptors, e.g. by providing sulphate-reducing bacteria with sulphate (D'Hondt *et al*., 2004). The spatial and temporal scales for such events would vary greatly.

Deep-sea hypersaline anoxic basins provide an example of the connectivity between 'ancient' and 'modern' hypersaline environments and can reveal the salinity limits of life

All solutes influence water's availability (water activity) and exert other activities (e.g. ionic, kosmotropic, chaotropic, and those that affect cell turgor), that in turn affect biological systems in different ways (see Brown, 1990; Hallsworth *et al*., 2003). Therefore, the nature of the dissolved salts in hypersaline environments will greatly influence whether and which halophilic microbes can survive and/or grow. As seawater evaporates and NaCl crystals form, brine enriched in more soluble ions such as Mg^{2+} is left behind. The precise precipitating conditions will radically affect the chemical composition of the brine trapped in fluid inclusions and between crystals, and this may vary over very short distances, i.e. millimetres.

As part of the EC project "BIODEEP" we have been investigating four deep-sea hypersaline brines about 3.5 km beneath the surface of the Mediterranean Sea, each with a different salt composition (van der Wielen *et al*., 2005). These hypersaline brines were derived by the dissolution of Messinian evaporites that formed when the Mediterranean started to dry 5.96 million years ago (see paper by Krijgsman *et al*., this volume). Evaporites were overlain by non-marine sediments, and seawater re-entered the Mediterranean basin around 5.33 million years ago. Tectonic activity caused by collision of the North African and Eurasian Plates resulted in uplifted rock salt becoming exposed to seawater, and being partially dissolved. Where the resultant dense salt-saturated brines have settled in topographical depressions, hypersaline brine lakes have formed and, owing to a lack of mixing with overlying seawater, have become depleted in oxygen, resulting in anoxic, salt-saturated brines with chemoclines of about 2 metres in depth (Camerlenghi, 1990; see paper by De Lange *et al*., this volume).

Our studies focussed on the interfaces between seawater and a NaCl-rich brine (Bannock basin) derived from dissolution of mainly halite, and a brine almost saturated with $MgCl_2$ (Discovery basin) derived from dissolution of bischofite (see paper by De Lange *et al*., this volume). Notably, microbial abundance, diversity and activity were high in the chemocline of Bannock basin, greatly stimulated by a convergence of complementary terminal electron acceptors, carbon and energy sources, and nutrients, (Daffonchio *et al*., 2006). A large number of microbes from the interface were cultured and characterised, including many showing specific adaptations to the particular physico-chemical conditions in the highly stratified chemocline. For example we isolated a Bacteroidetes species which could degrade biopolymers (probably derived from overlying seawater), and an *Epsilonprotobacteria* species that consumed organic acids (derived from the metabolic activity of microbes like the Bacteroidetes) using sulphur and sulphur oxyanions as terminal electron-acceptors (Daffonchio *et al*., 2006).

In contrast, in the interface of the Discovery basin, at a critical concentration, the stressful effects of $MgCl_2$ were found to over-ride the benefits gained from such energy-yielding redox couplings (Hallsworth *et al*., 2007). Messenger RNA from sulphate-reducing bacteria and methanogens could not be isolated from samples with $MgCl_2$ concentrations exceeding 2.3 M, whereas it was detected in L'Atalante basin which consisted of almost saturated NaCl-rich brine. Indeed, we could not culture any microbes from the Discovery basin interface in laboratory media containing $MgCl_2$ at concentrations above 1.3 M, whereas microbes could readily be grown in media containing 5 M NaCl. We concluded that the chaotropic, macromolecule-destabilising activity of $MgCl_2$ is, at sub-saturated concentrations, incompatible with life (see Hallsworth *et al*., 2007).

We have in culture several hundred isolates from these deep-sea hypersaline brines and associated interfaces with seawater, including some interesting haloarchaea that grow well (and indeed were enriched) under anaerobic conditions (Sass, Timmis, McGenity, unpublished). Numerous 16S rRNA sequences of the uncultivated microbiota of the deep-sea hypersaline brine lakes are also published, revealing many novel phylotypes (van der Wielen *et al*., 2005; Daffonchio *et al*., 2006; Yakimov *et al*., 2007). If we consecrate a similar effort to the study of Messinian rock salt, will we find common microbes that could indicate that rock salt serves as one source (of several, including seawater) of the microbes in deep-sea hypersaline brine lakes, thereby demonstrating the connectivity between so-called ancient and modern environments?

From their studies of Messinian salt deposits mined in Sicily, Lugli and co-workers (see paper by Lugli *et al*., this volume) found different forms of halite that precipitated at the top and bottom of a hypersaline water column. They also described a variety of minerals, in addition to halite, that form cyclically at the terminal stages of evaporation, namely kainite ($MgSO_4 \cdot KCl \cdot {}^{11}/_4 H_2O$) and carnallite ($MgCl_2.KCl \cdot 6H_2O$), and also report the presence of bischofite ($MgCl_2.6H_2O$). A systemic investigation of biomarkers, either living or fossilised, in these minerals and gypsum ($CaSO_4.2H_2O$), which outcrops at several locations throughout the Mediterranean, could provide valuable insights into both depositional settings and the preservation potential of different minerals.

CONCLUSION

It is proposed that the organisms best adapted to a salty subterranean existence would be able to tolerate long periods with very low levels of activity, yet respond rapidly when carbon, energy and nutrient sources become available. This mode of existence is certainly feasible because not only do salts contain fluids, but they are also fluid environments; and so brine movement can re-supply starved microbes with nutrients or transport microbes to new nutrient reserves. We need to determine the relative contributions of growth and survival to life in the subsurface, relate this to species abundance, persistence and spatial distribution, and elucidate the underlying mechanisms. The notion that microbes can be taken out of circulation and fixed in time, before re-release into surface environments needs further exploration. We need a better understanding of nutrient movement and cycling between the biosphere and geosphere, and start to consider subsurface evaporites and related sediments as more than just a repository but as an important and dynamic (over geological time) microbial habitat that contributes to global biogeochemical cycles, and in turn can affect interpretation of geochemical data from salt crystals. Care must be taken when using terms such as 'ancient' and 'modern' environments for the simple reason that so-called ancient environments, such as many sedimentary rocks, are active ecosystems (although the activity may sometimes be imperceptible over experimental/observational time scales); while 'modern' environments are inhabited by some microbes that have spent (or even are spending) a significant amount of time in a state of low activity, perhaps having been locked away in sedimentary rocks for millions of years.

Furthermore, we need an improved understanding of the conditions required for, and the limits of, life in extreme environments, in particular to elucidate the relative roles of different salts and combinations of salts that are most favourable for microbial activity and survival. Whereas salts at high concentrations may be considered hostile to life or inhibitory for life processes in the short term, evolutionarily they may be highly beneficial and constitute important means of conserving life over geological time scales by preferentially preserving microbial cells and their biological macromolecules. Interactions between ions in solution, and the effects of *inter alia* temperature and pressure on the state of water and the potential for life must guide expensive missions to detect extraterrestrial life.

More generally, although we have an overview of the limits of the various physico-chemical windows of life, for most parameters we have little information about the underlying molecular mechanisms of systems failure precipitated by exceeding those limits, nor about the specific tolerance mechanisms operating in organisms able to survive and grow at the limits, mechanisms that are presumably evolving and over geological time will result in further widening of the windows of life. One of the most exciting goals at present is to obtain new insights into the cellular processes and networks primarily impacted by, and involved in tolerance of, extreme conditions, because this will not only reveal new information about current life processes but also about the evolutionary trajectories of microbes and life processes in relation to the physico-chemical conditions obtaining in time and space on planet Earth.

Microbiota of hypersaline environments: Archaea, Bacteria and viruses

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Abstract

Multi-pond solar salterns are artificial hypersaline environments used for the commercial production of salt. They consist of a series of ponds that are initially fed with seawater and in which a sequential precipitation of salt occurs, from sodium carbonate to gypsum and finally sodium chloride, that precipitates in the ponds known as crystallizers. This change in salinity and salt composition is accompanied by a succession in prokaryotic diversity that changes from marine microbiota to specialized extremely halophilic microorganisms. This spatial succession could be used as a model of the temporal events that took place along the Messinian Salinity Crisis, widely discussed in this issue. In addition, crystallizer ponds show one of the highest number of virus-like particles (VLP) reported for planktonic systems. The abundance of viruses along the salinity gradient shows an increase from 4 x 10^8 to 2 x 10^9 VLP per ml, one fold over the number of cells. Here we present a culture-independent approach to the study of this vast viral community that has allowed the description of the first genome from an environmental virus associated with halophilic microorganisms.

Hypersaline environments have salt concentrations above that of seawater, very often close to saturation. These environments are among the most extreme on Earth since their microbial communities are normally exposed to more than one stress: high salt, high radiation, some times high pressure or high pH. Hypersaline ecosystems are widespread; they can be found from the Atacama salt plains to the Dead Sea, from the Great Salt Lake in Utah to the Deep Lake in the Antarctica, from artificial solar salterns all around the world to the African soda lakes. Besides, there are also sub-marine hypersaline environments such as the deep sea anoxic brines found in the Mediterranean sea whose microbiota has been recently described (see the report by McGenity *et al*., this volume). In general, high salt environments present very low microbial diversity.

We have focused our studies on an artificial hypersaline environment: the solar salterns. They consist of a series of shallow ponds connected in a sequence of increasingly saline brines and are used for the commercial production of salt from seawater. During evaporation of sea water, sequential precipitation of calcium carbonate and calcium sulfate occurs, leaving a hypersaline sodium chloride brine. Later, sodium chloride precipitates as halite, and dense magnesium chloride brines develop, which are hostile to life (Oren, 2002b) due to the low water activity and the macromolecule-destabilizing activity of $MgCl_2$ (see the report by McGenity *et al*., this volume). This spatial succession is used as a model of the temporal events taking place along the Messinian Salinity Crisis, widely discussed in this issue. The increase in salinity is accompanied by a decrease in prokaryotic diversity (Figure 1), which changes from marine microorganisms towards the specialized hyperhalophilic microbiota in the ponds where sodium chloride precipitates (Guixa-Boixareu *et al*., 1996; Benlloch *et al*., 2002). These last ponds are known as crystallizers and have a salinity above 30%. The prokaryotic community in crystallizers is dominated by dense populations of halophilic square Archaea and a lower proportion, from 5 to 30%, of extremely halophilic members of the Bacteria such as *Salinibacter ruber* (Antón *et al*., 2000; Elevi Bardavid *et al*., 2006) or, in some instances, *Salicola* spp. (Maturrano *et al*., 2006). Inside the Eukaryotic domain, the green alga *Dunaliella* acts as the primary producer. In addition, hypersaline environments show one of the highest number of virus-like particles (VLP) reported for planktonic systems (Guixa-Boixareu *et al*., 1996). The abundance of viruses along the salinity gradient shows an increase from 4 x 10^8 to 2 x 10^9 VLP per ml, onefold over the number of cells. The high number of prokaryotic cells and viruses in crystallizers clearly favours cell-virus interactions (Bettarel *et al*., 2004); on the other hand, the absence of bacterivory above 25% of salinity (Guixa-Boixareu *et al*., 1996) suggests that halophages might play an important role in controlling halophilic microbial communities.

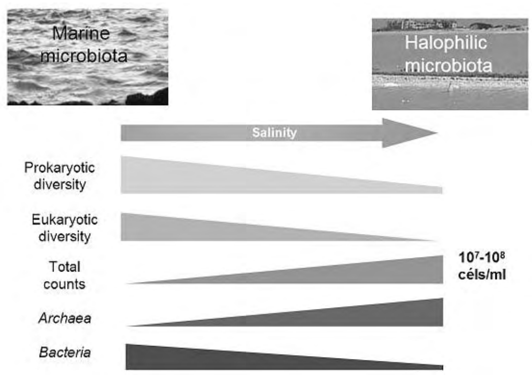

Fig. 1. Schematic representation of changes in the microbial community along the salinity gradient in a model multi-pond solar saltern.

Studies on marine ecosystems have reported the major importance of environmental viruses (CIESM, 2003; Hambly and Suttle, 2005) where viral abundance ranges from 3 x 10^3 to 4.6 x 10^8 VLP per ml (Wommack *et al*., 1999; Weinbauer, 2004) and a good part (10-40%) of the bacterial production is lysed by viruses, equalling on average grazing-induced mortality (Weinbauer and Rassoulzadegan, 2004). Viruses are known to structure microbial communities: (i) causing the lysis of a large portion of the ocean's biomass, (ii) transferring genetic material among host organisms and (iii) channelling nutrients (between 6 and 26% of the photosynthetically fixed carbon) (Weinbauer and Rassoulzadegan, 2004).

In environments such a as crystallizer ponds, where heterotrophic nanoflagellates and ciliates are missing and the ecological effects of competition or halocins have not been demonstrated, phage-induced lysis should be the main factor responsible for the control of microbial populations. Since bacterivory in salterns disappears above 25% salinity, viral infection may be the only mechanism that can cause losses in prokaryotic abundance in crystallizers. However, these losses are considered to be not higher than 5% per day (Guixa-Boixareu *et al*., 1996). The saturating concentrations of salts could explain this low percentage by the establishment of a carrier state which protects microorganisms from phage-induced lysis until certain factors, such as dilution of brines, activate the virulence state (Oren *et al*., 1997).

Culture-dependent methods have reported that 15 out of 5,000 described viruses infect halophilic Archaea, most of them infecting *Halobacterium salinarum*. However, nothing is known about halophages that may infect extremely halophilic Bacteria or *Haloquadratum walsbyi*, the main prokaryotic components in solar salterns analyzed around the world. To overcome the limitations of culture based approaches, three main culture-independent techniques can be used to analyze diversity of viral communities: transmission electron microscopy (TEM) observation of the virus assemblage, shotgun cloning and sequencing of viral metagenomes, and pulsed-field gel electrophoresis (PFGE) of viral nucleic acids from environmental samples. Sometimes PFGE shows a higher resolution than transmission electron microscopy (TEM), such as viral patterns found in a surface seawater sample from Monterey Bay (Stewart and Azam, 2000). Although part of the genetic diversity in a sample is not well resolved by this method since many different viruses can have the same or very similar genome size, the potential diversity within any particular PFGE band or bands of ecological interest can be further analyzed by cloning and sequencing (Stewart and Azam, 2000).

The application of PFGE to study viral genomes in solar salterns showed that the virioplankton community changes with salinity (Díez *et al.*, 2000; Sandaa *et al.*, 2003). Along the salinity gradient, there are genomic bands ranging from 10 to 533 kb. Between 15 and 20% salinity the number of PFGE bands decreases, with the lowest number of bands in crystallizers, where prokaryotic diversity is dominated by *Haloquadratum walsbyi* and *Salinibacter ruber*. Samples from crystallizers show in most cases an intense band around 37 kb. This reduction in viral diversity could be connected to the reduction in the host prokaryotic diversity. However, as in other environments (Paul and Sullivan, 2005) diversity of viruses in crystallizers seems to be higher than prokaryotic diversity. In general, viral diversity in the different ponds is considerably lower than that obtained in marine environments.

When the crystallizer samples were observed under TEM (Figure 2), four morphologies could be distinguished: icosahedral, tailed (with different degrees of complexity), lemon-shaped viruses and filamentous viruses. All except the filamentous phages had been previously observed in studies with crystallizers (Díez *et al.*, 2000), samples from the Dead Sea (Oren *et al.*, 1997), and from infected cultures (<http://www.microbiol.unimelb.edu.au/staff/mds/projects/HaloVirus>, and references therein). Lemon-shaped viruses have also been observed by TEM in hot springs (Breitbart *et al.*, 2004a; Häring *et al.*, 2005) and they could represent a morphology that could be common in extreme environments. High TEM diversity contrasted with the low diversity observed by PFGE, since only one band of around 37 Kb could be observed in the crystallizer samples.

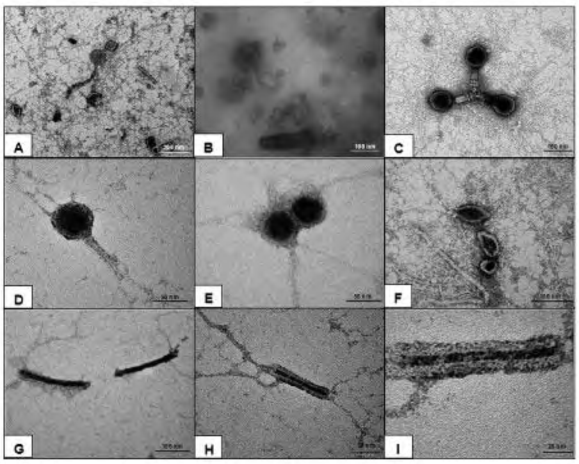

Fig. 2. Micrographs showing virus-like particles (VLPs). (A-B) VLPs in a 22% salinity sample. (C-D) Tailed halophages in 22% salinity samples. (E) Icosahedral halophages in 34% sample. (F) Lemon-shaped halophages in 22% salinity sample. (G to I) Filamentous VLPs in 34% salinity sample (G) and 31% (H-I) samples (Santos *et al.,* 2007).

Tailed phages present in our samples could belong to the group of tailed and dsDNA viruses (Podoviridae) that represent the main group of phages identified in the marine environment

(Breitbart *et al*., 2004b), given the physical connection between marine environments and solar salterns. Although RNA and single-stranded DNA (ssDNA) phages were thought to be rare in the water column (Breitbart *et al*., 2003), recently a significant occurrence of ssDNA phages has been reported for marine systems in Sargasso Sea water samples (Angly *et al*., 2006).

We constructed a metavirome (the global viral genome) from the PFGE 37 Kb DNA band (Santos *et al*., 2007), corresponding to complete viral genomes, that was cloned in fosmid vectors. This approach had not been previously used to obtain large fragments of DNA from environmental halophages and represents an alternative for shotgun cloning (Breitbart *et al*., 2002; Breitbart *et al*., 2003; Angly *et al*., 2006), a technique that has reported lots of data about the uncultured "metavirome" (Paul and Sullivan, 2005) but that represents a very problematical approach to obtain complete phage genomes. In our case, subcloning and sequencing of one of the fosmids, allowed the recovery of the nearly complete genome of the "Environmental Halophage 1" (EHP-1), a sequence with a G+C content around 51%, lower than the G+C content of characterized halophages. G+C content and codon usage in EHP-1 are similar to the recently cultivated and sequenced *Haloquadratum walsbyi,* the major prokaryotic component in solar salterns around the world. Forty open reading frames (ORFs) have been predicted, including genes that putatively code for proteins involved in DNA replication (ribonucleotide reductases, thymidylate kinase) normally found in lytic viruses.

A second library was constructed with viral DNA extracted from the same crystallizer ponds two years later. Southern hybridization indicated that sequences closely related to EHP-1 were present in the metavirome. Furthermore, a second complete viral genome (EHP-2) could be recovered from this sample.

This metagenomic approach, together with techniques such as TEM and PFGE, could be the starting point for ascertaining the role of phages in environments where the main components of the prokaryotic community have not been isolated and therefore infection experiments are not feasible.

Fungi in hypersaline environments – from brine to microbial mats

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ABSTRACT

Fungi, one of the ecologically most successful lineages, can adapt to natural extreme environmental conditions of water, temperature, pH and salinity. It was only recently that fungi were isolated from natural hypersaline environments. Before systematic studies on halophilic and halotolerant fungi in nature were conducted, it was believed that fungi occur only on food preserved with low water activity (a_w), while their occurrence in natural hypersaline environments was due to a random event caused by airborne inoculums. So far accumulated evidence indicates that diverse polyphyletic halophilic and halotolerant fungal species inhabit salterns and salt lakes world-wide. They grow and reproduce in hypersaline waters, on wood, form biofilms and, as recent evidence suggests, they also grow in microbial mats. Halophilic fungi are adapted to the extreme conditions by a number of different mechanisms, which can be understood by their special morphology, physiological characteristics and by special molecular mechanisms. The study of fungal communities is a challenging process due to the high diversity, complexity, difficulty of direct observations and low cultivability of many species. Molecular methods combined with physiological and biochemical characterizations and traditional, morphology-based techniques are needed to fully understand the composition and function of the fungal community.

BIODIVERSITY OF FUNGI IN THE SALTERNS

Only microorganisms are able to populate certain extreme environments. This holds true for natural haypersaline lakes or man-made salterns. In addition to high salinities (up to 35% NaCl), strong UV irradiation and low oxygen concentrations, represent extreme conditions (Javor, 1989). Until we have started our investigations on the presence of halophilic and halotolerant fungi in naural hypersaline environments (Gunde-Cimerman *et al.*, 1997) it was generally assumed that microbial life in concentrated sea water is composed only of Archaea, Bacteria, a few species of algae, and not fungi (Ventosa and Nieto, 1995). The xerophilic fungi known at that time did belong to a few genera that caused food spoilage (Northolt *et al.*, 1995), while the term halophile for fungi was introduced only in 1975 (Pitt and Hocking, 1985) for few xerophilic food-borne species that exhibited superior growth on media with NaCl as controlling solute. Fungi have been subsequently described in moderately saline environments, such as salt marshes (Newell, 1996), saline soil (Guiraud *et al.*, 1995) and sea water (Kohlmeyer and Volkmann-Kohlmayer, 1991), but were still considered to be unable to grow in highly saline waters. The occasional discoveries of fungi in hypersaline environments were interpreted as random events, caused by deposition of sturdy airborne spores. It was generally accepted that fungi do not have any specific ecological function in natural hypersaline environments.

Our studies were initiated in the Slovenian Adriatic marine salterns Sečovlje, that originate from the 13th century (Schneider, 1995). By using highly selective media with high concentrations of either NaCl or sugar and chloramphenicol to repress bacterial growth, we discovered a surprisingly rich diversity of fungi in the hypersaline brine (Gunde – Cimerman *et al*., 2000). Later, their presence and diversity were confirmed as well in brine of natural and man-made hypersaline environments in Croatia, France, Spain, Portugal, Israel, Namibia, Dominican Republic, Puerto Rico and Utah (Kis-Papo *et al*., 2003; Gunde-Cimerman *et al*., 2004, Butinar *et al*., 2005a; Díaz-Muñoz and Montalvo-Rodríguez, 2005), with NaCl concentrations up to 32% NaCl.

Meristematic black yeasts, *Cladosporium* sp. and genus *Wallemia* were identified among the most common species, along with certain species of ascomycetous and basidiomycetous nonmelanized yeasts, various species from the genera *Aspergillus*, *Penicillium* and their teleomorphs *(Eurotium)*.

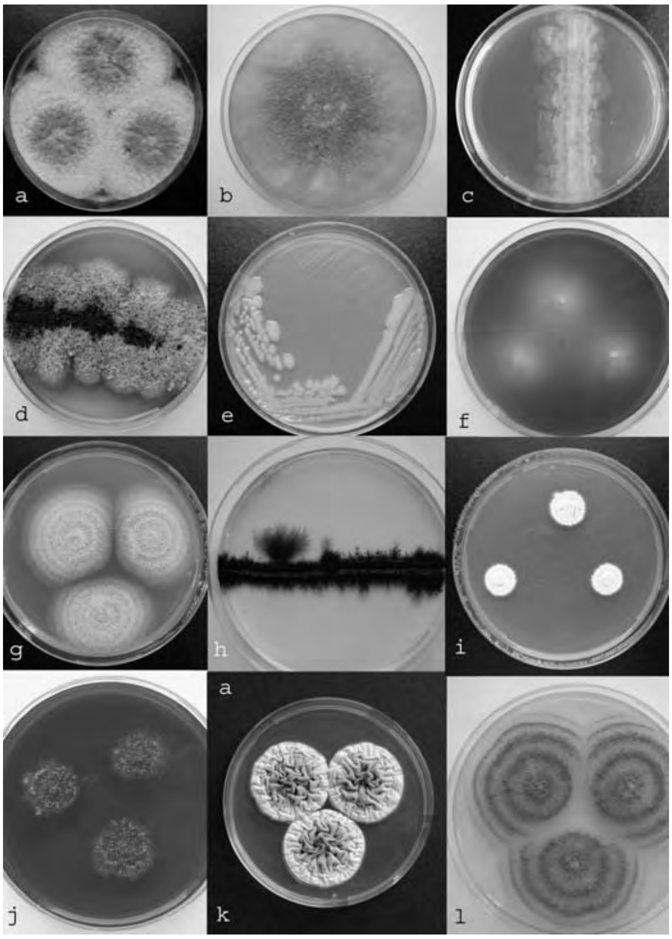

Fig. 1. Colorful fungal colonies and dynamic patterns of their life cycles. Colonies are richly pigmented and display a variety of colors, from black to white, with shades of orange, red, green.
-a- *Eurotium amstelodami*; -b, d, g- *Epicoccum nigrum*; -c- *Mucor* sp.; -e- *Rhodotorula mucilaginosa*; -f- *Penicillium chrysogenum*; -h- *Hortaea werneckii*; -i- *Aspergillus candidus;* -j- *Emericella variecolor*, -k- *Penicillium corylophilum*; -l- *Aspergillus flavus*;

Black yeasts of the order Dothideales have surprising abilities to grow in many different extreme environments and also in a wide range of salt concentrations (from 0 to 32% NaCl). Due to their constant presence in saltern waters, their polymorphism as a possible adaptation to a wide range of salinities, we described black yeasts as the natural inhabitants of hypersaline waters (Gunde – Cimerman *et al*., 2000). These melanized polymorphic fungi, as the group of black yeasts was also named, are able to grow in metabolically different forms. They represent an extremophilic ecotype, characterized by slow, often meristematic growth, reproduction by endoconidiation and thick, melanized cell walls (Zalar *et al.*, 1999). These organisms only rarely appear outside saline environments, which is probably a consequence of adaptive evolutionary processes. They can tolerate different concentrations of salt, but cannot grow at the same osmotic values of substrate, if water activity is lowered with sugar. The main representatives are halophilic *Hortaea werneckii*, *Phaeotheca triangularis*, *Trimmatostroma salinum* and halotolerant *Aureobasidum pullulans* (Gunde – Cimerman *et al.*, 2000; 2004).

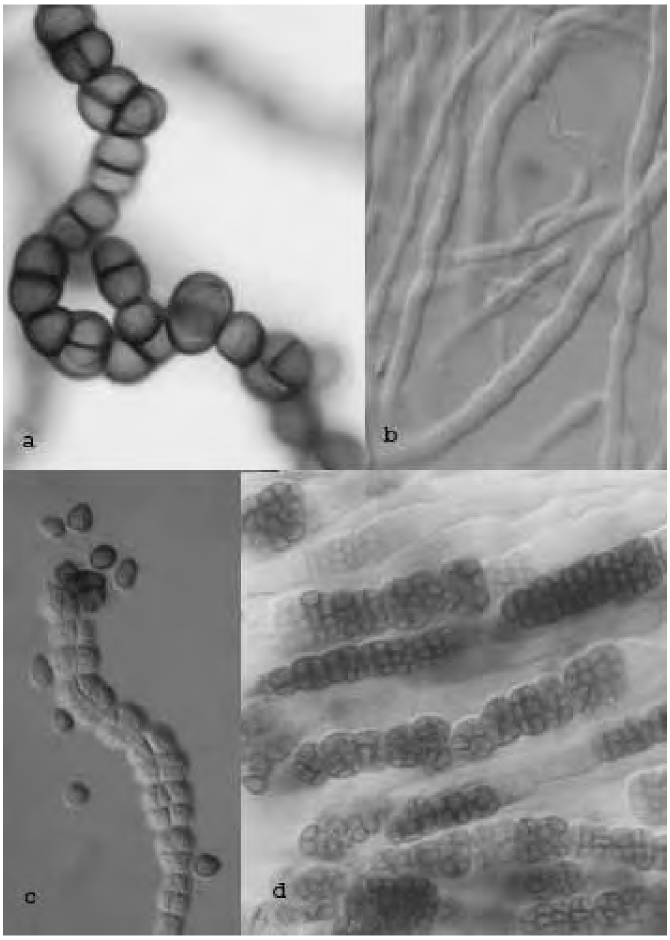

Fig. 2. Adaptations and diversity of forms of fungal mycelium.
-a- *Trimmatostroma salinum*; -b- *Aspergillus candidus*; -c, d- *Phaeotheca triangularis*.

The ubquitous, saprobic genus *Cladosporium* represents another, very adaptable group of fungi inhabiting the salterns. Morphologically *C. sphaerospermum*-like and *C. herbarum*-like isolates form a complex of several species, of which most showed halotolerance as a recurrent feature. Mainly on the basis of phylogenetic analyses but also of cryptic morphological and physiological characters, nine additional species were newly described (Schubert *et al.*, 2007; Zalar *et al.*, 2007).

Certain species of the ubiquitous genera Aspergillus and Penicillium with their associated teleomorphs constitute a stable fungal community in the hypersaline waters. The species geographically most widely distributed, numerous and consistently present in hypersaline waters worldwide were *A. niger*, *E. amstelodami* and *P. chrysogenum*. In the course of the taxonomic study of this fungal group five new species were retrieved: one from the genus *Eurotium* (Butinar *et al.*, 2005b) and four from *Penicillium*.

The presence of non melanized yeasts was investigated as well. Although twelve species were isolated, *Pichia guilermondii*, *Candida parapsilosis* and *Trichosporon mucoides* had the highest frequency of occurrence. Three novel yeast species were recognized; one from the genus *Pichia* and two from the genus *Candida* (Butinar *et al*., 2005c). It is noteworthy that most of the isolated yeasts are recognized for their opportunistic pathogenic nature, as well as that they occurred primarily in oligotrophic waters, characterized by both a high NaCl content, and a high $MgCl_2$ content.

From numerous hypersaline environments we also isolated osmophilic fungi, known as important contaminants of sweet and salty food. The representative of this group was the genus *Wallemia*, which appeared in environments with low water activity, not necessarily associated with the presence of salt (Samson *et al*., 2002). Our results have shown that *Wallemia* presents one of the most xerophilic fungal taxa. To acknowledge its unique morphology, evolution and xerotolerance, a new basidiomycetous class Wallemiomycetes covering an order Wallemiales was proposed. The genus *Wallemia* now contains three species, *W. sebi, W. muriae* and *W. ichthyophaga*, the latter being the most halophilic eukaryote known up to date (Zalar *et al*., 2005a).

Marine fungi are classified as halotolerant microorganisms, which are only rarely occurring outside this specific habitat. From hypersaline waters we isolated the only marine representative fungi belonging to the genus *Emericella*, otherwise known from tropical and subtropical regions. Two species were recorded in salterns, *E. filifera* and *E. stella-maris*, the latter described as a new species (Zalar *et al*., in press).

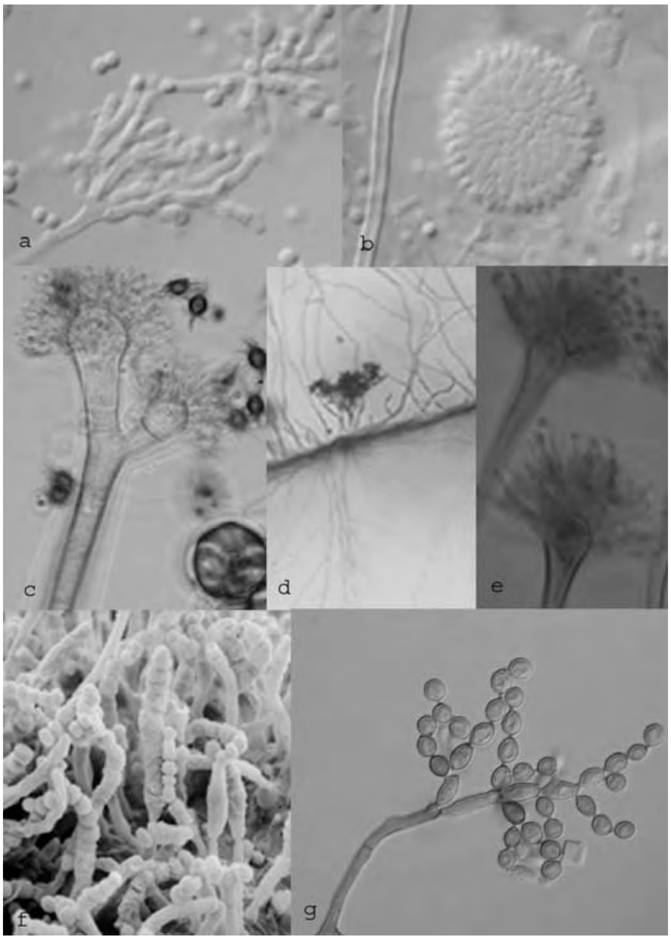

Fig. 3. Fungal conidiophores.
-a, b- *Aspergillus candidus*; -c- *Emericella stellamaris*; -d- *Cladosporium sphaerospermum*; -e- *Emericella appendiculata*; -f- *Wallemia ichthyophaga*; -g- *Cladosporium halotolerans*.

In conclusion, halophilic and halotolerant mycobiota have been found in two of four fungal phyla: in Ascomycota and in Basidiomycota. Comparison of phylogenetically divergent fungi has shown that species actively growing in hypersaline environments have evolved several times. Halophily and halotolerance are features most frequently encountered in Dothideales and Eurotiales. It seems that different groups of fungi are in different stages of adaptation to hypersaline environments, varying from a recent radiation (e.g. genus *Cladosporium*) with eurytolerance opening a new window of opportunity, to extremely flexible halotolerant fungi (e.g. black yeasts of genera *Hortaea*, *Phaeotheca*, *Trimmatostroma*) and stenotolerant phylogenetic end-stages of evolution, represented by the genus *Wallemia* (de Hoog *et al*., 2005).

Fungal counts of about 10 cells per litre are typical for ocean water while in polluted waters they can increase up to several thousands (Slavikova *et al*., 1992),. In the hypersaline waters of the salterns, temporal fluctuations in the density of fungi ranged between 10 and 40 000 CFU per litre. Their dynamic pattern across salinity gradient appeared generally in two pronounced peaks: the first at approx. 15% salinity (up to 5000 CFU per litre) and the second at approx. 20% salinity (up to 40 000 CFU per litre) (Gunde-Cimerman *et al*., 2000; 2004). Both peaks correlated with increased phosphorpus and nitrogen levels. Statistical canonical correspondence analysis showed the importance of temporal factor, a_w as well as nutrients on the distribution of species that form a stable core of fungal community in hypersaline waters.

Occurrence of fungi in saltern's microbial mats

Microbial mats are a laminated consortial system, functionally integrated and self-sustained,that can be found in tropical and temperate hypersaline waters (Van Gemerden, 1993; Paerl *et al*., 2000). Fluctuating diel and seasonal physicochemical gradients (predominantly the light regime) characterize these organosedimentary ecosystems and result in both strata and microenvironments that harbor specific microbial communities (Dupraz and Visscher, 2005; Visscher and Stolz, 2005). In the surface green layer, which is typically the most active metabolically, these consortia are dominated by phototrophs (cyanobacteria), heterotrophs and chemoautotrophs. In deeper layers, the role of phototrophs diminishes. During the formation of the microbial mat, two layers are typically formed: a surface oxic (green) and a lower, anoxic (black). A third pink stratum, which may form between these two layers, represents a redox transition zone. In a well-developed mat, the surface oxic layer is dominated by diverse cyanobacteria that are responsible for the primary production, fueling heterotrophic activity in the entire mat. The anoxic layer is dominated by colorless sulfur, anoxygenic phototrophic and sulphate reducing bacteria. Some eukaryotic organisms can be found there as well, including flagellates, ciliates, and algae (particularly diatoms) (Casillas-Martínez *et al*., 2005).

Besides this type of mat found in most salterns around the world, Slovenian Sečovlje salterns harbour a firm man-made mat called "petola", consisting mainly of the extremely halophilic phototrophic cyanobacterium *Microcoleus chthonoplastes* (Schneider, 1995). Petola was introduced to Sečovlje salterns in the 14th century, from the Adriatic island of Pag, famous for centuries throughout the Mediterranean for its production of very high quality salt. After its introduction six centuries ago, it has been continuously cultivated and maintained, because it is believed that the halophilic microorganisms in petola contribute to the quality of the salt by removing certain metals and other impurities. Due to its origin and longevity, it is protected as part of the Sečovlje National Park.

Until recently there were no reports of fungi in microbial mats. Their presence was for the first time investigated in tropical Puerto Rico salterns (Cantrell *et al*., 2006), and later on in a preliminary, not yet published study also in the temperate microbial mats of Slovenian Sečovlje salterns. A total of 30 species were isolated from both salterns: black yeasts, *Aspergillus niger*, *A. flavipes, Penicillium flavigenum, Cladosporium* spp. and *Rhodotorula* spp. were the most frequently encountered isolates. The number of isolates decreased from the first (green) to the third (black) layer.

When the upper layer was stained with Calcofluor, specific for fungal cell walls, fungal mycelium were observed. Phospholipid fatty acid analysis (PLFA) profiles generated from the different layers of the mat indicated that the uppermost layers contained fungal biomarker, 18:2w6. This fatty acid decreased with depth, and disappeared in the black bottom anoxic layer. DNA was extracted from the different layers of the mats and the fungal ITS (Internal Transcribe Spacer) rDNA region was amplified for terminal restriction fragment length polymorphism (TRFLP) analysis. The TRFLP profiles of the different layers indicated that diversity decreased from the green layer to the black layer and revealed the presence of 24 phylotypes. The preliminary results demonstrated that the diversity and abundance of fungi were higher during the wet season, as well as in the oxic (green) layer (Cantrell *et al*., 2006).

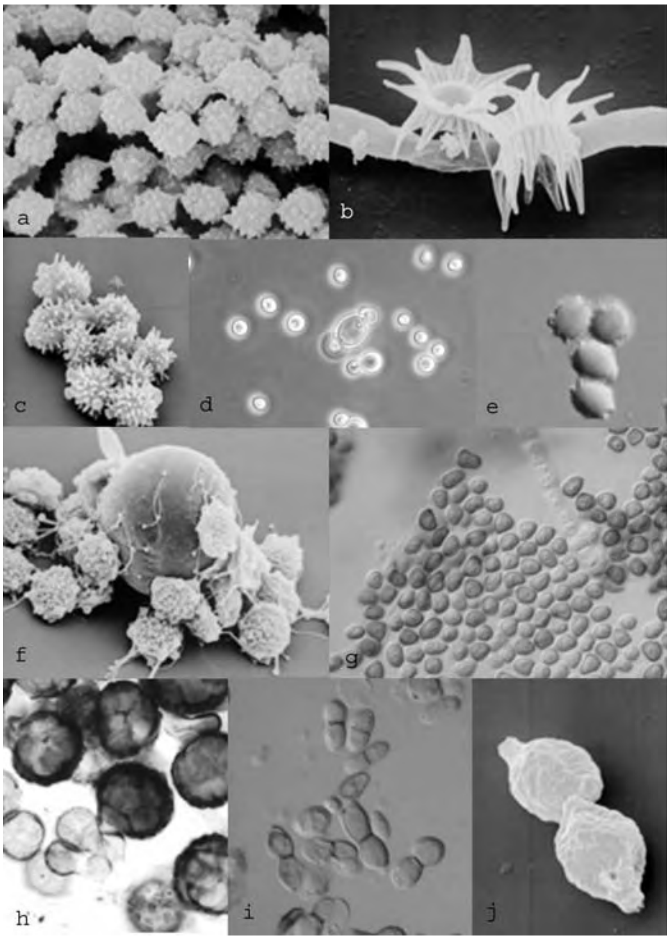

Fig. 4. Most of the filamentous fungi found in the salterns reproduce asexually, by conidia or in the case of yeasts, by budding. Some fungi undergo sexual reproduction, forming ascopores or basidiospores. Some are very sturdy, while others compensate for the weaker nature of their spores by producing spores in extremely large numbers, ensuring survival in this way. Many spores become richly ornamented or have long appendages, helping them to float in the water or glide through the air.
-a- *Aspergillus versicolor,* conidia; -b- *Emericella stellamaris,* ascospores; -c- *Cladosporium echinulatum.,* conidia; -d- *Candida albicans,* yeast cells; -e- *Eurotium amstelodami,* ascospores; -f- *Emericella filifera,* ascospores and Hülle cell; -g- *Phaeotheca triangularis,* conidia; -h- *Epicoccum nigrum,* conidia; -i- *Hortaea werneckii,* yeast cells; -j- *Cladosporim sphaerospermum,* conidia.

CONCLUSIONS

The study of the diversity of microbial communities in hypersaline environments is a challenging process due to the high complexity created by some of the mineral substrates and high salt content, the difficulty of directly observing microorganisms in this complex matrix and the low cultivability of many species. Although in recent years the study of microbial communities has benefited from the development of new culture-independent techniques such as TRFLP, qPCR, and large scale sequencing, most of the molecular microbial diversity studies have focused on bacteria, and only recently have a few studies been published on fungi. For fungi, most of the published molecular-based studies have used TRFLP or DGGE (Edel-Hermann *et al*., 2004; Lord *et al*., 2002; Viaud *et al*., 2000; van Elsas *et al*., 2000), and these only yield general indications of gross shifts in microbial communities (e.g., changes in fungal to bacterial ratios). A few of these studies, however, have applied qPCR and DNA sequencing from soil samples to assess fungal communities at a finer scale (Fierer *et al*., 2005; O'Brien *et al*., 2005). Not only can these techniques provide a better understanding of the fungal diversity in environmental samples, but they also can detect novel and unknown fungal groups (Jumpponen and Johnson, 2005).

The identification of halophilic and halotolerant fungi in the hypersaline waters, as well as in microbial mats, have been performed so far mainly using traditional cultivating techniques. To fully understand the composition and function of fungal communities inhabiting salterns and salt lakes, data obtained with physiological and biochemical characterizations and traditional, morphological-based techniques should be supplemented by molecular approaches. Future efforts should be focused on the extraction of DNA directly from the brine and microbial mats in temperate and tropical salterns, with the aim to construct comparable genomic libraries and to study the structure of the fungal community using such methods as TRFLP and TGGE. The experiments should include the use of other fungal primers and restriction enzymes as well as more extensive cloning efforts for the identification of fungal species *in situ* and subsequent comparisons with sequences obtained from pure cultures.

The use of molecular techniques will reveal unknown phylotypes and species. It is certain but likely, based on work carried out in other environments, that besides, more importantly, these techniques will shed more light on the understanding of the potential role of fungi in these extreme environments.

In terrestrial ecosystems fungi are key players in the decomposition process of detritus material. The different chemical compounds in detritus can be divided in recalcitrant that includes very complex carbohydrates such as lignin and labile that includes more simple carbohydrates such as sugars, hemicellulose and cellulose. Recalcitrant compounds are generally broken down by fungi, while labile ones by fast growing organisms such as bacteria. Thus during the decomposition process a succession of microorganisms occurs, mediated by the interaction of different organisms, resource composition and abiotic factors.

For example – prokaryotes, predominantly cyanobacteria in mats – produce large quantities of EPS (extracellular polymeric secretions) which are very complex carbohydrates (Decho *et al*., 2005; Dupraz and Visscher, 2005). These are consumed in the mats and it is highly likely that fungi in concert with the bacterial community contribute to the degradation of EPS and the subsequent mineralization of carbon. Evidence of an underestimated saprotrophic role of fungi in the salterns comes from the repeated isolation of black yeasts and other halophilic fungi from slimy EPS layers on the surface of the brine in the crystallizers and from wood immersed in hypersaline water. Isolated black yeasts *H. werneckii* and *T. salinum*, which colonized the wood, showed xylanolytic and lignolytic activity under hypersaline and non-saline conditions, while *T. salinum* displayed cellulolytic activity as well (Zalar *et al*., 2005b). These results suggest an active saprobic role of halophilic and halotolerant fungi in the environment.

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