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Recent advancements in the Messinian stratigraphy of Italy and their Mediterranean-scale implications

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ABSTRACT - A careful revisitation of Late Miocene successions of Italian basins carried out in the last ten years provided a significant advancement in the understanding of Messinian salinity crisis (MSC) events. New facies models for both primary and resedimented evaporites and an integrated stratigraphic approach allowed to trace key surfaces across the depositional settings of individual basins and to correlate the Messinian record of basins developed in different geodynamic settings. This results in a high-resolution and dynamic stratigraphic scenario which accounts for the effects of Mediterranean-scale and local forcing factors and allows to assess important and still obscure items, like the nature of deep basinal Lower Evaporites and the meaning of the Lago-Mare *event. As for the Lower Evaporites, this study suggests that they actually consist of both primary and resedimented facies fully separated in both time and space. Resedimented evaporite units have a clear chronostratigraphic value and were deposited in basinal settings during the MSC acme, following an important tectonic pulse; these deposits, which are associated with halite in Sicily and Calabria basins, fully postdate the primary evaporites (massive selenite gypsum) formed only in small, shallow and semiclosed basin in the first phase of MSC. The* Lago-Mare *event is characterized by the progressive dilution of surface waters after the MSC peak; the high-resolution stratigraphy obtained for the Late Messinian interval suggests that this important change in basin hydrology and precipitation regime, possibly resulting from a complex interplay between tectonic and climatic factors, occurred in all the basins at around 5.42 Ma, thus defining a much more homogeneous scenario than previously thought for this event.*

RIASSUNTO - [I recenti progressi nelle conoscenze stratigrafiche del Messiniano in Italia e le loro implicazioni a scala del Mediterraneo] - *Le successioni sedimentarie messiniane affioranti e sepolte dell'area italiana offrono nel complesso una registrazione completa ed espansa degli eventi associati alla crisi di salinità che ha interessato l'intero bacino del Mediterraneo e le aree limitrofe circa 6 milioni di anni fa. I diversi contesti geotettonici e deposizionali rappresentati nei bacini italiani, tra cui i più importanti sono senz'altro l'avanfossa appenninica, l'avanfossa siciliana, il bacino terziario piemontese, la Toscana e la Calabria ionica (Bacino di Crotone), consentono di ricostruire gli eventi messiniani da diverse angolazioni e di filtrare i forzanti locali mettendo in evidenza i fattori di controllo a scala mediterranea. I bacini messiniani italiani sono sempre stati oggetto di grande attenzione nell'ambito degli studi sulla crisi di salinità, a partire dagli anni '70 quando, in seguito alle scoperte effettuate nei bacini mediterranei profondi, venne intrapresa una grande stagione di studi di terreno che portò a risultati di estrema importanza sia in campo stratigrafico, sia sedimentologico. Negli ultimi dieci anni la stratigrafia di tutti i bacini messiniani italiani è stata profondamente revisionata nell'ambito di vari progetti da gruppi di ricerca che hanno lavorato in stretto coordinamento o comunque confrontandosi costruttivamente. Ciò ha portato all'elaborazione di modelli stratigrafici regionali per i singoli bacini basati su un approccio stratigrafico-fisico integrato con dati bio- e magnetostratigrafici; l'omogeneità dell'approccio consente il confronto e la correlazione dei vari bacini e la proposizione di scenari evolutivi della crisi di salinità con forti implicazioni a scala mediterranea. Uno dei risultati più significativi ottenuti consiste nel riconoscimento del valore cronostratigrafico dei depositi evaporitici risedimentati che caratterizzano i contesti deposizionali più profondi nei vari bacini e che sono sempre stati considerati coevi delle evaporiti primarie costituite in prevalenza da gessi selenitici massivi. In realtà le evaporiti risedimentate sono separate da quelle primarie dalla discontinuità intra-Messiniana, una superficie chiave sviluppatasi a partire da 5.61 Ma e che marca l'inizio della fase parossistica della crisi di salinità, dopo un primo stadio (5.96-5.61 Ma) caratterizzato da precipitazione di evaporiti primarie esclusivamente all'interno di piccoli bacini semichiusi e con acque relativamente poco profonde. La superficie di discontinuità può essere tracciata sul terreno dai bacini poco profondi che mostrano chiare evidenze di esposizione subaerea fino ai contesti bacinali dove la linea tempo corrispondente marca la base di sistemi torbiditici costituiti in prevalenza da gessoclastiti. Questo offre una risposta ad uno dei maggiori interrogativi che attualmente alimentano il dibattito internazionale sulla crisi di salinità e che riguarda la definizione precisa della natura, dell'età e dei rapporti stratigrafici con le successioni affioranti dell'unità sismica presente nei bacini mediterranei profondi denominata 'Evaporiti inferiori' e mai raggiunta sinora da sondaggi. La fase parossistica comprende anche la precipitazione locale di halite e sali potassici (Sicilia e Calabria), probabilmente correlabili con i grandi corpi salini presenti nei bacini profondi del Mediterraneo occidentale ed orientale. Il modello stratigrafico ricostruito su basi stratigrafico-fisiche e ciclostratigrafiche prevede che questa fase abbia avuto una durata molto breve, inferiore a 50 ka. Il ritorno a condizioni normali nel Mediterraneo con la trasgressione dello Zancleano a 5.33 Ma, è preceduta da una fase durante la quale si assiste ad una progressiva diluizione delle acque superficiali dei bacini mediterranei fino allo sviluppo di ambienti ipoalini. La stratigrafia ad alta risoluzione ottenuta su basi ciclostratigrafiche per l'intervallo tardo Messiniano consente di riconoscere trend evolutivi comuni ai vari bacini italiani (e anche mediterranei) con un'accelerazione decisa attorno a 5.42 Ma. L'intervallo compreso tra 5.42 e 5.33 Ma è caratterizzato da facies sedimentarie e associazioni paleontologiche che indicano un profondo cambiamento dell'idrologia dei bacini, del regime delle precipitazioni e dei sistemi di drenaggio fluviali; questa è la fase caratterizzata dalle più tipiche associazioni faunistiche e floristiche ad affinità paratetidea. La grande omogeneità riscontrabile nei vari bacini suggerisce un assetto idrologico e fisiografico probabilmente meno frammentario di quanto normalmente immaginato sinora; il trend trasgressivo e le sporadiche influenze marine registrate nella parte sommitale dell'intervallo, suggeriscono uno scenario caratterizzato da una complessa interazione tra fattori tettonici e climatici e connessioni con l'Atlantico via via più consistenti fino alla definitiva riapertura alla base del Pliocene.*

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INTRODUCTION

Outcropping and buried sedimentary successions of Italian basins offer the largest, most diversified and complete record of the events related to the Messinian salinity crisis (MSC), a complex of high-amplitude palaeoenvironmental changes which affected the perimediterranean area around 6 million years ago.

The fundamental role of Italian basins for elucidating causes, modalities and timing of such events was clear since the beginning of the 70's, when, immediately after the shocking data recovered in the deep Mediterranean basins by the DSDP Leg 13, a period of enthusiastic field and analytical studies started and led very soon to significant advancements of the general knowledge on this topic.

Carlo Sturani was an outstanding protagonist of that period, unfortunately too short for him, which definitely changed the way evaporite rocks were approached and considered by the geological community.

Thirty years after that season and the formulation of the 'deep-desiccated basin' model (Hsü et al., 1972), which soon became a still resisting paradigm, what actually happened during the MSC is still far to be fully understood. This is mainly due to the absence of a comprehensive stratigraphic model able to combine data and observations from successions outcropping in marginal basins and the ones buried below the deep western and eastern Mediterranean basins.

The uncertainties derive from the still unknown nature and age of the up to 2 km-thick evaporite suites preserved in the latter basins, thought to represent the deepest topographic depressions of the Mediterranean basin also during the Messinian. Such giant evaporite bodies, only imaged by seismic profiles and just scratched on top by DSDP and ODP boreholes, since more than 30 years represent a challenge for the scientific community. Waiting for ultra-deep boreholes able to cut through the whole deep evaporitic suites and reach the underlying deposits, our understanding of MSC events relies upon the recognition of outcrop analogs of deep basinal successions. The deep basin evaporitic suite is classically subdivided into three units, termed Lower Evaporites, Salt and Upper Evaporites, bounded by sharp and locally irregular surfaces which merge upslope into a deeply scoured erosional surface (Messinian erosional surface - MES). This 'trilogy' has been historically correlated to the Sicilian Messinian succession as reconstructed in the stratigraphic model of Decima & Wezel (1971). However many different opinions about the marginal vs. deep basinal character of Sicily basin during the Messinian exist (Clauzon et al., 1996, 2005; Krijgsman et al., 1999a, b; Butler et al., 1995) and this results in a number of stratigraphic models and related MSC scenarios (see Rouchy & Caruso, 2006 for an updated review).

Summarizing, the big conceptual problem that the "Messinian community" is currently facing, is the correlation of deep basins with marginal (or peripheral) basins, usually considered to have formed at shallower depths and now providing most of the outcropping successions; in particular, the genetic and stratigraphic relationships between the deep basin Lower Evaporites and their supposed outcrop equivalents ('Lower Gypsum' of Sicily and the other outcropping basins) are a critical point that needs to be clarified.

The detailed knowledge of Italian Messinian basins is a fundamental step for reconstructing stratigraphic models able to define shallow to deep-water relationships, for understanding the hydrologic relationships between western and eastern deep Mediterranean basins and for assessing the eventual occurrence of climate gradients during the MSC. This fact is particularly evident when considering their high sedimentation rates and potential stratigraphic resolution, the good outcrop quality, their north-south distribution in the central Mediterranean and the large variety of represented depositional and geodynamic settings.

Much work has been done in the last ten years by several research groups to sharpen our knowledge of Messinian stratigraphy of Italian basins; in this paper we will briefly summarize the main results of such studies and their implications at a Mediterranean scale.

GENERAL STRATIGRAPHIC FRAMEWORK

The Messinian and Zanclean GSSPs, formally defined respectively at Oued Akrech (Morocco, 7.251 Ma; Hilgen et al., 2000) and Eraclea Minoa (Sicily, 5.333 Ma, Van Couvering et al., 2000), have finally provided solid chronological constraints to assess the onset of MSC events from an outcrop perspective. Their formal definition came after a season during which the astronomical calibration of sedimentary cyclicity proved its great potential for erecting high-resolution stratigraphic schemes and promoting basinwide correlations.

Within the Messinian stage, the cyclostratigraphic approach allowed to define other important time-lines fundamental for the MSC (Hilgen et al., 2007). Detailed bio- and magnetostratigraphic studies carried out on the pre-MSC units, Tripoli Fm. of Sicily (Hilgen & Krijgsman, 1999; Bellanca et al., 2001) '*euxinic shales*' of the Northern Apennines (Krijgsman et al., 1997, 1999a; Hilgen et al., 1995), Abad marls of Sorbas basin, Spain (Sierro et al., 2001) and other coeval units in Cyprus and Crete (Krijgsman et al., 2002), led to date the base of the 'Lower Gypsum' and hence the onset of MSC in marginal basins at around 5.96 Ma, shortly after the base of the Gilbert inverse polarity chron. The synchronous vs. diachronous character of this event at a Mediterranean scale is still matter of debate, even if a certain consensus has been reached through the years around the Krijgsman et al. (1999b; Fig. 1) hypothesis of a synchronous event. A slight to strongly diachronous MSC onset is envisaged respectively by Rouchy & Caruso (2006) and Butler et al. (1995) based on their study of Sicilian basin. Clauzon et al. (1996, 2005) suggested a two step mode of MSC with evaporites deposited first in marginal basins and subsequently in the desiccated deep basins; a similarly differentiated evolution has been suggested by Riding et al. (1998) and Braga et al. (2006) but with evaporites first deposited in deep basins and then in marginal ones.

Anyway, the fine tuning to astronomic curves (van der Laan et al., 2006; Hilgen et al., 2007) has recently clarified that the MSC onset was not triggered by glacioeustatic factors (glacial isotope stages TG20-TG22), as previously suggested; instead, a tectonic forcing is envisaged which determined the progressive reduction of the Atlantic gateways in the Gibraltar area (Duggen et al., 2003).

Any further stratigraphic definition within the 5.96-5.33 Ma time interval can only rely upon cyclostratigraphic and physical-stratigraphic approaches, as the classic bio- and magnetostratigraphic tools cannot be used. In fact, due to the poor fossil content, this interval, which falls entirely within the lower part of the Gilbert reverse chron, has been defined as "non-distinctive zone" (Iaccarino & Salvatorini, 1982).

An important subaerial erosional surface developed during the MSC throughout the marginal settings of the Mediterranean basins, thus providing a first order physical element for defining the stratigraphic architecture of the 5.96-5.33 Ma interval.

This surface, called intra-Messinian unconformity or Messinian erosional surface (MES), is usually related to fluvial rejuvenation following a sea-level drop of more than 1.5 km leading to deep Mediterranean basins desiccation (the second MSC step of Clauzon et al., 1996) and deeply cuts primary evaporitic (mainly selenitic gypsum referred to as 'Lower Gypsum' and considered equivalent of the deep basin Lower Evaporites) - and even pre-evaporitic deposits - formed during the first MSC step in marginal basins. The well developed cyclical pattern of the primary 'Lower Gypsum' unit (PLG) and the constant number of cycles (up to 16) in the different basins allowed to define a minimum age of 5.61 Ma for the first development of the MES.

This fundamental point was first suggested by Hilgen et al. (1995) and Vai (1997) and subsequently refined by Krijgsman et al. (1999a, b), mainly based on data and observations on the Northern Apennines 'Lower Gypsum' succession (Vena del Gesso basin). The studies carried out in the Northern Apennines, and their comparison with Sicilian and Spanish successions, led to the interpretation of Messinian cyclicity as essentially controlled by precession, thus obtaining a powerful tool to disentangle the complex stratigraphy of the 5.96-5.33 Ma interval. However, a gap of around 90 ka (the 'Messinian gap') remained in the cyclostratigraphic reconstructions (Krijgsman et al., 1999a, b; Fig. 1); this hiatus was related by Krijgsman et al. (1999a) to tectonic activity locally associated with the development of the MES and was thought to correspond to the MSC acme and deep Mediterranean basins desiccation.

The different MSC scenario so far proposed essentially differs for the stratigraphic frameworks reconstructed for the 5.61-5.33 Ma interval (see Rouchy

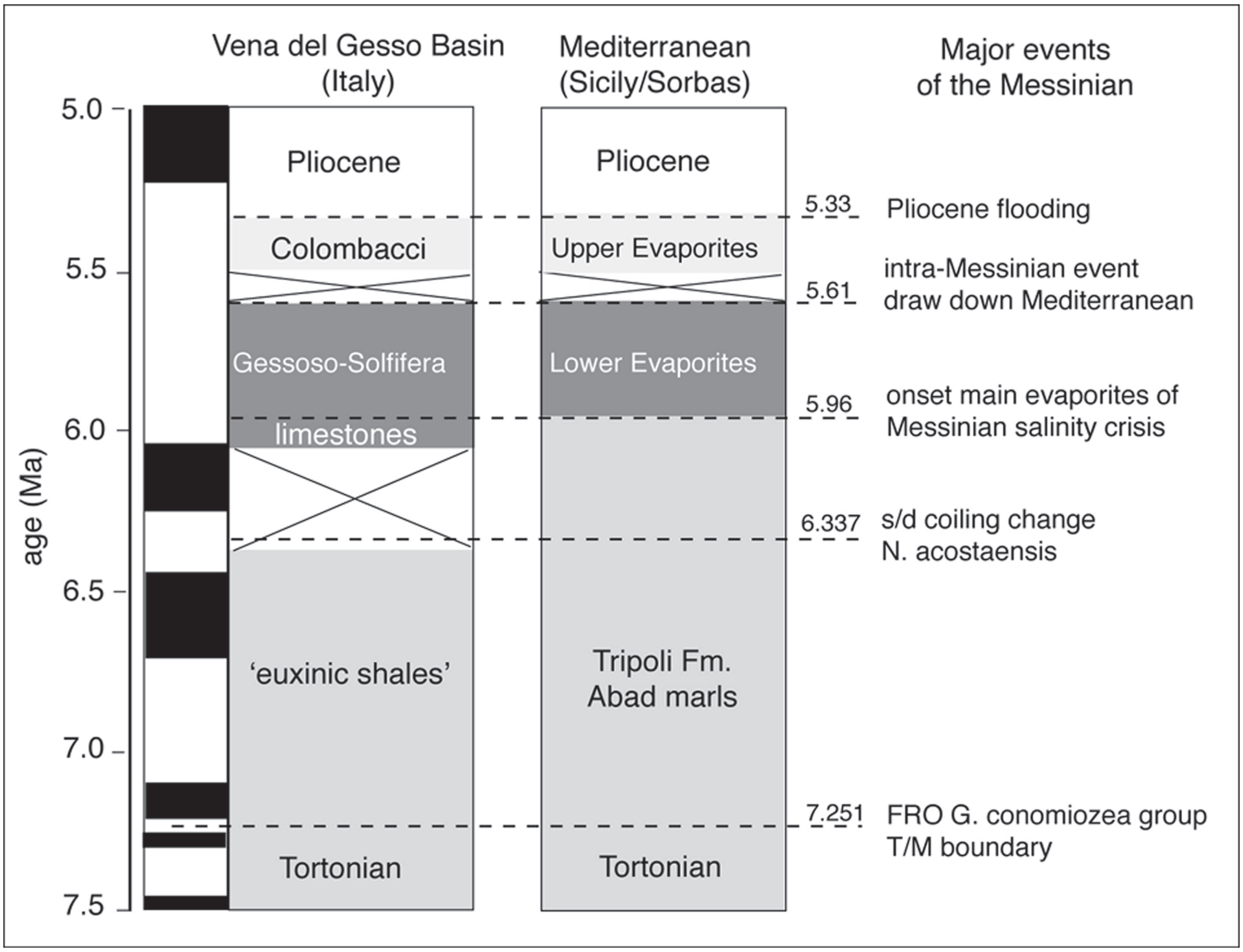

Fig. 1 - The chronology of Messinian events (modified from Krijgsman et al., 1999b).

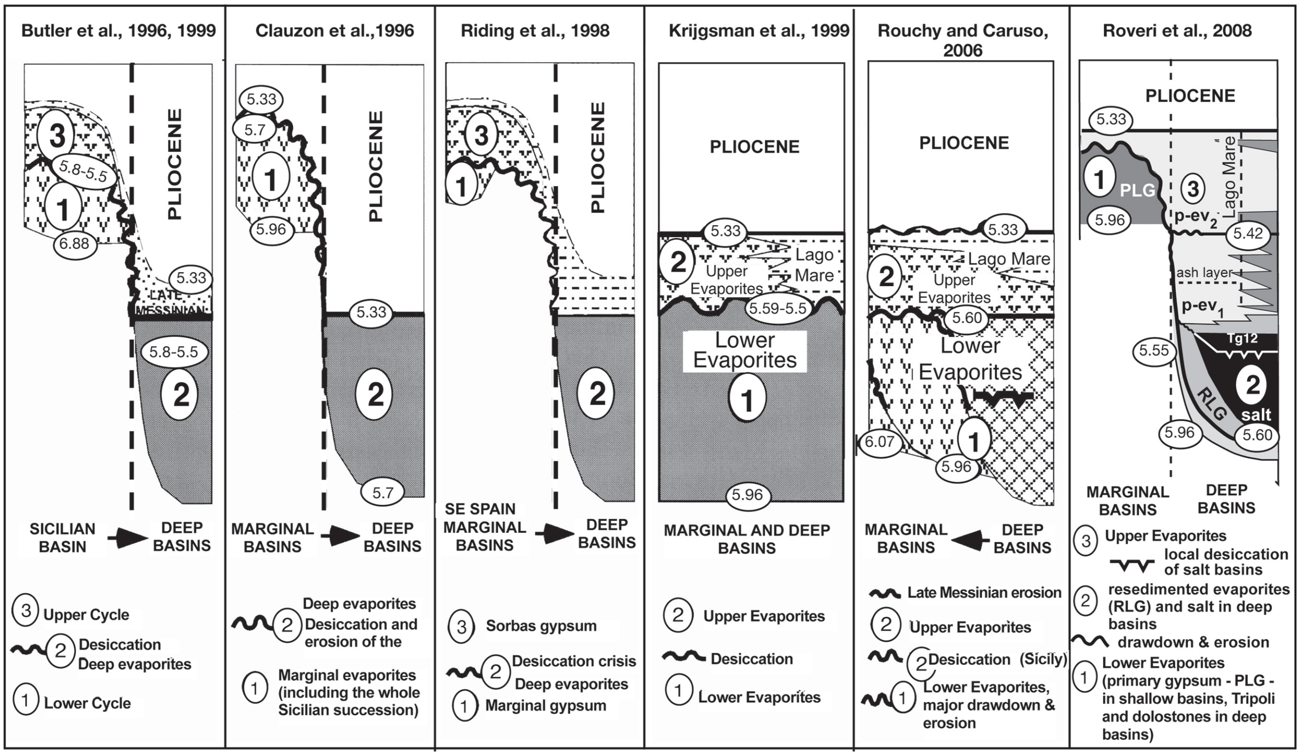

Fig. 2 - The different scenarios of the MSC (modified from Rouchy & Caruso, 2006).

& Caruso, 2006; Fig. 2). The main problems concern the genetic and stratigraphic relationships between marginal (or better shallow-water) and deep basins successions and the meaning of the *Lago-Mare* event, the basinwide development of non-marine conditions at the end of the MSC, just before the Zanclean flooding (see Orszag-Sperber, 2006 for an updated review). Shallow-water, marginal successions are often incomplete due to the MES; a complete record is expected in deep basins but tracing the MES downslope, thus defining a first order time line basinwide, is not an easy task in most basins.

Lofi et al. (2005), based on high-quality seismic record of the Gulf of Lion area (western Mediterranean), tentatively traced the MES to the base of the deep basin 'trilogy', thus envisaging a full diachronous development of deep-water successions with respect to marginal ones and casting some doubts about the nature of deep basin Lower Evaporites, which have been suggested to be deep-water clastic turbiditic deposits.

MESSINIAN BASINS OF ITALY

As stated above, the Messinian basins of Italy provide, when considered all together, a complete and variegated record of the MSC. The most significant basins are the Tertiary Piedmont basin, the Northern Apennines foreland system, the Tuscany basins, the Sicilian-Maghrebian foreland basin and the Crotone basin (Calabrian Arc).

The Messinian records of these basins offer the possibility to assess the effects of MSC in different geological, tectonic and depositional settings, thus allowing to filter out local effects from processes acting at a Mediterranean scale. Among these, surely the Apennine and Sicily basins are the most significant as they are the largest ones (also at a Mediterranean scale, compared to other 'marginal' basins) and are characterized by very thick successions (more than 1000 m). The Messinian successions of these two basins provided the basic elements in reconstructing a facies model for Lower and Upper Gypsum units (Vai & Ricci Lucchi, 1977; Schreiber, 1997) and in shedding new lights on the origin and meaning of huge halite deposits (Sicily) whose deep Mediterranean equivalents have not been reached by drillings yet.

The articulation of Messinian basins of Italy and the great emphasis classically paid by the different regional geologic schools to local features resulted in a very complex lithostratigraphic framework which made it difficult to obtain stratigraphic synthesis able to filter out local factors and to be compared with other Mediterranean basins. In the last years an effort has been made to simplify the Messinian lithostratigraphic framework; this resulted in a revisitation of the historical Gessoso-solfifera Fm. which has been elevated to the Group rank (Roveri & Manzi, 2006a) thus allowing to better represent and summarize within it the regional-scale frameworks (Fig. 3).

THE NORTHERN APENNINES FORELAND BASIN

The new stratigraphic model for the Northern Apennines foreland basin (Fig. 4), preliminarily depicted in a number of papers (Bassetti et al., 1994; Roveri et al., 1998, 2001, 2003; Ricci Lucchi et al., 2002; Roveri & Manzi, 2006b) is essentially based upon the correlation

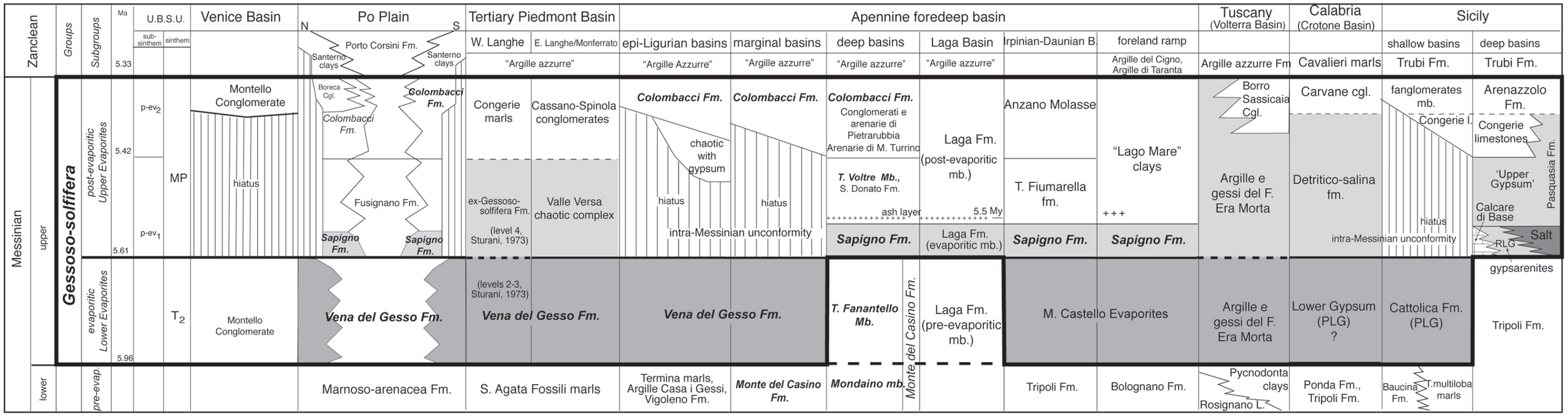

Fig. 3 - The lithostratigraphic framework of the Gessoso-solfifera Group of Italian basins (modified from Roveri & Manzi, 2006a).

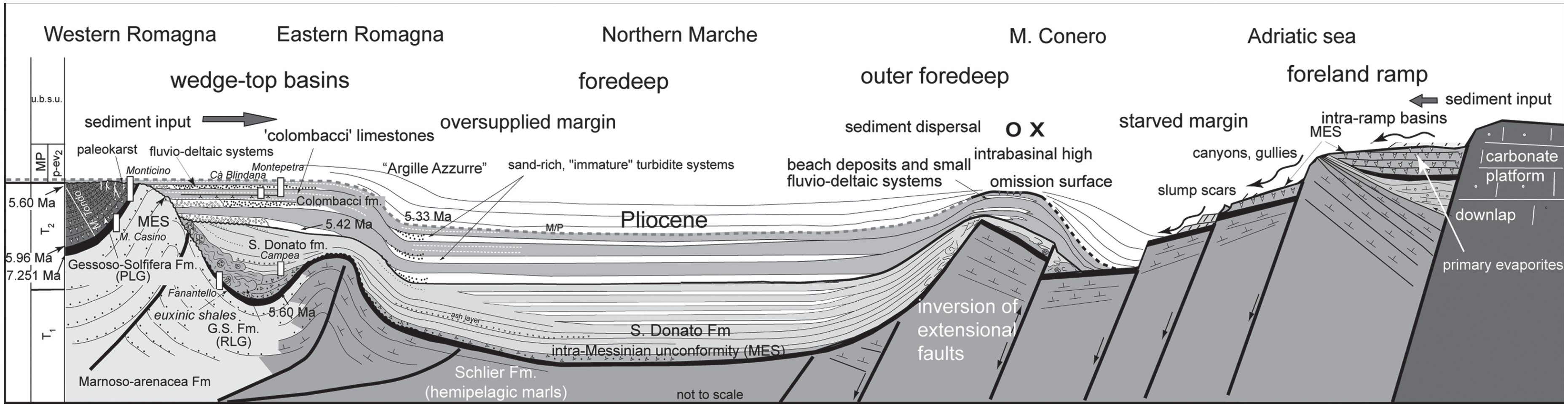

Fig. 4 - The stratigraphic model of the Apennine foredeep system (from Roveri et al., 2005).

of three main isochronous surfaces across the whole foredeep system comprising both shallow and deep-water depositional settings (Roveri et al., 2004, 2005, 2006a; Manzi et al., 2005, 2007a): 1) the onset of PLG and deep-water equivalents (5.96 Ma), 2) the onset of erosion (development of the MES) of marginal settings and deposition of clastic evaporites (Resedimented Lower Gypsum - RLG) in deeper basins (5.61 Ma) and 3) the base of the Zanclean marking the end of the MSC (5.33 Ma). The synchronous character of the latter surface has been recently put into discussion by several Authors (Popescu et al., 2007; Sprovieri et al., 2007), although their conclusions are opposite as the persistence of non-marine conditions well into the Pliocene (Sprovieri et al., 2007) and the marine nature of the Colombacci Fm. (Popescu et al., 2007) have been envisaged (see comment in Roveri et al., in press). However, based on detailed studies carried out on several outcrop sections and cores (Gennari, 2007; Grossi & Gennari, in press) and Roveri et al. (in press) demonstrated that the transition to fully marine conditions in the Northern Apennine foredeep basin can be considered, like in other Mediterranean basins (Iaccarino et al., 1999) a synchronous event coincident with the Zanclean GSSP. In fact the Authors of these studies were able to recognize the complete suite of biostratigraphic event related to the base of MPl1 biozone in all the studied sections from the northwestern sector (Piacenza) to the southeastern one (Marche region).

The three time lines allow to recognize throughout the foredeep system three main units, which correspond to three main stages of MSC evolution:

1) a pre-evaporitic unit (up to 5.96 Ma) characterized in marginal settings by shallow-water deposits with an overall transgressive trend and by organic-rich shales or rhythmic alternations of marls and sapropels in deeper settings;

2) an evaporitic unit (5.96-5.61 Ma) characterized by deposition of primary selenitic gypsum only in relatively shallow, semiclosed basins in the wedge-top and foreland ramp depozones while in deeper settings they are replaced by organic-rich and barren shales;

3) a post-evaporitic unit (5.61 - 5.33 Ma), separated from the underlying one by a regional scale tectonically-enhanced unconformity marking an important phase of deformation of the Apennine orogenic wedge and concurrent depocentre migration toward the E-NE. This unit is fully developed and shows its maximum thicknesses (more than 1 km) in the main depocentres of the foredeep basins (Po Plain and Laga basin) and is characterized by a complex vertical organization. The unit can be subdivided into two sub-units by a minor unconformity surface, which marks a clear change of facies, stacking pattern and overall trend. The lower sub-unit (p-ev$_1$ of Roveri et al., 1998, 2001) is present only in structural depressions and comprises a basal horizon made of resedimented evaporites and/or hybrid arenites (RLG) overlain by siliciclastic deposits containing an ash layer dated at 5.51±0.04 Ma (Odin et al., 1997) which represents a key bed of regional importance.

The p-ev$_1$ sub-unit shows in marginal settings a coarsening and shallowing upward trend corresponding to an aggradational and progradational stacking pattern locally leading to basin fill. This sub-unit also shows the clearest evidences of syntectonic deposition, as suggested by rapid lateral thickness and facies changes, overall trend and abundance of mass-wasting products.

The upper sub-unit (p-ev$_2$ of Roveri et al., 1998, 2001) is characterized by the sudden appearance of coarser-grained deposits in both shallow and deeper settings witnessing a drastic change in the fluvial drainage pattern. This sub-unit shows an aggradational-retrogradational stacking pattern and seals the intra-Messinian unconformity in previously uplifted and eroded areas; in many examples the uppermost Messinian deposits belonging to this sub-unit unconformably overlie eroded evaporites of stage 2 testifying for an overall transgressive trend. This sub-unit is also characterized by a clear cyclical stacking pattern, best developed in marginal settings where coarse-grained fluvio-deltaic and fine-grained basinal deposits are regularly alternated suggesting a strong climatic control of depositional systems (Roveri et al., 1998). Four to five cycles have been systematically recognized within this sub-unit throughout the whole basin; considering the time constraints offered by the M/P boundary on top and by the ash layer in the underlying unit, the precession-controlled character of the cyclicity have been envisaged for this sub-unit. This allowed to calibrate the uppermost Messinian succession against the insolation curve and to date its base at around 5.42 Ma (Fig. 7). The transition to the overlying marine Zanclean deposits in marked by a characteristic organic-rich, black horizon, especially in marginal settings where it locally overlies a palaeosoil (Roveri et al., 2006a).

THE SICILIAN FORELAND BASIN

The Messinian succession of Sicily is essentially known from its largest basin, the Caltanissetta basin, which corresponds to the main depozone of the Maghrebian-Sicilian foreland basin system, whose evolution was strictly related to that of the Apennines foredeep basin. As previously stated, the Sicilian succession as depicted by the classic Decima & Wezel's model (1971; Fig. 5a) is usually referred to as the best analogue of the deep Mediterranean basins. This model, subsequently revisited by Garcia-Veigas et al. (1995) and Rouchy & Caruso (2006) (see Fig. 5b, c), comprises two units or 'cycles' (according to Butler et al., 1995) separated by an angular discordance corresponding to the MES.

The lower unit comprises the Lower Gypsum (Gessi di Cattolica Fm., usually described as consisting of primary evaporitic facies and equivalent to the PLG of the Apennines) and its laterally equivalent at basin margins Calcare di Base Fm. (CdB).

The CdB is not well defined in the literature as it actually comprises several carbonate rocks with different genesis, mainly found in Sicily and Calabria Messinian basins: 1) thin-bedded dolostones interbedded with sapropels and diatomites; 2) sulphur-bearing limestones; 3) resedimented, often brecciated, micritic limestones of evaporitic/bacterial origin (Decima et al., 1988; Guido et al., 2007), showing lateral transitions to clastic gypsum. Type 3 is surely the most common CdB deposit throughout the Caltanissetta basin and for this reason is here referred to as 'true' Calcare di Base; type 1 bears more similarities with the Tripoli Fm., while type 2 is a diagenetic rock derived from the bacterial reduction of former gypsum (clastic) deposits.

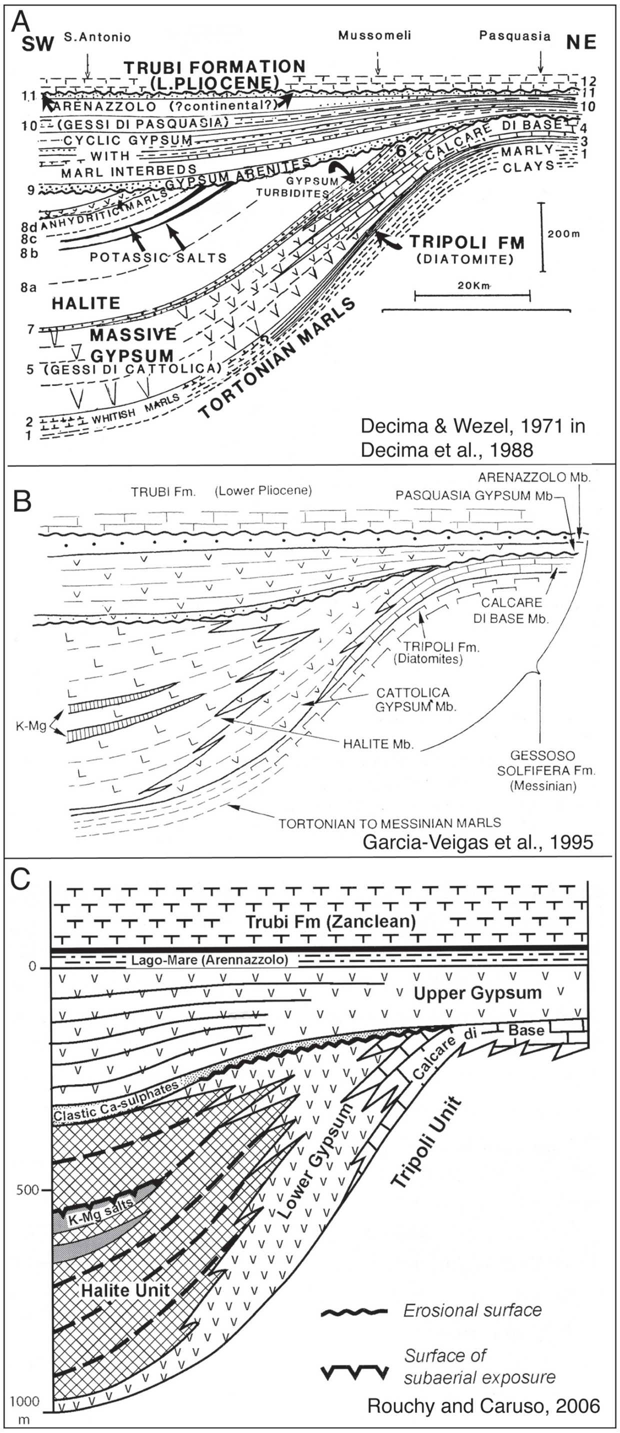

Fig. 5 - The stratigraphic models of Messinian Sicilian basin; a) modified from Decima & Wezel (1971) in Decima et al. (1988); b) from Garcia-Veigas et al. (1995); c) from Rouchy & Caruso (2006). Note the different stratigraphic relationships between salt and Lower Gypsum envisaged in the three models.

The upper unit consists of the Upper Gypsum (Gessi di Pasquasia Fm.), a cyclic alternation of primary gypsum beds (selenite and balatino) and brackish to continental marls overlain by a siliciclastic unit (Arenazzolo Fm.) in turn conformably and suddenly overlain by the fully marine Zanclean Trubi Fm. deposits.

In the Decima and Wezel's model the halite unit overlies the Lower Gypsum and Calcare di Base through an intervening horizon of gypsum turbidites; in the Rouchy & Caruso (2006) and Garcia-Veigas et al. (1995) models, the gypsum turbidite horizon disappears and lateral transitions between halite, Lower Gypsum and CdB were suggested (Fig. 5).

A recent revisitation of the Messinian succession (Roveri et al., 2006b, 2008) pointed out that, like in the Northern Apennines foreland basin, resedimented gypsum has a far larger importance of what usually thought, being widely distributed in the different depozones of the Sicilian foredeep system and particularly in the Caltanissetta main depocentre. Similarly to what happens in the Apennines, the vertical and lateral distribution of Messinian deposits appears to be controlled by the synsedimentary morphostructural evolution of the Maghrebian-Sicilian orogenic wedge (Fig. 6).

Primary Lower Gypsum deposits still maintaining their original stratigraphic position above relatively shallow water deposits (Terravecchia and M. Carrubba Fms) are only found in the innermost wedge top (Ciminna, Calatafimi; see Catalano et al., 1976, 1997) and in the foreland ramp (Licodia Eubea; see Pedley et al., 2007) depozones. PLG deposits are a perfect equivalent of the Vena del Gesso primary evaporites and are systematically cut on top by the MES and unconformably overlain by uppermost Messinian or Lower Pliocene transgressive deposits.

In deeper wedge-top basins (Belice basin; see Vitale & Sulli, 1997; Roveri et al., 2006b) and in the articulated Caltanissetta basin, Lower Gypsum deposits are only represented by deep-water resedimented facies comprising turbidites, debris flows, olistoliths and olistostromes; in the southwestern end of the basin (Cattolica Eraclea-Agrigento area) and in the Belice basin, large slabs of PLG detached from their original substrate are embedded into chaotic units made of shales and clastic gypsum, suggesting huge mass-wasting processes along Messinian slopes possibly related to tectonic instability. This clastic unit occupies the structural depressions together with halite bodies, which occur as huge lenses (up to 1 km thick of apparent thickness) passing laterally and vertically to resedimented gypsum as already recognized by Ogniben (1957), Selli (1960), and Decima & Wezel (1971).

The CdB is usually found, as recognized by Decima & Wezel (1971), Pedley & Grasso (1993) and Butler et al. (1995) above actively growing structural culminations. The complex unit made of RLG, halite and CdB has been always interpreted as a syntectonic unit, as suggested by rapid facies and thickness changes and wedging geometries (Suc et al., 1995).

The CdB has been generally considered to be a lateral equivalent of PLG thus marking the onset of MSC. However such lateral relationships cannot be observed in the field as the two deposits occur in different sub-

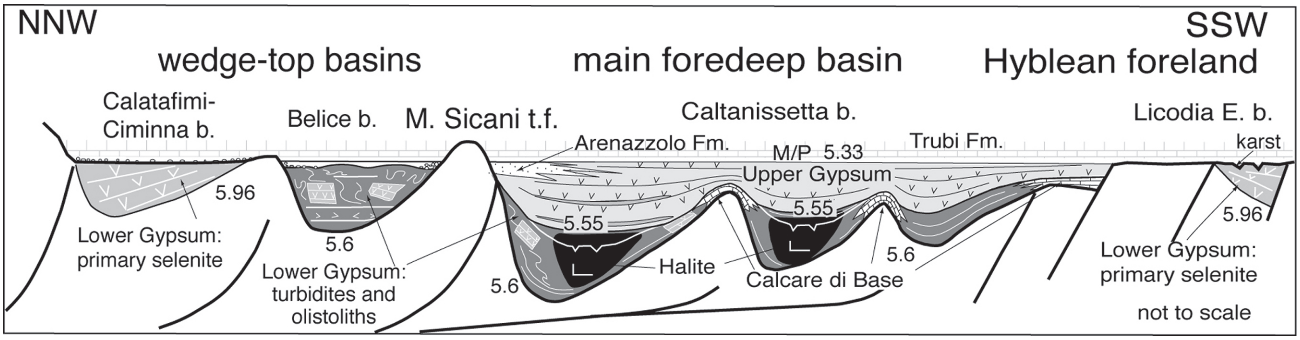

Fig. 6 - The stratigraphic model of the Sicilian-Maghrebian foredeep (from Roveri et al., 2006b).

basins and appear to be mutually exclusive: no CdB is present in innermost wedge-top and foreland ramp basins, and in situ PLG is absent in the main Caltanissetta basin depocentre. Moreover, the CdB is essentially a clastic unit (type 3, see above), often found associated with and genetically related to clastic gypsum (graded beds with a basal division made of brecciated limestones and an upper laminated gypsum one or showing a gypsrudite basal division followed upward by fine grained carbonate mud; see Roveri et al., 2006b; Manzi et al., 2007b).

The CdB sharply overlies a barren unit of variable thickness and consisting of interbedded dolostones, diatomites and sapropels (CdB type 1; see Falconara and Serra Pirciata sections; Hilgen & Krijgsman, 1999; Bellanca et al., 2001; Blanc-Valleron et al., 2002) and/or euxinic shales (Capodarso and Pasquasia sections; Suc et al., 1995; Selli, 1960) capping the interbedded marls, sapropels and diatomites of the Tripoli Fm. According to Hilgen & Krijgsman (1999), Krijgsman et al. (1999) and Blanc-Valleron et al. (2002), the transition between the Tripoli Fm. and the dolostone-bearing, barren unit records the MSC onset at 5.96 Ma. To this respect it worths noting that a similar barren unit found in the Northern Apennines foreland basin below the local RLG has been proven to be a deep-water counterpart of PLG (Manzi et al., 2007a).

In our opinion, the inclusion of this unit within the Calcare di Base Fm. can generate some confusion. The different ages of the Tripoli/CdB boundary reported in the literature (Bellanca et al., 2001), which led Rouchy & Caruso (2006) to envisage a diachronous onset of MSC, are probably due to the still undifferentiated character of the carbonate deposits referred to as CdB. Based on facies analysis, Roveri et al. (2006b, 2008) suggested alternatively that the basal contact of "true" CdB (type 3, see above) is actually unconformable at a regional scale, thus explaining the different ages reported for underlying deposits, represented by either type 1 CdB or even Tripoli Fm. The unconformable character of this contact can be recognized also locally, as suggested for example by the rapid thickness reduction of the topmost part of the Tripoli Fm. observed at Capodarso below the CdB base (Suc et al., 1995; Roveri et al., 2006b, 2008).

The general picture of the Sicilian basin emerging from the regional scale study of Messinian successions is very similar to the Apennine foredeep. The depozones of the foredeep system correspond to distinct shallow to deeper water depositional settings and are characterized by different Messinian stratigraphies. PLG formed between 5.96 and 5.61 Ma are only found in small and silled sub-basins in the wedge-top and foreland ramp area; the MES cutting on top these deposits, started to develop since 5.61 Ma and can be traced downbasin into a correlative conformity at the base of the RLG-CdB-halite unit characterizing the main foredeep depocentre. Like in the Northern Apennines foredeep basin, the barren unit on top of Tripoli is a possible deep-water equivalent of the PLG as suggested by preliminary data from new sections and from the reinterpretation of published data of Bellanca et al. (2001) as recently proposed by Manzi et al. (2007a). The salt deposits within this unit show a shallowing upward trend (Lugli et al., 1999) culminating with a desiccation surface (recognized in the Realmonte and Racalmuto mines) above which salt deposition starts again up to the transition to the overlying Upper Evaporites deposits. A complete revisitation of the latter unit (Manzi V., Lugli S., Roveri M. & Schreiber B.C., unpublished data) led to recognize two additional cycles in its uppermost part in the Eraclea Minoa and Casteltermini sections to the 7/8 usually envisaged (Schreiber et al., 1997; van der Laan et al., 2006; Hilgen et al., 2007); the precessional character of the gypsum or sand/marl alternations allow to place the lower boundary of this unit at around 5.55 Ma, thus constraining the underlying Salt-RLG-CdB unit in a very narrow window lasting more or less 50 ka.

THE TERTIARY PIEDMONT BASIN

Thirty years after the pioneer work of Sturani (1973, 1976) and Sturani & Sampò (1973) the Messinian succession of the Tertiary Piedmont Basin has been recently revisited at a regional scale (Irace et al., 2005). Despite the poor quality of outcrops, which are essentially concentrated in the Langhe area and in the Torino hill, the reconstructed stratigraphic framework allows to point out a great similarity with the Northern Apennine Messinian succession. Pre-evaporitic (S. Agata Fossili marls, equivalent of the Tripoli Fm.) and evaporitic deposits (mainly laminated gypsum described by Sturani in the Alba area) are unconformably overlain by a chaotic unit up to 300 m thick containing blocks of primary Lower Gypsum encased in a muddy matrix (Parona/Valle Versa chaotic unit; Dela Pierre et al., 2002, 2007). This unit in turn is overlain by siliciclastic non marine deposits locally characterized by a well developed sedimentary cyclicity given by the rhythmic alternation of coarse-grained fluvio-deltaic and fine-grained lacustrine deposits (Cassano Spinola Conglomerates; Ghibaudo et al., 1985). Stratigraphic position, overall trend and cyclic stacking pattern suggest that this latter unit can be correlated to the p-ev_2 deposits of the Northern Apennines (Colombacci Fm.). The Zanclean flooding is recorded both in the Langhe area and in the Torino Hill by the conformable superposition (Trenkwalder et al., 2006) of fully marine marls on *Lago-Mare* deposits through a characteristic organic-rich, black layer (Sturani, 1976), similarly to what observed in the Northern Apennines.

CROTONE BASIN (CALABRIA)

A thick Messinian succession crops out in the Crotone basin, in the Ionian side of the Calabrian Arc (Costa et al., unpublished data; Roveri et al., 2008). It consists of a basal unit made of resedimented gypsum and carbonate breccia layers unconformably 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 whose uppermost part is characterized by a barren horizon (Gennari et al., unpublished data). The resedimented gypsum unit in turn is overlain by hybrid (gypsum, carbonate and siliciclastic) clastic unit encasing halite lenses (referred to as Detritico-Salina Fm. *sensu* Roda, 1964, 1965) which in some cases are still in their original stratigraphic position; more frequently in this area the salt forms diapiric structures emplaced within the Lower Pliocene deposits (Cavalieri marls). The uppermost Messinian deposits are represented by the Carvane conglomerate (Roda, 1964, 1965), a fluvio-deltaic deposit associated with *Lago-Mare* deposits witnessing a sharp change in the fluvial drainage and in the precipitation regime, similarly to what happens in the Northern Apennines. The basal Zanclean transgression is sharp and marks the transition to the fully marine Cavalieri Marls; recent biostratigraphic revision of this boundary confirmed its perfect correspondence to the Zanclean GSSP.

TUSCANY BASIN

The Messinian succession of the Tuscany basin has a fundamental importance as it contains intermediate features between the Sicilian and Northern Apennines basins. While the extensional vs. compressional geodynamic setting of Messinian basins of Tuscany is still matter of debate within the geologic community (Bossio et al., 1998; Pascucci et al., 1999; Sandrelli, 2001; Bonini & Sani, 2002; Cerrina Feroni et al., 2006), a detailed stratigraphic revision of the most significant sections has been carried out in the last years in the Fine River and Volterra basins, leading to the reconstruction of a comprehensive regional-scale framework (Aldinucci et al., 2006; Riforgiato et al., in press). A fairly clear picture of Messinian events, essentially coeval with the main Mediterranean ones, derives from sub-basins lying to the west of the Mid-Tuscan Ridge, an important north-south trending structural high which acted as an important topographic barrier during the whole Neogene. The Messinian succession starts with fluvio-lacustrine to brackish deposits filling small and fault-bounded basins of Tortonian age; an important transgressive event, recently aged at around 6.255 Ma based on a high-resolution stratigraphic study of the Gello section (Volterra basin, Riforgiato et al., in press) transformed the area in a shallow-marine, articulated basin. This marine transgression appears to be coeval with a sharp vertical facies change from hemipelagic to dominantly clastic deposits (thin-bedded turbidites) recorded in the Apennine foredeep basin (Fanantello core; Manzi et al., 2007a) suggesting a tectonic event affecting both sides of the Apennine orogenic wedge. Normal marine conditions lasted till around 5.96 Ma (Riforgiato et al., in press), when primary Lower Gypsum started to deposit in shallower and semiclosed sub-basins. Reefal limestones with *Porites* (Rosignano Limestones) and muddy shelf deposits (*Pycnodonta* marls) were deposited during this interval and their areal distribution appears clearly controlled by the morphostructural settings. Primary evaporites consist of cyclically interbedded selenite gypsum and shales showing the same facies and stacking pattern characteristics of the Northern Apennines and Sicilian examples. These deposits formed in the shallowest part of the Fine River and Volterra basins (presently outcropping in the Migliarino, Marmolaio, and Spicchiaiola quarries) and often overlie the Rosignano Limestones reefs; they are cut on top by an intra-Messinian unconformity and sealed by uppermost Messinian *Lago-Mare* deposits. In relatively deeper settings (the depocentre of the Volterra basin) a thick succession of alabastrine gypsum, gypsrudites and gypsarenites with an upward increasing coarse-grained siliciclastic component, is present (Faltona and Cava Gesseri sections; Testa & Lugli, 2000). The first appearance of gypsum-bearing conglomerates associated with progressive angular discordances has been usually correlated at a regional scale with the intra-Messinian unconformity cutting on top PLG on basin margins. However, a recent careful revisitation of the 4/5 basal gypsum beds of this succession, commonly interpreted as primary in origin (Testa & Lugli, 2000), suggest that, despite the strong transformations suffered by gypsum, an original clastic nature can be also envisaged for such beds. This implies that in the depocentre no primary gypsum formed during the first MSC phase and that probably the correlative conformity of the MES should be lowered to the base of the first gypsum bed. The clastic gypsum unit is overlain by siliciclastic deposits formed in a fluvio-deltaic environment; best exposure are found in the Fine River basin where the classic Cava Serredi section has been studied in great detail leading to recognize a cyclic stacking pattern recording the periodic activation of fluvial systems and their subsequent abandonment (Aldinucci et al., 2005). The number of cycles and the overall transgressive trend are very similar to the Apennine foredeep basin p-ev_2 unit and also here the return to fully marine conditions at the end of the MSC appears to be coeval with the Zanclean GSSP (Riforgiato et al., 2007).

CENTRAL AND SOUTHERN APENNINE BASINS

Messinian deposits also occur in minor basins of the Central (Abruzzo and Lazio area) and Southern Apennines (Irpinian-Daunian basin), developed on top of the Apennine orogenic wedge along the Adriatic foreland ramp. The Messinian successions filling these basins are usually incomplete and of difficult interpretation due to strong tectonic overprint. However, the synthesis made by Cipollari et al. (1999), Cosentino et al. (2006), and Matano et al. (2005) pointed out that also in these basins a intra-Messinian unconformity can be recognized which separates a lower evaporite-bearing unit (Gessoso-solfifera Fm. of the Maiella area, Monte Castello Evaporites of Irpinian-Daunian basin, Fig. 3) from an upper one mainly represented by thick siliciclastic deposits with an overall transgressive trend and containing the typical *Lago-Mare* faunal assemblages.

MEDITERRANEAN-SCALE IMPLICATIONS

Shallow to deep water MSC record

A fundamental advancement for the comprehension of Messinian stratigraphy is represented by the recent revisitation of the 'Lower Gypsum' evaporites of the so called marginal basins, which actually consist of both shallow-water primary (PLG) and deep-water resedimented facies (RLG). In particular, much emphasis has been given to the latter deposit (Roveri et al., 1998, 2001, 2003, 2004, 2006a, b; Manzi et al., 2005, 2007a) and to their potential chronostratigraphic value. Deep-water resedimented evaporites have long been recognized as an important element of Messinian stratigraphy. However, these deposits have been largely overlooked in the literature as their origin, time and spatial distribution were related to local tectonic activity and hence considered as a sort of 'bottom noise' not relevant for the general scenario at a Mediterranean scale.

In the Italian basins, deep-water resedimented evaporites were first recognized in the Apennine foredeep (Parea & Ricci Lucchi, 1972) where they have long been considered as coeval deposits of the primary evaporites of the Vena del Gesso basin and hence included as an intrafacies in the Gessoso-solfifera Fm. (see Vai, 1988). Recent studies (Roveri et al., 2001, 2003; Manzi et al., 2005, 2007a) pointed out that primary and resedimented gypsum deposits are never found associated neither vertically nor laterally in the same succession. Actually they were deposited in different sub-basins of the Apennine as well as of the Sicilian-Maghrebian foredeep systems; the same situation seems to characterize also the Calabria, Tuscany and Piedmont basins.

In the Apennine and Sicily foredeep systems primary 'Lower Gypsum' formed in innermost, structurally and topographically more elevated wedge-top basins bounded by thrust-related anticlines which started to grow since the late Tortonian (Vena del Gesso basin; Roveri et al., 2003); the same deposits also formed on the Adriatic and Hyblean foreland ramps in small extensional basins (Roveri et al., 2005, 2006a, b; Pedley et al., 2007). PLG show the typical cyclic organization that is common to Spain and Greece equivalents (see Krijgsman et al., 2001). The revisitation of Vai & Ricci Lucchi's (1977) classic facies model shows that the nodular facies found in the upper part of the ideal evaporitic cycle and previously interpreted as formed in a sabkha environment, actually results from the subaqueous growth of a particular kind of selenite cones ('branching selenite', Lugli et al., 2006, 2008). This important observation rules out any significant subaerial exposure and erosion within or at the top of individual gypsum cycles and allows to conclude that the PLG is a fully subaqueous deposit formed in semiclosed, silled basins at a water depth not deeper than 150/200 m as light and oxygen are needed for the growth of selenite crystals and to sustain the cyanobacterial mats which are found within them. The unit as a whole experienced subaerial exposure after its deposition as testified by the MES on top with clear evidences of palaeokarst (Vai et al., 1988); this unconformity is associated with an angular discordance, documenting its development during an important phase of tectonic deformation of the Apennines orogenic wedge.

Resedimented Lower Gypsum deposits (RLG) form thick to very thick units (up to several hundred meters) which do not contain any in situ primary evaporitic facies; facies analysis document that they formed in deep-water settings through a complete suite of gravity-driven processes comprising low to high-density turbidite flows, debris flows, olistoliths and olistostromes (Manzi et al., 2005; Roveri et al., 2006a; Dela Pierre et al., 2007). Facies distribution is clearly controlled by basin topography and the vertical stacking pattern and overall coarsening-upward trend suggest syntectonic deposition with progressive exhumation and dismantling of PLG and underlying deposits (Manzi et al., 2005). This unit is overlain by upper Messinian siliciclastic deposits usually referred to as post-evaporitic unit or Upper Evaporites (in Sicily).

Facies characteristics of RLG and of the underlying lower Messinian and upper Tortonian successions together with considerations about the regional-scale evolution of the Apennine and Sicily foredeep systems indicate that they were emplaced in deeper water settings with respect to the Primary Lower Gypsum. A quick correlation of PLG and resedimented unit is not possible as they are always physically disconnected by intervening tectonic structures. As a consequence the only possibility to establish the stratigraphic relationships between these two gypsum-bearing deposits is using physical-stratigraphic concepts.

The key question is: where can we trace downbasin the subaerial erosional surface cutting on top the PLG unit? Almost thirty years of sequence-stratigraphic studies has led to recognize the stratigraphic relationships between deep and shallow-water depositional systems and to realize that deep-water turbidite systems are activated during relative base-level falls when basin margins experience a generalized phase of erosion and sediment bypass. As a consequence, it's a consolidated practice in basin analysis to trace main unconformities on basin margins to a correlative conformity at the base of deep-water turbidite systems.

This is what has been suggested first for the Apennine foredeep basin (Roveri et al., 2001, 2006a) and subsequently for Sicily and Calabria basins (Roveri et al., 2006b, 2008); of course, if this hypothesis is correct, a time-equivalent unit of the PLG should be present in deep-water successions. Manzi et al. (2007a) demonstrated that RLG of the Apennine basin are usually underlain by an organic-rich unit of variable thickness which is barren of marine fossils and which has no equivalents in the Messinian pre-evaporitic succession underlying PLG. The barren unit shows at its base a transition from normal marine deposits; fossil assemblages (foraminifera, calcareous nannoplankton, molluscs) progressively changes and decrease in diversity suggesting a gradual but rapid increase in water salinity. Detailed bio- and magnetostratigraphic analysis, together with cyclostratigraphic considerations, led Manzi et al. (2007a) to state that 1) the base of this barren unit can be placed at 5.96 Ma and hence can be considered the deep-water counterpart of PLG and 2) that the base of overlying RLG can be dated at around 5.61 Ma (i.e. the maximum age of the MES), thus demonstrating that PLG and RLG are fully diachronous deposits. As previously described a similar evolution can be reconstructed also for Sicily and Calabria basins as a barren unit underlying RLG is present and has been suggested to represent a deep-water counterpart of PLG.

This new interpretation of the stratigraphic relationships of PLG and RLG changes radically the Apennine and Sicily basins stratigraphy and sedimentary evolution during the Messinian, allowing to envisage a more dynamic scenario which accounts for ongoing tectonic deformation in the different morphostructural settings (Fig. 7). These results are also in good agreement with the scenario envisaged by Lofi et al. (2005) for the deep western Mediterranean basin and suggest the possibility and opportunity to apply the same stratigraphic approach to other basins. In particular, this stratigraphic revisitation seems to reinforce the role of Sicilian basin as a possible analogue of deep Mediterranean basin, as salt is strictly vertically and laterally associated with clastic deposits, as suggested by Lofi et al. (2005) in the Gulf of Lion (Western Mediterranean; see Roveri et al., 2008).

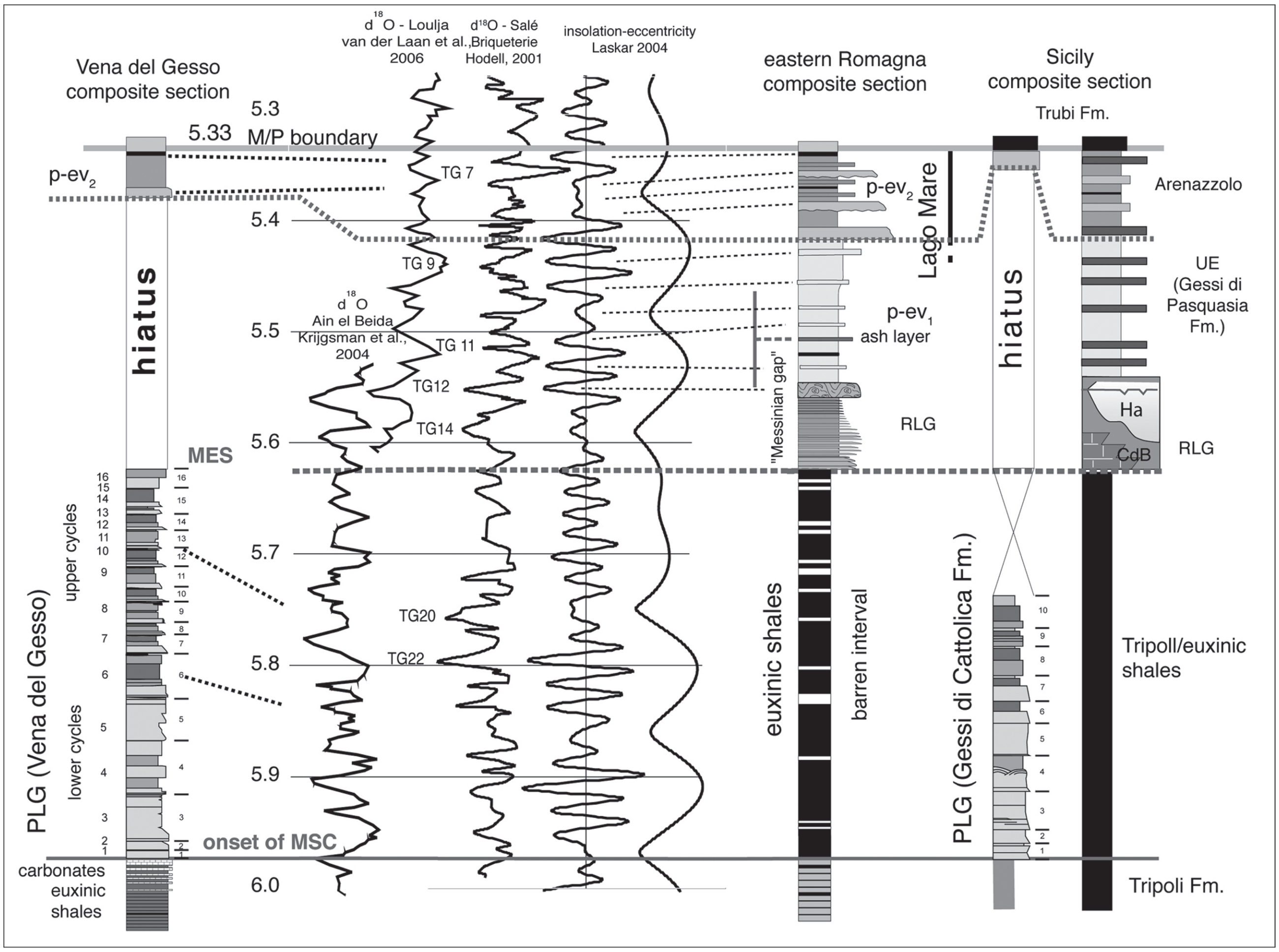

Fig. 7 - Chronology of Messinian events in the Apennine and Sicilian basins (modified from Roveri & Manzi, 2006b).

The Lago-Mare

An important implication of the high-resolution stratigraphic framework reconstructed through a cyclostratigraphic approach for uppermost Messinian deposits is the possibility to better frame the palaeoenvironmental evolution of the basins during the last MSC stage, which is characterized by the generalized development of non-marine environments ("*Lago-Mare*"; see Orszag-Sperber, 2006 for an updated review). The origin, timing and characteristics of such event are matter of a never ending debate, mainly due to the apparently contradictory palaeoenvironmental signals coming from different palaeontological and geochemical proxies. This led to envisage a scenario characterized by an almost desiccated Mediterranean basin with several lakes at different elevations, totally disconnected, with different hydrological characteristics but essentially filled with waters coming from the Paratethys, i.e. the complex of freshwater basins of the present-day eastern Europe, as suggested by faunal and floral assemblages. Most proxies point indeed to non-marine waters, ranging from oligohaline to mesohaline, but the presence of marine fauna (foraminifers, fishes) whose both *in situ* and reworked character has been claimed by different research groups, together with stable isotope data (see Carnevale et al., 2006, 2008), still represents a challenge for palaeoecologists.

When framed within a high-resolution stratigraphic model for the late Messinian, allowing to compare and correlate basinwide very narrow time slices (at the 20 ka precessional scale), palaeoenvironmental data actually define a much less disorganized pattern than previously thought (Roveri et al., 2006c, in press). In all the Italian basins, but also in Spain and Greece, the vertical distribution of ostracods, molluscs, pollen and dinocysts within this high-resolution framework led to recognize that the p-ev$_1$/p-ev$_2$ boundary is the physical feature which better approximates a clear, gradual but rapid change in fossil assemblages toward hypohaline conditions. This is more clearly indicated by ostracods, for which a new biozonation for the late Messinian has been proposed (Gliozzi et al., 2006); it consists of two new biozones (*Loxoconcha muelleri* and *Loxocorniculina djafarovi* biozones), corresponding to the *Non distinctive zone,* whose boundary is roughly coincident with the p-ev$_1$/p-ev$_2$ boundary. The uppermost Messinian deposits (p-ev$_2$ unit) contain on average the most clear signals of the presence of diluted surface waters; the abundance and diversity of faunal assemblages increases upward within this unit, suggesting the progressive enlargement and connectivity of the basins and the development of more suitable palaeoenvironments. 'Marine' signals mainly come from the uppermost cycles of this unit, just prior to the Zanclean flooding (Iaccarino & Bossio, 1999; Bassetti et al., 2004; Rouchy & Caruso, 2006), thus suggesting that the connections with the Atlantic, if they were interrupted or severely reduced at the MSC acme, were then progressively reestablished during the latest Messinian. The emerging scenario for the last MSC phase points to a complex interplay between tectonic and climatic processes (Griffin, 2002; Willett et al., 2006) leading to high-amplitude fluctuations of the precipitation regime and hence of the hydrological balance within the Mediterranean sub-basins.

FUTURE WORK

Much work is still needed in the Italian basins to strengthen our stratigraphic knowledge of the Messinian stage. Future researches should be addressed in particular to the detailed study of basinal deposits underlying resedimented evaporites to assess their age and palaeoenvironmental conditions. Preliminary data got from Apennines, Sicily and Calabria encourage to go along this road as it probably could shed new light on the deep basinal expression of the MSC. To this respect, the deposits underlying salt bodies of Sicily, Tuscany and Calabria need to be thoroughly explored, as well as the large family of carbonate deposits known as Calcare di Base, whose actual significance is still poorly understood. Another important item to be studied in the future is the stratigraphic and palaeoenvironmental framework of the *Lago-Mare* event, which in Italian basins is best recorded by expanded sections that could potentially provide a very detailed scenario of the final MSC phase.

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