A high-resolution stratigraphic framework for the latest Messinian events in the Mediterranean area

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ABSTRACT: A high-resolution stratigraphic model for the uppermost Messinian deposits of the Mediterranean basin is here proposed. The model provides new constraints for calibrating the time and space distribution of palaeoenvironmental proxies of the final phase of the Messinian salinity crisis (MSC), characterized, after the main phase of massive evaporite precipitation, by the progressive and generalized establishment of brackish to freshwater aquatic environments throughout the Mediterranean basin ('Lago Mare event'). The corresponding stratigraphic unit, bounded by the intra-Messinian unconformity (MES) at the base (~5.6 Ma) and the M/P boundary at top (5.33 Ma) is split into two sub-units by a minor unconformity marking a sharp facies change.

The lower sub-unit (p-ev$_1$) is localized in deepest and/or strongly subsiding basins and is commonly characterized by 'regressive' depositional trends. It records the transition from hyper- to hypohaline conditions over a short time span characterized by an acceleration of tectonic processes in many Mediterranean geodynamic contexts.

The upper sub-unit (p-ev$_2$) is more basin-wide distributed and records the generalized periodic activation of catastrophic flood-dominated fluvio-deltaic depositional systems, indicating important modifications in the drainage areas and/or in fluvial runoff. In this sub-unit four to five precessional cycles are usually recognized below the Miocene/Pliocene boundary, allowing basin-wide correlations and suggesting to place its basal age at around 5.42 Ma.

While p-ev$_1$ records the local and ephemeral development of Lago Mare environments with low-diverse, pioneer taxa, p-ev$_2$ is marked by the diffusion of conspicuous brackish to freshwater fossil assemblages of increasing diversity and complexity upwards. The change is best approximated by the boundary between the two sub-units.

No clear evidence of normal marine conditions established before the Zanclean flooding have been recognized. Converging sedimentary evolution and paleontologic record suggest that the last MSC phase was characterized by a dilution of the surface waters of a large, residual Mediterranean water body with strongly reduced ocean connections. These conditions likely resulted from a positive feedback loop between processes (increase of fluvial runoff, generalized subsidence, base-level rise, enlargement of shelf areas) promoting the establishment of progressively larger, more stable intra-basinal connections and water exchanges with the Paratethyan basins, up to the final full reopening of the Atlantic gateways.

INTRODUCTION

Following the main phase of massive marine evaporite precipitation (comprising the Lower Evaporites and Salt units), the last stage of the Messinian salinity crisis (MSC) of the Mediterranean basin shows the generalized development of brackish to freshwater environments usually referred to as "Lago Mare", after Gignoux (1936) and Ruggieri (1967).

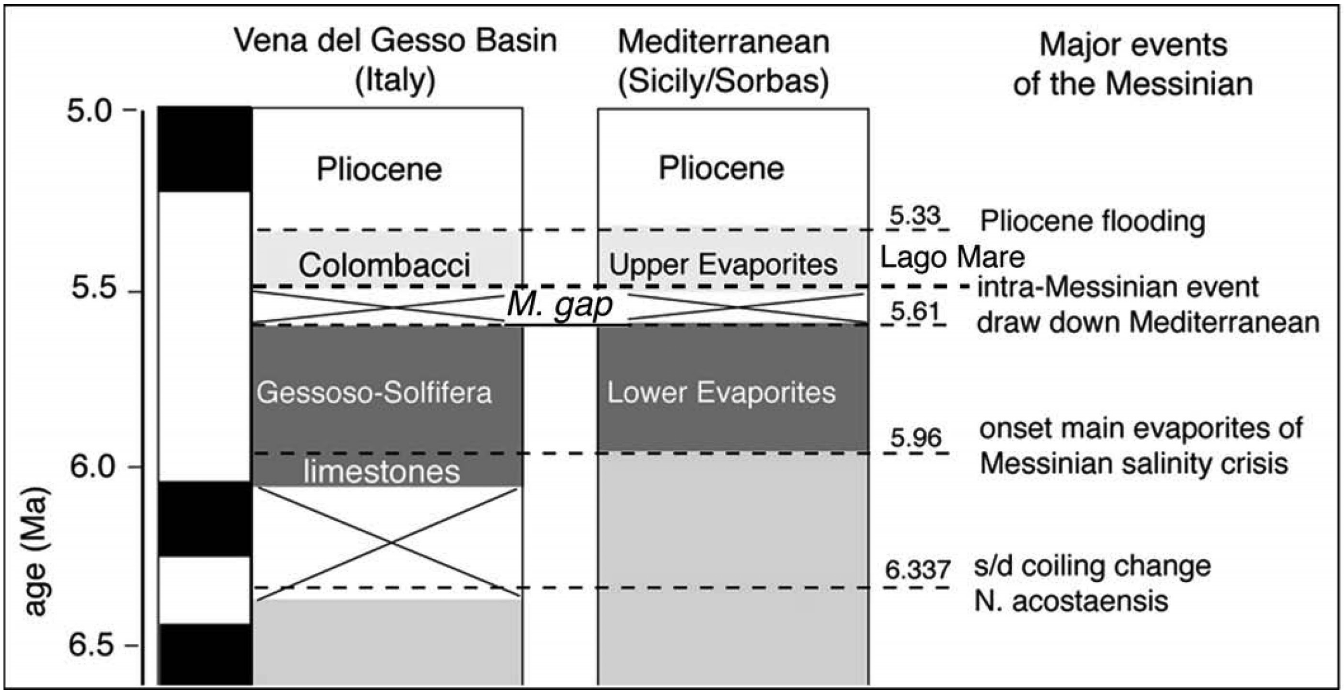
The first explanation for such a severe hydrological change envisaged 1) the closure of the Atlantic gateways, 2) an almost completely desiccated deep Mediterranean basin and 3) its partial refill by captured Paratethyan brackish to fresh waters (Hsü et al. 1977).

This classic scenario has been challenged in the last years by several authors (see Orszag-Sperber 2006 for an updated review) leading to a number of different evolutionary models for the final phase of the MSC, involving complex geodynamic and palaeoclimatic feedbacks (Griffin 2002; Rouchy and Caruso 2006; Willett et al. 2006).

In particular, the non-marine character of latest Messinian successions have been severely questioned or even rejected by the increasingly claimed occurrence of normal marine biota (foraminifera, calcareous nannoplankton, fishes) within Lago Mare deposits.

Normal marine conditions during latest Messinian have been suggested for the western Mediterranean area based on fossil assemblages of the Sorbas Mb. Feos Fm., Garruchal Fm., respectively in the Sorbas, Nijar and Bajo Segura basins (Betic Cordillera; Braga et al. 2006; Aguirre and Sanchez-Almazo 2004; Soria et al. 2008).

Based on the recovery of otoliths of adventitious marine or diadromous fishes found in several Apennines sections (on both the Adriatic and Tyrrhenian side), as well as on oxygen isotope data from ostracod and mollusk shells of Tuscany basins, normal marine conditions or, at least, active connections with normal marine water bodies have been recently suggested (Carnevale et al. 2006; 2008).



TEXT-FIGURE 1
Chronology of Messinian events according to Krijgsman et al. (1999) age model.

A marine character of uppermost Messinian deposits of Sicilian Arenazzolo Fm. and of the Northern Apennines Colombacci Fm. has been recently claimed by Clauzon et al. (2005), Londeix et al. (2007) and Popescu et al. (2007), suggesting water exchanges between the Mediterranean and the Paratethyan Basins during two successive base level high-stands prior and immediately after the Mediterranean deep basin desiccation.

The possible persistence of sporadic and limited marine influences during the latest Messinian has been also suggested and/or not excluded by Bassetti et al. (2004), based on oxygen isotope data from the "*colombacci*" limestone layers of the Northern Apennines, as well as by Rouchy and Caruso (2006).

Our impression is that the general palaeogeographic and palaeoenvironmental picture for this time interval, instead of being progressively elucidated by an increasing volume of data and by the adoption of more advanced analytical techniques and conceptual approaches, is getting more confused.

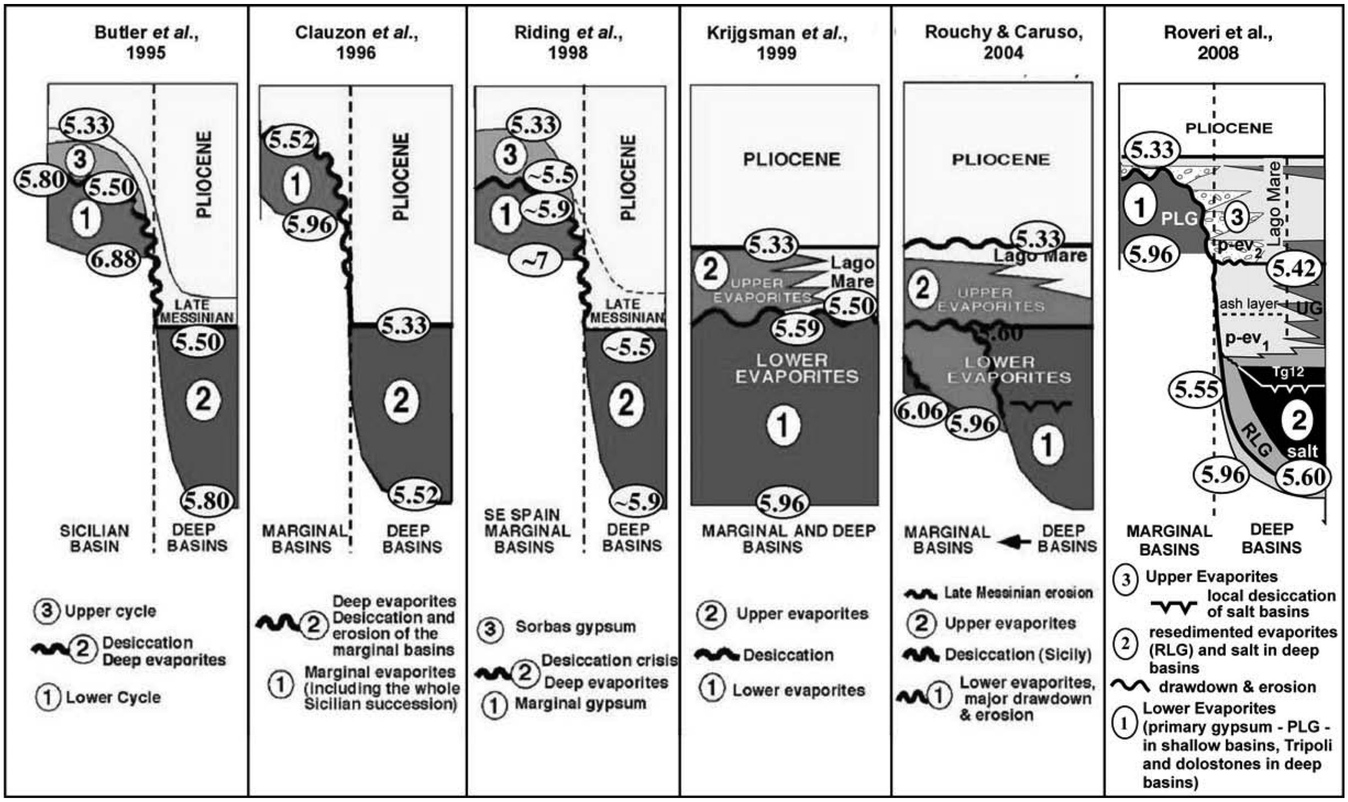
Many important observations and data are still too scattered in time. The attempts to frame all the available palaeoenvironmental data into a comprehensive scenario are still hampered by the difficulty of erecting a Mediterranean scale high-resolution stratigraphic scheme allowing to assess more reliable scenarios for successive, discrete and as shortest as possible time windows.

Erecting such a stratigraphic scheme and applying it to all Mediterranean sub-basins is not an easy task because this interval, in spite of its claimed marine character, is actually characterized by non marine faunal assemblages or by very poor and rare, poorly preserved and biostratigraphically not significant marine assemblages, often reworked. Moreover, if we consider that no magnetic reversals occur during the late Messinian, it is clear that the normal stratigraphic approaches are not useful to solve or at least to address the problem.

One possibility is offered by physical stratigraphy, which allows to reconstructing regional-scale chronostratigraphic frameworks based on the recognition of key surfaces, depositional trends and sedimentary cyclicity related to external forcings.

Our paper is the result of a multidisciplinary research project whose main aim was to contribute to disentangle such a complicate situation by reconstructing, through the integration of new and published data, a chronostratigraphic framework for the late Messinian based on physical-stratigraphy.

We started from the Apennine foredeep basin succession, which has been studied during the last 15 years by many researchers of this group, allowing to testing and strengthening our integrated stratigraphic approach. The stratigraphy of this succession has been refined by adding new field, seismic and core data (the latter recovering key-intervals defined through previous studies). A similar approach has been applied to Tuscany, Piedmont, Calabria, Sicily and Betic Cordillera basins, where new data have been obtained within our project. The results have been compared and integrated with other recently published data and finally synthesized in the comprehensive stratigraphic model that we present here. Many local data which concurred to the general model have been already published or presented in several meetings, while other are being published. In this paper we present and emphasize the synthesis of our work, thus addressing the readers interested to the details to more pertinent papers.



TEXT-FIGURE 2
The different scenarios for the Messinian salinity crisis (modified from Rouchy and Caruso 2006). Abbreviations in the Roveri et al.'s model mainly based on Northern Apennines and Sicily outcropping succession (see Roveri et al. 2008 for further information): PLG, Primary Lower Gypsum; RLG, Resedimented Lower Gypsum (including also the Calcare di Base), UG, Upper Gypsum.

The final MSC event(s): general time constraints

Following the Messinian chronology of Krijgsman et al. (1999), recently updated by Hilgen et al. (2007), Lago Mare conditions developed between 5.60 Ma (i.e. at the onset of subaerial exposure and erosion in marginal basins associated with the development of the intra-Messinian unconformity or Messinian erosional surface – MES – and following the deposition of Lower Evaporites unit) and 5.33 Ma (the re-establishment of full connections with the ocean at the base of the Pliocene; text-fig. 1). Within this 270 ka time interval, strongly fluctuating palaeoenvironmental conditions should account for the deposition of the Upper Evaporites unit (mainly in the southern and eastern sectors of the Mediterranean) as well as of large volumes of clastic deposits, suggesting increased fluvial runoff, higher seasonal contrast and hence a shift toward a more positive, albeit strongly fluctuating, hydrologic budget at the end of the MSC.

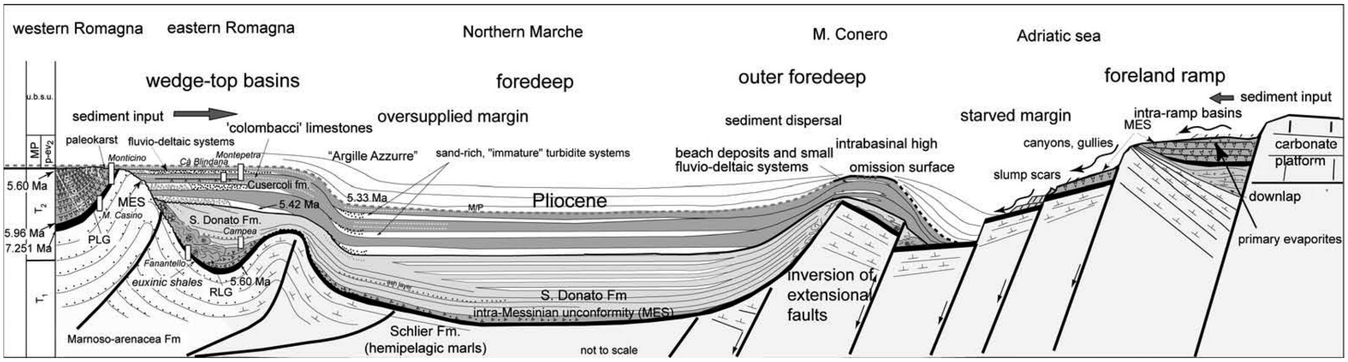
However, the ages of the base and top of the Lago Mare and its overall meaning are not fully agreed by some authors, as clearly shown by the different MSC scenarios so far proposed (text-fig. 2). The main problems concern the age of the basal unconformity (MES); more recently, also the base of the Pliocene has been challenged, by suggesting that the Zanclean base should be lowered to include units like the latest Messinian Arenazzolo and Colombacci Fm., based on their "marine" and overall transgressive character which would indicate the opening of the Atlantic gateways well before than usually thought (Clauzon et al. 2005; Londeix et al. 2007; Popescu et al. 2007).

It follows that the correct recognition and dating of the two physical features (the MES and the Miocene-Pliocene boundary - MPB) sandwiching the Lago Mare successions is the first step for the reconstruction of a high-resolution stratigraphic framework of late Messinian events.

The intra-Messinian unconformity (MES)

The intra-Messinian unconformity is a first-order discontinuity within the Messinian successions of the Mediterranean sub-basins, both outcropping and buried below the sea floor (Ryan and Cita 1978). In the latter settings this unconformity is better known as Messinian Erosional Surface (MES; Lofi et al. 2005). This discontinuity generally appears as an erosional surface deeply cutting the evaporites of the first MSC stage and/or the underlying deposits.

According to cyclostratigraphic considerations (Krijgsman et al. 1999), a maximum age of 5.60 Ma has been calculated for the initial development of the MES in marginal basins. The associated hiatus has highly variable amplitude according to local and regional factors; in most of marginal settings uppermost Messinian or early Pliocene deposits seals the MES. Clear evidence of prolonged subaerial exposure is present in karst features developed on top of Lower Evaporites, for example in the Vena del Gesso (Northern Apennines; Vai 1988) and in the Hyblean plateau (Sicily; Grasso et al. 2004). Seismic profiles document the widespread distribution of the MES along the Mediterranean continental margins (Ryan and Cita 1978; Lofi et al. 2005), especially in front of largest rivers, where deeply



TEXT-FIGURE 3
The geologic-stratigraphic model of the Apennines foredeep system (from Roveri et al. 2005). White rectangles show the location of shallow boreholes drilled in key stratigraphic intervals and discussed in text.

incised canyons are observed (Clauzon 1973; 1978; 1982; Chumakov 1973).

All these elements point to a phase of subaerial exposure of Mediterranean basin margins during a relative sea-level fall, whose amplitude is still matter of debate. Classic MSC models (see Rouchy and Caruso 2006; text-fig. 2) envisage a 1500m evaporative drop of sea level, leading to the desiccation of deepest Mediterranean basins and the consequent deposition of huge volumes of evaporites (halite).

However, the frequently observed angular discordance associated with the MES (Northern Apennines, Gulf of Lyon, Eastern Mediterranean, Sicily) suggests that a pan-Mediterranean tectonic event concurred to its genesis (Roveri and Manzi 2006). In any case the MES smoothes out basinward and passes to a correlative conformity in deep-water settings (Roveri et al. 2008b, c).

Deep-water basins show a fairly continuous Messinian succession comprising the volume of sediments accumulated during a phase of basin margin subaerial exposure and dismantling. As a consequence, the correct recognition of the MES correlative conformity within basinal successions is of fundamental importance, not only to obtain a reliable chronostratigraphic constraint (i.e. the ~5.60 Ma time line), but also to understand what really happened in deep water settings while basin margins were experiencing subaerial exposure and erosion.

Deep basins of the Northern Apennines are characterized by the widespread occurrence of a resedimented gypsum unit (RLG in text-fig. 2) containing also blocks of massive selenite and overlying a barren organic-rich shale unit (Roveri et al. 2001; Manzi et al. 2005). The latter unit has been recently suggested to be a deep-water equivalent of the Lower Gypsum deposits (PLG in text-fig. 2; Manzi et al. 2007), thus allowing to trace the MES at the base of the resedimented gypsum deposits.

This means that at around 5.60 Ma, when marginal basins began to be eroded and dismantled, deeper basins, at least in the Northern Apennines foredeep, started to be fed with clastic evaporites.

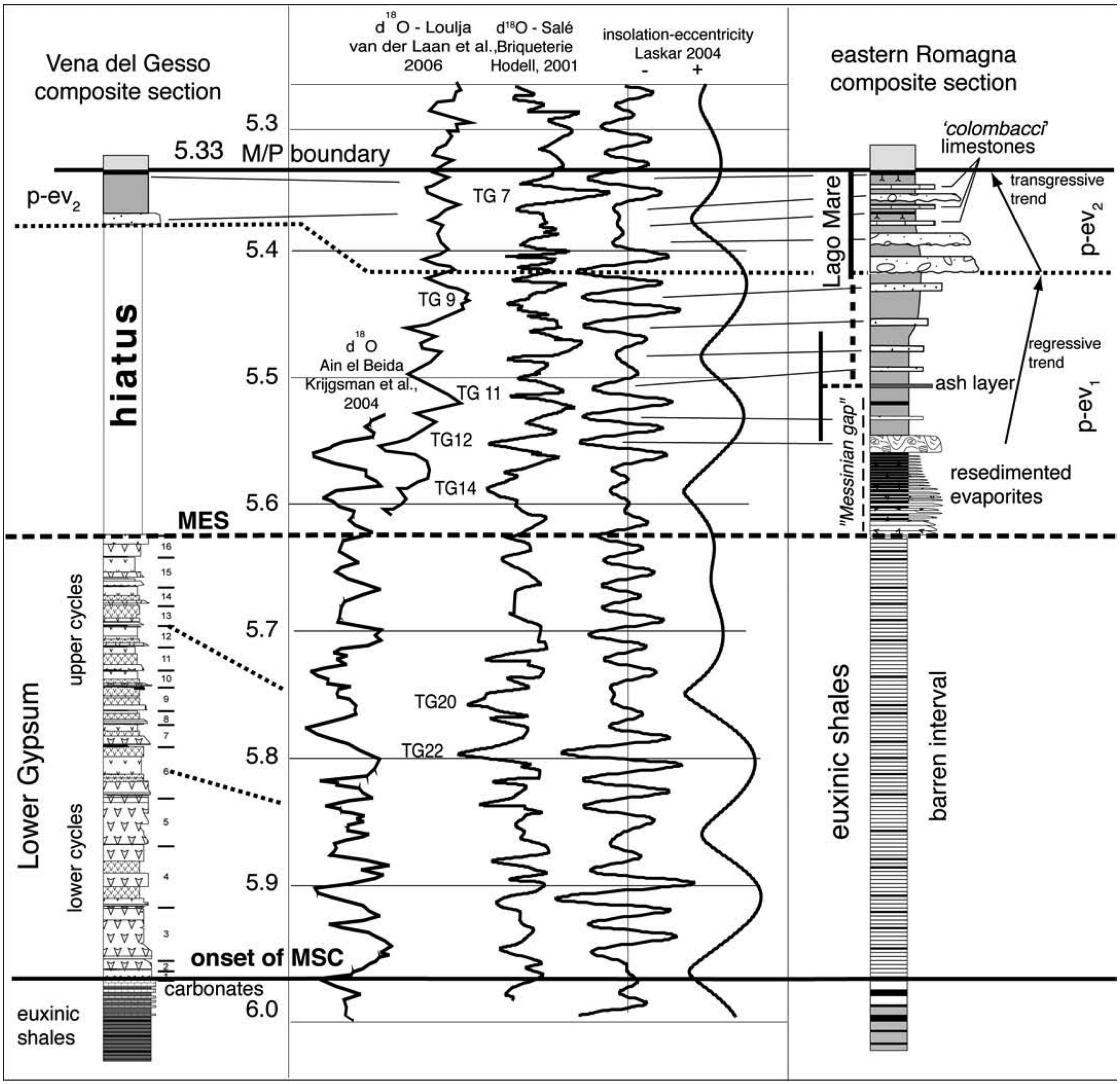
A possible clastic origin of the Lower Evaporites in the Mediterranean deeps, first suggested by Roveri et al. (2001), then envisaged by Hardie and Lowenstein (2004) and Manzi et al. (2005) based on facies analysis and petrological consideration, has been recently corroborated by Lofi et al. (2005), who proposed that the MES can be traced to the base of deep western Mediterranean basin Lower Evaporites. It follows that, as suggested by Roveri et al. (2006b; 2008b, c) in a revisitation of the Sicilian Messinian stratigraphy, the Lower Evaporites and Salt of deepest basins could have actually been deposited only after the primary sulfate evaporites of the first MSC stage (PLG), which precipitated only in shallow-water, restricted sub-basins (text-fig. 2).

The Zanclean flooding

The return to fully marine conditions in the Mediterranean area is marked by an abrupt facies change well recognizable throughout the different basins, albeit with different physical expressions. This discontinuity has been historically used to define the base of the Pliocene Series. The formal ratification, after long discussions, of the Zanclean Stage GSSP (Van Couvering et al. 2000), and hence of the base of the Pliocene Series, in the Eraclea Minoa section at the base of the Trubi Fm. has confirmed this commonly radicated use.

The Miocene/Pliocene boundary, placed at 5.33 Ma, is well defined by several astronomically-tuned bio- and magnetic events; the base of the Thvera normal chron occurs five precessional cycles above the boundary; two successive sinistral coiling shifts of *Neogloboquadrina acostaensis* in cycles 2 and 3, the acme of *Sphaeroidinellopsis* spp. between cycles 2 and 6 and the FCO of *Globorotalia margaritae* at cycle 10 (Di Stefano et al. 1996), *i.e.* within the Thvera magnetic event.

The virtually synchronous character, according to the stratigraphic resolution offered by cyclostratigraphy, of the facies change at the base of the Pliocene has been demonstrated by detailed studies (Iaccarino et al. 1999), supporting the idea of a sudden, nearly catastrophic re-establishment of the ocean connections. However, for many even historical sections, modern bio- and magnetostratigraphic studies are not available yet and this doesn't allow to rule out the possibility that in some basins or part of them the marine flooding could have been delayed or even anticipated, as hypothetically suggested by Roveri and Manzi (2006). The bio- and magnetostratigraphic events occurring at this boundary allow in any case to define with great accuracy this time line throughout the Mediterranean basin, thus making it possible the evaluation of local discrepancies.



TEXT-FIGURE 4
Simplified geologic-stratigraphic model of the Messinian of the Northern Apennines foreland basin along a W-E transect showing the relationships between shallow- and deep-water depositional settings (modified after Roveri and Manzi 2006). Note that Primary Lower Gypsum (PLG) is found only in shallow-water sub-basins of the wedge-top and foreland ramp depozones; in the main depocenter resedimented evaporites (RLG), derived from PLG dismantling was deposited above the MES correlative conformity.

High-frequency cyclicity

As previously stated, the only way to establish a high-resolution stratigraphic scheme within the 270 ka interval comprised between the MES and the M/P boundary is to look for cyclical sedimentary patterns that can be tuned to insolation and isotope curves. According to van der Laan et al. (2006), up to 12/13 precessional cycles are comprised within this time interval; two main glacials (TG14-TG12) and three main deglacials stages (TG11-TG9-TG7) also occur and are well recognizable on isotope curves.

Several attempts have been made in this direction, which led to the common recognition in marginal basins (Apennines, Sorbas, Sicily) of 8 precessional-driven sedimentary cycles starting from the top, *i.e.* from the Miocene/Pliocene boundary (Krijgsman et al. 1999; 2001; van der Laan et al. 2006). As a consequence, a hiatus of 90-100 ka remains (the 'Messinian gap' of

Krijgsman et al. 1999; text-fig. 1) which is usually related to the main deep basin desiccation phase (Hilgen et al. 2007).

Our results are substantially different; in the next sections we will show that deep-water or otherwise high-subsidence basins actually have a complete record of the 5.6-5.33 Ma interval.

Data for a high-resolution stratigraphy of the latest Messinian successions

Northern Apennines foredeep basin

Physical-stratigraphic studies carried out in the last 15 years (Bassetti et al. 1994; Roveri et al. 1998; 2001; 2004; 2005) allowed to recognizing and tracing across the Northern Apennines sub-basins several surfaces and sedimentary units within the 5.6-5.33 Ma interval. The two bounding surfaces, the MES and the M/P boundary, are well recognizable throughout the basin (text-fig. 3). For the first time the MES has been traced in this basin from marginal to deep settings (Roveri et al. 1998; 2001; Manzi et al. 2005; 2007) allowing to prove that the resedimented gypsum unit, which is the only evaporite deposit present in deep-water settings, fully postdates the massive primary selenite unit formed in shallower water, marginal settings (Manzi et al. 2005; 2007). This means that the Lower Evaporites actually consist of two gypsum units separated in time and space (Roveri et al. 2008b). It follows that the resedimented evaporite unit (RLG) represents the basal part of the 5.6-5.33 Ma interval, allowing to close, at least partially, the 'Messinian gap' of Krijgsman et al. (1999) (text-fig. 4).

The sedimentary succession of this interval is usually indicated in the Northern Apennines literature as 'post-evaporitic' as no primary evaporites occur and the deposits overlying the resedimented gypsum are mainly siliciclastics. This succession can be split into two units separated by a minor unconformity (Roveri et al. 1998; 2001; 2004) which marks a sharp change in terms of facies, stacking pattern and palaeoenvironment.

The lower post-evaporitic unit (p-ev_1, roughly corresponding to the *tetto*, S. Donato and Laga p.p. fms) comprises a basal horizon of resedimented evaporites overlain by a monotonous succession of mudstones with intercalated turbiditic sandstone bodies, usually thin and fine-grained (text-figs. 3, 4). In innermost wedge-top basins a clear coarsening and shallowing-upward trend is observed, pointing to a rapid basin fill; this trend, the progradational-aggradational stacking pattern, its occurrence only in deeper and/or more subsiding sub-basins, the local development at basin margins of progressive unconformities and the frequent occurrence of chaotic and slump horizons (Roveri et al. 1998; 2005), point to its deposition during a phase of tectonic deformation. Slightly above the resedimented gypsum unit a basinwide spread ash-layer occurs, allowing long-distance correlations; an absolute age of 5.51 ± 0.04 Ma has been obtained, thus constraining the age of the unit (Odin et al. 1997). The ash layer composition and the occurrence within its lower part support the syntectonic character of the p-ev_1 unit.

The overlying post-evaporitic unit (p-ev_2) is characterized at its base by the abrupt appearance in both shallow and deep-water settings of coarser-grained depositional systems (text-figs. 3, 4), testifying for an important change in the regional drainage pattern and precipitation regime. This unit has a clear aggradational to retrogradational stacking pattern and progressively laps onto the basin margins sealing the intra-Messinian unconformity and locally covering the eroded massive selenite. These characteristics point to deposition during a phase of more generalized subsidence and/or base-level rise. The unit has a well-developed and peculiar cyclic organization; this is more clearly expressed in marginal settings by the rhytmic alternation of coarse-grained and mudstone units, corresponding to the cyclic activation of fluvio-deltaic systems dominated by catastrophic fluvial floods. 3 to 4 carbonate layers ('*colombacci*') occur within the mudstone bodies (Roveri et al. 1998; Bassetti et al. 2004).

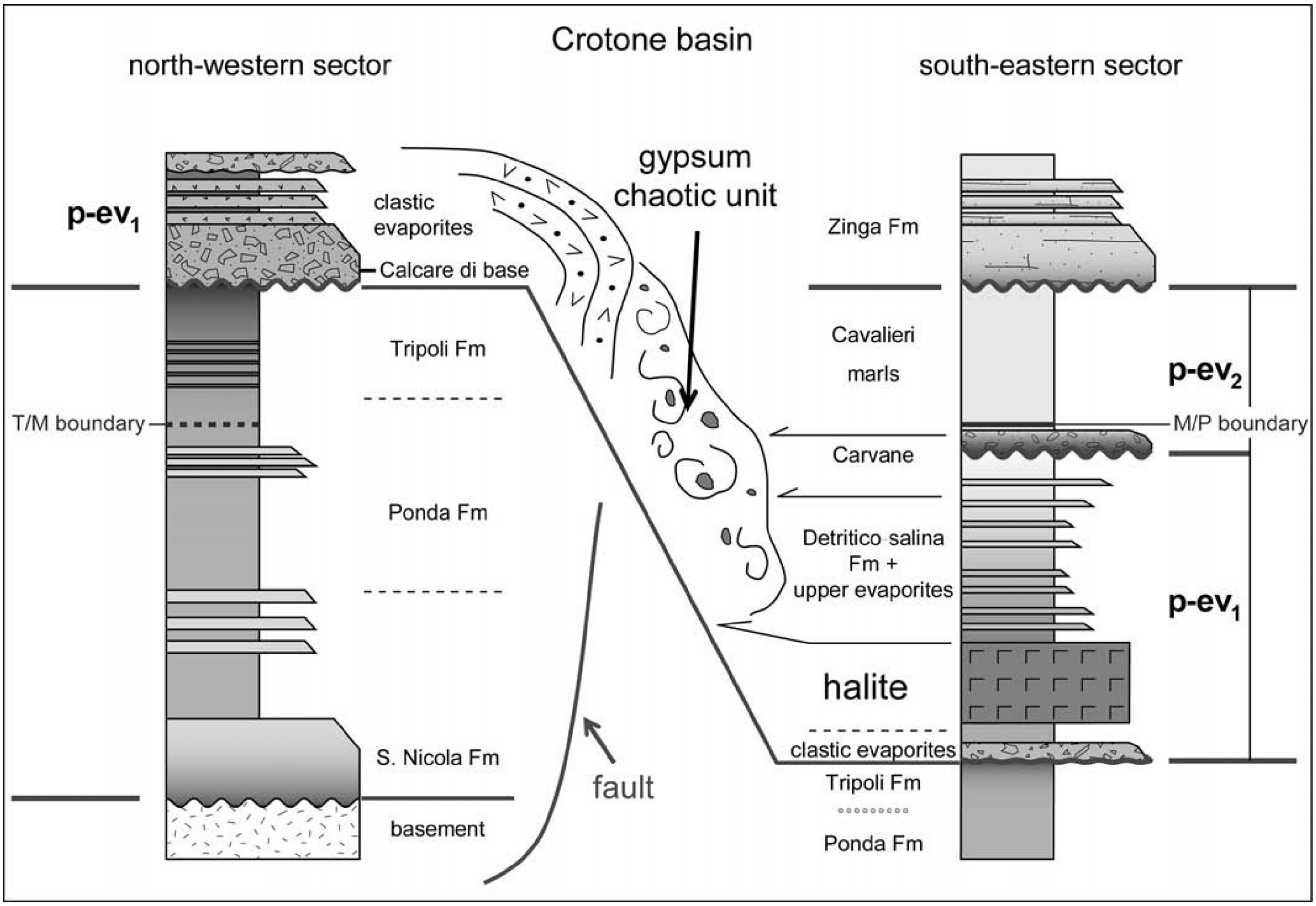
An overall transgressive trend is superimposed on this high-frequency cyclicity testified by the upward decrease of thickness and grain-size of coarse-grained deposits. An impressive tabular character and a constant number of cycles (4/5) characterize the unit at a regional-scale allowing basin-wide correlations and the reconstruction of a stratigraphic scheme for the whole Apennines foreland system (Roveri et al. 2005; 2006). The cycles have been interpreted as controlled by climatic factors with the alternation of wet and dry phases (Roveri et al. 1998); the time constraints given by the underlying ash layer and the upper boundary represented by the base of the Pliocene, points to a precessional periodicity for the p-ev_2 cyclicity; on this ground, a basal age of 5.42 Ma has been suggested (Roveri et al. 2004; 2006).

This preliminary framework has been tested in our work by studying in detail old and new sections and drilling shallow boreholes in key intervals (text-fig. 3). In particular, much attention has been paid to the definition of the Miocene-Pliocene boundary; the bio- and magnetostratigraphic analysis carried out in several sections allowed to recognize all the events characterizing the base of the Pliocene in the Eraclea Minoa GSSP. As a consequence, contrarily to what recently suggested in several papers (Clauzon et al. 2005; Popescu et al. 2007; Sprovieri et al. 2007), fully marine conditions developed in the Apennines foredeep basin at 5.33 Ma, like in the other Mediterranean basins (Gennari 2007; Gennari et al., this volume; Roveri et al. 2008a). The isochronous character of this surface confirms the preliminar age model suggested for the p-ev_2 unit. The studied sections allowed to define in more detail the facies characteristics and palaeoenvironmental meaning of each cycle and to refine the tuning to the astronomical curve.

Piedmont

The Messinian stratigraphic framework of the Tertiary Piedmont Basin, recently reconstructed by Irace et al. (2005), shows a great similarity with the Northern Apennines Messinian succession. Pre-evaporitic (S. Agata Fossili marls, equivalent of the Tripoli Fm.) and evaporitic deposits (mainly laminated gypsum in the Alba area) are unconformably overlain by a chaotic unit up to 300m 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 is overlain by cyclical alternations of coarse-grained fluvio-deltaic and fine-grained oligohaline deposits (Cassano Spinola Conglomerates; Ghibaudo et al. 1985). Stratigraphic position, overall trend and cyclic stacking pattern (4-5 cycles) suggest that this unit can be correlated to the p-ev_2 deposits of the Northern Apennines (Colombacci Fm.). Like in the Northern Apennines, the Zanclean flooding is recorded both in the Langhe area and in the Torino Hill by the sharp and conformable superposition (Trenkwalder et al. 2006) of marine marls on Lago Mare deposits through an organic-rich, black layer.



TEXT-FIGURE 5
Stratigraphic relationships between Messinian deposits filling the Crotone Basin (Calabrian Arc). Note that halite, like in Sicily, is found above the MES and strictly associated with resedimented gypsum.

Tuscany

The Messinian stratigraphy of Tuscany basins has been recently revised integrating outcrop and subsurface data (Aldinucci et al. 2006; Pascucci et al. 1999). Detailed stratigraphic and palaeo-environmental analyses have been carried out in the Cava Serredi section (Val di Fine basin), which was already studied in the past (Bossio et al. 1978; Corradini and Biffi 1988). This section shows a 150m thick post-evaporitic Messinian succession consisting of mainly siliciclastic, brackish to lacustrine deposits conformably overlain by marine Pliocene marls (Aldinucci et al. 2006). Like in the Apennines foredeep basin, the base of the marine deposits corresponds to the Miocene-Pliocene boundary as defined in the Eraclea Minoa GSSP (Riforgiato et al. 2006).

The detailed sedimentologic, micropaleontologic and magnetostratigraphic study carried out on this section rules out the possibility that the M-P boundary is unconformable, as claimed by Clauzon et al. (2005). The Messinian succession contains two main erosional surfaces marking abrupt vertical facies changes and bounding three sedimentary units. The lower unit consists of laminated mudstones and silts containing poor, restricted marine faunas; the intermediate and upper units are characterized by a coarser grain-size and by non-marine faunal assemblages. In particular the upper unit is characterized by a well-developed cyclicity given by the regular alternation of tens of m-thick coarse- and fine-grained bodies which allow to readily distinguishing it from the underlying, more homogenous one. Facies analysis suggests the cyclic activation and subsequent abandonment of small fluvio-deltaic systems; prograding mouth-bars with paleosoils on top are the most frequent facies sequence; in some cases poorly developed paleosoils also occur within fine-grained bodies. An overall transgressive trend is superimposed on high-frequency cyclicity as suggested by the progressive upward decrease of mean grain-size and thickness of fluvio-deltaic deposits; secondary gypsum is present throughout the section but in the uppermost cycle, some 20m below the M-P boundary, a thin, discontinuous layer of primary massive selenite is present.

Calabria

The Crotone Basin has been taken into consideration in our research. This basin formed during the Miocene on the Ionian side of the Calabrian Arc in an overall compressive tectonic regime. The Messinian succession is here characterized by diatomite-rich, Tripoli-like deposits at the base, cut on top by a locally high-relief erosional surface correlated with the intra-Messinian unconformity (text-fig. 5). A carbonate breccia, gypsum-rudite and gypsarenite stratified unit clearly onlaps this surface (Roveri et al. 2008b) and is overlain by a unit comprising halite lenses, gypsarenites beds and gypsum chaotic bodies ('detritico-salina fm.' of Roda 1965). This unit in turn is sharply overlain by coarser-grained deposits consisting of fluvio-deltaic sandstones and conglomerates (Carvane Conglomerate) with highly lenticular geometry, probably due to early halokinetic movements leading to the formation of an articulated paleotopography controlling the fluvial network. Sandstones and conglomerates rapidly pass laterally and vertically to mudstones with non-marine faunal assemblages which can be assimilated to the typical Lago Mare biofacies. This unit is abruptly overlain by open marine Pliocene marls of the Cavalieri Fm. This transition is conformable and coeval with the M-P boundary as defined in the Eraclea Minoa GSSP (R. Gennari, personal communication 2007).

Sicily

The upper Messinian succession of the Sicilian basins has been studied at regional scale (Roveri et al. 2006b; Roveri et al. 2008, c, in press; Manzi et al., submitted); it corresponds to the Upper Cycle of the Authors (Decima and Wezel 1971; Butler et al. 1995) and is formed by alternating massive selenite and laminar gypsum and mudstones (Gessi di Pasquasia Fm.; Selli 1960) overlain by silts and clays of the Arenazzolo Fm. Facies and thickness distribution of Messinian deposits is controlled by the structural position within the Sicilian-Maghrebian foredeep system (text-fig. 6). Innermost wedge-top (Calatafimi, Ciminna and Belice basins) and outermost foreland ramp basins (Licodia Eubea basin) show a very thin succession of non-marine deposits onlapping the intra-Messinian unconformity which cuts first stage massive selenite and/or older deposits; wedge-top basins in an intermediate position (Corvillo basin) are characterized by very thick, coarse-grained siliciclastic, fluvio-deltaic deposits cyclically arranged and showing an overall fining-upward trend (Grasso et al. 2004). These deposits unconformably overlie the Calcare di Base and older deposits at basin margins while more conformably contacts above halite bodies can be observed or reconstructed in the depocenters. In the main depocenters of the Caltanissetta basin this succession is represented by alternating gypsum and mudstone overlain by the Arenazzolo Fm.

While number and individual thickness of the gypsum beds keep constant along a transect from the inner to the outer margin of the basin (i.e. roughly NW-SE oriented), the mudstone intercalations dramatically thin toward the foreland ramp and on intra-basinal highs (Manzi et al., submitted). Seven gypsum beds, characterized by peculiar facies organization and stacking pattern (Schreiber 1997) which allow to easily distinguishing them from the Lower Gypsum (Gessi di Cattolica Fm.) can be recognized and correlated throughout the basin (Manzi et al., submitted).

However, in innermost southwestern sub-basins (the area comprised between Agrigento, Sciacca and Casteltermini) the most expanded sections allowed to recognize 2/3 additional cycles between the 6^{th} and the 7^{th} gypsum bed (Manzi et al., submitted).

These cycles are given by the rhytmic alternation of shales and sandstones horizons which have been recognized in the Eraclea Minoa and Gorgalonga (Casteltermini; see Decima and Sprovieri 1973) sections. Sandstone horizons consist of tabular shelfal lobes and/or more lenticular mouth bar pointing to the periodic activation of fluvio-deltaic systems in the upper part of the Gessi di Pasquasia (Manzi et al., submitted). These deposits are similar to the overlying Arenazzolo Fm., both in terms of composition and sedimentary facies, and this suggest that they probably should be ascribed to this formation.

As a consequence, a clear bipartition characterizes the Upper Gypsum unit, with a lower part dominated by evaporites and the upper one mainly consisting of siliciclastic deposits with the notably exception of the 7^{th} gypsum bed. This bipartition is much less evident or absent in outermost parts of the basin, where the siliciclastic intercalations progressively disappear, suggesting that the basin was mainly fed from the north, i.e. from the chain, while the foreland ramp was almost starved, also for the important karst processes affecting the Lower Gypsum.

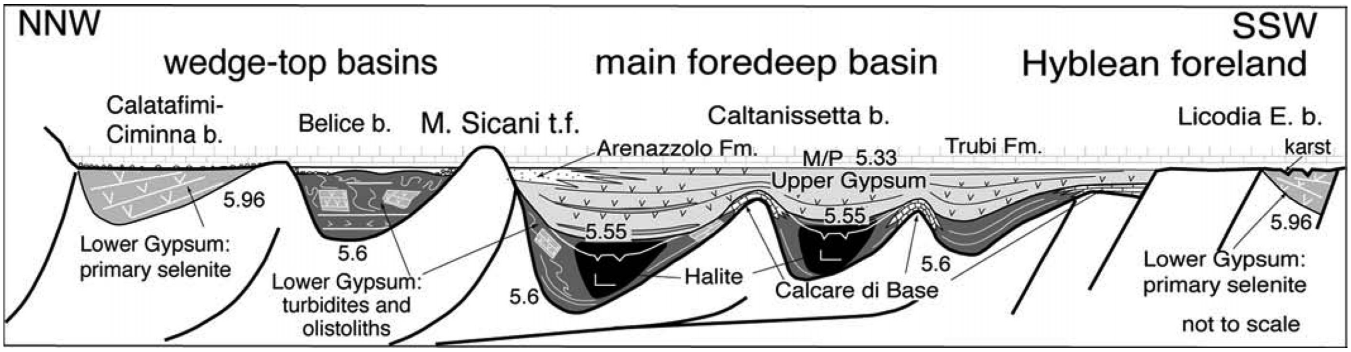
It should be noted here that the 7^{th} gypsum bed is usually separated from the overlying fine-grained sandstone and silts of the Arenazzolo Fm. by an intervening mudstone horizon containing abundant Lago Mare faunal assemblages (Decima and Sprovieri 1973). This horizon has been commonly referred to as 'Lago Mare' unit (Rouchy and Caruso 2006; Clauzon et al. 2005; Londeix et al. 2007), also based on the typical Paratethyan ostracod assemblages recognized by Bonaduce and Sgarrella (1997) which differs from those found in underlying mudstone deposits. An unconformable contact between this 'Lago Mare' unit and the overlying Arenazzolo deposits has been claimed by Clauzon et al. (2005) and Londeix et al. (2007), based on erosional features and lateral thickness reduction. We did not observe in the field any clear evidence for unconformities as both small-scale erosional features and lateral thickness change of 'Lago Mare' mudstones and Arenazzolo sandstones can be easily related to their genetic processes and depositional geometries.

The Arenazzolo Fm. consists of lenticular bodies made of shelfal sandstone lobes genetically linked to small deltaic systems as suggested by sedimentary structures (tabular cross-bedding, climbing ripples, hummocky cross-stratification); in other words they are part of the same depositional system which is expressed by thin sandstone lobes and clinostratified bars intercalated to the mudstone horizon underlying the 7th gyspum bed.

Betic Cordillera

Our research mainly focused on the Nijar basin which is one of the most important basins of the Betic Cordillera, bounded by the Sierra Cabrera and Sierra Alamilla to the north and by the Carboneras fault to the south. This basin was probably connected to the Sorbas basin with which it bears many similarities; however it probably underwent a different structural evolution during the Messinian and this explains some significant differences like the clear occurrence of a high relief erosional surface cutting on top the local Lower Gypsum unit (massive selenite of the Yesares Fm.).

Lower Gypsum massive selenite crop out in the northern side of the basin where they are cut by the intra-Messinian unconformity (Fortuin and Krijgsman 2003), above which a complex, mainly clastic unit develops. This unit consists of two superimposed formations showing very different lithological and facies characteristics. The lower one corresponds to the Upper Manco Mb., mainly consisting of marls, carbonate breccias and turbiditic sandstones, often showing evidence of gravity instability (intraformational slumps). Gypsarenite beds are locally common and a manganese-rich horizon, probably related to hy-



TEXT-FIGURE 6
Geologic-stratigraphic model of the Sicilian foreland basin during the Messinian along a NW-SE transect; note the striking similarities with the Northern Apennines foreland basin shown in text-fig. 4). Also in this case Primary Lower Gypsum is found only in shallow sub-basins of the wedge-top and foreland ramp depozones; in the main depocenter(s) clastic evaporites (RLG), comprising both clastic gypsym and carbonate, associated with halite were deposited above the MES correlative conformity (modified from Roveri et al. 2006b).

drothermal processes, forms a marker bed (Fortuin and Krijgsman 2003). Tens of m-thick coarsening-upward sequences with basal marls and gradual upward transition to sandstones and/or carbonate breccias are common and define a high-frequency cyclicity which, however, is not easily recognizable throughout the basin. This lower unit shows marked thickness changes mainly due to high-relief erosional surface at the base cutting the Lower Gypsum. In the main depressions the intra-Messinian unconformity passes to a correlative conformity (Los Castellones section); here, the base of the Upper Manco Mb. is characterized by small-scale cycles with both primary and reworked selenite forming m-thick shallowing-upward sequences.

The transition to the upper unit is abruptly marked by a change in composition and grain-size of sediments feeding the basin. The upper unit, corresponding to the Feos Fm., consists of cyclically alternating thick to thin polygenic conglomerates and pebbly-sandstones and white, laminated marls. Up to six cycles can be recognized and correlated throughout the basin (Omodeo-Salè 2007) below the transition to Pliocene marine deposits. Thickness and grain-size gradually decrease upward suggesting the superposition of a longer-term transgressive trend. Coarse-grained bodies show pedogenetic features; facies and geometries suggest their alluvial-fan nature with lateral transitions to basinal deposits represented by marls and interbedded sheet-sandstones. Microbialite buildups are locally found within or at top of coarse-grained bodies at the sharp transition to overlying marls (El Argamason section; see Aguirre and Sanchez-Almazo 2004).

The Upper Manco Mb. is almost barren of fossils; however, in the Gafares section the basal portion of the Upper Manco Mb. yields common *Ammonia tepida* and *Cyprideis agrigentina* oligotypic assemblages; in its upper portion assemblages are less abundant, but other brackish benthic foraminifera occur (*Elphidium* sp. and *Cribroelphidium* sp.) along with *A. tepida* and *C. agrigentina*. The overlying Feos Fm. deposits are characterized by fossil assemblages which have been differently interpreted. According to Aguirre and Sanchez-Almazo (2004) normal marine conditions characterize this interval, as testified by mollusk and foraminifer assemblages, thus supporting the hypothesis of well-established Atlantic connections during the late Messinian, at least in western Mediterranean basins. Marine foraminifer assemblages, occurring significantly only in the uppermost part of the Feos Formation, collected from the same sections has been considered largely reworked by Bassetti et al. (2006) which suggested a freshwater environment for the Feos Fm., essentially based on ostracod assemblages.

Basal Pliocene deposits consist of coarse-grained sandstones to pebbly-sandstones with marine mollusks; the true age of this transition is not known; the possibility that the surface marking the passage to marine deposits is actually a ravinement surface cannot be ruled out and this could also suggest its diachronous nature at a regional-scale. In other words, we cannot exclude that the uppermost cycle of the Feos Fm. is actually Pliocene in age.

In the Sorbas basin, lying immediately to the north of the Nijar basin, separated by the Sierra Cabrera and Sierra Alamilla mountain ranges, primary gypsum deposits of the first evaporitic stage are overlain by the Sorbas unit (Roep et al. 1998), a shallow-water carbonate-siliciclastic deposit whose age and palaeoenvironmental significance is not fully understood yet. This unit in turn is abruptly overlain by fluvio-deltaic conglomerates of the Zorreras Mb. This transition is very similar to the Upper Manco-Feos passage observed in the Nijar basin. The age of the Zorreras deposits are actually unknown but, according to the literature, they should span the Miocene/Pliocene boundary. A marine intercalation within fluvio-deltaic conglomerates is usually considered to represent such a boundary and, according to Krijgsman et al. (2001), 8 lithological cycles can be recognized between this horizon and the base of the Zorreras unit.

Ionian Islands, Crete, Cyprus, Nile delta

Other basins of central and eastern Mediterranean have been taken in consideration in our work. Several sections have been studied in the central basin of Crete (Faneromeni, Ano-Akria sections; Cosentino et al. 2007); here the Lower Gypsum massive selenite are cut by an erosional surface which is overlain by locally thick, disorganized conglomerates showing finer-grained intercalations with typical Lago Mare ostracod assemblages.

At Cyprus (Rouchy 1982; Rouchy et al. 2001; Orszag-Sperber 2006; Pierre et al. 2006) an Upper Evaporite succession with characteristics very similar to the Sicilian basin occur in the

Pissouri and Polemi basins. Upper Evaporites overlie a Lower Evaporites succession which, according to Robertson et al. (1995), actually consists of resedimented gypsum deposits capped by the so called '*Barre jaune*', a laterally persistent carbonate-gypsum breccia horizon. This vertical facies sequence, showing a upward transition from finer-grained, well-stratified gypsum-bearing turbidites to coarser-grained and chaotic deposits is very similar to what observed in the inner portions of the Northern Apennines and Sicily foreland basins (RLG unit, see above). This suggests a phase of tectonically-induced progressive dismantling of primary evaporites formed in marginal basins and their resedimentation in relatively deep basins (Manzi et al. 2005). Accordingly, these deposits would lie above the MES and/or its correlative conformity, thus representing the base of local p-ev$_1$ unit. Above the Upper Gypsum, an abrupt change of lithology is observed with the transition to a coarse-grained siliciclastic unit characterized by the cyclic alternation of conglomerates, shales, lacustrine carbonates and paleosoils. This unit is characterized by strongly variable thicknesses and rapid lateral facies changes but up to 4/5 lithological cycles can be recognized in more complete sections (*e.g.* Pissouri). The cycles, like in the Apennine basins, consist of conglomerate-mudstone couplets, recording a fluctuating fluvial activity. A very similar succession has been described from Corfu (Aghios Stefanos section; Pierre et al. 2006; Vismara-Schilling et al. 1978): here a uppermost Messinian unit, unconformably overlying lower Messinian marls and sandstones, comprises three thick conglomerate beds cyclically interbedeed with fine-grained deposits containing brackish fossil assemblages. At Zakynthos (Kalamaki section, Pierre 2006; Rouchy 1982), the local Upper Evaporites comprise six gypsum beds alternated with marls; the uppermost marly unit below the basal Pliocene Trubi limestones includes a lacustrine limestone bed and a thin conglomerate layer just below the Miocene/Pliocene boundary.

In the Nile delta area a late Messinian fluvio-deltaic unit characterized by a well-developed cyclicity and retrogradational stacking pattern has been described from subsurface data (Abu Madi Fm.; Dalla et al. 1997).

The physical-stratigraphic model

From the above descriptions it results that the Mediterranean sub-basins here considered show impressive similarities in the stratigraphic architecture of uppermost Messinian successions, suggesting that the evolution of depositional systems was strongly controlled by external forcing factors. This allows to suggest a general physical-stratigraphic model for the late Messinian successions whose architecture is characterized by three major surfaces: 1) the intra-Messinian unconformity and its correlative conformity at the base, 2) the surface marking the abrupt facies change at the base of coarse-grained deposits in the upper part and 3) the marine flooding surface at the Zanclean base.

As a consequence two main units can be defined throughout the Mediterranean basin in the 5.61-5.33 Ma interval, corresponding to the p-ev$_1$ and p-ev$_2$ units first recognized in the Apennines foredeep basin (text-fig. 7).

In deeper and/or more subsiding basins, the p-ev$_1$ unit contains at its base a variable thickness of resedimented evaporites (mainly gypsum) usually but erroneously considered coeval of the primary evaporites units. The stratigraphic position of resedimented evaporites above the correlative conformity of the MES rules out such a hypothesis and points to their definitely younger age. This has been clearly documented in the Apennines basin where a barren unit below the resedimented evaporites has been proven to be the true deep-water counterpart of the primary Lower Gypsum formed in shallower settings (Manzi et al. 2007).

Considerations which are beyond the scope of this paper and for this reason are presented and discussed elsewhere (Roveri et al. 2006a, b; Roveri et al. 2008b, c, in press), suggest that also the halite and potash salt bodies as well as the Calcare di Base of Sicilian basins can be placed within the basal part of the p-ev$_1$ unit and have more direct genetic and stratigraphic relationships with the resedimented evaporites. This opens a completely new scenario for the stratigraphy of Mediterranean Messinian successions and hence for the MSC events (Roveri et al. 2008b).

The p-ev$_2$ unit usually shows a much better developed cyclicity with respect to the p-ev$_1$; the number of sedimentary cycles (up to 5) recognized within this unit is impressively similar in all the considered basins; these cycles, in the different depositional settings recognized, seem to be clearly controlled by arid to wet climatic oscillations; as for the cyclicity recognized in evaporitic and pre-evaporitic units, a precessional periodicity is here suggested. The tuning of p-ev$_2$ cycles with the insolation curve suggests that the p-ev$_1$/p-ev$_2$ boundary could be placed at around 5.42 Ma, thus allowing a better constraint to the age of this surface.

As a consequence the p-ev$_1$ unit spans the 5.60-5.42 Ma time interval which comprises in its lower part two important glacial peaks (the isotope stages TG12-TG14) and the transition to warmer conditions starting from the TG11 isotope stage (van der Laan et al. 2006). The above mentioned considerations about Sicilian basins and the radiometric age of the ash layer occurring in the Apennines foredeep basin (5.51±0.4 Ma, Odin et al. 1997) are fully consistent with the age of the p-ev$_1$ unit and with the hypothesis that its lower part comprises the resedimented evaporites and the halite unit.

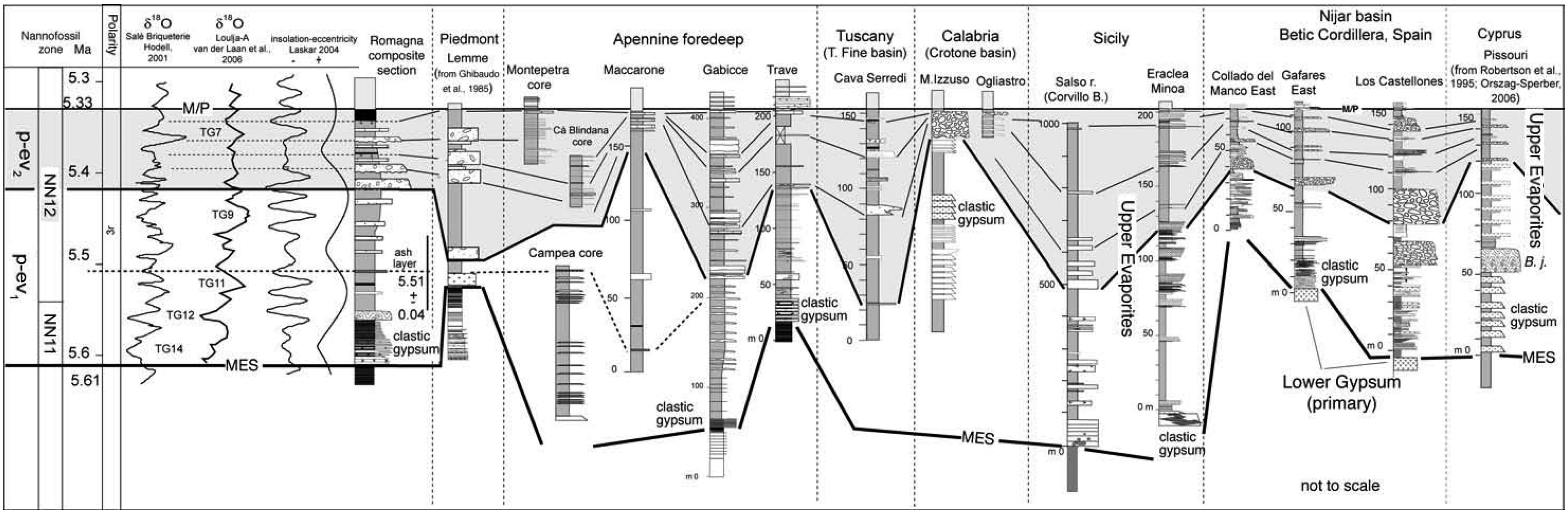
Closing the 'Messinian gap'

The sea-level falls related to glacial peaks TG12 and TG14 and the concomitant important phase of tectonic deformation which affected large part of the peri-Mediterranean basins account for the strong erosion of basin margins and consequent emplacement of huge volumes of resedimented evaporites in more subsiding basins and for the possible blockage of the Mediterranean outflow, leading to halite precipitation at the MSC acme.

In any case the p-ev$_1$ unit has in many contexts a clear syntectonic character and spans the time interval usually referred to as the 'Messinian gap' (Krijgsman et al. 1999). Further cyclostratigraphic considerations help to better define the succession of events recorded by this unit which is transitional between the main marine evaporitic phase and the Lago Mare event.

The 'Messinian gap' concept partially derives from an incorrect approach in recognizing and correlating through facies analysis and regional-scale work marginal and deeper settings in the peri-Mediterranean basins; an example is the overlooked chronostratigraphic importance of widespread resedimented evaporites units.

A further element of discussion is the possibly wrong cycle counting in the uppermost Messinian successions. Above the intra-Messinian unconformity 8 (precessional) cycles have been



TEXT-FIGURE 7
Physical-stratigraphic correlation of uppermost Messinian (5.6-5.33 Ma) successions across the Mediterranean basin. Despite the different geodynamic settings represented, this interval can be easily split into two units ($p\text{-}ev_1$ and $p\text{-}ev_2$) throughout the Mediterranean basin. Note that the $p\text{-}ev_1$ unit includes at its base resedimented gypsum deposits usually referred to as 'Lower Gypsum'. The latter deposits actually postdate primary, *in situ*, Lower Gypsum as they overlie the Messinian erosional surface (MES) and/or its correlative conformity.

commonly recognized in the Apennines foredeep basin, Sorbas and Sicily (Eraclea Minoa). Where this number comes from?

The eight cycles story starts with the fundamental Vai's paper (Vai 1997) concerning the cyclostratigraphic estimation of Messinian stage duration. In this paper for the first time the Colombacci Fm. of the Apennines foredeep basin (considered by the Author to represent the whole local post-evaporitic succession, i.e. our p-ev_1 (without the basal resedimented evaporites) plus p-ev_2 unit, was subdivided into 8 sedimentary cycles, essentially based on former, detailed studies by Colalongo et al. (1976) and Cremonini and Farabegoli (1982). This subdivision actually derives from the transposition of 9 (8 belonging to the Messinian and one to the Pliocene) sedimentary *stages* individuated by Colalongo et al. (1976) into sedimentary *cycles*; these cycles also include the 6 '*colombacci*' limestone layers recognized in the Romagna Apennines by Cremonini and Farabegoli (1982), which have long been considered as possible equivalents of the Sicilian Upper Evaporites cycles.

The two concepts are clearly different and a careful revisitation of the Colalongo et al.'s paper allows to readily assessing that each sedimentary *stage* basically corresponds to the individual coarse and fine-grained units which are rhythmically superposed in the p-ev_2 unit. A coarse/fine couplet forms a true sedimentary cycle recording a complete periodic oscillation in the climatically-modulated activity of fluvio-deltaic and turbidite depositional systems which are well developed in the uppermost Messinian (Bassetti et al. 1994; Roveri et al. 1998; 2001). The lowest stage of Colalongo et al. (1976) corresponds to the whole p-ev_1 deposits, which are much more lithologically homogeneous; the other stages thus refer to the p-ev_2 unit and their number is in good agreement with the 4/5 sedimentary cycles here suggested. It is worth noting that, as clarified in Roveri et al. (1998), the 6 '*colombacci*' limestone layers claimed by Cremonini and Farabegoli (1982) are actually only 3 in the classic Romagna Apennines sections and up to 4 in the whole Apennines foredeep basin. These limestone layers are only found in the p-ev_2 fine-grained deposits; within each cycle they record a phase of highest base level and most diluted waters (see below).

The inferred precession-driven character of these 8 cycles led Krijgsman et al. (1999) to suggest the existence of a ~90/100 ka hiatus across the intra-Messinian unconformity cutting the local Lower Gypsum primary evaporites. This unconformity is clearly associated to a hiatus only in marginal settings where it cuts primary Lower Evaporites and the p-ev_1 deposits are systematically absent, while in deeper settings the succession is continuous and a large volume of resedimented evaporites and siliciclastic deposits are found above its correlative conformity thus closing the 'Messinian gap'.

Besides the Colombacci Fm. in the Apennines foredeep basin, other uppermost Messinian units have been subsequently suggested to be characterized by eight precessional cycles: the Zorreras Fm. in the Sorbas Basin (Krijgsman et al. 2001) and the Upper Evaporites (Gessi di Pasquasia Fm.) in Sicily (van der Laan et al. 2006).

As for the Zorreras Fm., we observe that the Zanclean base was never unequivocally recognized, as the late Messinian to Early Pliocene succession is entirely continental and made of conglomerates. Up to 4 lacustrine carbonate horizons have been recognized within the fluvio-deltaic conglomeratic succession (Mather et al. 2001); the possible cyclostratigraphic significance of such horizons ('*colombacci*'s' equivalents?) should be more deeply explored by future researches.

In Sicily, the Upper Evaporites have been usually studied in the Eraclea Minoa section where up to 7 gypsum-marl cycles have long been recognized (Schreiber 1997). An additional (the eight one) has been recently added by van der Laan et al. (2006) and Hilgen et al. (2007) considering the thick marly interval between the first and the second gypsum bed.

However, as previously stated, in a recent revisitation of the Sicilian succession (Roveri et al. 2008b, in press; Manzi et al., submitted), the stratigraphy of the Upper Evaporites-Arenazzolo units appears more complex than previously thought. Actually 9 to 10 lithological cycles formed by the rhythmic alternation of shales with gypsum and/or sandstone beds can be recognized and correlated at regional scale; the additional cycles with respect to the 7 usually envisaged come from the thick fine-grained interval between the 6th and 7th gypsum bed.

This observations allow to astronomically calibrate the base of the Upper Evaporites, and hence of the top of the underlying salt unit, very close to the TG12 glacial stage, at around 5.53-5.55 Ma. The p-ev_1/p-ev_2 boundary is placed in correspondence with the 6th gypsum beds where a clear increase of siliciclastic sediment input is observed. Considering that the Upper Evaporites overly the complex unit formed by resedimented evaporites, halite and Calcare di Base, whose base correlates with the onset of the intra-Messinian unconformity (5.61 Ma) it follows that the Caltanissetta basin succession is fairly continuous, as well as the deep settings of the Apennines foredeep basin.

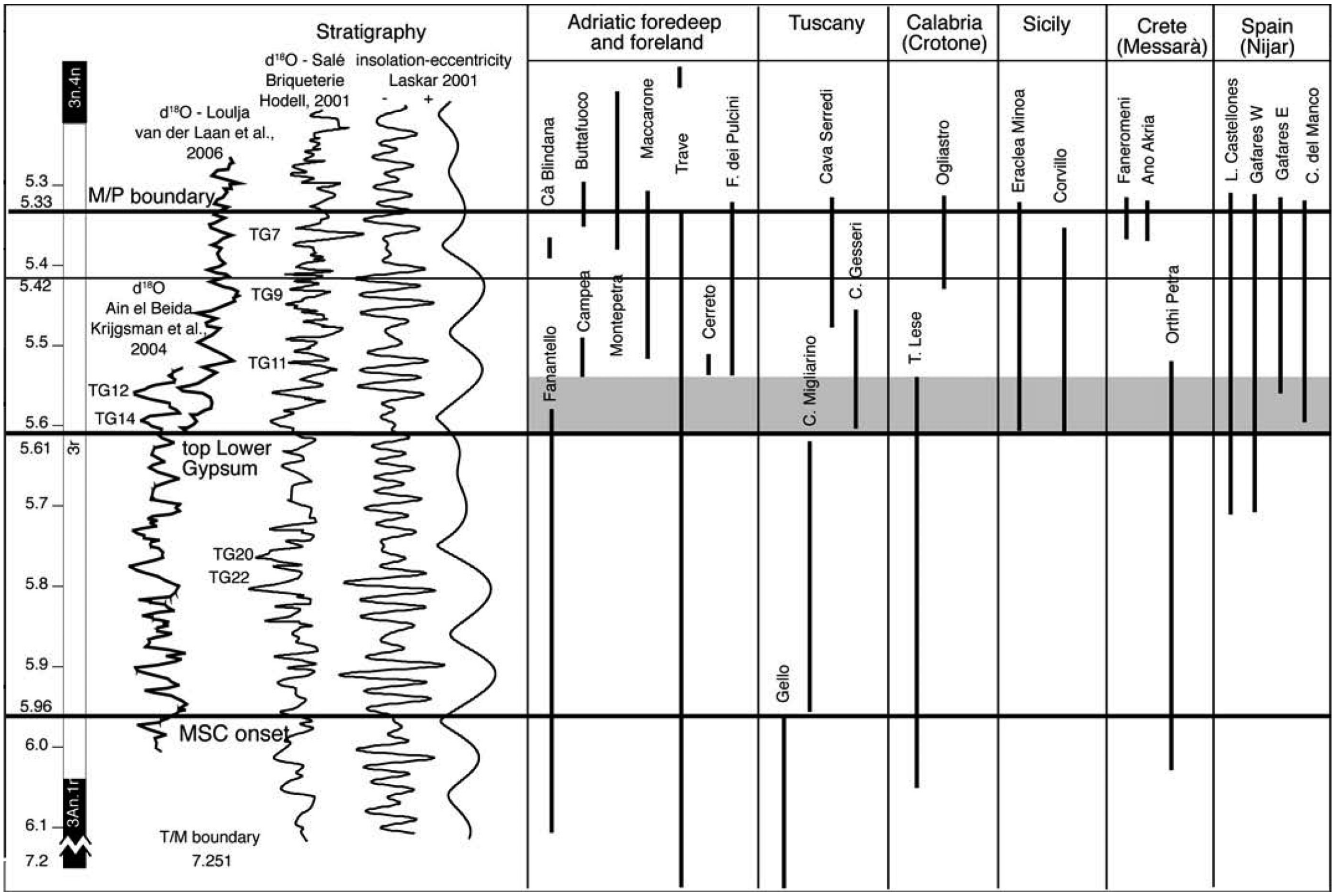
Summarizing, a high-resolution stratigraphic framework for the uppermost Messinian can be reconstructed using a physical-stratigraphic approach integrated with cyclostratigraphy. This allows to defining and correlating at a Mediterranean scale a hierarchy of sedimentary units bounded by time lines and corresponding to very short time windows. This is fundamental to compare the time and spatial distribution of palaeoenvironmental proxies and thus deriving more reliable information about the final stage(s) of the MSC. The 'Messinian gap' can be closed by taking into consideration not only the deep Mediterranean successions but also those filling the deepest and/or more subsiding depocenters of outcropping basins, which commonly consist of resedimented evaporites and clastic deposits.

Palaeoenvironmental proxies

When framed into the previously described high-resolution stratigraphic framework, the paleontologic and geochemical data from the different Mediterranean sub-basins from both studied sections and literature show remarkably consistent and homogenous trends and patterns (text-figs 7, 8).

Calcareous Nannofossils. The calcareous nannofossil assemblages are invariably dominated by reworked specimens, as already evidenced in other studies. No evidence for sporadic marine incursions have been found even in the sections (*e.g.* Maccarone and Trave sections; Roveri et al. 2008a; Iaccarino et al., this volume) in which the presence of Pliocene marine taxa (*Ceratolithus acutus*) in the p-ev_2 unit has been recently claimed (Popescu et al. 2007).

Foraminifers. Foraminifer assemblages do not show particular changes in the studied interval; as already known from previous studies, the assemblages are generally scarce and mainly repre-



TEXT-FIGURE 8
Areal and stratigraphic distribution of sections studied in this work. The grey area shows the interval represented in the different sections by resedimented gypsum (RLG), halite and/or Calcare di Base.

sented by reworked or dwarf planktonic specimens; benthic assemblages are also scarce and dominated by taxa typical of brackish environments (*Ammonia*, etc.). This points to palaeoenvironmental conditions inhospitable for normal marine fauna; careful analysis carried out in selected sections and cores did not show in both p-ev$_1$ and p-ev$_2$ unit unequivocal trace of marine incursions.

Ostracods. The ostracod assemblages are characterized in the studied interval by the absence of *in situ* marine taxa, which are found in the marls underlying the Lower Evaporites and in the overlying Pliocene deposits. The assemblages are dominated by brackish to freshwater taxa and their vertical distribution allowed Gliozzi et al. (2007) to propose an ostracod biozonation for the late Messinian interval. Two biozones are suggested: a lower *Loxoconcha mulleri* biozone and an upper *Loxocorniculina djafarovi* one; the boundary between the two biozones is given by the FOD in the Mediterranean area of *L. djafarovi*, usually considered to be an immigrant taxon from the Paratethyan basin.

The two biozones are roughly coincident with the p-ev$_1$ and p-ev$_2$ units as the *L. djafarovi* appears close to the p-ev$_1$/p-ev$_2$ boundary; they also partially correspond to the Lago Mare Biofacies 1 and 2 of Bonaduce and Sgarrella (1999). The lower biozone is characterized by rare and poorly diversified skizohaline assemblages dominated by *Cyprideis, Amnicythere* and *Tyrrhenocythere pontica*. The upper biozone has a more marked oligohaline to freshwater signature and marks the rapid increase of Paratethyan taxa; the high-frequency cyclicity of the p-ev$_2$ unit allowed to assess more details of this biozone which can be subdivided in two sub-zones; the lowest one is characterized by scarce and low-diversity ostracod assemblages while the highest one, corresponding to the uppermost precessional cycle of the unit, shows a significant increase in abundance and diversity. Detailed studies carried out in cores and sections of the p-ev$_2$ unit show the good correspondence between the palaeoenvironmental indications derived from vertical changes of ostracod assemblage parameters and the sedimentary facies cyclicity. Within an individual precessional cycle, deeper and more diluted waters are indicated by pointed Candoninae occurrence (Grossi and Gennari, in press); such an assemblage is observed around the "*colombacci*" limestone layers which represent the deepest facies of the cycle and are correlated with insolation maxima.

Molluscs. The typical Lago Mare assemblages (*'Congeria* and *Melanopsis beds'*) with *Dreissena, Limnocardium, Melanopsis*, are more abundant and diversified in the p-ev$_2$ unit, while only the uppermost part of the p-ev$_1$ unit usually contains fossils. However, this could be related to the fact that in most of the studied basins only the uppermost part of the p-ev$_1$ unit is characterized by deposits formed in a paleobathymetric range suitable for such a mollusc assemblages. Rare, reworked brackish to freshwater mollusc assemblages have been actually found in graded beds deposited by gravity flows in the intermediate and upper part of the p-ev$_1$ unit in the northern Apennines , suggesting a possibly earlier development of shallow-water settings characterized by diluted waters.

Palynomorphs. Pollen and dinoflagellate cysts assemblages show a marked change close to the p-ev$_1$/p-ev$_2$ boundary. P-ev$_1$ deposits are characterized by clearly reworked (often pre-Neogene) dinocyst marine taxa and/or by marine taxa of uncertain age attribution. In several studied sections a drastic change of dinocyst assemblages occurs around the p-ev$_2$ base with the sudden appearance of brackish to freshwater Paratethyan taxa, among which *Galeacysta etrusca* is the most representative species (Bertini and Corradini 1998; Bertini 2006). This event is in good agreement with the concurrent appearance of the freshwater algae *Pediastrum* indicating a significant dilution of the water column and is preceded by the decrease of *Lygeum*. No evidence for marine incursions has been observed in the late Messinian successions, while a clear shift to open marine conditions occurred at the base of the Pliocene, with the abrupt disappearance of Paratethyan taxa. Pollen assemblages suggest drier conditions in the p-ev$_1$ unit, as testified by the northward migration of *Lygeum* (Bertini 2006; Londeix et al. 2007). The decrease of *Lygeum* in the upper part of p-ev$_1$ and within the p-ev$_2$ and the concurrent increase of *Pinus*, *Tsuga* and *Cedrus* indicate the establishment during the latest Messinian of overall wetter conditions, with high-amplitude periodical climate fluctuations (Bertini 2006).

Fish. The occurrence of diadromous fish assemblages, mainly based on otoliths recovered in Northern Apennines and Tuscany sections (Carnevale et al. 2006; 2008), has been recently considered as the proof indicating that fully marine conditions established in the late Messinian well before the Zanclean flooding. In our opinion this interpretation is too extreme as 1) the possible reworked nature of otoliths has been discarded by the Authors but with not definitive arguments, 2) the paleoenvironmental indications coming from the other faunal groups (molluscs, ostracods, foraminifera, calcareous nannofossils, dynocists) have been considered (quite surprisingly indeed) not reliable. Even admitting the non-reworked character of the otoliths, we observe that the occurrence of more marine fish taxa actually occur only in the uppermost cycle of the p-ev$_2$ unit (5.35-5.33 Ma), very close to the base of Pliocene. This could suggest sporadic marine connections just before the Zanclean flooding, even if in this case they would be clearly recorded only by fish assemblages.

Stable isotopes. Oxygen, carbon and strontium isotope data from latest Messinian deposits are usually characterized by values indicating a drastic hydrologic change with respect to the first MSC stage. Isotope data from both primary evaporites and fossils from non-evaporitic deposits point to the substantial contribution of continental input, causing the formation of strongly diluted water masses, at least in their uppermost part (Lugli et al. 2007; Flecker and Ellam 1999). Moreover, negative $\delta^{18}O$ values from mollusc and ostracod shells are in good agreement with the ecological meaning of such assemblages. Only recently (Carnevale et al. 2008), $\delta^{18}O$ values falling in the normal marine field have been reported from fish otoliths and from brackish to fresh-water mollusc and ostracod assemblages of Tuscany basins. On these bases, and on the marine nature of some of the recovered fishes (see above), the marine character of upper Messinian Mediterranean waters has been suggested, despite the clear contradiction between the palaeoecological meaning of mollusc and ostracod assemblages and isotopic data. We believe that this contradiction could be only apparent as oxygen and strontium isotope values are likely altered by local sources related to the strong magmatic activity of the Tuscan province, a possibility not considered by Carnevale et al. (2008) in the interpretation of their data. Nevertheless, evidences for significant input of hydrothermal waters are testified by heavily enriched $\delta^{18}O$ travertine bodies occurring within Lago Mare deposits of the Volterra basin (Pignano travertines; Bossio et al. 1994; A. Gandin, pers. comm.). Another important source of enriched oxygen and strontium isotopes is represented by the abundant detritus delivered to Tuscan basins from the exhumation and erosion of magmatic rocks (abundant eurite pebbles from the Elba pluton; Lazzarotto et al. 2002) characterized by high Sr, and O signal (Taylor and Turi 1976; Juteau et al. 1984) and of Triassic carbonates (*'Calcare cavernoso'*, Gandin et al. 2000).

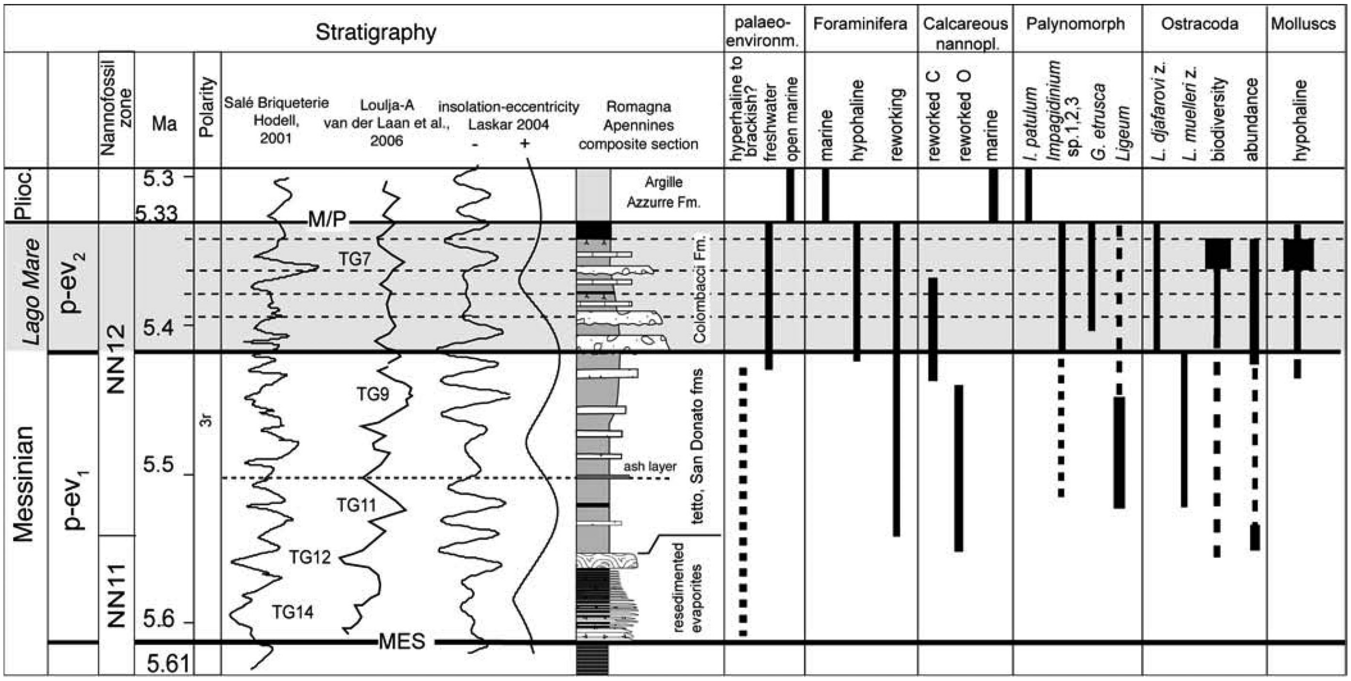
The still too scattered areal and vertical distribution of isotope data prevent any attempt to frame them into our stratigraphic scheme; in a recent study (Bassetti et al. 2004) on the nature and significance of the "*colombacci*" lacustrine limestone layers of the Apennine basin, a generalized, gradual vertical trend toward more 'marine' conditions have been pointed out based on the isotopic values from bulk carbonate samples, suggesting that the Zanclean flooding could have been heralded by sporadic marine incursions in the late Messinian or alternatively that the Atlantic connections could have progressively increased. However, these isotope-based hydrological reconstructions are not supported by the palaeoecological indications from fossil assemblages.

LAGO MARE: ORIGIN AND HIGH-RESOLUTION STRATIGRAPHY

Our study demonstrates that uppermost Messinian successions can be subdivided into two physical stratigraphic units, p-ev$_1$ and p-ev$_2$; these units can be easily differentiated also for their paleontological content indicating that palaeoenvironmental changes in the final MSC stage occurred almost simultaneously throughout the Mediterranean basin, despite the great palaeogeographic fragmentation often envisaged for this time interval. The most typical Lago Mare assemblages, indicating the development of highly diluted waters, are more commonly observed in the p-ev$_2$ unit and appear just below its lower boundary (text-fig. 9), placed at around 5.42 Ma.

In more continuous successions, the p-ev$_1$ deposits overlying resedimented evaporites or halite are usually characterized by very poor faunal assemblages indicating the development of extremely stressed conditions, not suitable for normal marine communities. Coeval shallow and deep-water settings facies can be compared in the different sub-basins; in the Apennines foredeep, Calabria and Nijar basins, relatively deep-water deposits record this interval and they can be considered virtually barren, as fossil assemblages, even scarce, are more frequently reworked. In Sicily, the lower part of the Upper Evaporites succession, which formed in shallower water settings, is characterized by the sporadic occurrence of mesohaline faunal assemblages while oligohaline assemblages are more common in the upper part, i.e. above the 6th gypsum bed.

While the p-ev$_1$ unit records the local and ephemeral development of Lago Mare environments with low-diverse, pioneer taxa, the p-ev$_2$ is marked by the diffusion of conspicuous



TEXT-FIGURE 9
Palaeoenvironmental proxies framed into the reconstructed chronostratigraphic model for the late Messinian. Note the simultaneous change toward more diluted water conditions across the p-ev$_1$/p-ev$_2$ boundary and the upward increase of diversity and abundance of brackish to freshwater fossil assemblages within the p-ev$_2$ unit. The grey area highlights the interval corresponding to the full establishment of Lago Mare conditions throughout the Mediterranean basin.

Parathetyan assemblages (ostracods, dinoflagellate cysts, molluscs) of increasing diversity and complexity upwards (text-fig. 9). This change is best approximated by the boundary between the two sub-units.

The late Messinian erosional features observed along the Mediterranean margins point to a rejuvenation of drainage systems, usually related to a large sea-level drop occurred at the acme of the MSC. However, such features could also have been caused or enhanced by the Late Miocene uplift of peri-Mediterranean and Asian mountain belts. The relationships between large-scale geodynamic processes and late Messinian climate in the Mediterranean area and their effects on precipitation and fluvial regimes have not been deeply explored yet and may lead to envisage different scenarios for the final phase of the MSC. As pointed out by Griffin (2002) during the late Messinian the northern Africa belt experienced the most humid phase of the Tertiary, as documented by the development of several large rivers (most of which now disappeared) carrying water to the eastern Mediterranean basin; this phase (Zeit phase) is thought to have been caused by a change in the monsoonal system related to the uplift of the Tibet plateau.

Converging sedimentary evolution and paleontologic record suggest that the Lago Mare event likely resulted from positive feedbacks between processes (increase of fluvial runoff, generalized subsidence, base-level rise, enlargement of shelf areas) which eventually promoted the establishment of progressively larger, more stable intra-Mediterranean connections and water exchanges with the Paratethyan basins, up to the final full reopening of the Atlantic gateways.

A NEW SCENARIO FOR THE FINAL MSC STAGE

The recent reconstructions of MSC chronology (Hilgen et al. 2007; Roveri et al. 2008b) and the consequent calibration of isotope data from primary evaporites suggest that Atlantic connections persisted, albeit reduced, at least till ~5.55 Ma, which is the inferred age of uppermost halite deposits in the Sicilian basin. As a consequence, the last MSC stage (Stage 2.2 of Roveri et al. 2008b), comprising the progressive development of Lago Mare facies, lasted around 200 ka.

The new considerations about halite timing and modalities of formation imply that between 5.6 and 5.55 Ma the Mediterranean basin underwent a severe reduction of water exchanges with the ocean and a base-level drop whose amplitude is difficult to assess. However, according to Sicily data and interpretations, total desiccation and basin fill probably occurred only in peripheral basins and for a very limited time span due to a combination of evaporative drawdown and extremely fast halite aggradation (Roveri et al. 2008b, c; in press).

After the short desiccation episode recognized in Sicily (Lugli et al. 1999), shallow-water halite precipitation resumed and the transition to overlying Upper Evaporites deposits is marked by a dissolution surface reconstructed from subsurface data and usually correlated with the angular unconformity separating the lower and upper evaporitic cycles (i.e. the MES), but never directly observed (Butler et al. 1995; Grasso et al. 2004). We argue that such a surface might be not necessarily related to the subaerial MES and could have formed in a subaqueous setting following an initial change of the Mediterranean hydrological budget resulting in a dilution of surface waters.

This switch to an essentially brackish mode could have been caused by the rapid transition to a long-lasting interval characterized by more humid conditions following the glacial stage TG12 (van der Laan et al. 2006) and by the closure of the Atlantic gateways, thus eliminating or strongly reducing the contribution of marine waters to the Mediterranean hydrological budget. In such conditions it seems reasonable to expect that during this stage regional climate oscillations and their consequences on drainage areas feeding the Mediterranean basin were more effective on water isotope composition as well as on the time and space distribution of depositional systems.

The final MSC stage is usually depicted as being characterized by an extreme variability of palaeonvironmental settings controlled by the complex morphology of an almost desiccated Mediterranean basin. The data presented in this study indicate that the last MSC stage was actually characterized by a higher articulation with respect to the previous ones, as reflected for example by the distribution of evaporites. During the first MSC stage, calcium-sulphate evaporites accumulated in shallow basins throughout the Mediterranean area; during the last stage the former evaporitic basins underwent erosion and/or deposition of clastic deposits (e.g. Sorbas, Northern Apennines, Tuscany, Piedmont, Calabria) while shallow-water evaporites accumulated only in southern and eastern sectors of the Mediterranean (Sicily, Ionian Islands, Cyprus). This suggests indeed the development of north-south and east-west climate and hydrological gradients that need to be fully investigated. The usually envisaged scenario comprising several disconnected basins formed at different elevations well below the ocean level and characterized by distinct hydrologic budgets, is obviously feasible and tempting.

However, our data also point out a surprising homogeneity in terms of general characteristics and evolutionary trends of depositional systems and biota during this stage all around the Mediterranean basin. We believe that this could be better explained by an alternative scenario characterized by the permanence, after the MSC peak, of a relatively large, residual, hyperhaline water body which underwent a progressive dilution of surface water mainly due to the input of continental waters. In other words, we favor a scenario similar to the present-day Caspian Sea, the largest brackish basin of the world characterized by variable salinity values (1-14‰, up to evaporitic conditions in the Kara-Bogaz Gol) related to a combination of climate gradient, morphology and areal distribution of freshwater fluvial input.

The evidences for a generalized and substantial increase of fluvial discharge related to the activation of the Asian monsoon (Griffin 2002) and to the Late Miocene uplift of peri-Mediterranean and Asian mountain belts, support the hypothesis of the development of a stratified Mediterranean water body during the latest Messinian. However, the feedbacks between large-scale geodynamic processes and late Messinian climate in the Mediterranean area and their effects on precipitation and fluvial regimes has not been deeply explored yet.

The absolute water depth of such remnant basin is not easily assessed as well as the possible connections with the Paratethyan basin. The aggradational stacking pattern observed in p-ev$_1$ and even more clearly in p-ev$_2$ successions indicate a relative base-level rise during this stage. Admitting an initial base level significantly lower than the global ocean, the remnant Mediterranean basin could have been gradually refilled before the Zanclean marine flooding by continental waters and, to a lesser extent, by Atlantic underflow.

Shallow-water faunal and floral assemblages indicate generalized brackish to hyperhaline conditions at the onset of this stage gradually evolving toward hypohaline conditions; it is worth noting that deeper water deposits are usually barren thus hampering the complete reconstruction of the hydrologic structure of the water column. The generalized tectonic quiescence characterizing the latest Messinian interval after the peak of activity which led to the almost complete closure of the ocean gateways, could have favored the gradual enlargement of the basin and intra-Mediterranean connections. These processes could have promoted the development of progressively larger and hydrologically more homogenous and stable shallow-water settings which provided favorable conditions for the irradiation and diversification of Paratethyan biota. Subsidence could have affected also the Atlantic gateways area promoting a progressive increase of ocean water inflow up to the final full re-opening at the Zanclean base.

The permanence of a large, Caspian-like, water body during the latest Messinian allows to solve the apparent paradox of coexisting 'marine' and freshwater biota characterizing the Lago Mare event. Climate gradients and the distribution of large rivers could have resulted in a complex pattern of salinity and water temperature cyclically changing through the time like the one observed in the present-day Caspian Sea.

CONCLUSIONS

Physical- and cyclostratigraphic approaches allow to establish a high-resolution chronostratigraphy of latest Messinian sedimentary successions of the main outcropping basins of the Mediterranean area. The ~270 ka time interval, bounded by the MES (5.6 Ma) and by the Messinian-Pliocene boundary (5.33 Ma), records the MSC acme with the widespread deposition between 5.6 and 5.55 Ma of halite and K-salts in deeper and/or more subsiding basin and the subsequent gradual transition to more diluted water conditions (Lago Mare stage; 5.53-5.33 Ma). According to this reconstruction, the deposition of massive halite could have been caused by a combination of tectonic and glacio-eustatic factors, as the involved time interval corresponds to two important glacial peaks (TG12-TG14). The gradual onset of Lago Mare conditions at around 5.53 Ma corresponds to the transition to a longer-term deglacial interval comprising isotope stages TG11-TG9-TG7.

The depocenters of many outcropping basins show a fairly continuous record of the 5.6-5.33 Ma, allowing to close the so called 'Messinian gap'. New cyclostratigraphic considerations allow to lower the base of the Upper Evaporites at around 5.53 Ma. As a consequence, the Lago Mare phase lasted about 200 ka, corresponding to 9/10 precessional cycles. This interval can be subdivided into two units by a generalized facies and stacking pattern changes observed at around 5.42 Ma. The lower unit (p-ev$_1$) records the progressive but rapid switch from hypersaline to brackish waters. The upper unit (p-ev$_2$) is characterized by a clear upward transition toward fresh water conditions. The high-resolution stratigraphic framework established through the correlation of precessionally-controlled cyclicity allows to compare the palaeoenvironmental conditions developing during the terminal MSC phase and to recognize that much more homogenous conditions characterize the late Messinian.

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REFERENCES

AGUIRRE, J. and SÁNCHEZ-ALMAZO, I.M., 2004. The Messinian post-evaporitic deposits of the Gafares area (Almería-Níjar Basin, SE Spain). *Sedimentary Geology,* 168: 71–95.

ALDINUCCI, M., BERTINI, A., DA PRATO, S., DONIA, F., FORESI, L.M., MAZZEI, R., RIFORGIATO, F., SANDRELLI, F., SALVATORINI, G. and ZANCHETTA, G., 2006. The Messinian in Tuscany: an integrated high resolution stratigraphic framework from selected sections. R.C.M.N.S. International Congress Parma 2006 "The Messinian salinity crisis revisited II" Abstract Volume, Acta Naturalia De "L'Ateneo Parmense", 42-2: A.02.

BASSETTI, M.A., MANZI, V., LUGLI, S., ROVERI, M., LONGINELLI, A., RICCI LUCCHI, F. and BARBIERI, M., 2004. Paleoenvironmental significance of Messinian post-evaporitic lacustrine carbonates in the northern Apennines , Italy. *Sedimentary Geology,* 172: 1-18.

BASSETTI, M.A., RICCI LUCCHI, F. and ROVERI, M., 1994. Physical stratigraphy of the Messinian post-evaporitic deposit in central-southern Marche area (Apennines, central Italy). *Memorie della Società Geologica Italiana,* 48: 275-288.

BASSETTI, M.A., MICULAN, P. and SIERRO, F.J., 2006. Evolution of depositional environments after the end of Messinian Salinity Crisis in Nijar basin (SE Betic Cordillera). *Sedimentary Geology,* 188-189: 279-295.

BERTINI, A. and CORRADINI, D., 1998. Biostratigraphic and palaeoeocological significance of *Galeacysta etrusca* in the "lago-mare" facies from the Mediterranean area (Neogene). Dino 6. NTNU Vitensk. Mus. Rapp. Bot. ser. 1998, Abstract: 15-16.

BERTINI, A., 2006. The Northern Apennines palynological record as a contribute for the reconstruction of the Messinian palaeoenvironments*. Sedimentary Geology* 188/189: 235-258.

BONADUCE, G. and SGARRELLA, F., 1999. Paleoecological interpretation of the latest Messinian sediments from southern Sicily (Italy)*. Memorie della Società Geologica Italiana,* 54: 83-91.

BOSSIO, A., CERRI, R., MAZZEI, R., SALVATORINI, G. and SANDRELLI, F., 1994. The Neoautochthonous succession of the Spicchiaiola–Pignano area, east of Volterra (Southern Tuscany Italy). *Memorie della Società Geologica Italiana*, 48: 425–430.

BOSSIO, A., ESTEBAN, M., GIANNELLI, L., LONGINELLI, A., MAZZANTI, R., MAZZEI, R., RICCI LUCCHI, F. and SALVATORINI, G., 1978. Some aspects of the upper Miocene in Tuscany. In: Messinian Seminar, 4, Pisa, Pacini; 88 pp.

BRAGA, J.C., MARTÍN, J.M., RIDING, R., AGUIRRE, J., SÁNCHEZ-ALMAZO, I.M. and DINARÈS-TURELL, J., 2006. Testing models for the Messinian salinity crisis: The Messinian record in Almería, SE Spain. *Sedimentary Geology,* 188-189: 131-154.

BUTLER, R.W.H., LICKORISH, W.H., GRASSO, M., PEDLEY, H.M., and RAMBERTI, L., 1995. Tectonics and sequence stratigraphy in Messinian basins, Sicily: constraints on the initiation and termination of the Mediterranean salinity crisis. *Geological Society of America Bulletin,* 107: 425-439.

CARNEVALE, G., LANDINI, W., and SARTI, G., 2006. Mare versus Lago-mare: marine fishes and the Mediterranean environment at the end of the Messinian Salinity Crisis. *Journal of the Geological Society, London*, 163: 75–80.

CARNEVALE, G., LONGINELLI, A., CAPUTO, D., BARBIERI, M., and LANDINI, W., 2008. Did the Mediterranean marine reflooding preceded the Mio-Pliocene boundary? Paleontological and geochmical evidence from upper Messinian sequences of Tuscany, Italy. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 257: 81-105.

CHUMAKOV, I.S., 1973. Pliocene and Pleistocene deposits of the Nile Valley in Nubia and Upper Egypt. In: Ryan, W.B.F., Hsü, K.J., Cita, M.B. et al., Eds., *Initial Reports of the Deep Sea Drilling Project,* volume 13:1242–1243. Washington, DC: US Government Printing Office.

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

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

———, 1982. Le canyon messinien du Rhone: une preuve decisive du desiccated deep-basin model [Hsü, Cita et Ryan, 1973]. *Bulletin Societé Geologique du France*, 24: 597– 610.

CLAUZON, G., SUC, J.P., POPESCU, S.M., MARUNTEANU, M., RUBINO, J.L., MARINESCU, F., and MELINTE, M.C., 2005. Influence of Mediterranean sea-level changes on the Dacic Basin (Eastern Paratethys) during the late Neogene: the Mediterranean Lago Mare facies deciphered. *Basin Research,* 17: 437-462.

COLALONGO, M.L., CREMONINI, G., FARABEGOLI, E., SARTORI, R., TAMPIERI, R. and TOMADIN, L., 1976. Palaeoenvironmental study of the "Colombacci" Formation in Romagna (Italy): the Cella section. *Memorie della Società Geologica Italiana,* 16: 197–216.

CORRADINI, D. and BIFFI, U., 1988. Etude des dinokystes à la limite Messinien-Pliocene dans la coupe Cava Serredi, Toscane, Italie. *Bulletin Centre Recherche Exploration Production Elf-Aquitaine,* 12: 221-236.

COSENTINO, D., GLIOZZI, E. and PIPPONZI, G., 2007. The late Messinian Lago-Mare episode in the Mediterranean Basin: preliminary report on the occurrence of Paratethyan ostracod fauna from central Crete (Greece). *Géobios*, 40: 339-349.

CREMONINI, G. and FARABEGOLI, E., 1982. *Carta geologica 1/25000 della Regione Emilia-Romagna, tavv. Cusercoli e Borello (con note illustrative).* Bologna: Pitagora, pp. 25.

DALLA, S., HARBY, H. and SERAZZI, M., 1997. Hydrocarbon exploration in a complex incised valley fill: an example from the late Messinian Abu Madi Formation (Nile Delta Basin, Egypt). *Leading Edge*, 1819–1824.

DECIMA, A. and SPROVIERI, R., 1973. Comments on late Messinian microfaunas in several sections from Sicily. In: Drooger, C.W., Ed., *Messinian events in the Mediterranean,* 229-234. Amsterdam: North-Holland Pub. Co.

DECIMA, A., and WEZEL, F.C., 1971, Osservazioni sulle evaporiti Messiniane della Sicilia centro-meridionale. *Rivista Mineraria Siciliana*, 130-134: 172-187.

DELA PIERRE, F., CLARI, P., CAVAGNA, S. and BICCHI, E., 2002. The Parona chaotic complex: a puzzling record of the Messinian (Late Miocene) events in Monferrato (NW Italy). *Sedimentary Geology,* 152: 289-311.

DELA PIERRE, F., FESTA, A. and IRACE, A., 2007. Interaction of tectonic, sedimentary, and diapiric processes in the origin of chaotic sediments: An example from the Messinian of Torino Hill (Tertiary Piedmont Basin, northwestern Italy). *Geological Society of America Bulletin*, 119: 1107-1119.

DI STEFANO, E., SPROVIERI, R. and SCARANTINO, S., 1996. Chronology of biostratigraphic events at the base of the Pliocene. *Paleopelagos*, 6: 401-414.

FORTUIN, A. and KRIJGSMAN, W., 2003. The Messinian of the Nijar Basin (SE Spain): sedimentation, depositional environments and paleogeographic evolution. *Sedimentary Geology,* 160: 213-242.

GANDIN, A., GIAMELLO, M., GUASPARRI, G., MUGNAINI, S. and SABATINI, G., 2000. The Calcare Cavernoso of the Montagnola Senese (Siena, Italy): mineralogical-petrographic and petrogenetic features. *Mineralogica et Petrographica Acta,* 43: 271-289.

GENNARI, R., 2007. "Cause e modalità della formazione messiniana "Lago-Mare" e passaggio al Pliocene." Ph.D. Thesis. University of Parma, 126 pp.

GENNARI, R., IACCARINO, S.M., DI STEFANO, A., STURIALE, G., CIPOLLARI, P., MANZI, V., ROVERI, M. and COSENTINO, D., 2008. The Messinian – Zanclean boundary in the Northern Apennines. In: Manzi V., Iaccarino S.M., Lugli S., Roveri M., Eds., The Messinian salinity crisis revisited II, *Stratigraphy* 5(3-4): 309-325. (this volume).

GHIBAUDO, G., CLARI, P. and PERELLO, M., 1985. Litostratigrafia, sedimentologia ed evoluzione Tettonico-sedimentaria dei depositi miocenici del margine sud-orientale del Bacino Terziario Ligure-Piemontese (Valli Borbera, Scrivia e Lemme). *Bollettino della Società Geologica Italiana,* 104: 349-397.

GIGNOUX, M., 1936. *Géologie stratigraphique* (2°édition), Paris: Masson.

GLIOZZI, E., CECI M.E., GROSSI, F. and SILVIA LIGIOS, 2007. Paratethyan Ostracod immigrants in Italy during the Late Miocene. *Geobios*, 40: 325–337.

GRASSO, M., BUTLER, R.W.H. and SCHMINCKE, H.U., 2004. The Neogene thrust-top basins in central Sicily and the Neogene volcanism of the Northern Monti Iblei. B30 Field trip guidebook, 32nd International Geological Congress, Firenze, 20-28 Agosto 2004. In: Guerrieri, L., Rischia, I., Serva, L., Eds., *Field Trip Guidebooks, 32nd IGC Florence 20-28 August 2004, Memorie Descrittive della Carta Geologica d'Italia, 63 (2), from B16 to B33* Roma: APAT, B19, 44 pp.

GRIFFIN, D.L., 2002, Aridity and humidity: two aspects of the late Miocene climate of North Africa and the Mediterranean. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 182: 65-91.

GROSSI, F. and GENNARI, R., in press. Palaeoenvironmental reconstructions of the Messinian/Zanclean boundary using ostracods and forams: the Montepetra borehole (North Apennine, Italy). *Atti del Museo Civico di Storia Naturale di Trieste,* Trieste.

HILGEN, F.J., KUIPER, K.F., KRIJGSMAN, W., SNEL, E. and VAN DER LAAN, E., 2007. High-resolution integrated stratigraphy and astronomical tuning as prerequisites for deciphering the intricate history of the Messinian Salinity Crisis. *Stratigraphy*, 4: 231-238.

HODELL, D.A., CURTIS, J.H., SIERRO, F.J. and RAYMO, M.E., 2001. Correlation of late Miocene to early Pliocene sequences between the Mediterranean and North Atlantic. *Paleoceanography*, 16: 164-178.

HSÜ, K.J., MONTADERT, L., BERNOULLI, D., CITA, M.B. and ERICKSON, A., 1977. History of the Mediterranean salinity crisis. *Nature*, 267: 399–403.

IACCARINO, S.M, BERTINI, A., DI STEFANO, A., FERRARO, L., GENNARI, R., GROSSI, F., LIRER, F., MANZI, V., MENICHETTI, E., RICCI LUCCHI, M., TAVIANI, M., STURIALE, G. and ANGELETTI, L., 2008. The Trave section (Monte dei Corvi, Ancona, Central Italy): an integrated paleontological study of the Messinian deposits. In: Manzi V., Iaccarino S.M., Lugli S., Roveri M., Eds., The Messinian salinity crisis revisited II, *Stratigraphy* 5(3-4):283-308. (this volume).

IACCARINO, S.M., CASTRADORI, D., CITA, M.B., DI STEFANO, E., GABOARDI, S., MCKENZIE, J.A., SPEZZAFERRI, S., and SPROVIERI, R., 1999. The Miocene/Pliocene boundary and the significance of the earliest Pliocene flooding in the Mediterranean. *Memorie della Società Geologica Italiana,* 54: 109-131.

IRACE, A., DELA PIERRE, F. and CLARI, P., 2005. "Normal" and "chaotic" deposits in the Messinian Gessoso-solfifera Fm. at the north-eastern border of the Langhe domain (Tertiary Piedmont Basin). *Bollettino della Società Geologica Italiana,* Vol. Sp., 4: 77-85.

JUTEAU, M., MICHARD, A., ZIMMERMANN, J.L. and ALBAREDE, F., 1984. Isotopic Heterogeneities in the Granitic Intrusion of Monte Capanne (Elba Island, Italy) and Dating Concepts. *Journal of Petrology,* 25: 532-545.

KRIJGSMAN, W., FORTUIN, A.R., HILGEN, F.J., ROEP, T.B. and SIERRO, F.J., 2001. Astrochronology for the Messinian Sorbas Basin (SE Spain) and orbital (precessional) forcing for evaporite cyclicity. *Sedimentary Geology,* 140: 43–60.

KRIJGSMAN, W., GABOARDI, S., HILGEN, F.J., IACCARINO, S., DE KAENEL, E., and VAN DER LAAN, E., 2004. Revised astrochronology for the Ain el Beida section (Atlantic Morocco): No glacio-eustatic control for the onset of the Messinian salinity crisis. *Stratigraphy*, 1(1): 87–101.

KRIJGSMAN, W., HILGEN, F.J., RAFFI, I., SIERRO, F.J., and WILSON, D.S., 1999. Chronology, causes and progression of the Messinian salinity crisis. *Nature*, 400: 652-655.

LASKAR, L.J., ROBUTEL, P., JOUTEL, F., GASTINEAU, M., CORREIA, A.C.M., and LEVRARD, B., 2004. A long term numerical solution for the insolation quantities of the Earth. *Astronomy and Astrophysics,* 428: 261–285.

LAZZAROTTO, A., SANDRELLI, F., FORESI, L.M., MAZZEI, R., SALVATORINI, G., CORNAMUSINI, G. and PASCUCCI, V, 2002. *Note illustrative della Carta Geologica d'Italia alla scala 1:50.000, Foglio 295 Pomarance.* Presidenza del Consiglio dei Ministri, Dipartimento per i servizi tecnici nazionali, Servizio Geologico d'Italia. L.A.C. Firenze. 140 p.

LOFI, J., GORINI, C., BERNE, S., CLAUZON, G., DOS REIS, A.T., RYAN, W.B.F., and STECKLER, M.S., 2005. Erosional processes and paleo-environmental changes in the western Gulf of Lions (SW France) during the Messinian Salinity Crisis. *Marine Geology,* 217: 1-30.

LONDEIX, L., BENZAKOUR M., SUC J.P. and TURON J.L., 2007. Messinian palaeoenvironments and hidrology in Sicily (Italy): The dinoflagellate cyst record. *Geobios*, 40: 233-250.

LUGLI, S., SCHREIBER, B.C. and TRIBERTI, B., 1999. Giant polygons in the Realmonte mine (Agrigento, Sicily): evidence for the desiccation of a Messinian halite basin. *Journal of Sedimentary Research,* 69: 764-771.

MANZI ,V., LUGLI, S., RICCI LUCCHI, F., and ROVERI, M., 2005. Deep-water clastic evaporites deposition in the Messinian Adriatic foredeep (northern Apennines , Italy): did the Mediterranean ever dry out? *Sedimentology* 52 (4), 875-902.

MANZI, V., LUGLI, S., ROVERI, M. and SCHREIBER, B.C., submitted. A new facies model for the Upper Gypsum (Sicily, Italy): chronological and palaeoenvironmental constraints for the Messinian salinity crisis in the Mediterranean. Submitted to *Sedimentology*.

MANZI, V., ROVERI, M., GENNARI, R., BERTINI, A., BIFFI, U., GIUNTA, S., IACCARINO, S.M., LANCI, L., LUGLI, S., NEGRI, A., RIVA, A., ROSSI, M.E., and TAVIANI M., 2007. The deep-water counterpart of the Messinian Lower Evaporites in the Apennines foredeep: The Fanantello section (Northern Apennines, Italy). *Palaeogeography, Palaeoclimatology, Palaeoecology,* 251: 470-499.

MATHER, A.E., MARTIN, J.M., HARVEY, A.M. and BRAGA, J.C., Editors, 2001. *A Field guide to the Neogene sedimentary basins of the Almeria Province, South-east Spain: International Association of Sedimentologists Field Guide.* London: Blackwell Science, 350pp.

ODIN, G.S., DEINO, A., COSCA, M., LAURENZI, M.A. and MONTANARI, A., 1997. Miocene geochronology: methods, techniques, results. In: Montanari, A., Odin, G.S. and Coccioni, R., Eds. *Miocene Stratigraphy – An Integrated Approach,* 583–596. Amsterdam: Elsevier.

OMODEO-SALÉ, S., 2007. "The post-evaporitic deposits in the Nijar basin (SE Spain)." Unpublished Thesis, University of Parma.

ORSZAG-SPERBER, F., 2006. Changing perspectives in the concept of "Lago-Mare" in Mediterranean Late Miocene evolution. *Sedimentary Geology*, 188-189: 259-277.

PASCUCCI, V., MERLINI, S. and MARTINI, I.P., 1999. Seismic stratigraphy of the Miocene-Pleistocene sedimentary basins of the Northern Tyrrhenian Sea and western Tuscany (Italy). *Basin Research,* 11: 337-356,

PIERRE, C., CARUSO, A., BLANC-VALLERON, M.M., ROUCHY, J.M. and ORZSAG-SPERBER, F., 2006. Reconstruction of the paleoenvironmental changes around the Miocene–Pliocene boundary along a West–East transect across the Mediterranean. *Sedimentary Geology,* 188–189: 319–340.

POPESCU, S.M., MELINTE, M.C., SUC, J.P., CLAUZON, S., QUILLÉVÉRÉ, F. and SUTO-SZENTAI, M., 2007. Earliest Zanclean age for the Colombacci and uppermost Di Tetto formations of the "latest Messinian" northern Apennines: New palaeoenvironmental data from the Maccarone section (Marche Province, Italy). *Geobios*, 40: 359-373.

RIFORGIATO, F., ALDINUCCI, M., DONIA, F., FORESI, L.M., MAZZEI, R., SALVATORINI, G., SANDRELLI, F. and STURIALE, G., 2006. The Miocene/Pliocene boundary in Tuscany (Italy): micropaleontological evidence from the Serredi Quarry succession. *Acta Naturalia de "L'Ateneo Parmense",* 42-2: A43.

RIO D. and NEGRI A., 1988. Calcareous nannofossils (Monticino Quarry, Faenza). In: De Giuli, C., and Vai, G.B., Eds., *Fossil Vertebrates in the Lamone valley, Romagna Apennines, International Workshop: Continental Faunas at the Mio-Pliocene Boundary, Faenza, March 28–31, 1988, Guidebook*, 55–57. Faenza: Litografica Faenza.

ROBERTSON A.H.F., EATON, S., FOLLOWS, E.J. and PAYNE A.S., 1995. Depositional processes and basin analysis of Messinian evaporites in Cyprus. *Terra Nova,* 7:233-253.

RODA, C., 1965. Geologia della tavoletta Belvedere di Spinello (prov. Catanzaro, F° 237, I-SE). Bollettino della Società Geologica Italiana, 84: 159-285.

ROEP, TH.B., DABRIO, C.J., FORTUIN, A.R., and POLO, M.D., 1998. Late highstand patterns of shifting and stepping coastal barriers and washover-fans (late Messinian, Sorbas Basin, SE Spain). *Sedimentary Geology* 116: 27-56.

ROUCHY, J.M., 1982. La genèse des évaporites messiniennes de Méditerrannée. *Mémoires, Museum Nationale d'Histoire Naturelle, (Paris), Sciences de la Terre*, 50: 280 pp.

ROUCHY, J.M. and CARUSO, A., 2006. The Messinian salinity crisis in the Mediterranean basin: A reassessment of the data and an integrated scenario. *Sedimentary Geology,* 188-189: 35-67.

ROUCHY, J.M., ORSZAG-SPERBER, F., BLANC-VALLERON, M.-M., PIERRE, C., RIVIÈRE, M., COMBOURIEU-NEBOUT, N. and PANAYIDES, I., 2001. Paleoenvironmental changes at the Messinian–Pliocene boundary in the eastern Mediterranean (southern Cyprus basins): significance of the Messinian Lago-Mare. *Sedimentary Geology*, 145: 93-117.

ROVERI, M., and MANZI, V., 2006. The Messinian salinity crisis: looking for a new paradigm? *Palaeogeography, Palaeoclimatology, Palaeoecology,* 238: 386-398.

ROVERI, M., BASSETTI, M.A., and RICCI LUCCHI, F., 2001. The Mediterranean Messinian salinity crisis: an Apennines foredeep perspective. *Sedimentary Geology,* 140: 201-214.

ROVERI, M., BERTINI, A., CIPOLLARI, P., COSENTINO, D., DI STEFANO, A., FLORINDO, F., GENNARI, R., GLIOZZI, E., GROSSI, F., IACCARINO, S.M., LUGLI, S. and MANZI, V., 2008a. Comment on 'Earliest Zanclean age for the Colombacci and uppermost Di Tetto formations of the "latest Messinian" northern Apennines: New palaeoenvironmental data from the Maccarone section (Marche Province, Italy)' by Popescu et al. (2007). *Geobios* 41: 669-675.

ROVERI, M., BOSCOLO GALLO, A. ROSSI, M.E., GENNARI, R., IACCARINO, S.M., LUGLI, S., MANZI, V., NEGRI A., RIZZINI, F. and TAVIANI, M., 2005. The Adriatic foreland record of messinian events (central Adriatic Sea, Italy). *Geoacta*, 4: 139-158.

ROVERI, M., LANDUZZI, A., BASSETTI, M.A., LUGLI, S., MANZI, V., RICCI LUCCHI, F., and VAI, G.B., 2004. The record of Messinian events in the Northern Apennines foredeep basins. 32nd International Geological Congress, Florence 2004. August 20-28, 2004 (vol. Field Trip Guide Book B19 pp. 1-44). In: Guerrieri, L., Rischia, I., Serva, L., Eds., *Field Trip Guidebooks, 32nd IGC Florence 20-28 August 2004, Memorie Descrittive della Carta Geologica d'Italia, 63 (2), from B16 to B33* Roma: APAT, B19, 44 pp.

ROVERI, M., LUGLI, S., MANZI, V. and SCHREIBER, B.C., 2008b. The shallow- to deep-water record of the Messinian salinity crisis: new insights from Sicily, Calabria and Apennines basins. In: Briand, F., Ed., *The Messinian Salinity Crisis mega-deposits to microbiology – A consensus report.* CIESM Workshop Monographs, 33: 73-82.

———, 2008c. The Messinian salinity crisis: a sequence-stratigraphic approach. *GeoActa,* Special Volume 1: 117-138.

———, in press. The Messinian Sicilian stratigraphy revisited: new insights for the Messinian salinity crisis. *Terra Nova.*

ROVERI, M., LUGLI, S., MANZI, V., GENNARI, R, IACCARINO, S.M, GROSSI, F. and TAVIANI, M., 2006a. The record of Messinian events in the Northern Apennines foredeep basins. R.C.M.N.S. International Congress "The Messinian salinity crisis revisited II", Parma 2006. Pre-congress Field-trip. *Acta Naturalia de l'Ateneo Parmense,* 42-1: 47-123.

ROVERI, M., MANZI, V., BASSETTI, M.A., MERINI, M. and RICCI LUCCHI, F., 1998. Stratigraphy of the Messinian post-evaporitic stage in eastern-Romagna (northern Apennines, Italy). *Giornale di Geologia,* 60: 119-142.

ROVERI, M., MANZI, V., LUGLI, S., SCHREIBER, B.C., CARUSO, A., ROUCHY, J.M., IACCARINO, S.M., GENNARI, R. and VITALE, F.P., 2006b. Clastic vs. primary precipitated evaporites in the Messinian Sicilian basins. R.C.M.N.S. International Congress "The Messinian salinity crisis revisited II", Parma 2006. Post-congress Field-trip. *Acta Naturalia de l'Ateneo Parmense,* 42-1: 125-199.

RUGGIERI, G., 1967. The Miocene and later evolution of the Mediterranean Sea. In: Adams, C.G. and Ager, D.V., Eds., *Aspects of Tethyan Biogeography.* London: Systematics Association Publication, 7: 283–290.

RYAN, W.B.F. and CITA, M.B., 1978. The nature and distribution of Messinian Erosional Surfaces; indicators of a several-kilometer-deep Mediterranean in the Miocene. *Marine Geology*, 27 (3–4): 193– 230.

SCHREIBER, B.C., 1997. *Field trip to Eraclea Minoa: Upper Messinian: "Neogene Mediterranean Paleoceanography". Excursion Guide Book Palermo-Caltanissetta-Agrigento-Erice (Sicily), 24-27 September 1997,* 72-80. Roma: Società Geologica Italiana.

SELLI, R., 1960. Il Messiniano Mayer-Eymar 1867. Proposta di un neostratotipo. *Giornale di Geologia,* 28: 1-33.

SPROVIERI, R., DI STEFANO, E., BONOMO S., TAMBURINI F. and MCKENZIE J., 2007. The Messinian-Pliocene boundary in the north Italy regions. *Geophysical Research Abstract*, 9: 06041.

TAYLOR, H.P. and TURI, B., 1976. High ^{18}O igneous rocks from the Tuscan Magmatic Province Italy. *Contributions to Mineralogy and Petrology,* 5: 33-54.

TRENKWALDER, S., IRACE, A., VIOLANTI, D. and DELA PIERRE, F., 2006. The Miocene-Pliocene boundary in Piedmont (North-Western Italy): subsurface (Narzole borehole) and outcrop (Moncucco quarry) data. R.C.M.N.S. International Congress Parma 2006 "The Messinian salinity crisis revisited II" Abstract Volume, *Acta Naturalia De "L'Ateneo Parmense"*, 42-2: A58.

VAI, G.B., 1988. A field trip guide to the Romagna Apennines geology. The Lamone valley. In: De Giuli, C. and Vai, G.B., Eds., *Fossil vertebrates in the Lamone valley, Romagna Apennines, International Workshop: Continental faunas at the Mio-Pliocene Boundary, Faenza, March 28-31, 1988, Guidebook,* 7-37. Faenza: Litografica Faenza.

———, 1997. Cyclostratigraphic estimate of the Messinian Stage duration. In: Montanari, A., Odin, G.S. and Coccioni, R., Eds., *Miocene Stratigraphy – An Integrated Approach*, 463–476. Amsterdam: Elsevier.

VAN COUVERING, J.A., CASTRADORI, D., CITA, M.B., HILGEN, F.J. and RIO, D., 2000. The base of the Zanclean Stage and of the Pliocene Series. *Episodes*, 23: 179-186.

VAN DER LAAN, E., SNEL, DE KAENEL, E., HILGEN, F.J., and KRIJGSMAN, W., 2006. No major deglaciation across the Miocene-Pliocene boundary: Integrated stratigraphy and astronomical tuning of the Loulja sections (Bou Regreg area, NW Morocco), *Paleoceanography*, 21: PA3011.

VISMARA-SCHILLING, A., STRADNER, H., CITA, M.B. and GAETANI, M., 1978. Stratigraphic investigations on the late Neogene of Corfou (Greece) with special reference to the Miocene/Pliocene boundary and to its geodynamical significance. In: Catalano, R., Ruggieri, G., Sprovieri, R., Eds., Messinian evaporites in the Mediterranean. *Memorie della Società Geologica Italiana* 16: 279–318.

WILLETT, S.D., SCHLUNEGGER, F. and PICOTTI, V., 2006. Messinian climate change and erosional destruction of the central European Alps. *Geology*, 34: 613-616.