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The Messinian salinity crisis: Looking for a new paradigm?

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Abstract

The importance of the sedimentary record of Messinian events in the Apennines foredeep is due to its geological and structural settings, which allow the reconstruction of the relationships between marginal and basinal settings and provide fundamental insights into some important issues. A geologic–stratigraphic model of the Messinian Apennine foredeep indicating a possible solution for closing the last 'Messinian gap' is here presented. Moreover, the establishment of a preliminary high-resolution stratigraphy for the terminal Lago Mare stage allows us to attempt Mediterranean-scale correlations across different structural settings.

The Messinian evolution of the Apennine foredeep and some considerations of adjacent areas suggest the great importance of tectonic deformation in controlling Messinian events. The intra-Messinian unconformity is a common feature of the marginal basins of the Mediterranean, and it is associated in many cases to the collapse and resedimentation of primary evaporites. The genesis of such unconformity seems to be strictly related to a general tectonic reorganization of the Mediterranean area. Preliminary observation on the stratigraphy of the Lago Mare stage suggest that the high-frequency lithological cyclicity observed in the non-marine deposits of this stage, as well as the superimposed transgressive trend, are common to many Mediterranean basins. These characteristic features might reflect the interplay between a longer-term tectonic trend and higher-frequency, precession-related, climatic changes; this could represent a fundamental tool for establishing a high-resolution stratigraphic framework of the latest Messinian allowing long-distance correlations between terrestrial and marine ecosystems and hence more accurate palaeoenvironmental studies.

Keywords: Messinian salinity crisis; Apennines foredeep; Physical stratigraphy; Mediterranean; Palaeoenvironmental change; Evaporites

1. Introduction

The dramatic palaeoenvironmental changes of the Mediterranean area related to the Messinian salinity crisis still represent a largely debated item for the scientific community. The significant enhancement of stratigraphic techniques and approaches achieved in the last few years with the establishment of an astronomical polarity timescale for the last 10 My and the diffusion of physical–stratigraphic concepts have greatly improved our chances for a more detailed knowledge of the geological evolution of the Mediterranean marine and terrestrial domains during the Neogene.

However, more than 30 years after the formulation of the Deep Desiccation Model, the basic palaeoenvironmental questions about the Messinian salinity crisis still remain unanswered. The palaeogeography of the Mediterranean area, as well as the physical and chemical

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structure of the water column through the different Messinian stages and the role of biota, which are key points for the assessment of the evolution of marine and terrestrial ecosystems, are still far from being fully understood.

The lack of a reliable palaeogeographic framework for the Mediterranean area during the Messinian puts severe limitations to the attempts of many international research groups the quantitative model palaeoclimatic and palaeoceanographic scenarios of the Messinian salinity crisis. Three main factors are responsible for this situation: 1) the still unknown nature of the Messinian deposits buried in the deepest Mediterranean basins, 2) the possibly overlooked amplitude and velocity of Messinian tectonic events and 3) the lack of a high-resolution supra-regional stratigraphic framework for the latest Messinian interval (the Lago Mare stage).

All these problems ultimately arise from the great difficulties in establishing correct stratigraphic relationships between marginal and basinal successions in the different regional contexts. This is mainly due to the peculiar characters of the late Messinian deposits that do not allow use of common biomagnetostratigraphic correlation tools. Moreover, outcropping Messinian successions are often representative of marginal depositional contexts, while deep basinal settings are usually buried below the Mediterranean sea-floor and only rarely accessible through commercial seismic and well data.

In this respect, the Apennine foredeep basin represents an exception; due to its geological setting, the relationships between marginal and basinal successions can be established and a geologic and stratigraphic model for its evolution during the Messinian has been recently reconstructed, based on the integration of surface and subsurface data and the use of a physical stratigraphic approach (Roveri et al., 1998, 2001). The Apennine record of the Messinian events has been usually overlooked in the past, being considered an anomaly in the larger-scale Mediterranean framework. On the contrary, we believe that, although not necessarily representative of all the different conditions

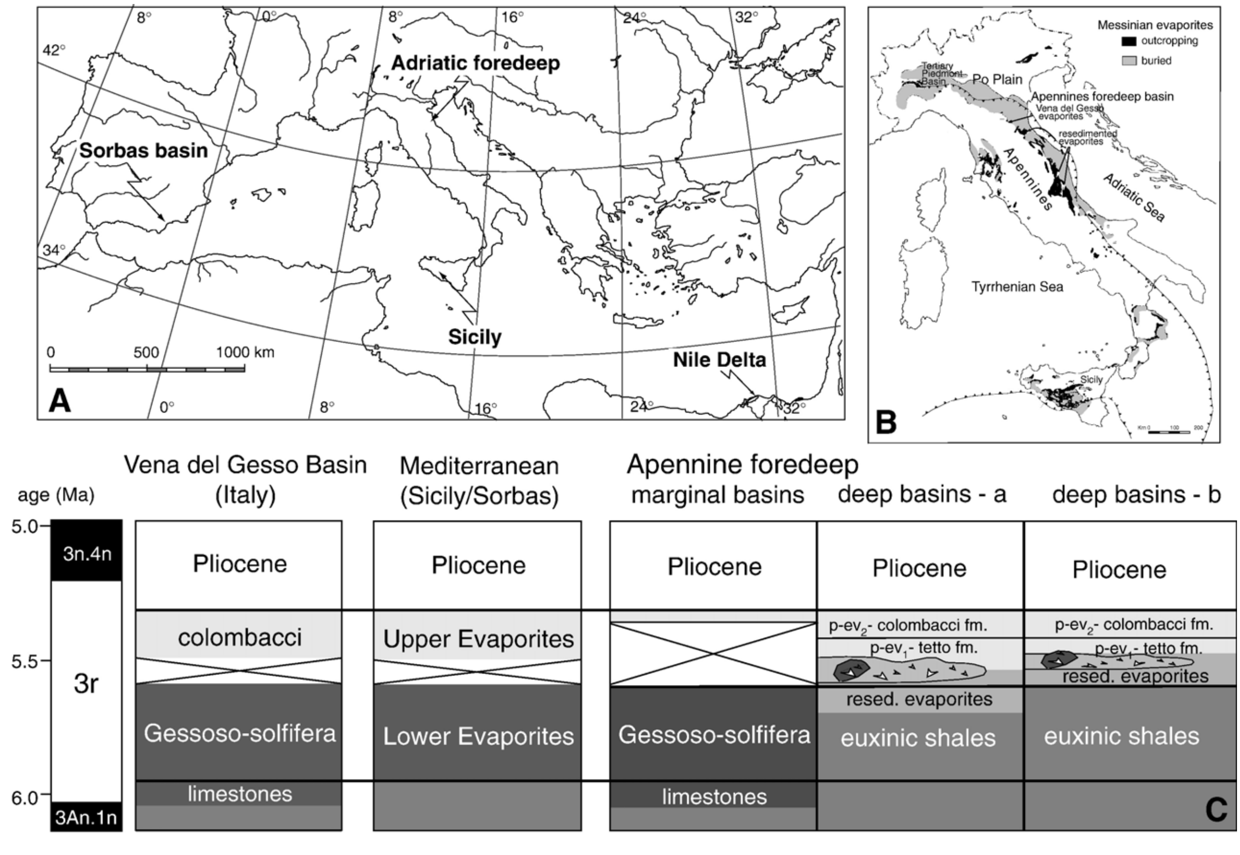

Fig. 1. A) Index map with the main Messinian basins cited in the text. B) Close-up of the Apennine–Maghrebian chain with the distribution of Messinian deposits. C) Chronology of the main Messinian events. Correlations between the Messinian successions of the Apennine foredeep and of the Western Mediterranean (modified after Krijgsman et al., 1999a).

experienced in the Mediterranean area, the Apennine sedimentary record of Messinian events provides important insights on the MSC, whose larger-scale implications are probably more important than usually thought.

We are well aware that the chronology of Messinian events is still a controversial issue; however, we will adopt here the cyclostratigraphic model of Krijgsman et al. (1999a,b; Fig. 1), that supports the classical three-fold subdivision of the Messinian stage: 1) a pre-evaporitic (7.251–5.96 Ma) phase, characterized by the common occurrence of euxinic, organic-rich deposits, which record a reduced circulation of deep Mediterranean waters; 2) Lower Evaporites (5.96–~5.60 Ma), with precipitation of shallow-water evaporites in marginal basins; 3) Upper Evaporites, or post-evaporitic Lago Mare stage (~5.60–5.33 Ma), showing the development of non-marine deposits with mollusc, ostracod and dinoflagellate assemblages of Paratethyan affinity (Lago Mare biofacies; Ruggieri, 1967; Iaccarino and Bossio, 1999). The astronomically calibrated time scale for the Neogene still has at the base of this interval a gap lasting 90 ky (Krijgsman et al., 1999a,b), usually related to the deep desiccation of the Mediterranean and the associated tectonic movements resulting from isostatic rebound; the end of this stage is represented by the sudden, almost synchronous return to fully marine conditions in the Mediterranean Basin (Iaccarino et al., 1999). This reconstruction of Messinian events is in good agreement with the two-step model of the MSC proposed by Clauzon et al. (1996), that pointed out the diachronous deposition of evaporites across marginal and basinal settings.

In this paper, after a brief review of the main characters of the Apennine foredeep Messinian stratigraphy, we will discuss some of its most important implications for the MSC and we will put forward some issues and considerations that in our opinion should be addressed to future research projects.

2. The Apennine foredeep record of Messinian events

In the last 10 years a complete stratigraphic revision of the Apennine Messinian deposits has been carried out using a physical–stratigraphic approach, based on the recognition and basin-wide correlation of unconformities, key-surfaces and sedimentary cycles (Bassetti et al., 1994; Roveri et al., 1998; Bassetti, 2000; Manzi, 2001; Roveri et al., 2001; Ricci Lucchi et al., 2002). The regional-scale studies were inspired by the pioneering work of Gelati et al. (1987) carried out in the subsurface of the NW Po Plain. This led to the establishment of a high-resolution stratigraphic framework (Fig. 1) and to the reconstruction of a regional-scale geological model (Roveri et al., 1998, 2001; Ricci Lucchi et al., 2002; Fig. 2), a fundamental base for future integrated studies.

The sequence of events as recorded by the lithostratigraphy of the Apennine foredeep basins is basically the same as in the other Mediterranean basins; significantly, the boundaries between the main units appear to have the same age (Krijgsman et al., 1999a,b).

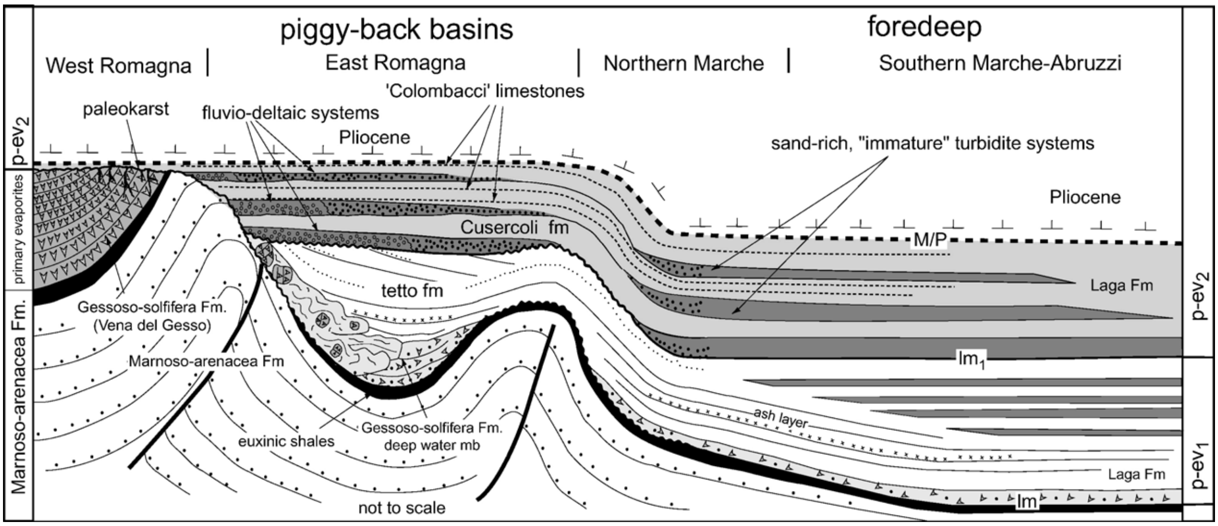

Fig. 2. Idealized cross-section of the Adriatic foredeep during the Messinian with its structural articulations into marginal and deeper basins. Resedimented evaporites occur as layered turbidites in deeper basins and as slides and debris flows in marginal ones. Note the well-developed cyclicity in coarse-grained fluvio-deltaic systems of the upper post-evaporitic unit (p-ev$_2$) (modified after Roveri et al., 1998).

The onset of the salinity crisis is heralded by the cyclical, astronomically controlled deposition of organic-rich euxinic shales (equivalent to the Tripoli Fm. of Sicily; Vai, 1997); the evaporitic phase is represented by the cyclical deposition of primary gypsum, a perfect equivalent of the Lower Evaporites of Spain (Sorbas basin), Greece and Sicily. Regional correlations show that deposition of Lower Evaporites was not widespread, but that it was limited to shallow-water, marginal basins formed on top of the uplifting Apenninic orogenic wedge during a phase of tectonic deformation which started in the late Tortonian (i.e. the Vena del Gesso basin, Manzi, 2001; Roveri et al., 2003).

Evaporite deposition in the Vena del Gesso basin was controlled by tectonics and consequent changes of basin topography. The growth of a structural high led to the creation of a small, almost starved thrust-top basin, with reduced connections with the open sea. During the main evaporitic phase, the adjacent deeper basin was characterized by the accumulation of organic-rich shales. Like in all the other marginal Mediterranean basins (see Clauzon et al., 1996), the Lower Evaporites are cut by a subaerial erosional surface associated to an angular unconformity, related to a paroxistic tectonic phase leading to the first emersion of the Apennine chain (Ricci Lucchi, 1986).

This surface, when traced to the deeper part of the basin, is shown to floor a complex of clastic evaporites, resedimented through gravity flows (high to low-density turbiditic flow, debris flow and olistostrome) in

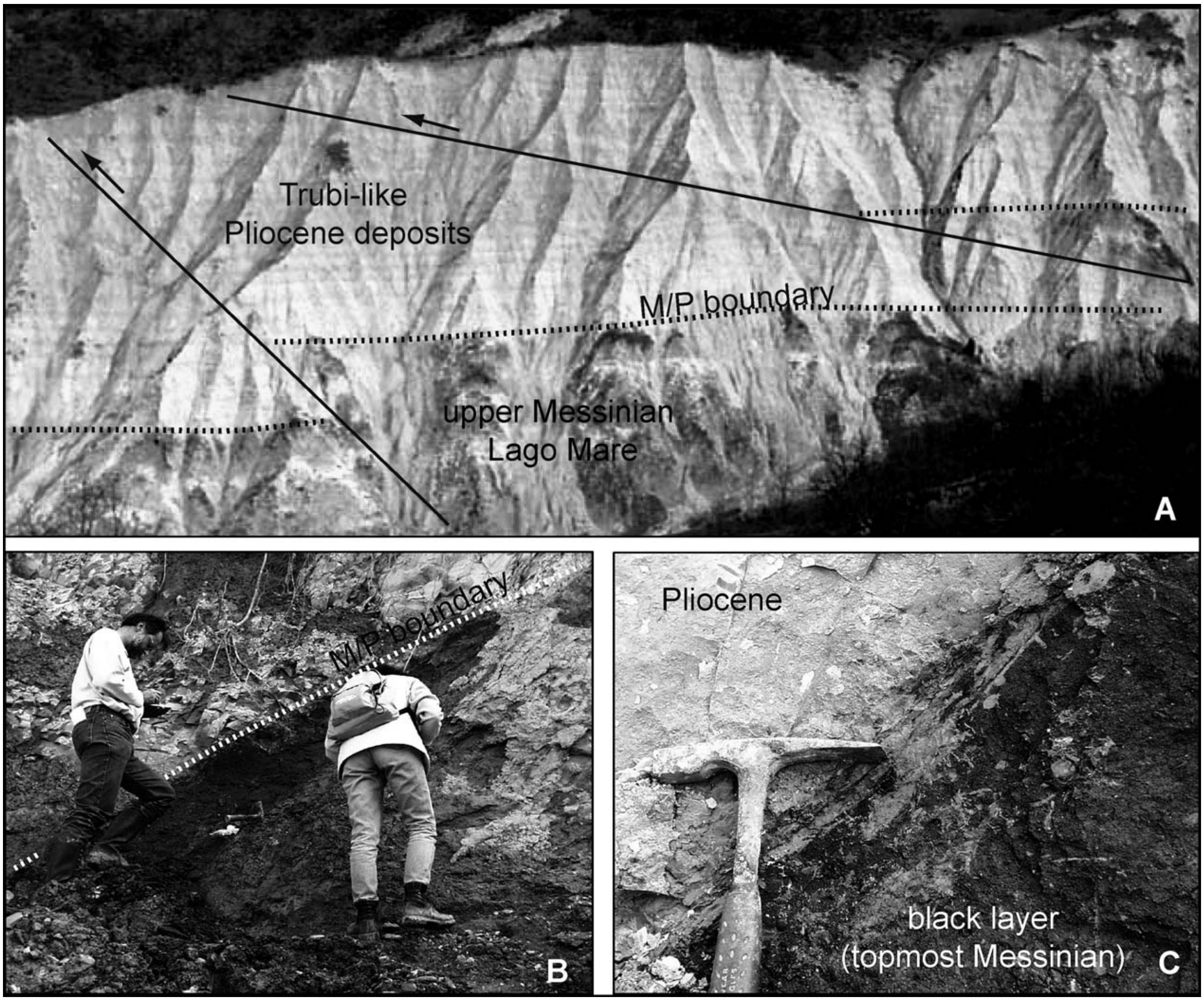

Fig. 3. Typical aspect of the Miocene–Pliocene boundary in the Apennine foredeep. Note the strong lithological contrast between the late Messinian “Lago mare” deposits and the cyclic alternation of light and dark marls very similar to the Sicilian Trubi Fm (A, Rio Nasseto, Northern Marche). In B and C (Riccò, Taro valley, Emilia Apennine) a closer view of the black, organic-rich layer marking the Miocene/Pliocene boundary (V. Mosbrugger and M.A. Bassetti for scale in b).

relatively deep, subaqueous settings, as already documented in the early 1970s (Parea and Ricci Lucchi, 1972; Ricci Lucchi, 1973), and deriving from large-scale collapses of primary evaporites triggered by the tectonic uplift. Above the resedimented evaporites, a terrigenous unit recording the rapid transition to hyposaline conditions is found only in basinal settings (Roveri et al., 1998, 2001).

These lines of evidence indicate that the end of the evaporitic phase and the sudden switch to hyposaline conditions, the so-called "Lago Mare" phase, were concomitant and likely caused by an important tectonic phase. Post-evaporitic Lago Mare deposits are here exceptionally thick (>1 km) and show in the upper part a well-developed cyclical pattern that can be used to trace regional correlations across different sub-basins (Roveri et al., 1998, 2001). Based on the physical characters of the post-evaporitic successions (discontinuities of different hierarchical rank, stacking pattern and cyclic organization of depositional system, key horizons) a detailed regional stratigraphic framework for this interval has been reconstructed, useful for comparison with the other Mediterranean basins.

A regional unconformity splits the hyposaline deposits into two units; the lower one (p-ev$_1$ of Fig. 1) is composed of the basal resedimented evaporites, overlain by a mainly fine-grained, terrigenous succession showing an overall coarsening and shallowing upward trend. This lower unit has no depositional equivalents in the marginal settings, which experienced a phase of subaerial exposure and erosion. The upper unit (p-ev$_2$ of Fig. 1), usually made up of coarser-grained deposits, has a general transgressive trend, well expressed by a systematic onlap against basin margins; this unit seals all the previously uplifted tectonic structures, suggesting a phase of tectonic quiescence and generalized subsidence and/or a base level rise. This upper post-evaporitic unit is characterized by a well-developed sedimentary cyclicity expressed by the periodical activation of coarse-grained deltaic systems dominated by catastrophic fluvial floods (Roveri et al., 1998). In this unit, 3 to 4 sedimentary cycles consisting of decametric-thick coarse and fine-grained couplets reflecting a high-frequency climatic control with rapid switches from arid to wet conditions and consequent base-level changes, are recognized throughout the basin in both shallow and deeper depositional settings. In the latter, the forestepping, constructive phase of deltaic systems is expressed by the development of turbidite-like deposits consisting of coarse-grained, thick-bedded and amalgamated sandstones, forming thick, tabular bodies (Fig. 2).

The return to open marine conditions at the base of the Pliocene is a sudden event, like in the rest of the Mediterranean, occurring within the overall transgressive trend that started with the p-ev$_2$ unit. The transition to deep marine deposits is typically marked by a characteristic black, organic-rich horizon (Fig. 3), above which cyclically alternating light and grey mudstones and marls, very similar to the Trubi Fm. of Sicily, are found (Fig. 3).

3. Main implications for the Messinian salinity crisis (MSC)

In this section we will discuss some general open problems concerning the different phases or stages of the MSC, arising from the experience derived from the Apennine foredeep record. In the next paragraphs we will particularly concentrate on the problems concerning the second and third stages of the MSC, which were characterized by the most important and enigmatic palaeoenvironmental changes.

3.1. The onset of MSC and the Lower Evaporites

The main problems related to the second stage of the MSC concern 1) the diachronous vs. synchronous age of the beginning of Lower Evaporites deposition, 2) the unknown character of basinal equivalents of the Lower Evaporites, 3) the meaning of the apparently abrupt sea-level drop at the base of the Lower Evaporites and 4) the mechanisms driving the commonly observed aggradational stacking pattern of primary evaporites across different morphostructural settings.

As for point one, some models claim diachronous development related to a continuous evaporative sea-level fall, a mechanism bearing striking similarities with the forced regression concept (Butler et al., 1995). Biomagnetostratigraphic data from the Apennine foredeep support the hypothesis of a synchronous development of evaporite deposition at 5.96 Ma, even if, as discussed later, this transition is often characterized by severe deformations (Krijgsman et al., 1999a).

The second point is an old, fundamental problem of the MSC, that will be resolved only when the Messinian deposits buried under the deep Mediterranean basins are reached and cored (McKenzie, 1999). Preliminary data from the basinal successions of the Apennine foredeep (Manzi, 2001) has pointed out the occurrence, below the resedimented evaporite complex, of a totally barren, organic-rich and fine-grained unit. This unit does not occur in marginal settings below the primary evaporites and consequently represents a good candidate for being considered their deep-water equivalent.

The onset of the evaporitic stage is commonly associated to a sea-level fall whose amplitude is not easily determined (100 m according to Clauzon et al., 2001). The vertical facies change from euxinic shales to selenitic gypsum observed in the Vena del Gesso basin (Apennine foredeep) is apparently abrupt, even if no reliable palaeodepth indicators occur in the upper part of the pre-evaporitic deposits, due to the strongly reduced values of oxygen concentrations at the sea-bottom in this phase. Moreover, the Lower Evaporites are affected by severe post-depositional deformations (rotated blocks, thrust faults) emanating from a decollement surface at their base (Marabini and Vai, 1985). The upper part of the underlying euxinic shales is characterized by abundant shear planes connected to this surface.

The origin of such deformations has been recently related to large-scale sliding of gypsum units along its basal surface (Manzi, 2001; Roveri et al., 2003); primary gypsum was removed from its original position and transferred downslope following a phase of tectonic uplift affecting the whole Apennine thrust belt (Ricci Lucchi, 1986; Van der Meulen et al., 1999). According to the transfer extent along the palaeoslope, gypsum actually overlies sediments deposited at greater depth than those above which it originally precipitated. Rough, preliminary estimates based on the reconstructed palaeoslope indicate a possible vertical displacement in the order of 150–200 m (Manzi, 2001). Due to the strong lithologic contrast between euxinic shales and evaporites, large-scale sliding of gypsum could be a common phenomenon; for this reason we believe also that in many other examples the “abrupt” vertical transition from euxinic shales to primary evaporites could be overestimated.

The aggradational geometry of the Lower Evaporites is a common feature of all the Mediterranean geodynamic settings, and indicates a generalized subsidence or a sea-level rise; the latter hypothesis (Clauzon et al., 2001) would imply a larger water exchange with the Atlantic ocean, a point that seems in agreement with isotopic data (Flecker and Ellam, 1999). The vertical facies changes observed in the evaporitic cycles of the Apennine foredeep (upper cycles characterized by a increasing volume of shallowest-water facies within the individual cycles) indicate that a longer-term shallowing-upward trend is superposed upon small-scale cycles. This suggests a gradual upward reduction of the rate of subsidence and/or of sea-level rise.

3.2. The tectonic vs. eustatic origin of the intra-Messinian unconformity

The transition between the second and the third stage of the MSC is marked in all the marginal basins of the Mediterranean area by the development of a great erosional surface (the intra-Messinian unconformity), associated to a hiatus of variable amplitude. The origin of such an erosional surface is commonly related to an evaporative sea-level fall in excess of 1000 m, responsible for the subaerial exposure of continental margins and for a generalized fluvial drainage rejuvenation with the incision of deep canyons in front of larger rivers (Nile, Rhone; Clauzon, 1973; Ryan, 1978; Ryan and Cita, 1978; Clauzon, 1982) and leading to the desiccation of the deepest Mediterranean basins.

The origin of such an intra-Messinian unconformity is a key point; the possible superposition to the eustatic fall of a tectonic component related to a supra-regional deformational phase, has been commonly considered negligible. However, in many basins (Apennine foredeep, Tyrrhenian basins, Tertiary Piedmont Basin, Sicily, Eastern Mediterranean, Western Mediterranean) this erosional surface is clearly associated with an angular unconformity developed across different but tightly linked regional tectonic settings.

Evidence for tectonic activity during the late Tortonian–early Pliocene interval is known from many Mediterranean areas, suggesting an important phase of structural reorganization along the Africa–Eurasia collisional margin (Meulenkamp et al., 2000; Garcés et al., 2001). Complex deep-crustal or mantle processes occurring between 6.3 and 4.8 My (i.e. during the Messinian salinity crisis) have been envisaged to explain the abrupt changes in magma composition of the Alboràn volcanic belt and the large uplift (1 km) of the African–Iberian margin required to close the marine connections between the Atlantic and the Mediterranean (Duggen et al., 2003). A similar amplitude uplift, related to a Messinian phase of extensional tectonics and crustal thinning, has been envisaged for the Eastern Pyrenees and Gulf of Lion margin (Lewis et al., 2000; Mauffret et al., 2001). However, the significance and the role of such large-scale tectonic processes among the factors controlling the Messinian salinity crisis and its record in the sedimentary successions have not been clearly defined yet. This argument holds a great interest that could lead to the definition of a palaeogeographic scenario different from the one commonly envisaged.

Unraveling the genetic meaning of such supra-regional unconformity is a very important issue, also taking into consideration the concomitant dramatic palaeogeographic changes leading to the formation of several non-marine basins (Lago Mare), more or less interconnected.

3.3. The importance of resedimented evaporites

As previously described, only the marginal basins of the Apennine foredeep were characterized by the deposition of in situ primary evaporites. Moreover, due to subsequent tectonic deformation, these basins were rarely preserved. As a matter of fact, most of the Messinian evaporitic rocks occurring in the Apennine foredeep are actually clastic deposits derived from the dismantling of in situ evaporites and resedimented through gravitative processes into relatively deep waters, below the wave base (Parea and Ricci Lucchi, 1972; Ricci Lucchi, 1973; Manzi, 2001; Roveri et al., 2001; Fig. 4). According to the physical stratigraphic framework proposed by Roveri et al. (1998, 2001), these deposits postdate the main evaporitic phase (corresponding to the Lower Evaporites of Spain and Sicily); as a consequence they conceptually belong to the post-evaporitic stage of the MSC.

We believe that resedimented evaporites are a far more common feature than usually envisaged in many other depositional settings of the Mediterranean area. Their correct recognition and the definition of their time-relationships with primary evaporitic deposits could represent a fundamental step for a better comprehension of the Messinian palaeogeography and environmental changes. Good examples of clastic evaporites resedimented in subaqueous settings through gravitative processes are being increasingly reported from the outcropping successions of the Tertiary Piedmont Basin, Tuscany, Sicily (Ciminna, Eraclea Minoa and Belice basins), Cyprus, and also from the buried offshore succession of the Valencia trough (Martinez del Olmo, 1996, 2000), pointing to a widespread phenomenon whose origin should be thoroughly investigated. Of course, the recognition of subaqueously deposited clastic evaporites associated with the intra-Messinian unconformity, casts some doubts on the true extent of the Mediterranean deep desiccation as commonly envisaged.

3.4. The onset of the Lago Mare event

During the latest Messinian interval (<300 ky), known as post-evaporitic, Upper Evaporites or Lago Mare stage, the Mediterranean basin is commonly thought to have been disconnected from the Atlantic Ocean. During this stage, a sudden switch to non-marine conditions is observed throughout the Mediterranean area, leading to the widespread development of freshwater to brackish, endorheic basins, with hydrological budgets and climatic conditions strongly diversified, up to the sudden reopening of marine connections at the base of the Pliocene. Causes, modality and timing of such dramatic palaeogeographic change are still obscure, the capture of Paratethyan non-marine waters by a lowered Mediterranean base level being the most commonly accepted explanation.

According to Clauzon et al. (2001) the salinity crisis evolved with different modalities in the different geotectonic settings (Sicily, Apennine foredeep, Andalusia, northwestern Mediterranean). During this stage, after the complete closure of ocean connections, the total desiccation and evaporite deposition in the deepest Mediterranean basins is envisaged, with the exception of the Apennine foredeep. The ‘Apennine anomaly’, its non desiccated character, is commonly explained by the particular palaeoclimatic and structural context, that would have led to its premature isolation from the other Mediterranean basins, and the persistence of a deep-water, non marine basin.

The articulation of Mediterranean basins in this interval is mirrored by a great lithostratigraphic variability; the inadequacy of common stratigraphic tools and criteria for reliable and detailed long-distance correlations is responsible for low-resolution palaeogeographic reconstructions and does not allow an understanding of the mechanisms, velocity and role of the factors controlling environmental changes in the different realms. Moreover, the distribution of deposits recording this important event is limited to the deepest parts of the Mediterranean basins and this fact, as previously stated, represents an obvious obstacle to our reconstructions. The time interval corresponding to this event is a 90 ky hiatus (the last Messinian gap) in the Messinian chronology (Krijgsman et al., 1999a,b), due to the fact that such reconstruction has been based on the sedimentary record of marginal basins.

3.5. The closure of the ‘Messinian gap’

As stated above, one of the main Messinian problems derives from the difficulty in defining the relationships between marginal and basinal depositional settings when tracing the intra-Messinian unconformity downslope (e.g. Sorbas basin; Riding et al., 2000; Fortuin et al., 2000). In the Apennine foredeep basin this exercise, carried out through the integration of surface and subsurface data, led to the recognition of a sedimentary unit deposited in topographic lows during

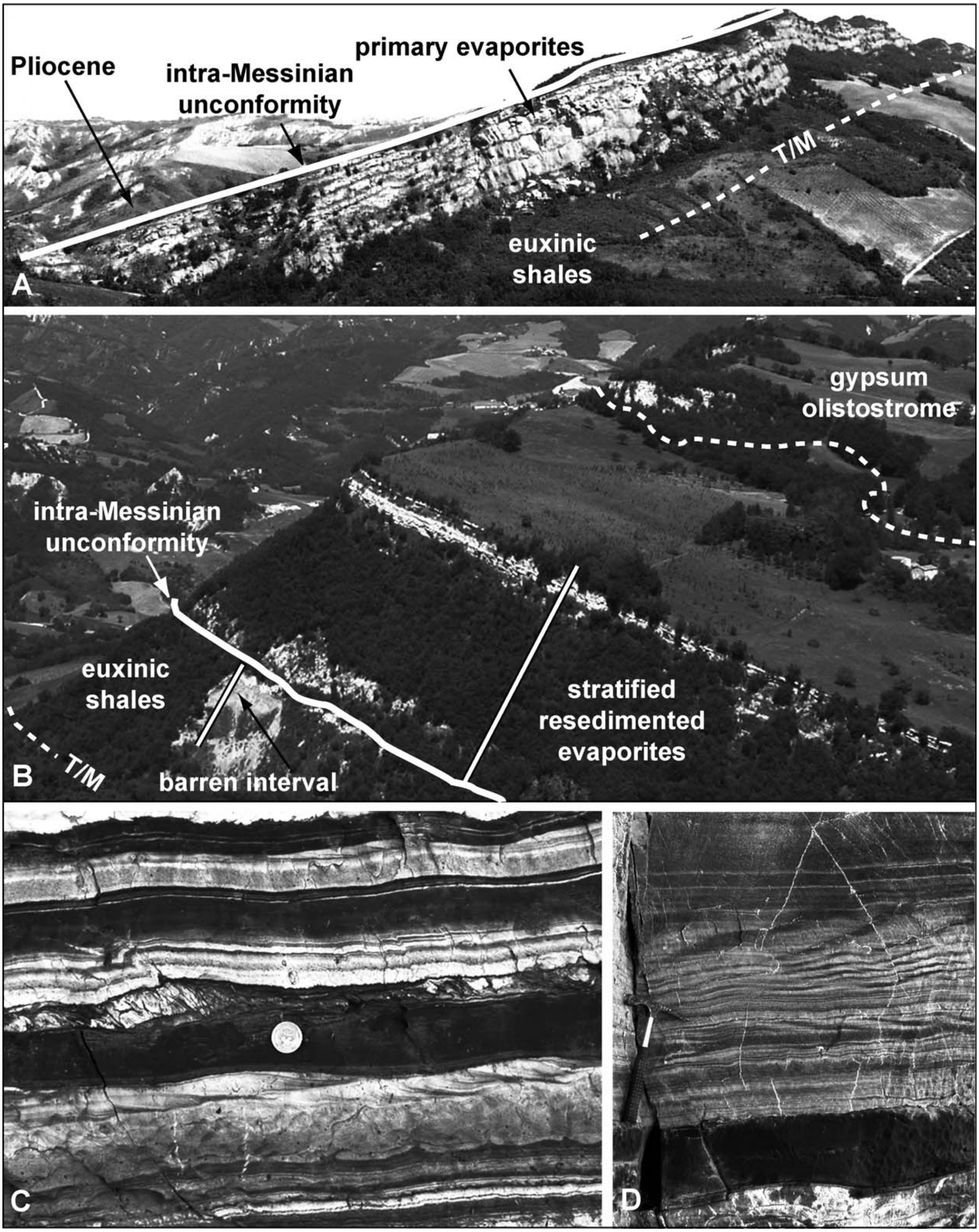

Fig. 4. Comparison between the marginal shallow-water primary evaporites of the Vena del Gesso basin (Aa) and the deeper-water resedimented evaporites of the eastern Romagna–northern Marche area (B). Note the cyclic alternation (C and D) made up by black, organic-rich shales and white, low-density gypsum turbidites. Erosional bases, load casts, normal gradation, traction (C) and traction-plus-fallout (D) structures are commonly found in the resedimented evaporitic strata.

the subaerial exposure of basin margins, thus bridging the last Messinian gap (Manzi, 2001); in the other basinal settings this time interval is still virtually unknown (Fig. 5).

The gap in Messinian stratigraphy between 5.50 and ~5.60 Ma related to the subaerial unconformity is a common feature of Mediterranean successions and is usually related to the desiccation of deeper basins and

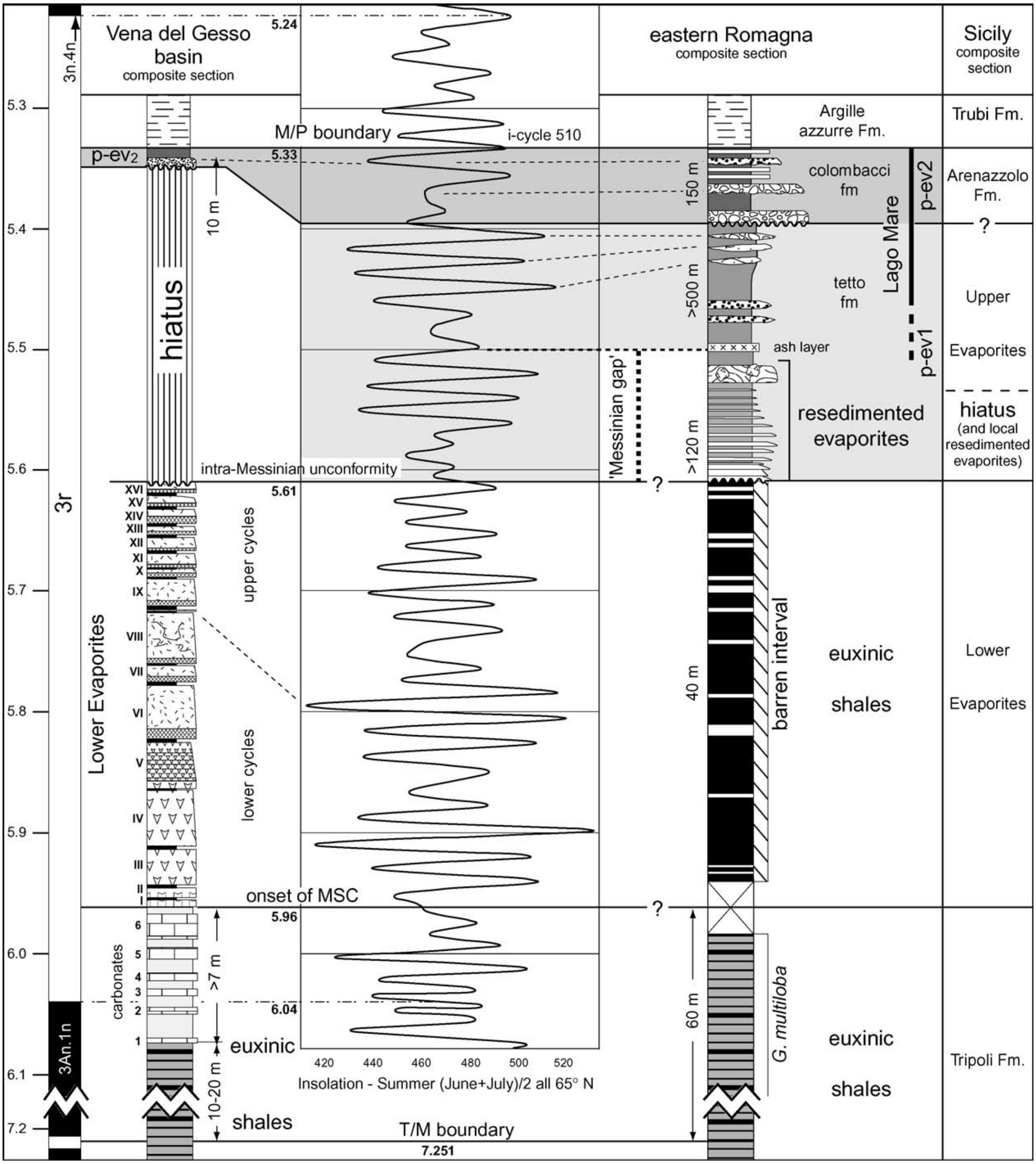

Fig. 5. Correlation between marginal and basinal succession of the Apennine foredeep and the insolation curve, showing the possible astronomical forcing of Messinian events in its different evolutionary stages. In basinal settings, barren euxinic shales correlate with marginal primary evaporites; the last 'Messinian gap' is closed by the basal p-ev$_1$ unit with resedimented evaporites. Note also the tentative correlation between Lago Mare deposits of the Apennine foredeep and Sicily.

associated isostatic rebound processes (Krijgsman et al., 1999b). In the Apennine foredeep this gap only occurs above uplifted areas; in deeper, subsiding basins the record is continuous and the hiatus corresponds to a syntectonic unit made up of resedimented gypsum and terrigenous sediments deposited in a series of basins rapidly evolving toward hyposaline conditions (unit p-ev_1 of Fig. 5).

3.6. High-resolution stratigraphic and palaeogeographic framework of the Lago Mare stage

Unfortunately, due to its short duration (<300 ky), non-marine character and lack of magnetic reversals, a Mediterranean-scale, high-resolution stratigraphic framework for the last Messinian evolutionary stage, allowing detailed long-distance correlations, is not available yet; this makes the palaeoenvironmental reconstructions highly speculative and also the structural evolution of the different geodynamic settings can be only roughly defined and compared. In our opinion, the establishment of a detailed stratigraphy of this stage should be given high priority; this challenge requires a common effort of the Messinian scientific community in the next few years.

In this respect, good preliminary indications coming from the studies carried out in the last few years, suggest the existence of striking similarities in the late Messinian successions of the Apennine foredeep, TPB, Tyrrhenian–Tuscany and Sicilian basins and some other Mediterranean basins. This fact encourages the efforts to achieve a higher stratigraphic resolution through the integration of different methodologies applied to the analysis of sedimentary cyclicity, whose eventual astronomic periodicities would provide a powerful key to unravel the complex geological history of this interval.

The studies carried out in the last few years by different research groups on the Messinian sedimentary and tectonic evolution of the Apennine foredeep (Iaccarino and Papani, 1980; Gelati et al., 1987; Bassetti et al., 1994; Roveri et al., 1998, 2001) have led to the reconstruction of a detailed physical–stratigraphic framework (Figs. 2 and 5).

The Lago Mare successions of all these basins are typically bipartite, with two units separated by an abrupt vertical facies change, corresponding to a regional-scale unconformity. This is a well recognizable but usually overlooked characteristic of the Lago Mare succession.

An example is given by the p-ev_1 and p-ev_2 units of the Apennine foredeep, that in our opinion could be tentatively correlated with respectively the Upper Evaporites and Arenazzolo Fms. of Sicily (see Fig. 5). The lower unit is made up of basal clastic evaporites (also comprising large-scale collapse products), usually overlain by mainly terrigenous deposits showing a coarsening and shallowing upward trend. Only the upper part of this unit, which is locally characterized by the deposition of shallow-water, sabkha-like evaporites (Sicily), shows a fairly well-developed cyclical lithological pattern.

The upper unit seems to be much more homogeneous at a Mediterranean scale, being characterized by a well-developed high-frequency cyclical pattern superimposed upon an overall transgressive trend. These two characteristics are widely recognized and could represent good criteria for high-resolution correlations across the different Mediterranean basins; 3 main cycles have been traced from shallow to deep-water successions of the Apennine foredeep (Roveri et al., 1998; Ricci Lucchi et al., 2002), 4 cycles have been recognized in the uppermost Messinian deposits at Cyprus (Rouchy et al., 2001), 3–4 cycles in the latest Messinian Nile Delta deposits (Abu-Madi Fm., Dalla et al., 1997; Fig. 6), 4 cycles in the fluvio-deltaic deposits of the TPB (Ghibaudo et al., 1985); in the Corvillo basin (Sicily) and 3 to 4 cycles are reported from a thick terrigenous Lago Mare succession unconformably overlying the Lower Evaporites (Keogh and Butler, 1999). All these cycles, with the exception of Cyprus where they are expressed by the periodic development of palaeosoils (Rouchy et al., 2001), appear related to the periodic activation of lacustrine fluvio-deltaic systems and consist of a regular alternation of coarse and fine-grained facies.

Assuming that this cyclicity, like in the pre-evaporitic and evaporitic stages, has a climatic origin driven by precession, the upper unit could span a time interval of 60–80 ky immediately preceding the return to fully marine conditions at the base of the Pliocene (Fig. 5).

The widespread diffusion of the Lago Mare deposits across the Mediterranean, the common transgressive trend of their uppermost part, the occasional marine incursions reported from different basins (Snel et al., 2001), considerations based upon isotopic composition of the typical faunal associations (Keogh and Butler, 1999), suggest the possibility that during this stage, or at least in its final part, a water body, much larger than normally envisaged, was present in the Mediterranean. We believe that, in order to get a better understanding of the latest Messinian events, all these important but scattered pieces of information, which have severe palaeogeographic implications, need first to be tightly framed in

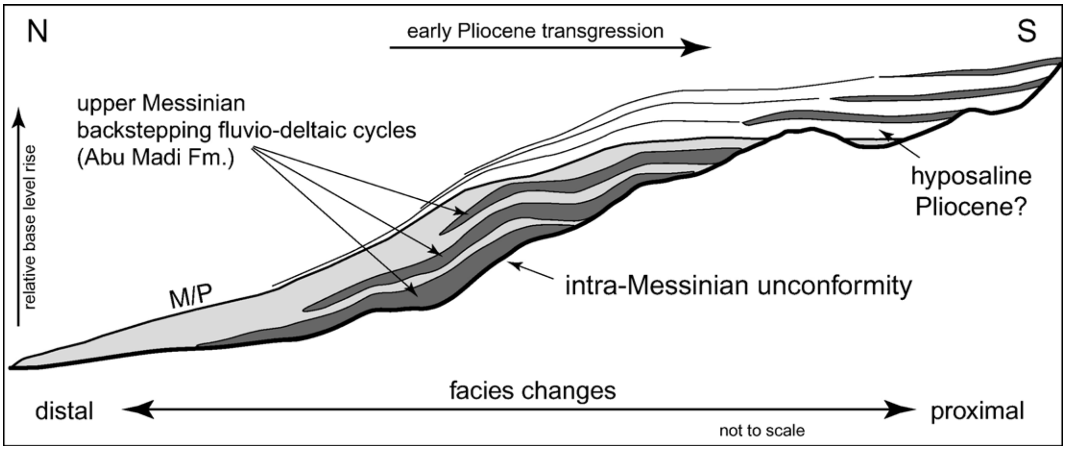

Fig. 6. Simplified stratigraphic scheme of the Nile delta succession showing the typical backstepping stacking pattern of the upper Messinian Lago Mare sequence (p-ev$_2$; modified after Dalla et al., 1997). According to this model, hyposaline deposits could be preserved during the early Pliocene in marginal settings (see text).

a highly detailed stratigraphic scheme, essentially based on a physical–stratigraphic approach.

3.7. The Mio/Pliocene boundary

The Mio/Pliocene boundary, marking the sudden return to fully marine conditions, appears to be synchronous along a W–E transect in the southern Mediterranean, as shown by the detailed study of ODP cores and land sections in Sicily and Calabria (Iaccarino et al., 1999), where the basal Pliocene has a deep-water character. The same degree of stratigraphic detail is actually lacking in the other basins; for this reason it cannot be ruled out that, due to the high resolution potential of early Pliocene integrated stratigraphy, detailed studies could point out a different scenario, according to local and regional morphostructural settings.

One important point is that lowest Zanclean deposits have never been observed above sedimentary successions older than the uppermost Messinian. In other words, where lowest MPl1 sediments are found they are invariably associated with latest Messinian Lago Mare deposits, as part of a longer-term transgressive sequence.

As stated above, this fact and the widespread distribution of Lago Mare deposits, as well as their commonly observed transgressive trend, suggest the existence at the end of the Messinian of a large Mediterranean non-marine water body and a higher degree of connection among the different sub-basins. According to this scenario, the Miocene/Pliocene transition would better be explained by a sudden hydrologic change associated with a bathymetric change somewhat less pronounced than usually envisaged.

This raises some fundamental questions: when did the marine waters actually start to refill the Mediterranean? What's the meaning of the transgressive trend observed in the uppermost Lago Mare deposits? Is it related to tectonic causes, i.e. a generalized subsidence acceleration throughout the Mediterranean, to a gradual, episodic, climatically modulated refill of marine waters from the Atlantic, or to a combination of the two?

Whatever the answers to such questions that obviously need further studies, a little delay in the transition to marine condition has been observed in the eastern part of the southern Mediterranean transect. One to three of the basal Pliocene precessional cycles are apparently missing (Iaccarino et al., 1999). This hiatus, in our opinion, could be only apparent; we envisage that, due to the particular refill mechanisms and the complex topography of the Mediterranean basin, the Lago Mare could have persisted longer in some distal areas. This implies that some Lago Mare deposits could have an early Pliocene age.

4. Conclusions

The generally poorly defined relationships between marginal and basinal successions, the lack of a high-resolution stratigraphic framework for the Lago Mare stage and the poor consideration for the role of Mediterranean-scale tectonic deformations in controlling the main stratigraphic events, limit our full understanding of the MSC. Many problems arise from the "one section" approach, largely diffused in the past;

good data and observations, if isolated or not well framed into their regional geological context, are potentially misleading. In this respect, regional-scale studies have an obviously higher significance and hopefully will be carried out in the future.

Such an attempt has been carried out in the Apennine foredeep basin in the last years. It is well known that the Apennine perspective of the Messinian salinity crisis is different from the current paradigm and raises some important questions about the deep desiccation theory. We believe that, far from being an 'anomaly', as usually considered, the Messinian sedimentary succession of the Apennine foredeep offers a unique opportunity to better understand the timing and modes of the salinity crisis; for this reason it should be taken into greater consideration for its implications at a Mediterranean scale.

The main implications of the Apennine foredeep record for Messinian events concern 1) the closure of the last Messinian gap, with the recognition in basinal settings of a unit recording the switch to non-marine conditions, 2) the establishment of a preliminary high-resolution stratigraphy for the Lago Mare stage and 3) the assessment of the importance of tectonics in controlling Messinian events. As for the latter point, the deposition of Lower Evaporites and the onset of the Lago Mare event in the Apennine foredeep, that occurred during the final stage of a long-lasting uplift phase affecting the whole thrust belt, are well framed within the tectonic history of the region and do not merely appear as the result of the superposition of far distant, 'out of sequence' events.

The comparison with adjacent basins (Tyrrhenian Sea, Tertiary Piedmont Basin and Sicily), but also with the eastern (Cyprus, Nile Delta) and western (Spain) Mediterranean basins, suggests a similar strong tectonic overprint on the Messinian sedimentary evolution, especially as far as the Lago Mare stage is concerned. These observations indicate a large-scale tectonic reorganization of the Mediterranean area, whose role in determining the salinity crisis should be addressed by future researches. For a better understanding of this important issue, a high-resolution stratigraphy of the Lago Mare stage is sorely needed. Preliminary observations suggest that the high-frequency lithological cyclicity observed in several fluvio-deltaic successions might be controlled by precession and this could represent a fundamental tool for long-distance correlations and palaeoenvironmental studies.

The fascinating Deep Desiccation Model of the Mediterranean (Hsü et al., 1972) is questioned by the serious stratigraphic, tectonic and palaeoenvironmental problems that have arisen in the last years with the progressive increase of our knowledge; it is possible that in the future the answers to the questions raised will necessarily imply the formulation of a new paradigm.

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