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R.C.M.N.S. Interim Colloquium
"The Messinian salinity crisis revisited-II"
Parma (Italy), 7th - 9th September 2006

THE RECORD OF MESSINIAN EVENTS IN THE NORTHERN APENNINES FOREDEEP BASINS

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front cover:
panoramic view of the Vena del Gesso (Lower Evaporites), west side of the Santerno valley at Borgo Tossignano.

Foreword

These notes represent an upgraded version of the Field Excursion Guidebook prepared for the International Geological Congress held in Florence in 2004 (Roveri et al., 2004).

This version retains the general scheme of the 2004 field excursion; the programme has been slightly shortened to be adapted to a three days field trip.

On the other hand, some parts have been expanded or modified to incorporate new data and ideas collected and developed in the last two years by our group. In particular, the new facies model for primary evaporites, their correlation with deep-water counterparts as well as the boreholes data are unpublished data which will be the subject of oral presentations during this Colloquium.

Many new data derive or benefit from the researches carried out within the 2003-2005 PRIN-Cofin Project "The late Messinian Lago Mare event: high-resolution stratigraphy, tectonic and climatic control on high-frequency paleoenvironmental changes related to the final stage of the Messinian Salinity Crisis of the Mediterranean area" (scientific coordinator M. Roveri) funded by MIUR (Italian Ministry of University and Research). All the researchers involved in the Project are here acknowledged for the positive scientific discussions which helped to improve this Guidebook.

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The record of Messinian events in the Northern Apennines foredeep basins

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The record of Messinian events in the Northern Apennines foredeep basins

Roveri M., Lugli S., Manzi V.

INTRODUCTION

Why a field trip on the Messinian salinity crisis in the Romagna Apennines? We believe there are many good reasons indeed. We are going to introduce in these brief notes only some of the most relevant arguments, hoping the participant at the end of the field trip would have completed their own list with many others.

Firstly, although not adequately recognized by the scientific community, the Northern Apennines keep one of the most complete memory of the large amplitude paleoenvironmental changes that affected the Mediterranean area during the Messinian age (i.e. the time interval lasting about 2 million years between 7.251 and 5.33 My) and usually referred to as the "Messinian salinity crisis" (MSC).

Moreover, in few other places of the Mediterranean area, like Sicily, the fascinating history of the Messinian salinity crisis has left so many indelible signs on both the physical and cultural landscape like in the Northern Apennines area extending from Bologna to Rimini.

Gypsum rocks formed during Messinian events constitute an almost continuous and prominent belt (the so called *Vena del Gesso*) along the Apennines foothills. This rocky belt is characterized by peculiar morphology and ecosystems and has been attractive for man use since the antiquity, providing the base for an important social, artistic and economic development. The large-size, twinned crystal variety of gypsum, known as *selenite*, has been used as building stone since Roman times, and may be even before. A short walk downtown in Bologna may quickly account for this; the basement of many Middle Age buildings, included the famous towers, as well as the ancient walls (IV-VIII century AD) are made up of squared selenite blocks (Fig. 1), many of which were recycled from the Roman theatre. Selenite derived from quarries located in the foothills of Bologna and more to the east in the Santerno and Lamone valleys (western Romagna). Also from Messinian gypsum-bearing successions, but dominated by the microcrystalline, thin-laminated variety of gypsum known as *balatino*, derives the sulphur mineral extensively exploited till the early 60ties in many small quarries and mines of eastern Romagna, i.e. from the Rabbi to the Marecchia valleys.

The great economic value of gypsum rocks stimulated early geological studies, at least since the beginning of the 18th century. As recently pointed out by Marabini and Vai (2003), Luigi Ferdinando Marsili, an outstanding scientist of the *Istituto delle Scienze* of Bologna, carried out around 1717 what can well be considered the first modern stratigraphic study at a regional scale. In an unpublished manuscript, partially reproduced in Marabini and Vai (2003), he describes in great detail the vertical superposition of gypsum and shale beds in the sulphur mines of eastern Romagna, suggesting correlations and recognizing their close relationships with the selenite rocks occurring to the west and pointing out the occurrence of a continuous gypsum belt from Bologna to Ancona. Enclosed to the Marsili's manuscript, is what can be regarded to as the first geologic map in the world (Fig. 2): an accurate representation of outcropping gypsum bodies connecting and accounting for a series of aligned sulphur mines in the Forlì and Cesena foothills. During the second and third day of this field trip we will run over the Marsili's outcrops again, this standing in witness of the still unchanged interest of this area through the time. The distinct spatial distribution of selenite and sulphur mines, as already recognized by Marsili, mirrors two different stratigraphic and geologic settings developed during the Messinian in the Romagna Apennines. Roughly speaking, selenite formed through primary precipitation of gypsum from dense brines in shallow-water settings, while extensive sulphur mineralization is related to the diagenetic transformation of clastic gypsum deposits, accumulated in somewhat deeper waters, into limestones. In the field trip area these

Fig. 1 - Remnants of the IV-VIII century AD selenite walls, preserved and recycled in the Ghisilardi Fava Palace at Bologna

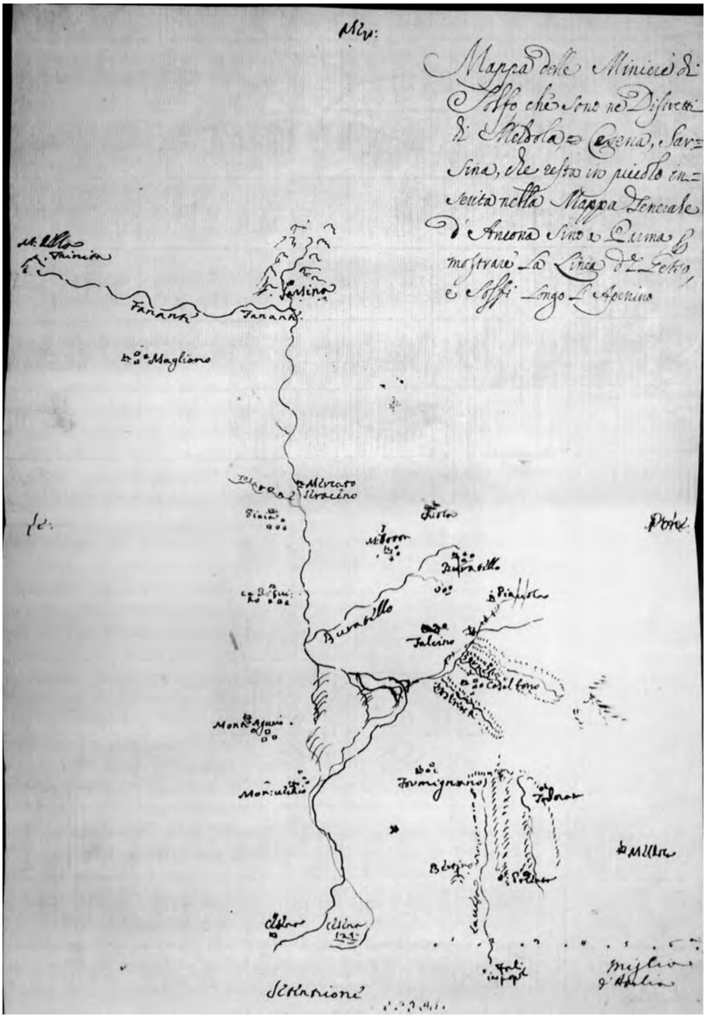


Fig. 2 – The 1717 geological map by L.F. Marsili (from Marabini and Vai, 2003).

depositional settings are separated by a tectonic feature oblique to the main Apennine structural trend.

Three centuries after the pioneer work of Marsili, the Messinian outcrops of this area still offer the unique opportunity to observe a complete sedimentary succession developed in both shallow- and deep-water settings, thus allowing the reconstruction of their genetic and stratigraphic relationships.

In fact, contrary to the Apennines, Messinian successions preserved on Mediterranean continental margins are always reduced and incomplete, being more or less deeply cut by a subaerial erosional surface developed in the time span during which, according to the popular *"deep desiccated basin"* model (Hsü et al., 1972), the Mediterranean basin almost completely dried up. The lacking part of the story is recorded by those huge salt accumulations buried in the deepest Mediterranean basins whose true nature and stratigraphy still wait to be fully unravelled.

The complete and expanded record of the Apennine will allow us to focus on several, still open questions concerning the different evolutionary stages of the Messinian salinity crisis and, in particular, on a usually overlooked topic, i.e. the role of tectonics in controlling Messinian stratigraphic patterns.

Concluding these introductory notes, we hope the field trip participants will find it a stimulating chance for thorough discussion. For them as well as for those who will use this guidebook to make the field trip by their own, we hope they would appreciate the strong character of this land, of its people and products, formed and developed through the time, in a continuous interlacing of geology, culture and history of science.

Messinian events chronology and modalities

The comprehension of the different aspects related to the MSC is a long-lived issue in the scientific debate. Many important questions remain unanswered. The paleogeography and paleoclimatology of the Mediterranean area, the physical and chemical structure of the water column through the Messinian and the possibly active role of biota during the crisis are still poorly understood. The great advance in stratigraphic resolution obtained in the last years after the adoption of astronomical calibrations and physical-stratigraphic concepts, has certainly improved our general knowledge and chances. The Messinian stage is now well time-constrained; the Messinian GSSP has been defined in the Oued Akrech section (Morocco) and an age of 7.251 Ma has been assigned to the Tortonian-Messinian boundary (Hilgen et al., 2000); the top of the Messinian corresponds to the Zanclean GSSP, defined in the Eraclea Minoa section (Sicily) with an age of 5.33 Ma (Van Couvering et al., 2000). Different views actually exist about the chronology of Messinian events, leading to evolutionary models (Fig. 3) implying the synchronous (Krijgsman et al., 1999a,b) vs slightly (Rouchy and Caruso, 2006) or fully diachronous (Butler et al., 1995; Clauzon et al., 1996; Riding et al., 1998) onset of the MSC in marginal and basinal settings. These scenarios of the MSC, implying very different stratigraphic approaches, but otherwise all retaining the fundamental concepts of the deep

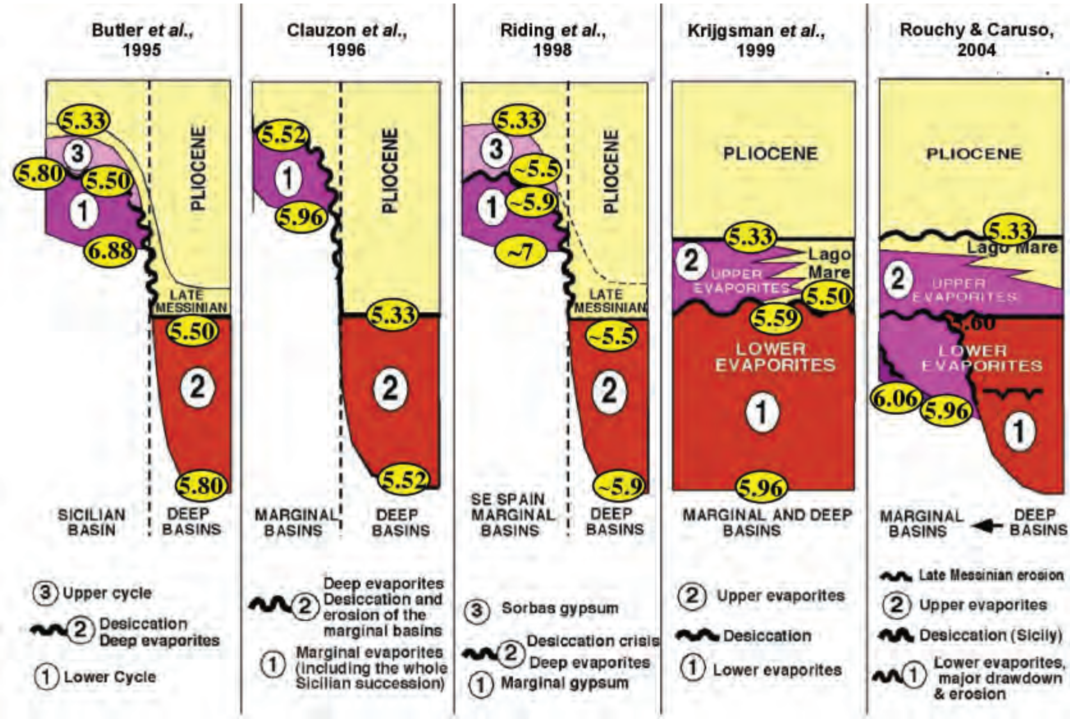


Fig. 3 – The different stratigraphic and evolutionary models for the Messinian salinity crisis (modified after Rouchy and Caruso 2006).

desiccated basin model, have been recently summarized by Rouchy and Caruso (2006).

According to Krijgsman et al. (1999a,b; Fig. 4), which proposed the synchronous development of the MSC throughout the Mediterranean and a relatively deep-water character of the Lower Evaporites, a classical three-fold subdivision of the Messinian stage can be envisaged: 1) pre-evaporitic (7.251-5.96 Ma), characterized by the common occurrence in deep-water settings of organic-rich, laminated deposits, which record sea-bottom low-oxygen conditions related to a progressive reduction of water circulation within the Mediterranean; 2) Lower Evaporites (5.96-~5.61 Ma), the first episode of primary evaporites precipitation in marginal basins ended by a dramatic sea-level drop with consequent deep erosion along continental margins and salt deposition in almost desiccated deep basin; 3) Upper Evaporites, or post-evaporitic Lago Mare stage (~5.61-5.33 Ma), showing the widespread development of non-marine deposits with Mollusk, Ostracod and Dinoflagellate assemblages of Paratethyan affinity (Lago Mare biofacies; Ruggieri, 1967; Iaccarino & Bossio, 1999); this stage records the progressive refill of the Mediterranean basin(s) after the acme of the crisis. The dramatic sea-level drop was also responsible for changing the drainage pattern in the peri-Mediterranean area, leading to the partial refill of desiccated basins with fresh to oligohaline waters of Paratethyan origin. The end of the MSC is represented by the sudden, catastrophic return to fully marine conditions at the base of the Pliocene (Iaccarino et al., 1999). This age model has been made possible by the well-developed cyclical arrangement of Messinian deposits which also allowed refining the astronomic polarity time scale (APTS) for the Neogene. However the APTS still shows a gap lasting 90 ka at the base of the post-evaporitic stage (Krijgsman et al., 1999a-b), related to the deep desiccation of the Mediterranean. According to such model, the duration of the various Messinian 'phases' can thus be estimated: 1.2 Ma for the pre-evaporitic, 0.35 Ma for the evaporitic and 0.35 Ma for the post-evaporitic phase. This age-model fits quite well with the two-step MSC proposed by Clauzon et al. (1996), which however implies a diachronous deposition of evaporites across peripheral and deep basins. This model includes Sicily in the peripheral basins, thus implying a complete repetition of the evaporitic suite (lower gypsum, salt and upper gypsum) separated by a subaerial erosional surface (Messinian erosional surface – MES) deeply cutting the continental margins and developing during the acme of the MSC, when the Mediterranean sea-level dropped more than 1000 meters and shallow-water evaporite precipitation was shifted toward the deepest parts. The MES in Sicily is thus placed at the boundary between Upper Evaporites (Pasquasia gypsum) and Arenazzolo.

According to Riding et al. (1998) and Braga et al. (2006) which call for a MES underlying the Yesares gypsum in Sorbas basin, the development of the MSC was diachronous but evaporite deposition started first in deepest basins and only subsequently affected peripheral ones.

In their model for Sicily, Butler et al. (1995) pointed out the important role played by the tectonically-induced topography in controlling the areal and time distribution of evaporitic bodies during the MSC, and proposed a fully diachronous onset of Lower Evaporite deposition, starting from around 6.8 Ma, across an array of wedge-top basins driven by a progressive relative sea-level fall up to the main desiccation of deepest Mediterranean basins. According to this model, the MES developed on top of progressively exposed subbasins. The subsequent gradual refill of the Mediterranean was responsible for the overall transgressive deposition above the

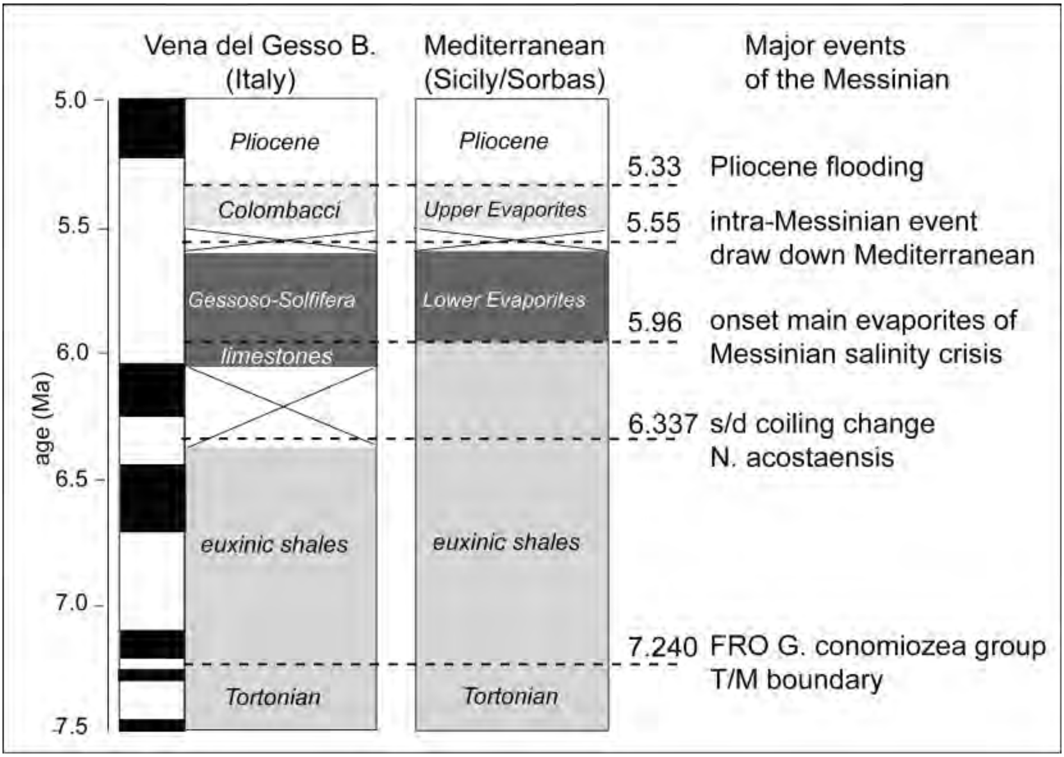


Fig. 4 – Chronology of Messinian events according to Krijgsman et al. (1999a-b).

MES of the Upper Evaporites and Lagomare deposits.

Rouchy and Caruso (2004, 2006) suggest a classic two-step model for the MSC, with lower and upper evaporites separated by the MES, but calling for a slightly diachronous onset of Lower Evaporites starting from around 6.14 Ma according to the basin topography. In this model Sicily is considered an equivalent of deep Mediterranean basins, even not so deep due to its geodynamic setting. Interestingly, some of these models (Butler et al., 1995, Clauzon et al., 1996) imply, even not clearly explicitated, the occurrence in deeper basins of non-evaporitic successions coeval to Lower Evaporites formed in shallower settings.

The Apennine foredeep record of Messinian events

All the above described scenarios of the MSC, despite the different age-models proposed, imply the discontinuous character of Messinian successions due to the polyphased development of the MES. We can tentatively group all these shallow to deep-water successions into a **Mediterranean-type** modality of the MSC.

The Apennine foredeep, which can be considered, like Sicily, a peripheral basins, actually offers to the discussion a different point of view, as its depocenters are characterized by continuous relatively deep-water successions lacking any evidence for desiccation during the whole MSC; such successions represent what we call the **Apenninic-type** modality of the MSC.

It has long been recognized that the sedimentary record of Messinian events of the Apennine foredeep basin does not support the deep-desiccation model. No evidence for the desiccation has been ever found; which is usually explained by the particular paleoclimatic and structural context that would have led to its premature isolation from the other Mediterranean basins, and to the persistence of a deep-water, non marine basin. For this reason the Apennine foredeep has always been considered an anomaly within the general picture and, consequently, often overlooked in the Messinian debate.

The "anomaly" of the Apennine foredeep is that, due to its geodynamic setting and post-Messinian evolution, both modalities actually occur in outcrop and that the stratigraphic and genetic relationships among them can be clearly defined. In other words, all along the Apennine foredeep system a true Mediterranean-type succession can be recognized in shallow, marginal sub-basins, while an Apenninic-type developed in deeper ones. Based on a careful review of Messinian stratigraphy carried out in the last ten years by several research groups through the integration of surface and subsurface data and the use of a physical stratigraphic approach (Gelati et al., 1987; Rossi et al., 2002;

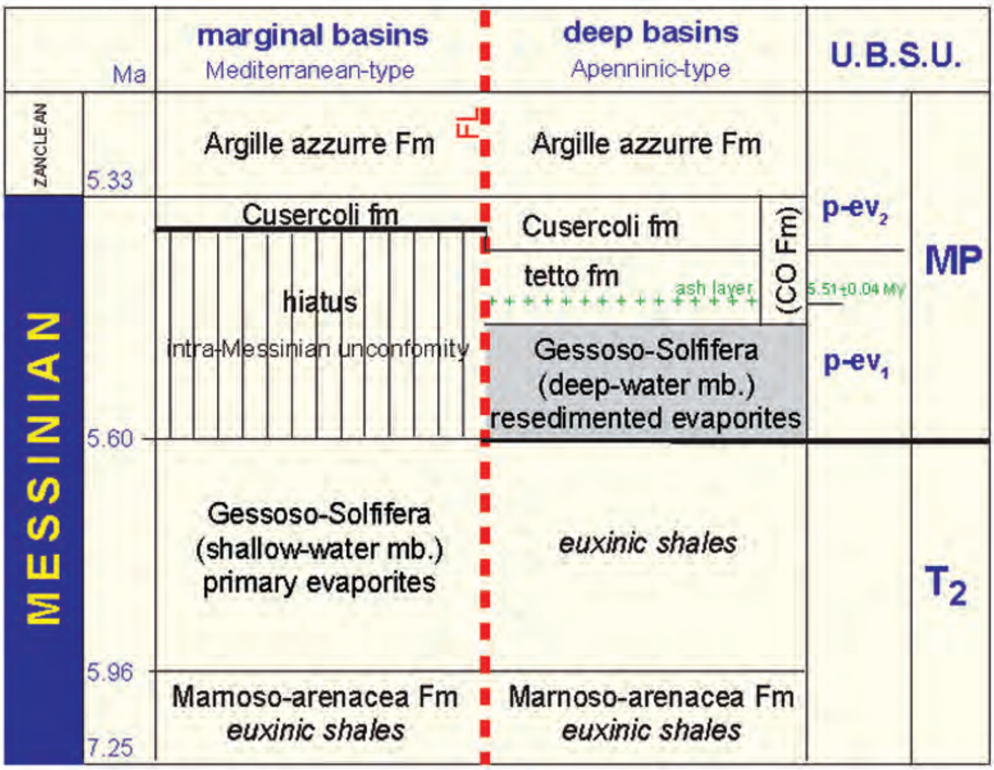


Fig. 5 – Chronology of Messinian events in the Apennine foredeep. CO, Colombacci Fm., FL, Forlì Line (modified from Roveri et al., 2003).

Bassetti et al., 1994; Bassetti, 2000; Roveri et al., 1998; Roveri et al., 2001; Roveri et al., 2003; Manzi et al., 2005, Roveri et al., 2005, Roveri & Manzi, 2006), a geologic and stratigraphic model for the Apennine foredeep Messinian deposits has been reconstructed. Such model is summarized in Figures 5 and 6 and assumes the development of pre-evaporitic and evaporitic stages synchronous and with the same modalities of the other Mediterranean basins. Primary evaporites were deposited only in shallow thrust-top basins whose formation date back to the upper Tortonian, when the ensuing propagation of the Apennine compressive front led to the progressive fragmentation of a larger and deeper foredeep basin. The end of evaporite deposition is coincident with a paroxysmal acme of a regional tectonic phase determining the uplift and emergence of the Apennine chain and the concomitant migration of the foredeep depocentres toward the foreland. The intra-Messinian unconformity, a perfect equivalent of the erosional surface cutting Lower Evaporites throughout the Mediterranean, is associated to an angular discordance and hence it is strictly related to a regional tectonic uplift leading to the dismantling and resedimentation of Lower Evaporites in deep basins through large-scale mass-wasting and gravity flows in shelf and slope areas. Tracing down basin the intra-Messinian unconformity is a problem solved placing its correlative conformity at the base of the resedimented evaporites complex (Roveri et al., 1998, 2001, Manzi et al., 2005; see topic 5). This unit accumulated in topographic lows during the subaerial exposure of uplifted basin margins, thus allowing to bridge the last Messinian gap (Roveri & Manzi, 2006). Based on its physical characters, a high-resolution stratigraphic framework for the post-evaporitic successions (discontinuities of different hierarchical rank, stacking pattern and cyclic organization of depositional system, key horizons) has been reconstructed. A second,

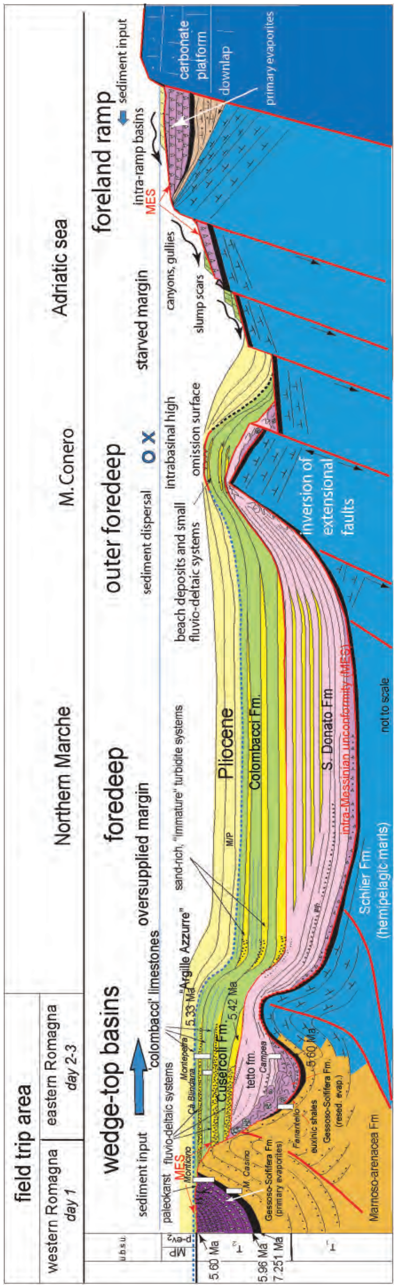


Fig. 6 – The geologic-stratigraphic model for the Messinian deposits of the Apennine foredeep (from Roveri et al., 2005).

younger regional unconformity splits the post-evaporitic Lago Mare deposits into two units; the lower one (p-ev$_1$), only occurring in structural depressions, is composed by resedimented evaporites at the base, overlain by a siliciclastic coarsening and shallowing-upward succession; the upper unit (p-ev$_2$), made up of coarser-grained deposits, has a general transgressive trend and seals all the previously uplifted tectonic structures, generalized subsidence and/or a base level rise, heralding the Zanclean flooding.

The relatively small field trip area has the great advantage to sum-up all the elements of the larger-scale stratigraphic model. This area corresponds to a series of wedge-top basins (Fig. 6) characterized by different absolute paleobathymetry and subsidence rates. The two main foredeep Messinian depocenters are presently buried below the Po Plain and crop out in Southern Marche and Abruzzi (Laga Basin) and their sedimentary succession can be easily correlated to that developed in wedge-top basins through very distinctive physical elements. The distinction between p-ev$_1$ and p-ev$_2$ unit is substantiated by the clear upward transition from high-efficiency to low-efficiency turbidite systems. Moreover, an ash layer of regional extent is an excellent key-bed in the p-ev$_1$ unit. The first day of the field-trip will be spent in a marginal, Mediterranean-type context, the second and third day in a Apenninic-type one. This will give the participants the chance to contrast and correlate the two stratigraphies and, consequently, to assess some basic Messinian items.

Regional geologic setting

The Romagna Apennines, extending from the Sillaro valley to the west, to the Marecchia valley to the east (Fig. 7), is part of the Northern Apennines, a ENE-verging arc, characterized by compression along the external front and extension in the inner western part (i.e. the Tyrrhenian area).

The Apennine chain formed since the late Eocene as a post-collisional fold and thrust belt in the more general context of convergence between the African and Eurasian plates. The Romagna Apennine is characterized by an outcropping succession of early Miocene to Pleistocene siliciclastic deposits, overlying buried Mesozoic to Cenozoic carbonates. This sedimentary succession represents the infill of a foredeep basin system actively migrating to the northeast since the Oligocene (Ricci Lucchi, 1986) and formed above the Adria plate in what is defined the Umbria-Marche domain, the lowest structural unit of the Apennine orogenic wedge (for an updated review of the Apennine geology, see Vai and Martini, 2001).

To the west of the Sillaro valley, this unit is covered by the Ligurian nappe (Fig. 7), a chaotic complex of Jurassic to Eocene deep-marine sediments and ophiolithic slabs (Castellarin and Pini, 1989), formed as an accretionary wedge during the late Cretaceous Alpine compressional phases and thrust over the Adria plate, since the Oligocene (Kligfield, 1979; Boccaletti et al., 1990).

The uppermost structural unit of the Romagna Apennine consists of the Langhian to Messinian Marnoso-arenacea Fm, a turbiditic complex more than 3000 m thick (Ricci Lucchi, 1975, 1981), detached from its carbonate basement along a basal thrust, and showing a deformational style dominated by fault propagation folds (Capozzi et al., 1991). Seismic data show that the outermost front of the Apennine thrust belt lies in the subsurface of the Po Plain (Castellarin et al., 1986, Castellarin, 2001), where several ramp anticlines are buried by a thick succession of marine Plio-Pleistocene deposits. The Romagna Apenninic is split into two sectors (western and eastern) by the Forlì line (FL, Fig. 7), a complex fault zone oblique to the Apenninic trend. The two sectors defined by this feature has a different structural arrangement at surface; the foothills of

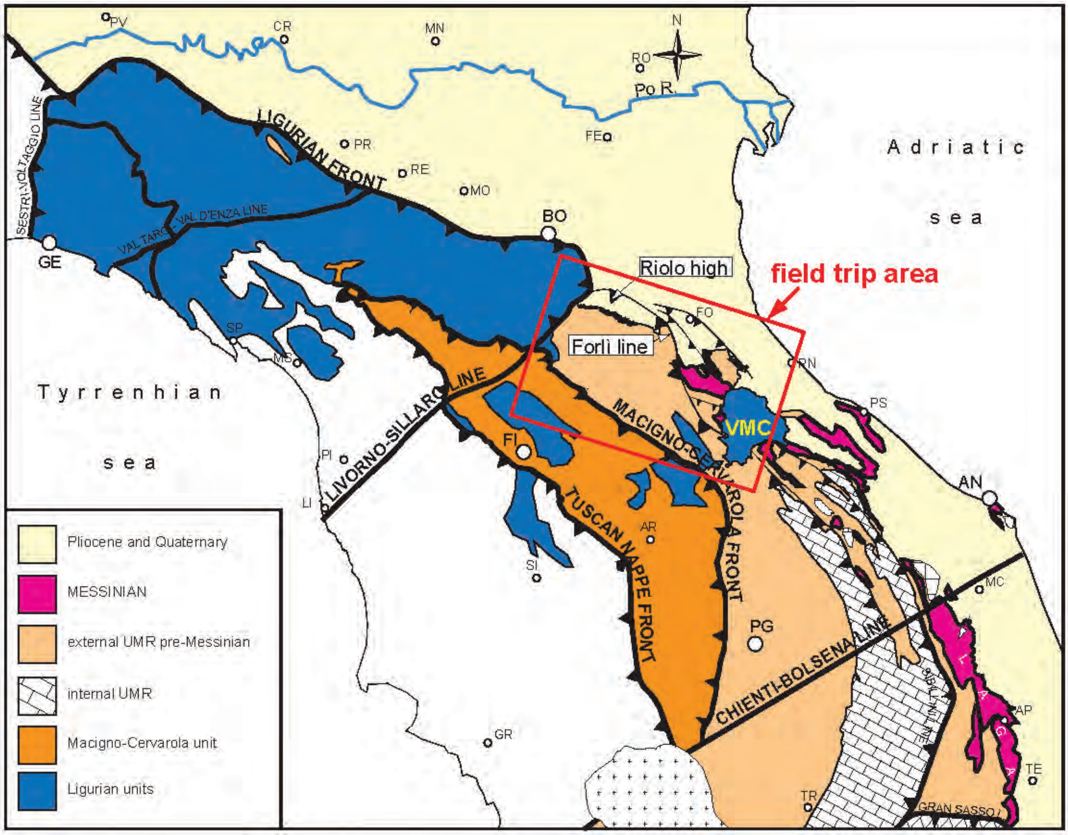


Fig. 7 – Simplified structural map of the Northern Apennines.

the western sector shows a gentle N-NE dipping monocline of Messinian to Pleistocene deposits resting above the Marnoso-arenacea Fm., while the same succession is deformated by several thrust-related anticlines with Apenninic trend in the eastern one. The Forlì line played a primary role in the geological evolution of the area at least since the late Tortonian (Ricci Lucchi, 1986; Roveri et al., 2002).

In a NW-SE cross-section, flattened at the Miocene/Pliocene boundary (Fig. 8), dramatic facies and thickness changes within the Messinian succession occur across structural high related to the Forlì line. Such changes finally correspond to the two above mentioned different Messinian stratigraphies whose comparison and correlation is the main aim of the field trip.

The lithostratigraphy of the Langhian to Pliocene sedimentary succession of the Romagna Apennines consists of four formations (Vai, 1988; Fig. 9):

i) the ***Marnoso-arenacea Fm*** (MA, Langhian-Messinian), made up of deep-water siliciclastic turbidites, derived from the Alps and, subordinately, from the central Apennines, is a huge clastic wedge, up to 3000 meters thick, filling a large foredeep basin elongated in a NW-SE direction, whose depocenter migrated

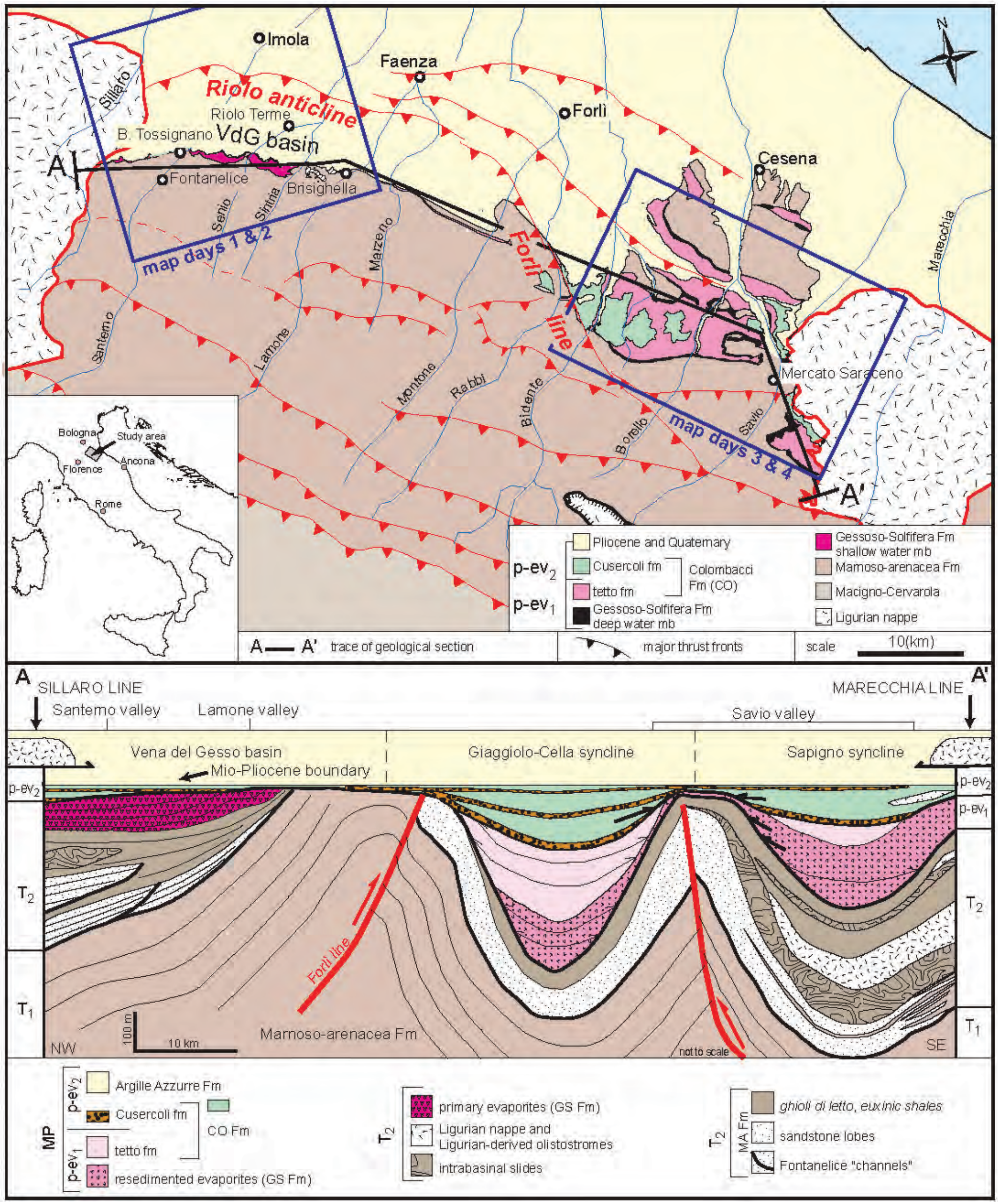


Fig. 8 – Simplified geologic map (above) and cross-section (below) of the Romagna Apennines. The cross-section is flattened at the Miocene/Pliocene boundary to better illustrate the great facies and thickness changes characterizing the Messinian succession across main structural elements (modified from Roveri et al., 2003).

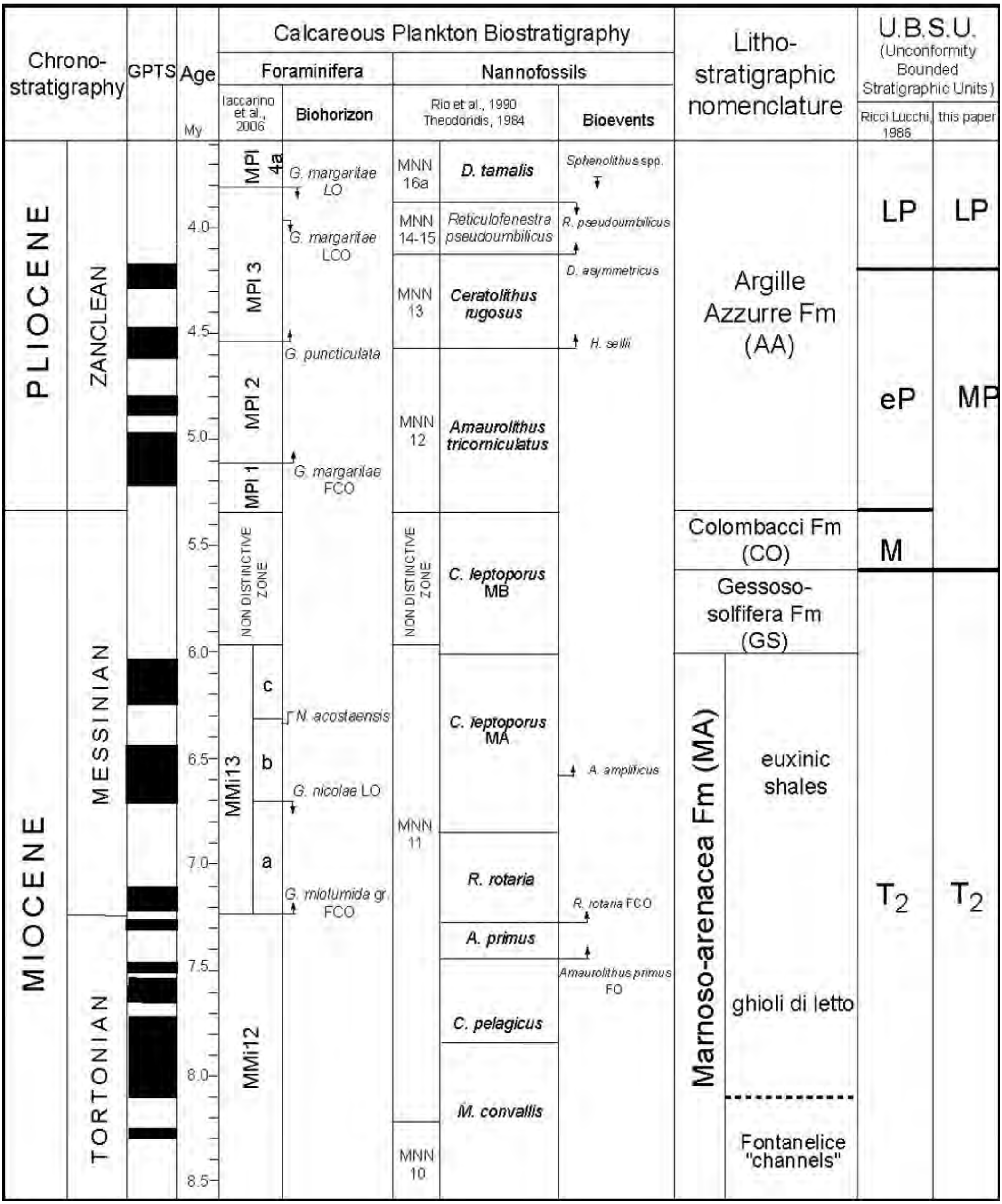


Fig. 9 – Stratigraphic scheme of the Apennine foredeep Tortonian to early Pliocene time interval. Note that lithostratigraphy refers to marginal successions, i.e. those characterized by deposition of primary, shallow-water evaporites during the main evaporative event.

toward the NE following the propagation of the compressional front. Toward the top thick and laterally continuous turbiditic lobes are replaced by slope mudstones (*ghioli di letto*) containing minor turbiditic sandstone and chaotic bodies; this is in turn overlain by a unit straddling the Tortonian-Messinian boundary and made up of finely interbedded organic and diatomite-rich laminites and mudstones, informally named *euxinic shales* (upper Tortonian-lower Messinian. Like the coeval Tripoli Fm in Sicily and Spain such deposits show a well developed cyclical pattern and record the paleoceanographic changes associated to the ensuing MSC.

The euxinic shales span a 1.5 Ma time interval, characterized by well-defined bio- and magnetostratigraphic events; their calibration with astronomical cyclicity allowed a detailed chronostratigraphy to be established (Krijgsman et al., 1999a,b; Vai, 1997).

ii) the ***Gessoso-solfifera Fm*** (GS, Messinian), is made up of both primary and clastic, resedimented evaporites with interbedded organic-rich shales, deposited during the evaporitic and post-evaporitic stages of the MSC;

iii) the ***Colombacci Fm*** (CO, Upper Messinian), consisting of mainly siliciclastic sediments derived from Apenninic sources, was deposited in both shallow and deep brackish or freshwater basins developed during the Lago Mare phase of the MSC. Based on a sharp vertical facies change and to remark the important differences in terms of lithology, evolutionary trends and palaeoenvironmental meaning, Roveri et al. (1998) proposed to replace and subdivide the Colombacci Fm. into two informal units, the **Tetto fm.** (below) and the **Cusercoli fm.** (above). The Cusercoli fm is characterized in marginal basins by coarser-grained lithology and by the occurrence of thin lacustrine micritic limestone beds (*colombacci* limestones).

iv) the ***Argille Azzurre Fm*** (AA, Lower Pliocene), is made up of relatively deep marine mudstones deposited in a series of more or less connected wedge top basins locally encasing fan-delta conglomerates and shelf to perched-basin turbiditic sandstone bodies and small, isolated carbonate platforms deposits (“***Spungone”***).

From a physical-stratigraphic point of view, the Tortonian to early Pliocene succession has been subdivided into three large-scale synthems separated by regional-scale unconformities recording important phases of tectonic deformation of the Apennine orogenic wedge. From the base to the top they are the T_2 (Tortonian-Messinian) synthem, the *MP* (Messinian-Pliocene), and *LP* (Lower Pliocene) synthems (Roveri et al., 1998; Roveri et al., 2001; Roveri et al., 2003). These large-scale units only slightly differ from those defined by Ricci Lucchi (1986) and can be further subdivided into lower rank U.B.S.U. delimited by minor unconformities and flooding surfaces (Roveri et al., 1998), still having a regional significance. The more reliable key events for long-distance correlations are the Tortonian/Messinian boundary (7.251 My), the Miocene/Pliocene boundary (5.33 My) and a widespread ash-layer within the post-evaporitic Lago Mare deposits, which holds a radiometric age of 5.51$\pm$0.04 Ma (Odin et al., 1997). Messinian deposits fall in the T_2 (pre- and evaporitic stage) and MP (pos-evaporitic stage) synthems. Hereafter the successions developing in the western and eastern sectors will be described separately.

Western sector

The western area extends from the Sillaro valley to the West up to the Bidente valley to the East. These physiographic boundaries correspond to two important tectonic alignments, as previously reported. The Tortonian to Pliocene succession of this sector is particularly well exposed (Figs. 10, 11) along the Santerno valley which will be visited during the first day of the field trip. The second day will be devoted to important details from outstanding outcrops along the Sintria and Lamone valleys.

T_2 synthem (late Tortonian-Messinian)

The base of the T_2 synthem corresponds to an abrupt facies change within the Marnoso-arenacea Fm. In previous stages turbiditic deposits are characterized by tabular geometries and high lateral continuity, suggesting deposition by unconfined currents flowing parallel to basin axis (i.e. in a NW-SE direction) in a nearly flat sea-bottom.

In the T_2 synthem, sandstone bodies are coarser-grained and show a lower lateral continuity; the abundance of basal scours, cut and fill and water-escape structures suggest deposition from flows strongly affected by topographic constriction (Mutti et al., 1999). This facies change has been usually related to a regional phase of tectonic uplift and basin narrowing (Ricci Lucchi, 1981, 1986). In the western sector, this is well represented by the Fontanelice “channels”, two turbiditic sandstone bodies confined within large-scale erosional depressions and separated by a mudstone horizon (Ricci Lucchi, 1968, 1969, 1975, 1981). The larger and thicker upper channelized body is encased in upper Tortonian mudstones (*ghioli di letto*). In a section almost normal to paleocurrents, the basal erosional surface deepens toward the SW and a spectacular NE-ward onlap of sandstone strata can be observed. The sedimentary fill is composite, with basal conglomerate bars (pebble composition indicating an Alpine source, Ricci Lucchi, 1969), and at least two distinct sandstone bodies in the upper part. The upper Fontanelice system is overlain by a mudstone unit with interbedded smaller-size turbiditic sandstone bodies, forming an overall thinning-upward sequence. In the Santerno river section the mudstone unit contains a slump body, up to 50

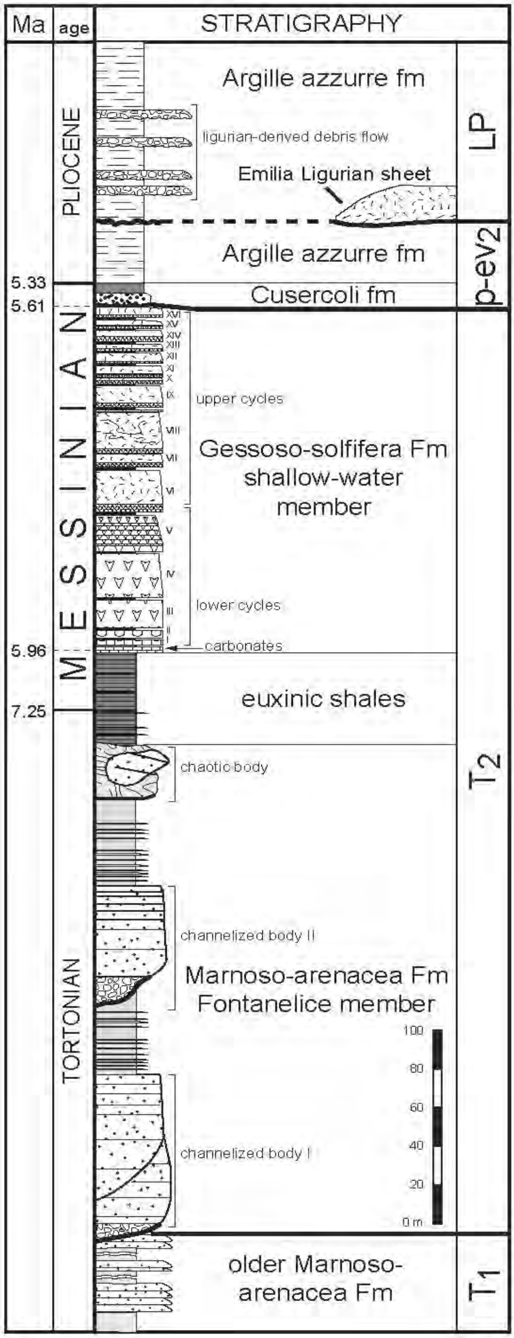


Fig. 10 – Stratigraghy of the western sector.

m thick, characterized by sandstone olistoliths, derived by minor turbiditic bodies. In turn, the mudstone unit is capped by a 40 m thick horizon of organic-rich *euxinic shales*. The euxinic shales, characterized by a well-developed lithologic cyclicity, have been studied in detail for bio-magneto- and cyclostratigraphic reconstructions in several sections (Monte del Casino, Monte Tondo, Monticino, Fig. 12; Vigliotti, 1988; Negri and Vigliotti, 1997; Krijgsman et al., 1999a; Vai, 1997).

The topmost cycles are characterized by the development of thin carbonate layers. The T_2 synthem is topped by the relatively shallow-water evaporites of the Gessoso-solfifera Formation, forming a continuous belt, up to 150 m thick

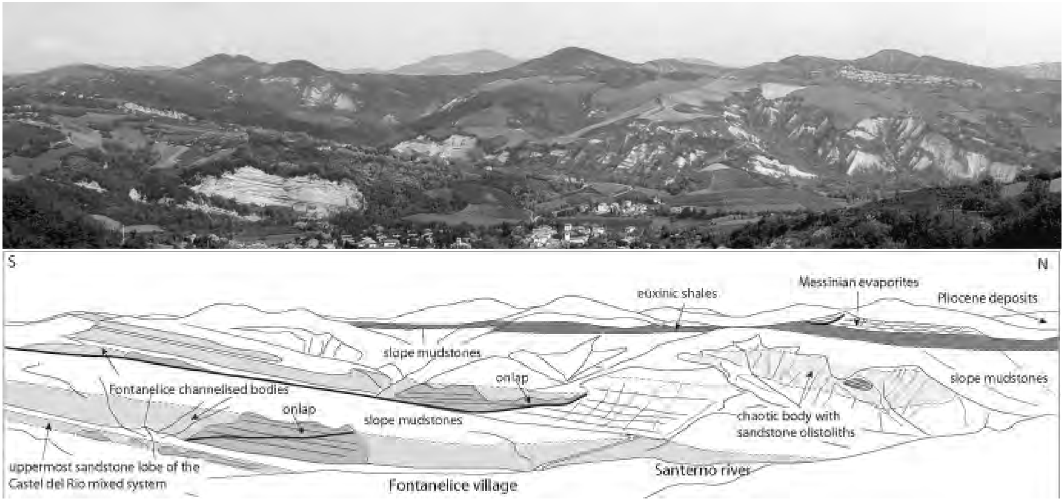


Fig. 11 – Panoramic view of the stratigraphic succession cropping out in the Santerno valley (see stop 1.1).

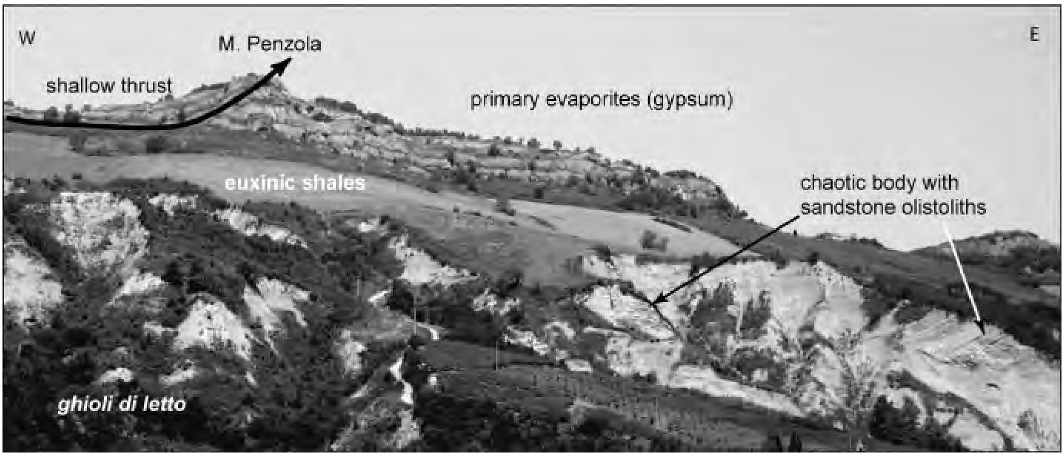


Fig. 12 – Panoramic view of the late Tortonian-Messinian succession in the Santerno valley (stop 1.1). Note the chaotic horizon below the euxinic shales and the deformed gypsum unit on top.

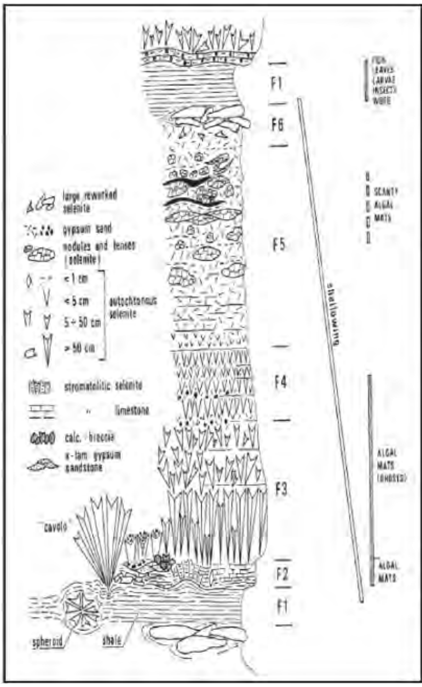
Fig. 13– Massive selenite (facies F3-EF3) in a block of the Garisenda tower of Bologna.

from the Sillaro to the Lamone valleys. Gypsum deposits have a strong cyclical organization, as first recognized by Vai and Ricci Lucchi, (1977) which counted up to 16 small-scale, decametric-thick, shallowing-upward cycles recording the progressive evaporation of moderately deep lagoons.

These cycles have been later interpreted as controlled by periodic changes of orbital parameters (Vai, 1997; Krijgsman et al., 1999b).

The only available facies model for the Messinian Lower Evaporites in the Mediterranean is the ideal cycle" proposed by Vai and Ricci Lucchi (1977) for the Vena del Gesso basin. A revisitation of these sulfates and a comparison with other basins in the Mediterranean (Sicily, Tuscany, Calabria, Crete and Spain) suggest a new facies model for their deposition (Figs 14, 15).

The Vena del Gesso evaporites consist of 16 cycles separated by organic-rich shales. The first two cycles are thinner and consist of giant selenite crystals (up to more than 2 m-tall). The 3[rd], 4[th] and 5[th] cycles consist of the thicker beds



Vai & Ricci Lucchi, 1977	This work
	EF8 - Gypsarenite* EF7 - Gypsrudite*
F6 - Chaotic and flat-laying selenite	EF6 - Displacive selenite
F5 - Nodular and lenticular selenite	EF5 - Branching selenite
F4 - Banded selenite	EF4 - Banded selenite
F3 - Massive selenite	EF3 - Massive selenite
F2 - Cal-gypsum algal laminate (stromatolite), breccia and sandstone	EF2 - Limestone, massive, laminated (stromatolite), breccia
F1 - Bituminous shale	EF1 - Bituminous shale

*other facies not included in the ideal cycles of Vai and Ricci Lucchi (1977)

Fig. 14 – The ideal depositional cycle of the Vena del Gesso evaporites.

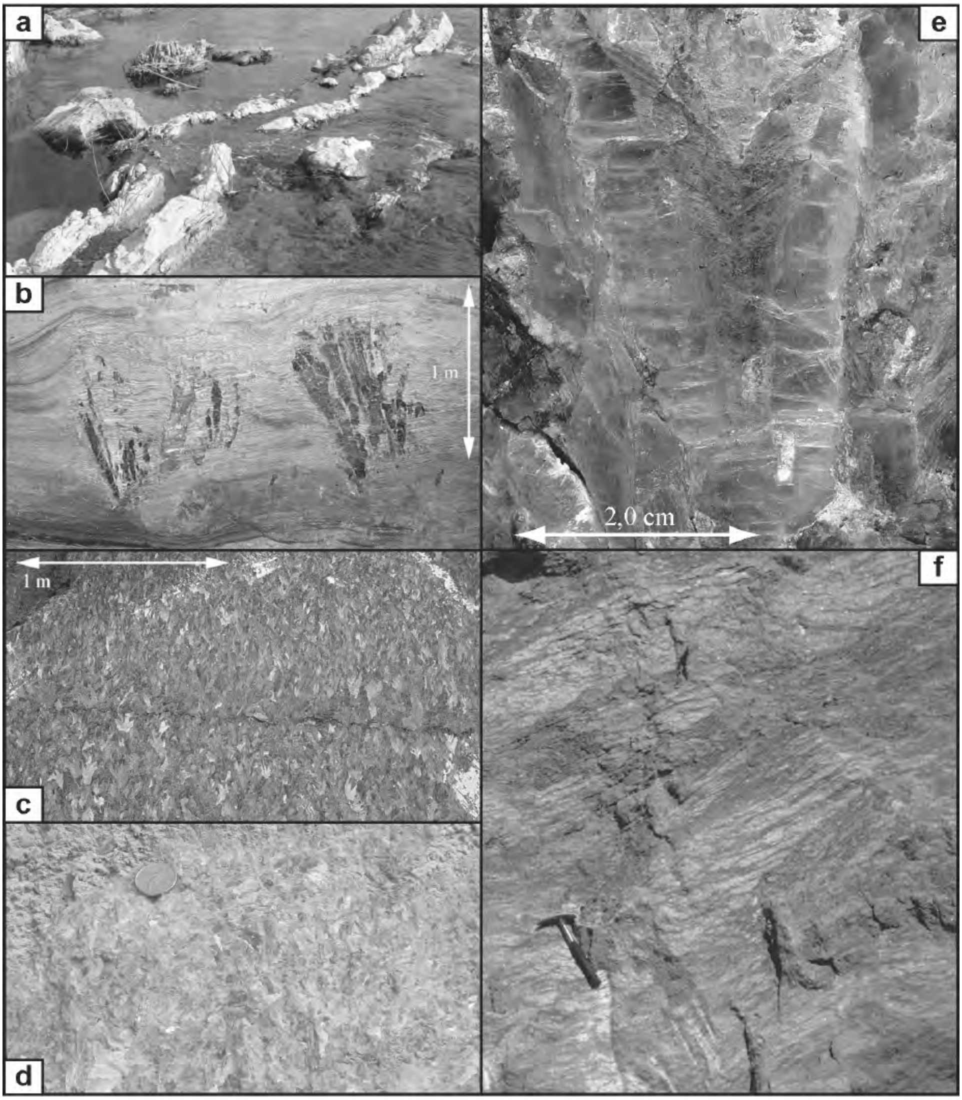


Fig. 15. Vena del Gesso evaporites. A) Santerno river bed. Slumped stromatolitic limestone (F2) and limestone breccia ("calcare di base") embedded in the topmost pre-evaporite mudstones; b) Rio Sgarba Quarry, Borgo Tossignano. GS, 2nd cycle: euxinic shales (below, F1), and calc-gypsum laminites (above) enclosing meter-sized "palisade"-type crystals of stromatolite-bearing gypsum (F2); c) Montebello Quarry, Marecchia Valley. GS, 3rd cycle: vertically grown swallow-tail selenite crystals (F3), a marked dissolution surface is visible at center; d) Monte Tondo Quarry, 6th cycle, branching selenite (EF 5): close-up of a cluster of selenite crystals that grew laterally, grouped in branches; coin is 2,5 cm across; e). "Swallow-tail" selenite crystal (F3): dark core of crystal contains spaghetti-like algal filaments; the core is surrounded by a transparent portion which did not trap the filaments during its growth; f) Monte Tondo Quarry, 7th cycle, branching selenite (EF 5): branches (white) projecting outward into a gypsiferous carbonate-marly matrix (dark gray) these structures are part of subaqueous selenite supercones but no obvious conical shape may be recognized: only the branch terminations against the host matrix are visible.

(up to 30 m) of vertically-grown massive selenite grading into banded selenite (EF3 and EF4 facies, respectively). The upper part of the section (from the 6th to the 15th cycle) consists of thinner beds (average thickness 15 m) with cycles showing a basal massive and banded selenite, followed by nodular and lenticular selenite (F5 of Vai and Ricci Lucchi, 1977). This nodular and lenticular selenite was considered as a clastic deposit (gypsarenite) that was subaerially exposed and developed sabkha features, such as anhydrite nodules that were then rehydrated back to form gypsum. The detailed study of this facies shows no clastic and supratidal features, but reveals that clusters of selenite crystals grew laterally, grouped in branches projecting outward from a nucleation zone into a gypsiferous carbonate-marly matrix. We interpret this facies as an extreme evolution of subaqueous selenite supercone structures described in the Sorbas basin (Spain) by Dronkert (1985). In the case no obvious conical shape may be recognized, but only the branch terminations against the host matrix are visible, we proposed the use of the term “branching selenite” (EF 5) to emphasize the aspect that this crystals grew in organized structures. The reason why the conical shape may be difficult to recognize is that cones are widely spaced and very broad so that the nucleation points can not be visible. Another factor influencing the conical shape recognition is that the matrix surrounding the cones may consist mostly of gypsum and the cone structures are not sticking outside the outcrop as in the case of the Sorbas basin, where the matrix consists of a easily erodible mudstone.

The stacking pattern of these facies appears to describe a complete small scale sedimentary cycle made up of both regressive and transgressive phases: respectevely EF 3 facies represents the initial fall, EF 4 the lowstand, EF 5 the transgression and, finally, EF 1 the highstand:

1) initial evaporite precipitation at relatively low salinity produced the vertical massive selenite in a relatively deep setting (large massive selenite, EF 3); the crystals are always covered by supersaturated brine;

2) continuous evaporation and drawdown produced relatively higher salinity conditions and growth of sulfate crystals was controlled by oscillating brine level (banded selenite, EF 4);

3) a general brine level rise and dilution introduced carbonate material in the system; selenite crystals growth was characterized by formation of large supercones branching laterally (branching selenite, EF 5); growth of cones and branches was controlled both by brine level, spacing of cones, and amount and composition of matrix surrounding the cones (fine-grained gypsum, carbonate and/or marls); local gypsum reworking may form cause the accumulation of clastic facies between growing selenite branches;

4) flooding by undersaturated water stops gypsum precipitation and deposits argillaceous sediments (EF 1, Northern Apennines) and/or carbonates (EF 2, Sicily);

Evaporite geochemistry indicates that the development of the branching selenite (EF 5) occurs in correspondence of major oceanic influxes in a general setting dominated by solutions strongly modified by continental waters (Lugli et al., in press). The predominance of continental water is suggested by the organic matter content of the shale and gypsum showing mostly terrestrial elements and by the Sr isotope ratios which are lower than expected from gypsum precipitated from the Messinian seawater.

Clastic deposits (gypsrudite EF 7 and gypsarenites EF 8) are limited to the uppermost part of the succession (16th cycle) in the Monte Tondo section and may be present locally throughout the upper part of the Lower Evaporite sections. Large selenite crystals laying flat at the top of the evaporite cycles were interpreted as fallen vertically-grown swallow-tail reworked by currents (F 6 of Vai and Ricci Lucchi, 1977), but consist mostly of lenticular crystals which grew displacively into the shale (EF 6, displacive selenite). The crystals probably grew into the mud (EF 1) from downward seeping brines after saturation was reached again at the beginning of the next evaporite cycle.

MP synthem (Messinian-Pliocene)

An angular unconformity is associated to the erosional surface (Vai, 1988) marking the T_2/MP boundary, clearly indicating its tectonic nature. This surface preserves spectacular evidences of subaerial exposure (karstic dykes filled by continental deposits rich in mammal fauna were found in the Monticino section, near Brisighella; Costa et al., 1986; De Giuli et al., 1988). The erosion associated to the MP unconformity deepens toward the southeastern end of this sector (Marzeno valley), where the evaporitic and pre-evaporitic Messinian deposits are completely missing.

Deposits of this synthem belonging to the Colombacci Fm and Argille Azzurre Fm are very thin and separated by the Miocene/Pliocene boundary. The uppermost Messinian Colombacci Fm consists mainly of grey to varicolored clays containing a hypohaline faunal assemblage (*Melanopsis spp*., *Limnocardium spp*.). Small lenses of sandstone and pebbly sandstone and calcareous conglomerate locally occur. At places, a white micritic layer is also found; locally named *colombaccio* it gives the name to the formation. The Miocene/Pliocene boundary is marked by a characteristic dark, organic-rich horizon, whose origin is still poorly understood. Through the boundary the typical abrupt transition from non marine to relatively deep-marine waters is observed; such change is witnessed by the rich and diversified planktonic assemblages of the basal Pliocene. Lower Pliocene deposits of this synthem consist of a thin unit (only 2 m thick in the Santerno section, according to Colalongo et al., 1982 and Cremonini et al., 1969) of deep-marine mudstones draping the whole area. Detailed biostratigraphic studies carried out in the Santerno and Monticino sections show that a large hiatus is associated to the regional unconformity (LP) marking the top of the MP synthem. The LP unconformity occurs in the upper part of the Gilbert chron and is related to the advance of the Apennine compressive front. This event is recorded in the Sillaro-Santerno area by the sudden appearance within deep marine clays of coarse, chaotic deposits (pebbly mudstones and debris flow) derived from the Ligurian units (Cremonini and Ricci Lucchi, 1982). The low thickness of the early Pliocene deposits of the MP synthem in this area is essentially related to the locally strong erosion associated to the LP unconformity.

Deformation of primary evaporites

The gypsum unit of this sector is characterized by extensional and compressional deformations (Marabini and Vai, 1985), with rotated blocks and shallow thrust faults, partially affecting also the top of the underlying *euxinic shales*. Most of these deformations emanate from a detachment surface in the upper part of the *euxinic shales* (Marabini and Vai, 1985) and are sealed by MP deposits of the Colombacci Fm.

From W to E the deformation shows different characteristics. To the west (Santerno-Sillaro sector), the gypsum unit, which is thinner and more discontinuous, shows both compressive and extensional deformations. Rotational listric faults affect the gypsum unit on the left bank of the Santerno river (see stop 1.2, Fig. 33), while further to the west (M. Penzola) shallow thrust faults are responsible for the vertical repetition of the lower gypsum cycles (Figs 12, 32). Traces of anhydritization (due to higher lithostatic loading during burial) and subsequent rehydration have been observed from M. Penzola to the westernmost edge (Sillaro-Santerno valleys, Roveri et al., 2003).

To the east (Sintria valley) the deformation is more severe. At M. Mauro the gypsum unit forms a complex imbricate structure made of three or more SW verging thrust sheets (Marabini and Vai, 1985; see stop 2.2, Figs 38-39).

Eastern sector

No unconformities associated with angular discordance occur in this sector throughout the considered stratigraphic interval. The uppermost Marnoso-arenacea Fm. here consists (Fig. 16) of a thick pile of tabular turbiditic sandstone bodies, made up of thick-bedded, coarse to very coarse and pebbly sandstones, with frequent amalgamated beds and basal scours. Such deposits form the Savio turbidite system, a composite unit consisting of up to five sandstone bodies vertically arranged in a overall fining-upward sequence with a maximum thickness of some 200 m, cropping out discontinuously along the Savio valley. A direct genetic link with the channelized systems of the western sector (Fontanelice systems) has been recently suggested (Roveri et al., 2002; Roveri et al., 2003) on the base of facies and regional geologic considerations.

As in the western sector, these sandstone bodies are overlain by a mudstone unit, here more developed and containing two chaotic bodies separated by an undisturbed muddy horizon, 400 m thick. The chaotic bodies are made up of both intra and extrabasinal deposits (Lucente et al., 2002); their thickness reaches some 300 m.

An organic-rich unit corresponding to the *euxinic shales* of the western area occurs above the chaotic horizon; here such unit is thicker (100 m) and show a less evident lithologic cyclicity, due to the higher terrigenous content. As in the western sector, the Tortonian/Messinian boundary lies at the base of this unit allowing reliable correlations.

The most striking difference with respect to the western sector is the total absence of

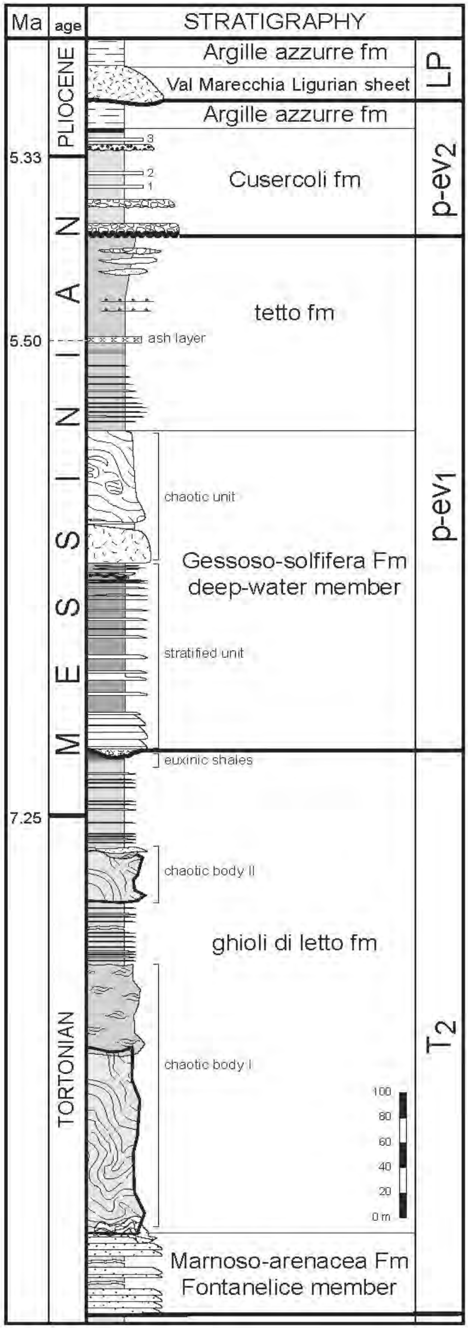


Fig. 16 – Stratigraphy of the eastern sector.

primary, shallow-water evaporites. The Gessoso-solfifera Fm. consists here of a thick complex of resedimented evaporites made up of well-stratified, thin-bedded gypsum turbidites and huge olistostromes containing large blocks of primary selenitic gypsum. These evaporites were deposited in relatively deep-waters, well below wave-base, as suggested by the observed sedimentary structures (Parea and Ricci Lucchi, 1972; Ricci Lucchi, 1973; Roveri et al., 2001; Manzi, 2001). Interbedded mudstones have a moderate organic content, decreasing upward. Neither traces of subaerial exposure, nor an obvious cyclical pattern can be recognized.

Clastic gypsum deposits are overlain by a large thickness (up to 600 meters) of terrigenous non-marine deposits of the San Donato and Colombacci Fms in turn followed by Pliocene deep-marine deposits. The best outcrops of upper Messinian and lower Pliocene deposits occur in two large synclines (Giaggiolo-Cella and Sapigno synclines in Figs. 8, 16), possibly corresponding to local Messinian depocenters developed above the orogenic wedge. The basal Pliocene deposits have here the same facies character of the western sector (epibathyal mudstones belonging to the Argille Azzurre Fm.) as well as the Miocene/Pliocene boundary, characterized by the typical black shale horizon.

Summarizing, the Messinian succession has an overall basinal character. In such a depositional context, a reliable stratigraphic framework can be based on the recognition of abrupt vertical facies changes, characterized by both compositional and/or grain-sizes changes in deep-water deposits. Such change would correspond to large-scale reorganization of basin geometry and drainage pattern related to main tectonic events.

Using this approach with the integration of bio- and magneto-stratigraphic data, the T_2 unconformity can be traced at the base of the Savio turbidite system. As for the MP unconformity, clearly developed in the western sector, Roveri et al. (1998, 2001) and Manzi (2001) suggested that it could be traced into a correlative conformity at the base of the resedimented evaporitic complex of this area. According to this view, the Gessoso-solfifera Fm. would belong to the MP synthem, and a time equivalent of primary evaporites occurs within the local euxinic shales.

Preliminary bio-magneto-stratigraphic data (Manzi, 2001) pointed out the occurrence of a highly organic-rich, barren horizon, never observed in marginal, “Mediterranean-type” successions. This horizon would represent the deep-water counterpart of the primary evaporites.

The MP synthem can be subdivided into two units (p-ev$_1$ and p-ev$_2$, see Roveri et al., 2001; Fig. 5), separated by a minor unconformity marking important paleogeographic and structural changes.

The lower unit (p-ev$_1$) only occurs in structural depressions and bridges the final Messinian gap (Krijgsman, 1999a, b). The p-ev$_1$ unit consists of a basal complex of resedimented evaporites, overlain by a thick, monotonous succession of finely laminated mudstones and siltstones containing minor turbiditic sandstone bodies and showing an overall coarsening-and shallowing-upward trend related to the progressive and rapid basin infill (tetto fm.); an ash layer, dated at ca. 5.51+0.04 Ma (Odin et al., 1997), represents an exceptional lithostratigraphic marker throughout the whole Apennine foredeep basin, allowing to recognize the p-ev$_1$ unit across different sub-basins (Bassetti et al., 1994). Sedimentary facies and vertical trends together with geometric characteristics (the cross-section triangular shape and stratal convergence toward structural highs reconstructed through surface and subsurface data) indicate the syntectonic nature of this unit.

The upper unit (p-ev$_2$) is tabular and thickens in structural depressions but also overlies and seals all the previously uplifted and subaerially exposed areas. This unit consists of a cyclic alternation of coarse and fine-grained tabular lithosomes arranged in a overall fining-upward trend. The basic cyclicity records the periodical, climatically controlled, activation of fluvio-deltaic systems dominated by catastrophic floods (Roveri et al., 1998). 4 to 5 sedimentary cycles are normally observed in the upper unit; a similar, but less evident, cyclicity is observed in the upper part of the p-ev_1 unit. The overall fining-upward trend suggests a backstepping of fluvio-deltaic systems possibly related to the progressive basin enlargement.

Geological cross-sections clearly show the onlap of this unit against the Forlì structural high and the progressive upward decrease of thickness and grain-size of the fluvio-deltaic sediments. Paleocurrents and facies changes (Manzi, 1997; Roveri et al., 1998) show that the entry points of fluvio-deltaic systems feeding the eastern Romagna basins (extensively outcropping in the Giaggiolo-Cella syncline – day 3 of the field trip) were located along the Forlì line. Coarse-grained bodies are regularly interbedded with muddy units containing three limestone horizons (*colombacci*). As in the western sector the uppermost one lies just below the M/P boundary, here marked, like elsewhere in the Apennine foredeep by a characteristic dark, organic-rich horizon.

Messinian events and the tectonic evolution of the Apennine foredeep

The comparison and correlation of the western and eastern sectors of the Romagna Apennines (Fig. 8) allow to reconstruct the sedimentary evolution of the Apennine foredeep basin during the Messinian. The most important feature that clearly arises from field data of this as well as of the other sectors of the Apennine thrust belt is the strong control of tectonically-derived topography on the areal distribution and vertical evolution of depositional systems. During the Messinian an important uplift phase affected the Apennine thrust belt, leading to the closure and fragmentation of the Marnoso-arenacea foredeep basin, to its accretion to the orogenic wedge and to the development of a new depocenter in a more external position, now buried under the Po Plain. This phase of tectonic deformation led to the emersion of the Apennine backbone and to the development of an embrional Apenninic drainage system, as witnessed by the abrupt change of sediment composition and dramatic increase of sedimentation rate.

The most impressive fact is the close time and genetic relationship that can be recognized between the tectonic history of the area and the main Messinian events. The Mediterranean-type Messinian succession of the western sector developed above and was delimited by an uplifting anticline related to the Forlì line (Riolo anticline in Figs. 8 and 18).

Seismic data allowed Roveri et al. (2003) to trace this structure in the subsurface and reconstruct a single ENE verging arcuate structure plunging to the west, of which the FL represents the eastern lateral ramp (Fig. 18). The continuous uplift of this structure starting from the late Tortonian (Fig. 19) was responsible for the observed sedimentary evolution of the area. The first evidence of the growth of the Riolo anticline was the creation of a small topographic relief elongated parallel to the basin axis leading to the progressive narrowing of the Marnoso-arenacea basin with consequent lateral confinement of turbiditic flows running from the NW to the SE. The larger volume flows, accelerated by this lateral constriction, increased their erosional power and cut large-scale erosional features (the Fontanelice “channels”); their sediment load was probably carried further down basin to feed the Savio turbidite system. The thick sandstone beds of “channel” fills can be considered as lobes

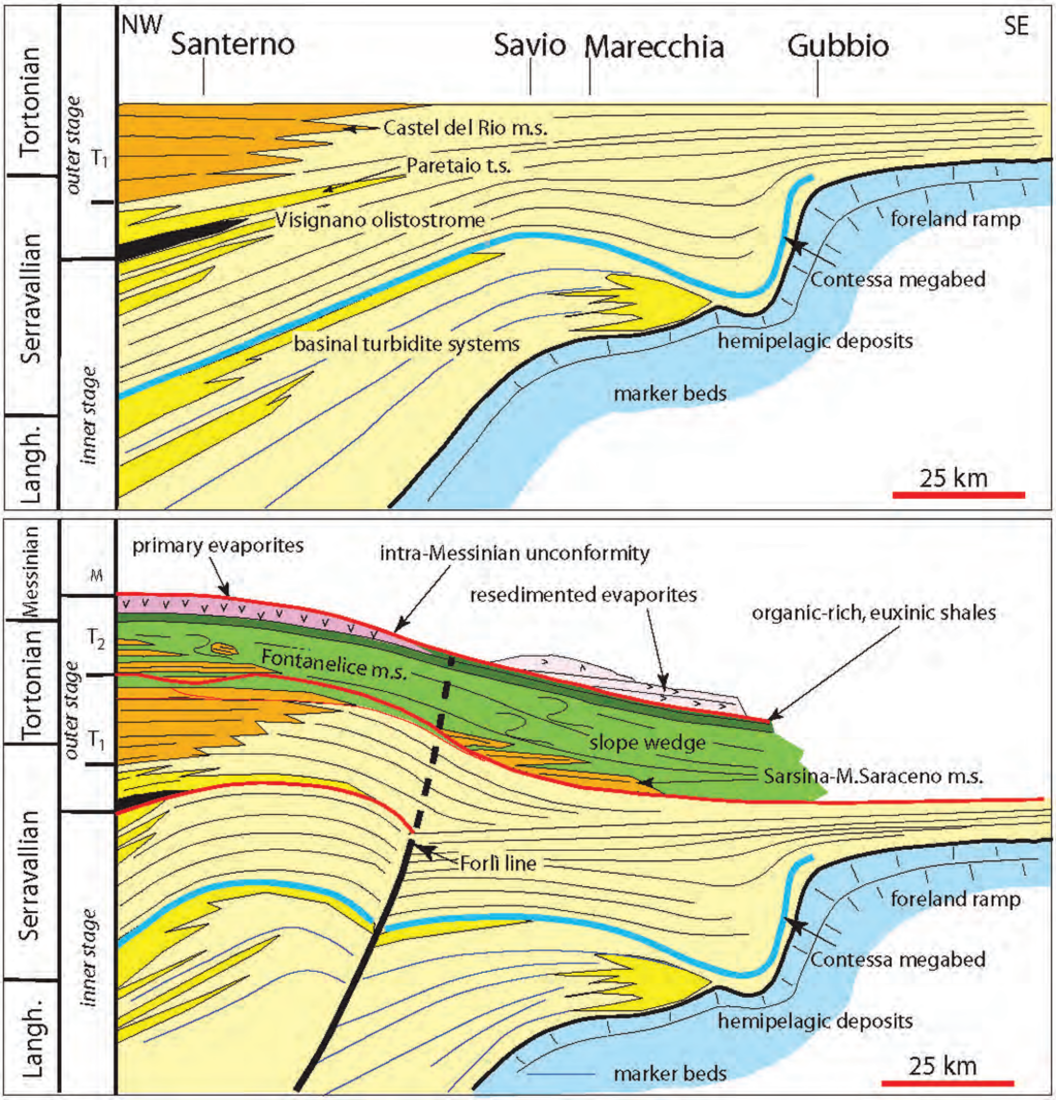


Fig. 17 - Tortonian to late Messinian evolution of the Apennine foredeep basin (axial section) showing the longitudinal fragmentation due to the growth of the Forlì line - related structural high (Roveri et al., 2002).

formed in a confined basin by smaller volume flows.

The anticline growth along the frontal and lateral ramp split the foredeep into two different subbasins: an uplifting basin to the west and a subsiding basin to the north and to the east. The former foredeep basin was gradually cut-off from coarse-grained turbiditic sediment input and a muddy slope developed in both sectors. This tectonically active slope was characterized by strong instability leading to huge sediment failures. The deeper and more subsiding character

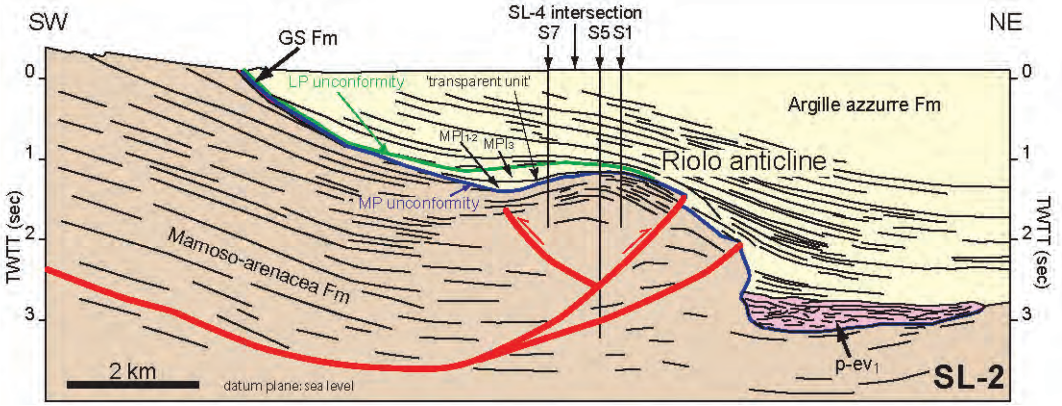


Fig. 18 – Line drawing of a seismic profile showing the buried culmination of the Riolo anticline. See location in the geological map of Fig 24 (from Roveri et al., 2003).

of the eastern sector is witnessed by the higher thickness of Tortonian to lower Messinian succession and by the higher terrigenous content of the local euxinic shales.

Independent evidence for the uplift of the western sector during the late Tortonian and early Messinian are given by sediment rates and paleobathymetric reconstructions (Kouwenhoven et al., 1999; van der Meulen et al., 1999); their combination suggests a sediment rate decrease and a concurrent shallowing upward trend.

The decrease of sedimentation rate is essentially due to the suppression of the terrigenous component related to the progressive cut-off of this uplifting area from turbidity currents. During the Messinian the role of the Riolo anticline is clearly defined. Primary, shallow-water evaporites deposited only in the western sector within a large, semiclosed wedge-top basin. The longer-term shallowing-upward trend superposed on the small-scale gypsum cycles suggests a gradual upward reduction in the amount of accommodation space created. The evaporites are cut by an erosion surface – the intra-Messinian unconformity – of inferred subaerial origin that can be traced to the SE on the outcropping culmination of the structural high associated to the Forlì line lateral ramp and to the NE above the buried anticline crest revealed by seismic and well data. The unconformity is associated to an angular discordance and formed during a paroxysmal phase of tectonic activity. The time elapsed by erosion in marginal uplifting areas is recorded in topographic depressions by a volume of sediment corresponding to the lower post-evaporitic unit occurring in the eastern sector. As a consequence, in the Apennine foredeep basin a large-scale tectonic pulse stopped primary evaporite deposition and caused the transition from hypersaline to hyposaline basin. Deep-water settings never experienced desiccation and evaporitic sediments were emplaced by gravity flows, forming a thick unit with tabular geometry and onlap terminations against basin margins.

After the emergence following the evaporitic phase, the FL structural high was sealed in the latest Messinian; the Lago Mare deposits resting above the intra-Messinian unconformity in the western sector belong to the uppermost p-ev$_2$ unit, as indicated by the occurrence of the colombacci limestones. The basal Pliocene flooding occurred over an almost flat topography developed in a phase of slow and generalized subsidence and basin enlargement following the intra-Messinian

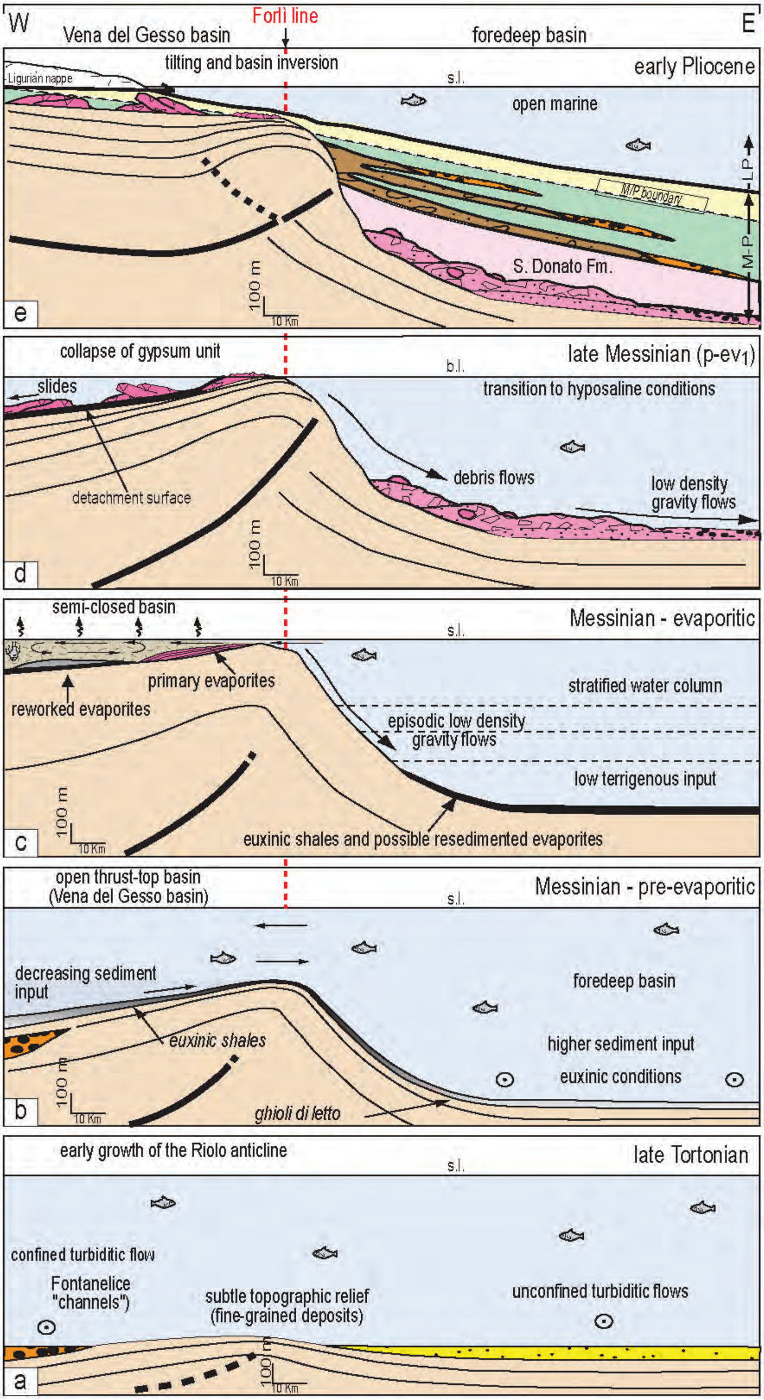


Fig. 19 – Evolution of the Riolo anticline during the Upper Tortonian-Lower Pliocene time interval (from Roveri et al., 2003).

tectonic pulse. This phase lasted the whole early Pliocene, during which fine-grained, deep-water sediments accumulated throughout the Apennine orogenic wedge. A new important tectonic event, occurred at 4.2 Ma (LP unconformity), marking a significant propagation of the Apennine thrust front toward the Po plain area (Ricci Lucchi, 1986). During this phase a generalized NE-ward tilting of the western sector led to the present-day structural setting, with the northern culmination of the Riolo anticline buried by a 1500 m thick Plio-Pleistocene cover.

Hot Messinian topics

In this section, some of the "hottest" Messinian topics are briefly introduced. They derive from data and interpretations presented in this field trip and should stimulate and focus the discussion around the larger scale implications of the Apennine foredeep Messinian record.

1. The onset of the MSC

The onset of the evaporitic stage is commonly associated to a sea-level fall whose amplitude is not well-constrained (100 m according to Clauzon et al., 2001). The transition from euxinic shales to selenitic gypsum observed in the Apennine foredeep marginal successions is apparently abrupt. However, no reliable paleodepth indicators occur in the upper part of the pre-evaporitic deposits, due to low oxygen concentrations at the sea-bottom. Moreover, the stromatolitic limestones marking the base of the evaporitic unit do not necessarily imply a shallow-water origin (i.e. the photic zone). On the other hand, the Lower Evaporites are affected by severe post-depositional deformations flattening out within the upper part of the euxinic shales that are characterized by abundant shear planes. The commonly envisaged purely tectonic origin of such deformations has been recently questioned by Manzi (2001) and Roveri et al. (2003). Indeed, the reconstruction of the sedimentary and tectonic evolution of the western sector as essentially related to the uplift history of the Riolo anticline, also provide arguments for the Messinian development of a low-angle W-SW dipping paleoslope, corresponding to the southern, inner flank of the anticline. Renewed uplift during the intra-Messinian tectonic phase could have triggered large-scale gravity failures of the gypsum unit on a detachment surface within the euxinic shales, thus accounting for the observed SW verging thin-skinned deformation. According to the extent of translation along this paleoslope, gypsum is actually superposed to sediments deeper than those above its original substratum. A possible vertical displacement of 150-200 m has been calculated (Manzi, 2001). As a consequence, the "abrupt" vertical transition from euxinic shales to primary evaporites could be overestimated.

2. Cyclicity and stacking patterns of Lower Evaporites

The aggradational stacking pattern of the Lower Evaporites is a common feature across all the Mediterranean geodynamic settings, and necessarily implies a generalized relative sea-level rise or their relatively deep-water character (paleobathymetries in the order of 100-150 m). The first hypothesis (Clauzon et al., 2001) would imply a larger water exchange with the Atlantic Ocean, as also supported by the evaporite isotopic composition (Flecker and Ellam, 1999). The vertical facies changes observed in the evaporitic cycles of the Apennine foredeep indicate that a longer-term shallowing-upward trend is superposed upon small scale cycles. This indicates a gradual upward reduction in the rate of space creation suggesting competition between sea-level rise and tectonic uplift; the latter was possibly heralding the strong intra-Messinian tectonic pulse. With the second hypothesis the long-term trend could be more easily explained by a progressive basin fill due to a combination of vertical gypsum accretion and tectonic uplift.

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

The transition between the Lower Evaporites and the Upper Evaporites or Lago Mare stages of the MSC is marked in all marginal basins of the Mediterranean area by the development of a large erosional surface (the intra-Messinian unconformity), associated to a hiatus of variable amplitude. The origin of this erosional surface is commonly related to an evaporative sea-level fall in excess of 1,000 meters implying desiccation of the deepest Mediterranean basins. Such catastrophic event led to the subaerial exposure of Mediterranean continental margins and to a huge fluvial rejuvenation with the incision of deep canyons in front of largest rivers (Nile, Rhone; Clauzon, 1973, 1982; Ryan, 1978; Ryan & Cita, 1978).

The tectonically enhanced nature of the intra-Messinian unconformity due to a supra-regional deformational phase has been commonly rejected. However, in many basins developed in different geodynamic settings (Apennine foredeep, Tyrrhenian basins, Tertiary Piedmont Basin, Sicily, Eastern Mediterranean, Western Mediterranean) this erosional surface is clearly associated to an angular unconformity.

This suggests an important phase of structural reorganization all along the Africa-Eurasia collisional margin (Meulenkamp et al., 2000). Duggen et al., (2003) envisaged complex deep-crustal or mantle processes occurring between 6.3 and 4.8 My, 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. In the Apennine foredeep, this unconformity is associated to the most important deformational phase since the early Miocene, as it marks the emersion of the Apennine chain. The consequences of such paleogeographic changes on climate have not been investigated yet.

4. Resedimented evaporites: origin and significance

The term clastic evaporites was first used in the late 60's-early 70's to indicate some "gypsiferous sandstones" cropping out in the Laga basin (the southern depocenter of the Messinian Apennine foredeep). These deposits where often associated with the "balatino gypsum", a well-laminated alternation of gypsum and bituminous shales, usually interpreted as a deep-water primary evaporitic facies. The occurrence within the "balatino gypsum" of sedimentary structures interpretable as megaripples (Fanantello river, Schreiber, 1973; see stop 2.2; Figs. 20, 21) was not adequately taken into consideration. Actually, due to the recognition of very indicative sedimentary structures (load casts, fluid-escape structures, bed gradation, cross-lamination and tractions-plus-fallout structures), almost all the "balatino" gypsum facies of the Apennines has clearly to be re-interpreted as deposited from gravity flows. The "balatino" facies is part of a wide spectrum of mass-flow deposits ranging from olistostromes to low-density turbidity currents. As a matter of fact, this class of deposits should be dealt with like the siliciclastic gravity flow deposits. However, due to the strong diagenetic effects typically underwent by evaporitic rocks, their study is a very difficult task.

Most of the evaporites of the Apennine foredeep are actually clastic deposits derived from the dismantling of primary, *in situ* evaporites and resedimented through gravity processes into relatively deep waters, below the wave base (Parea and Ricci Lucchi, 1972; Ricci Lucchi,

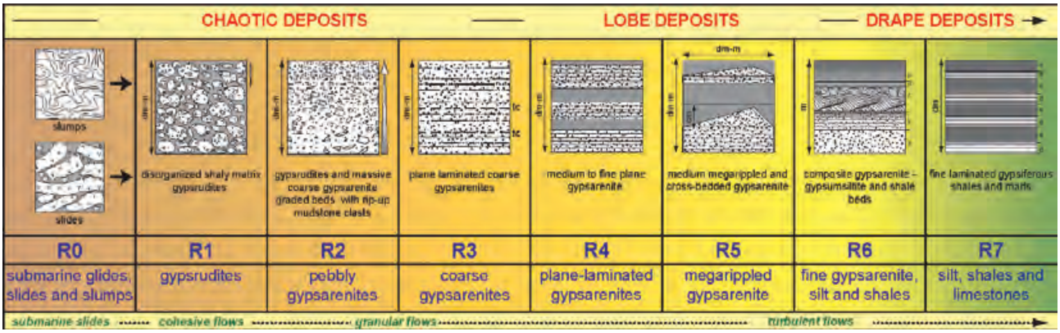


Fig. 20 - Scheme of the main facies recognised in the gypsumclastites of the northern Apennines. They are genetically organised following a theoretical down-current evolution of a hypothetical gypsumclastites-bearing flow.

1973; Manzi, 2001; Roveri et al., 2001; Manzi et al., 2005). Despite their common occurrence, they have been virtually ignored until recent times. Based on an integrated sedimentologic, petrographic and geochemical study, Manzi et al. (2005), have proposed a new facies classification and a genetic model for resedimented evaporates, which implies a close similarity with siliciclastic turbidites. This sedimentologic interpretation is strictly linked with the geodynamic model, which provides some constraints for the modalities of gypsum detritus production and the definition of trigger mechanisms for the initiation of flow.

One basic problem is the definition of original grain-size of clastic evaporites; in Manzi et al. (2005) a siliciclastic-derived relationship between grain size and sedimentary structures is proposed in order to indirectly define this important parameter in diagenetically transformed deposits. Using this approach, several facies and facies associations have been recognized. Their areal distribution is in good agreement with the hypothesis of the removal of primary evaporites formed in shallow thrust-top basins through large submarine collapses and glides triggered by tectonic-induced gravitational instability and their down-current transformations into high and low-density turbidity currents. This is well evident considering facies distribution along a NW-SE transect from the Forlì Line to the eastern Romagna and northern Marche basin (Figs. 22, 23). Of course, local tectonically induced topography provides further complication to the general picture.

The general poor to absent terrigenous component in the resedimented evaporite unit could suggest a genesis from submarine collapses. Fluvial floods can be thus discarded, also considering the paleogeographic setting of the Messinian. Resedimented evaporites were accumulated at the very beginning of the intra-Messinian tectonic phase that led to the first emersion of the Apennine chain. A land area with a relatively well-developed fluvial drainage only formed at the end of this uplift phase, as witnessed by the composition of terrigenous sediments of the p-ev$_1$ and p-ev$_2$ units. This is also suggested by the vertical facies sequences observed in the resedimented evaporite unit; a clear bipartition very often occurs, with a lower part made up of well-stratified, fine-grained deposits and by an upper part made up of disorganized, very coarse clastites, dominated by slumping and olistostromes often containing large blocks of lithified primary selenite. This vertical organization could well reflect a sort of “progradation” of the system related to the ongoing tectonic deformation; however, we believe that it rather records the progressive uplift and consequent exhumation and denudation of

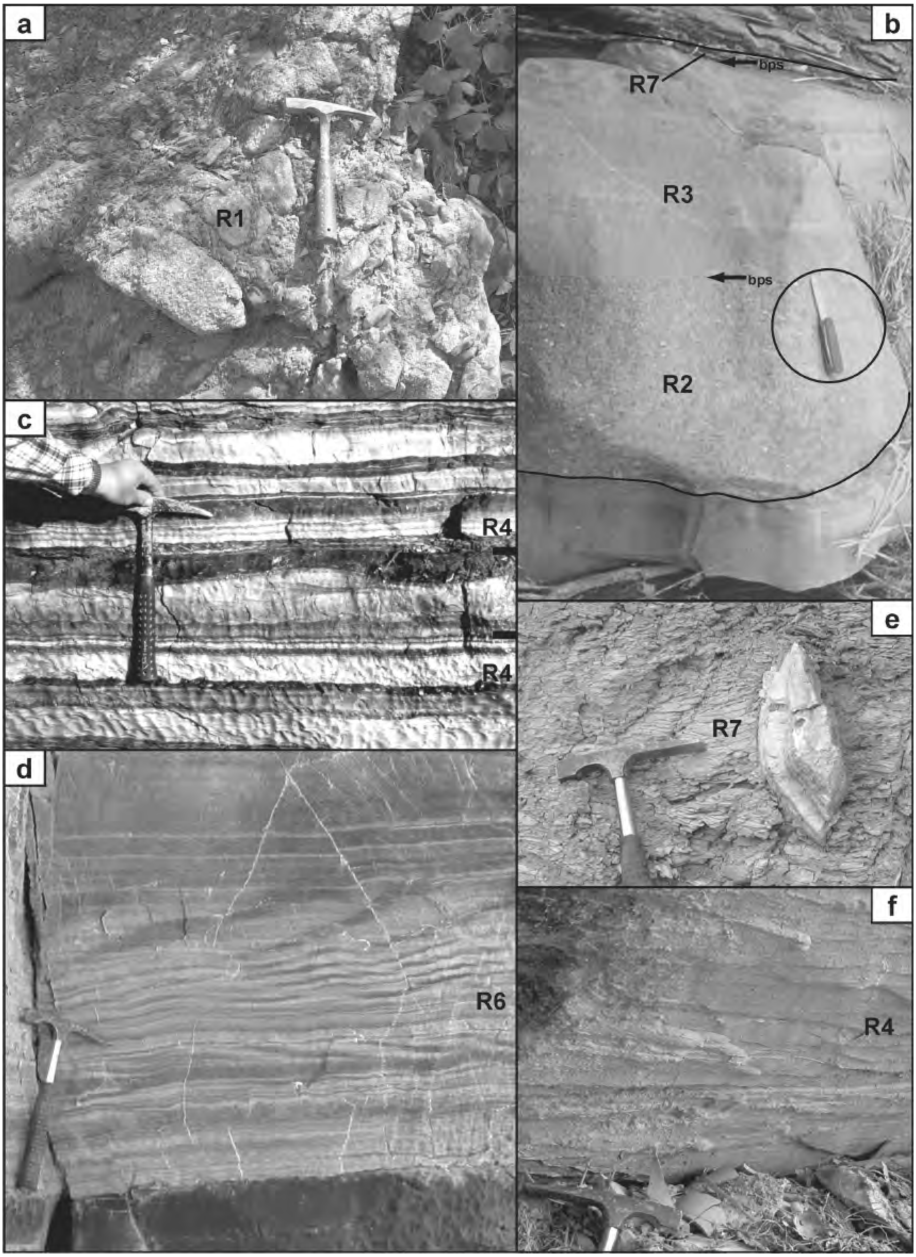


Fig. 21- a) Facies R1 (gypsrudites); b) Facies R2 (pebbly gypsarenites), R3 (coarse gypsarenites) and R7 (gypsiltite) - composite graded bed with erosional base made up of three divisions of massive gypsrudites, laminated gypsarenite and gypsiltite separated by by-pass surfaces (bps). c) Alternation of plane laminated (facies R4) and cross bedded (R5) thin bedded fine-grained gypsarenites and pelite. Fanantello riverbed, Sapigno syncline, northern Marche. d) Facies R6 (fine-grained gypsarenites, gypsumsiltites and shales) - Coarser-grained lower portion of a 4 m thick composite graded bed (megabed I, Fig. 1 in Manzi et al., 2005) made up of plane laminated, cross-laminated and convolute fine gypsarenites and gypsum siltites. Fanantello riverbed, Sapigno syncline, northern Marche. e) Facies R7 (gypsum siltites and limestone) – Large lenticular gypsum crystals that grew within grey massive or lightly laminated marls. f) flute casts at the base of a gypsarenitic bed (after Manzi et al., 2005).

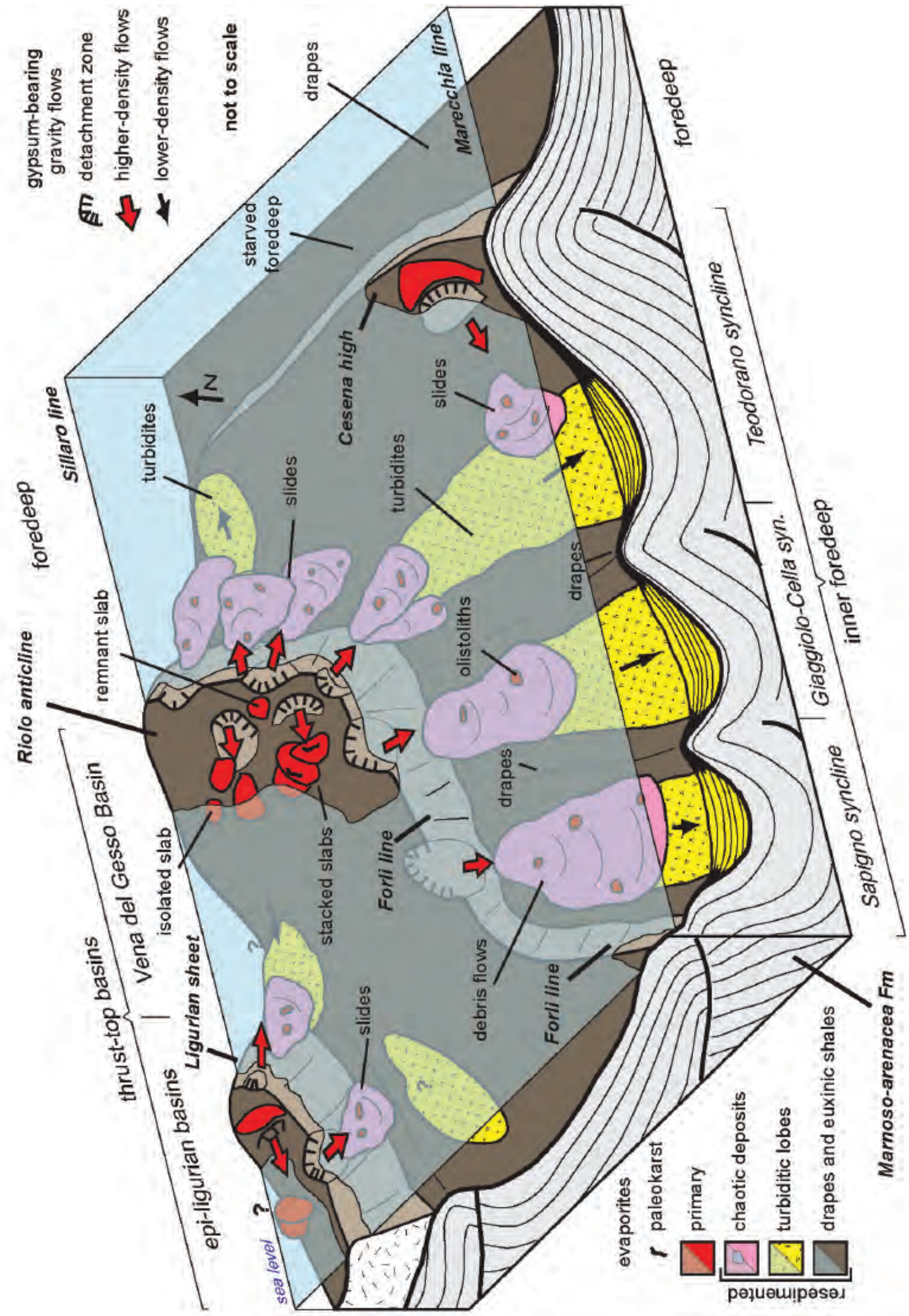


Fig 22 - Three-dimensional reconstruction of the Romagna sector of the Adriatic foredeep during the Messinian. Clastic evaporites, mainly discharged by structural culminations, were accumulated in structurally-controlled topographic lows, finer-grained deposits occurred onintrabasinal highs and in the undeformed foredeep, tectonically isolated from the gypsum-bearing flows. After Manzi et al., 2005.

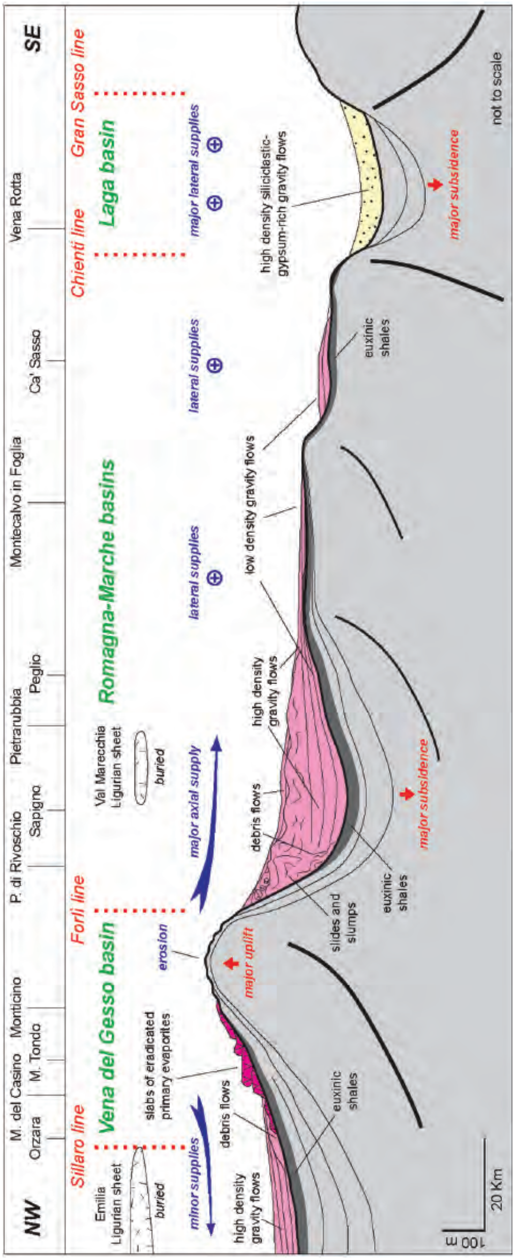


Fig 23 - Stratigraphic setting of the Messinian foredeep during evaporite resedimentation. Note the thick sedimentary wedge developed close to the Forlì Line bordering the Vena del Gesso Basin. After Manzi et al., 2005.

primary evaporitic units formed above or around structural highs (Figs 22-23). According to this view, basal fine-grained resedimented evaporites could derive from the erosion of the thinner-bedded, mainly reworked and unlithified uppermost cycles. The subsequent erosion of the early-cemented, thicker-bedded and coarser-grained primary evaporites lower cycles could produce olistostromes and debris flows.

As a consequence, a sort of "inverted stratigraphy" is recorded by the resedimented evaporitic unit, which could follow-up with the muddy deposits of the p-ev1 unit deriving from the euxinic shales and underlying upper Tortonian slope mudstones (Fig. 24). Resedimented evaporites could be a common feature in other Messinian basins of the Mediterranean area. Their correct recognition would represent a fundamental step for a better comprehension of the Messinian paleogeography and environmental changes. Of course, the recognition of other subaqueously deposited clastic evaporites associated to the intra-Messinian unconformity, would put into discussion the true extent of the Mediterranean deep desiccation.

5. *Time and genetic relationships between marginal and basinal Lower Evaporites*

This is one of the main problems still hampering our full comprehension of Messinian events. Are what we usually call deep-basin Lower Evaporites coeval and genetically linked to the shallow-water mainly gypsum units?

In the Apennine foredeep the two depositional settings are characterized by very different evaporitic facies. Roveri et al. (1998, 2001) suggested that the intra-Messinian unconformity cutting the shallow-water Lower Evaporites could either be traced at the base or within the deep-water resedimented evaporites unit occurring in basinal settings. A thick barren horizon in the

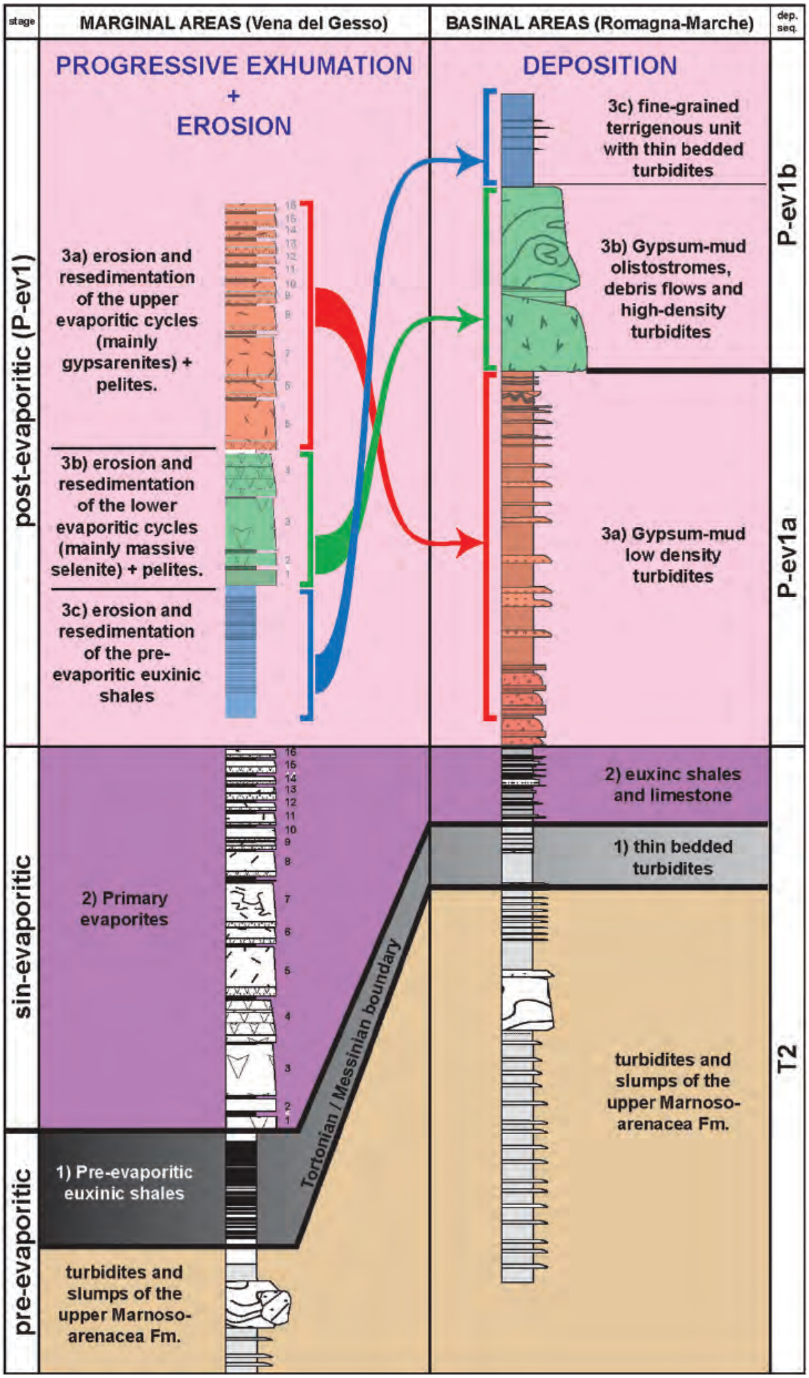


Fig. 24 - The two phases of resedimentation of the primary evaporites related to the progressive exhumation and erosion of the Vena del Gesso Basin (marginal areas) and resedimentation in the Romagna-Marche basins. Note that basinal areas show an overall inverted stratigraphy with respect to the marginal ones (after Manzi et al., 2005).

underlying euxinic shales had no equivalent in the pre-evaporitic succession of the Vena del Gesso basin. The results of an integrated study carried out on a long core through the basinal pre-evaporitic deposits (Fanantello core, see stop 2.2) suggest that such barren horizon could actually be the deep-water equivalent of the marginal Lower Evaporites. This means that resedimented evaporites fully postdate the main evaporitic phase. This opens a completely new scenario for the interpretation of the deep-basin Messinian stratigraphy.

6. *Gypsum diagenetic transformation and origin of sulphur mineralization*

The Gessoso-solfifera Fm. of the Romagna and Marche Apennine contains sulfur deposits that were mined since Roman time until the ‘60s (Scicli, 1972). The sulfur mineralization consists of discontinuous, thin lenses mostly restricted to the base of the evaporite formation and particularly at the contact of the sulfate layers with the basal organic-rich shales (euxinic shales). In some areas (Perticara) the mineralization is also present in higher stratigraphic levels into sulfate layers having particularly organic-rich shale interbeds. Sulfur-limestone layers appear to replace sulfate layers up to a few meters thick, but generally less than 1 m. The sulfur mean reaches up to 40%, but is generally around 12%. The sulfur mineralization shows mostly nodular and breccia-veins textures and less common ribbon and massive textures. Native sulfur is associated to calcite, celestite, barite, bitumen and emissions of sulfuric acid and methane.

These characteristics indicate that elemental sulfur formed by sulfate reduction. Characteristics and timing of sulfur formation are unknown and detailed textural, petrographic and geochemical studies are at their initial stage. One of the significant aspects is that economically important sulfur concentrations are present only in the clastic sulfate evaporites of the Romagna-Marche area that were transformed into anhydrite at burial diagenesis and not in the unaffected autochthonous selenite of the Vena del Gesso Basin. This suggests that early synsedimentary formation was negligible and that most sulfur originated by bacterial sulfate reduction triggered by hydrocarbons migrated from the associated organic-rich shales and marls. A thermochemical sulfate reduction origin for the sulfur can be excluded because the evaporite formation was buried at relatively shallow depth (~500 -1000 m). Most sulfur deposition possibly occurred by oxidation of sulfuric acid by dissolved oxygen carried by groundwater during rehydration of anhydrite.

7. *The closure of the ‘Messinian gap’ and the onset of the Lago Mare event*

In Messinian Mediterranean successions, the common stratigraphic gap between 5.50 and ~5.60 Ma is usually associated to the desiccation of deeper basins (Krijgsman et al., 1999b; Fig. 3). This gap does not allow a full understanding of the most important Messinian events: the switch from hypersaline to hyposaline waters leading to the Lago Mare stage. Causes, modality and timing of such dramatic paleogeographic change are obscure; the most commonly accepted explanation is the capture of Paratethyan waters by a lowered Mediterranean base-level.

As stated above, in the Apennine foredeep this gap only occurs above uplifted areas (e.g. the western sector of the Romagna Apennines); in deeper, subsiding basins the record is continuous and the hiatus being bridegd by the lower part of the p-ev$_1$ unit, made up of resedimented evaporites and by a thick pile of terrigenous fine-grained sediments (Figs. 5, 25). This means that the Apennine successions have recorded such event and for this reason a detailed study of this interval is being carried out by a multidisciplinary

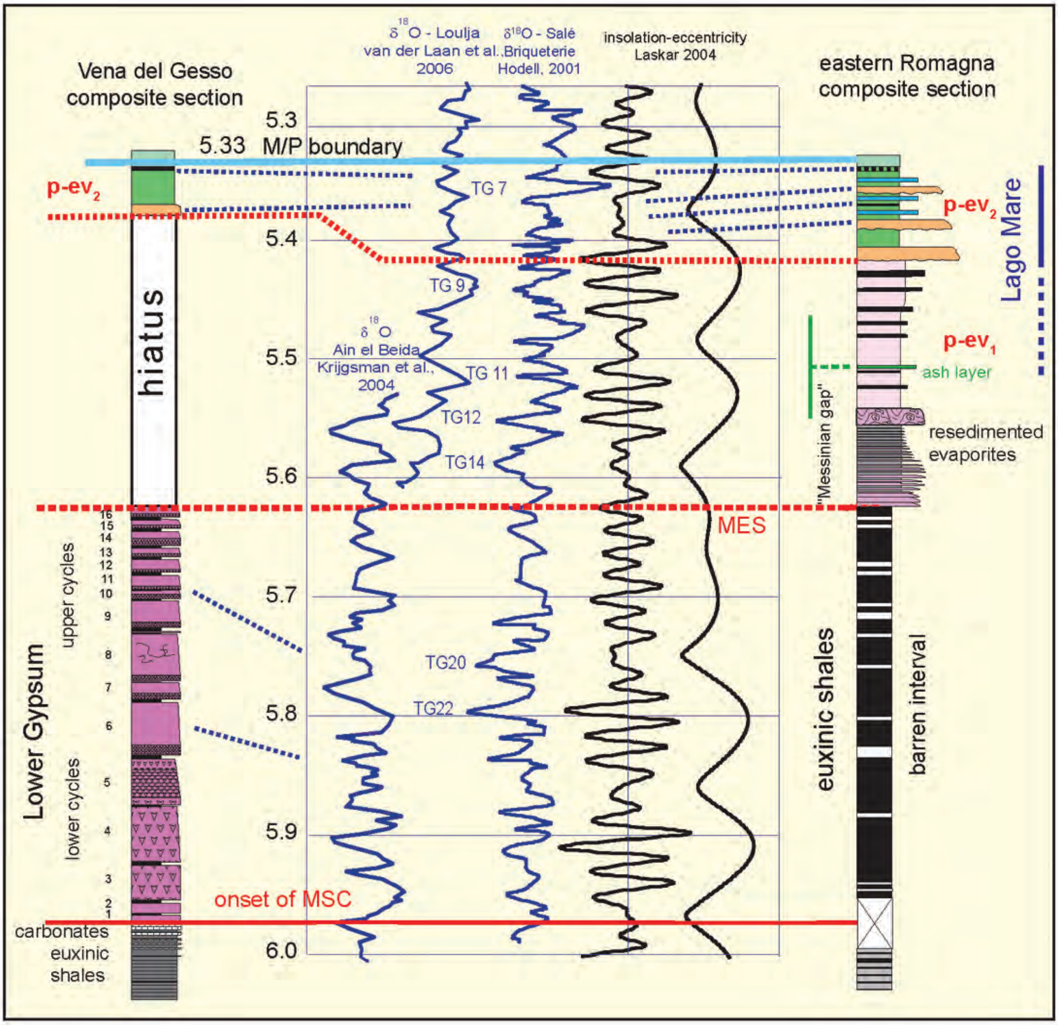


Fig. 25 – Correlation of Messinian Apennine foredeep succession with astronomically forced insolation cyclicity. Post-evaporitic deposits show a well-developed cyclic pattern especially in the upper unit (p-ev2).; p-ev1 deposits, having a stronger syntectonic character, show a less-evident cyclicity, especially in the lower part.

research group. Preliminary observations and analysis carried out on a continuous core (Campea well, stop 4.1) led to the recognition of the typical Lago Mare ostracod, pollen and dynoflagellate assemblages immediately above the resedimented evaporite complex. This means that the typical Lago Mare hydrology was already established immediately after or during the deposition of the resedimented evaporite complex. Cores have also pointed out the occurrence of well-defined organic-rich horizons, which are being studied to assess their paleoenvironmental meaning and potential as regional lithostratigraphic markers.

8. High-frequency Milankovitch-type climatic cyclicity in the Lago Mare deposits

Like pre-evaporitic deposits and lower Evaporites, the Lago Mare successions show a fairly well developed cyclic organization that can be used to establish a high-resolution stratigraphy otherwise impossible to obtain in a non-marine unit encompassing a very short time span. According to Krijgsman et al. (1999a-b) the Lago Mare stage lasted more or less 270 Ka, 90 of them recorded by deep Mediterranean evaporites and by the basal p-ev$_1$ unit of the Apennine foredeep (Fig. 25). The bipartite character is a well recognizable but usually overlooked feature of the Lago Mare successions, not only in the Apennine foredeep but also in many other basins (see for example the Upper Evaporites and Arenazzolo Fm. of Sicily). Only the upper part of the lower unit, locally characterized by the deposition of shallow-water, sabkha-like evaporites (Sicily), shows a well-developed cyclical lithological pattern only in its upper part.

In the Apennine foredeep basins up to five cycles, defined on the base of the regular alternation of coarse and fine-grained lithosomes or by the occurrence of laterally persistent paleosoils, can be recognized above the ash layer, which provides an independent, even if not particularly accurate, time calibration. The upper p-ev$_2$ unit, which is widely recognized at a Mediterranean scale, is characterized by a well-developed high-frequency cyclical pattern superimposed upon an overall transgressive trend. These two characters represent good criteria for high-resolution long-range correlations; 4/5 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), 4 cycles in the fluvio-deltaic deposits of the Tertiary Piedmont Basin (Ghibaudo et al., 1985); 3 to 4 cycles are reported from a thick terrigenous Lago Mare succession unconformably overlying the Lower Evaporites in the Corvillo basin (Sicily; Keogh and Butler, 1999). As a consequence, a total of 8/9 cycles can be recognized in the 180 ka interval between the ash-layer and the Miocene/Pliocene boundary.

This is consistent with a precessionally-driven climatic origin of small-scale sedimentary cycles, like during the pre-evaporitic and evaporitic stages. The p-ev$_2$ unit would span a very short time interval of 80-90 Ka and a tentative tuning of its small-scale sedimentary cycles to the insolation curve is shown in Figs 25 and 27. According to Roveri et al. (1998), the basic lithological cyclicity given by the vertical repetition of sharp-based coarse to fine-grained couplets, observed in both shallow, marginal basins developed above the orogenic wedge, as well as in the foredeep depocenters, would reflect the periodic activation of catastrophic flood-dominated fluvial systems carrying coarse sediments into the Lago Mare during dry intervals or at the transition between dry and wet periods (Fig. 26). During this phases, small forestepping deltaic systems formed in shallow basins with low gradient shelves; in basins with reduced or steep shelves, catastrophic fluvial floods could develop hyperpycnal flows able to carry their sediment load down basin forming small, turbidite systems of "low-efficiency" (*sensu* Mutti et al., 1999). Water carried with sediments to the basin contributed to rapidly rise the base-level and caused, together with a concomitant climate change toward wetter conditions, the de-activation of flood-dominated deltaic systems and their landward migration. During wet phases, base level reached its maximum but sediment input was drastically lowered for both the reduction of catchment's area and the possibly lower erosion rate due to the increased vegetation cover. In this phase only fine-grained, thinly laminated

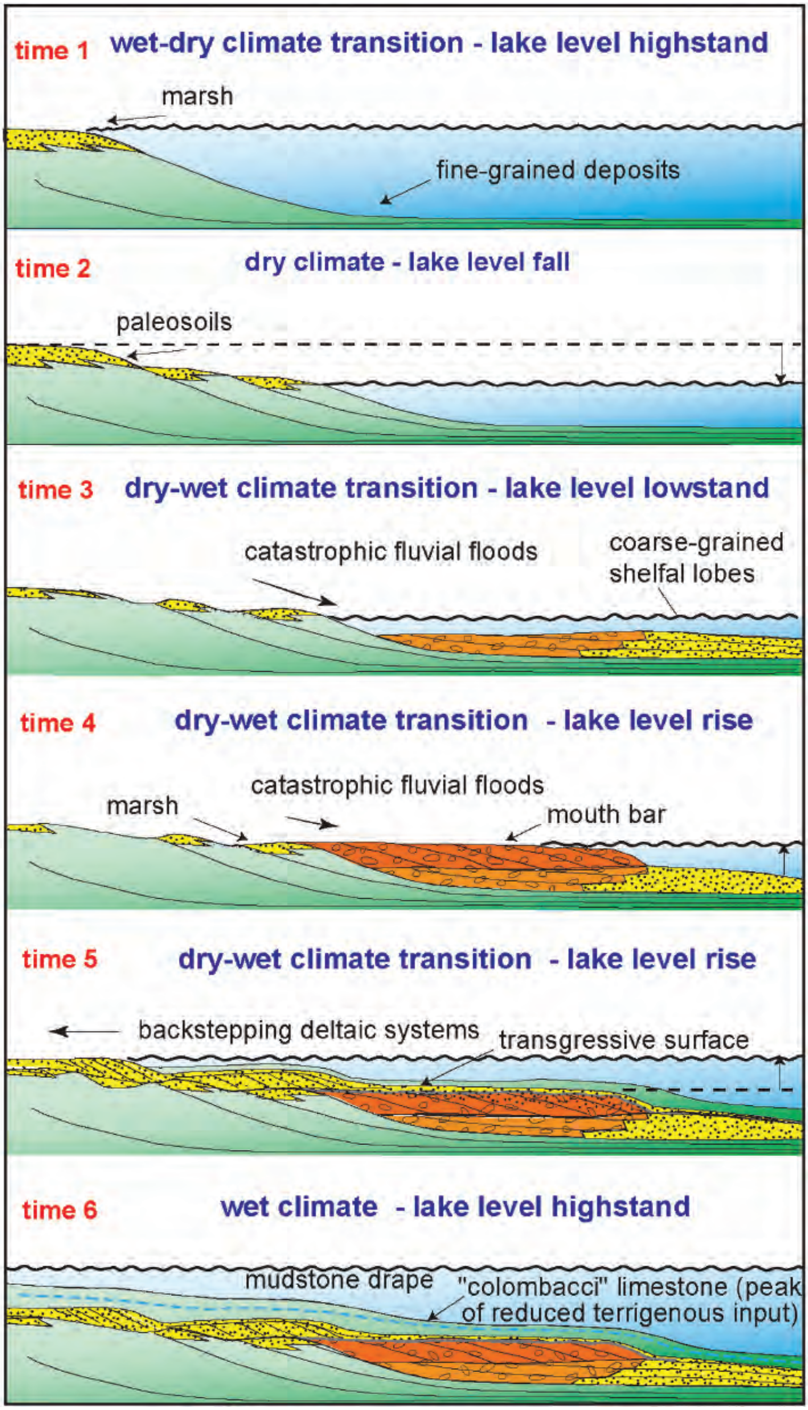


Fig. 26. Ideal evolutional scheme showing the reconstruction of Lago–Mare cyclical sedimentation in the Apennines. Modified from Roveri et al. (1998).

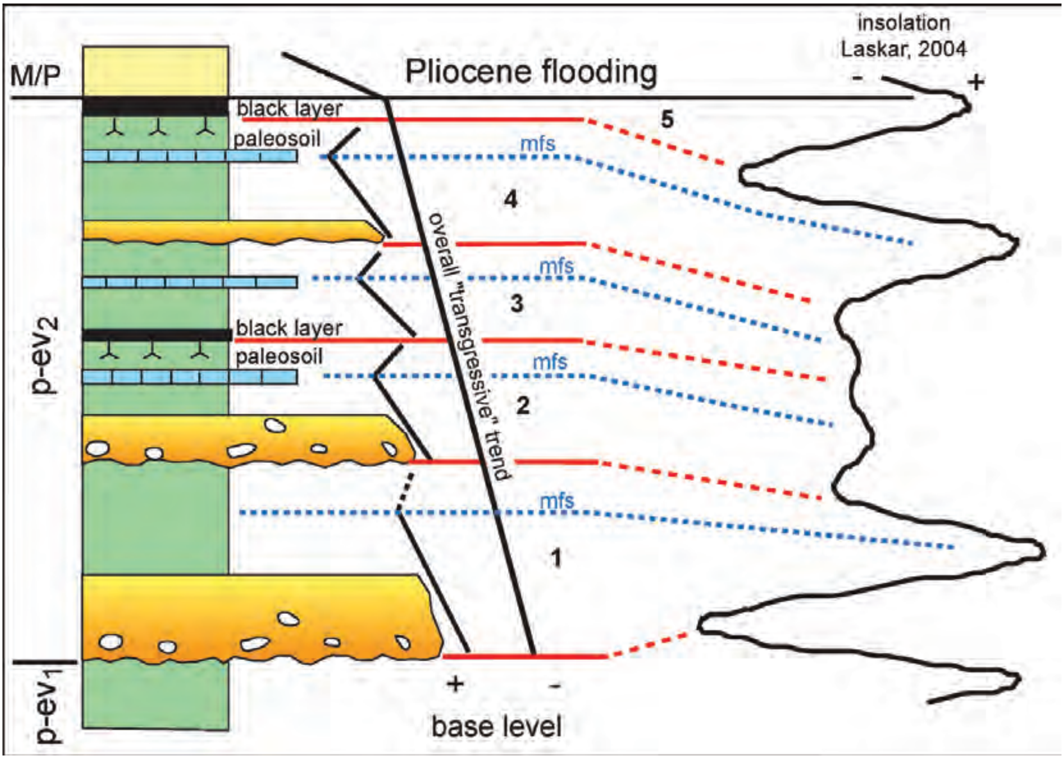


Fig. 27 – The high-frequency cycles in the p-ev2 unit; each cycle recorda a cllimatically related fluctuation of the base level and is tentatively tuned o the insolation curve. Mfs= maximum fllooding surface.

mudstones accumulated into the basin. In some places, rhythmic alternations of light and dark mudstone horizons give a typical banded aspect to the deposit, probably representing a distal lacustrine facies. Thin-bedded, finely laminated limestone horizons ("colombacci") are usually found in the upper half of the cycles associated to mudstone deposits.

According to Bassetti et al. (2004 - see topic 9), they derive from inorganic precipitation of micrite-size crystals in a relatively deep-water environment, possibly anoxic and related to events of permanent water mass stratification during periods of lake level maxima and associated peaks of reduced terrigenous input; thus, the *colombacci* limestones would represent a sort of condensed section marking the maximum retreat of clastic sediment sources and subdividing the fine-grained lithosome into a lower transgressive and an upper regressive unit, the latter topped by a subaerial erosional surface produced during base level fall in dry phases. In other words, a regressive hemicycle is preserved in the uppermost part of the cycles.

Organic-rich clay horizons rich in specialized mollusc assemblages (*Congerie*) and interpreted as palustrine deposits occur at different levels on top of coarse-grained bodies or within fine-grained lithosomes; they are tightly associated with slightly erosional surfaces showing weak pedogenetic structures. According to the model of Fig. 26, palustrine horizons could develop above the subaerial exposure surfaces during initial base-level rises, thus representing transgressive deposits. These evidences suggest a more complicated stratigraphic architecture and evolutionary trends, as tentatively illustrated in Fig. 27. In fact, the cycles are not only defined by coarse to fine-grained couplets; this is the case of the thick mudstone lithosome between the second and third coarse-grained unit outcropping in the field-trip area; it contains two *colombacci* limestone horizons and a palustrine bed in between. In previous works (Roveri et al., 1998), this lithosome was entirely assigned to the second cycle; subsequent closer inspections and core data (Cà Blindana and Montepetra cores, see stops 2.4 and 3.4) showed that the palustrine bed was actually associated with a paleosoil, thus providing evidence for an extra cycle and explaining the apparent occurrence of two *colombacci* limestones within the same cycle.

This is also the case of the uppermost cycle, where the dark layer marking the Miocene/Pliocene boundary locally overlies an irregular surface with weak pedogenetic traces (well

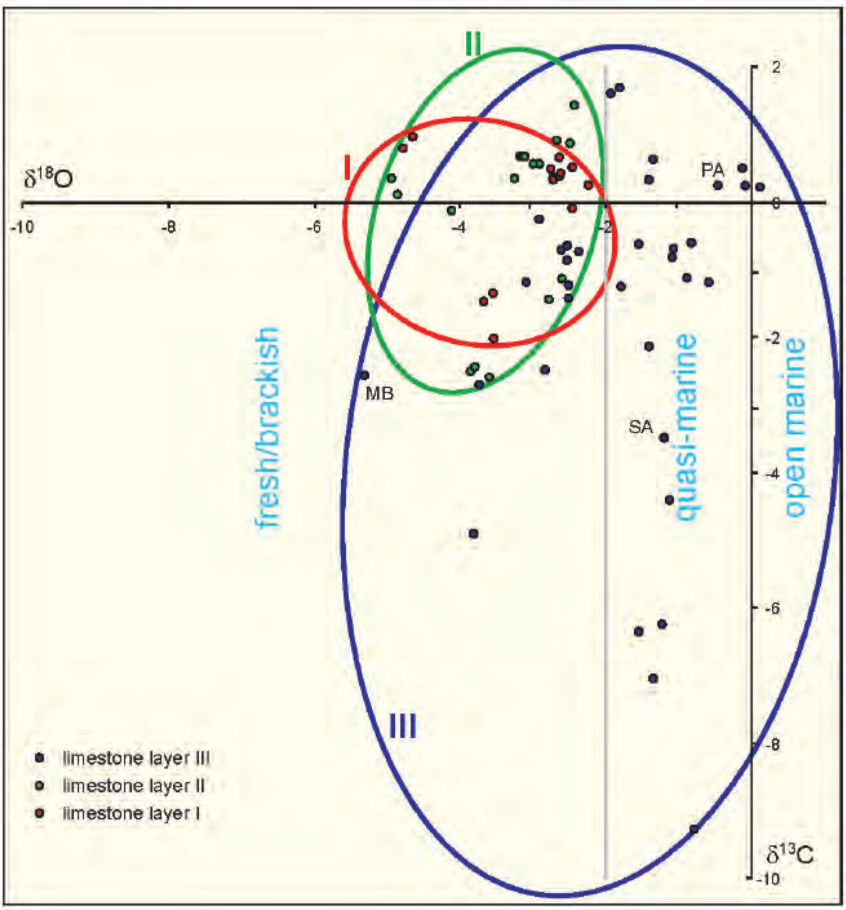


Fig. 28. Cross-plot of stable isotope composition of samples from I, II and III colombacci horizons in a 18O and 13C diagram. It shows the distribution of isotopic values according the stratigraphic position. (After Bassetti et al., 2004).

visible in the Botteghino section, Giaggiolo-Cella syncline), thus suggesting that the marine flooding occurred in the transgressive hemicycle of a fifth cycle.

Sedimentary cyclicity patterns show a good correspondance with insolation curves, confirming the main precessional forcing but also suggesting other considerations. The regular alternation of cycles with dry phases recorded either by catastrophic flood-dominated fluvio-deltaic deposits or by paleosoils would suggest a possible interference of obliquity on precessional cyclicity; moreover, the interval comprising cycle 3 corresponds to a 100ka eccentricity minima (Figs 25, 27). However, these are only preliminary considerations; detailed studies of these deposits, which bear very strong analogies with the Lago Mare cycles recently described at Cyprus (Rouchy et al., 2001) from the topmost Messinian succession, are being carried out to better understand their organization and paleoenvironmental meaning.

9 - Origin of the colombacci limestones

As previously reported, the colombacci limestones are a typical lithofacies closely associated to basinal mudstones of the p-ev_2 unit. They are abiotic and formed as inorganic precipitates from the surface waters of the Lago Mare. According to Bassetti et al. (2004), their precipitation required the periodic supersaturation of the epilimnion, possibly driven by climatically-induced events of lake-water stratification. This carbonate lithofacies is quite common in Lago Mare deposits of the Mediterranean basins; geochemical composition provide good elements to derive the hydrological structure of the basins and their degree of connection. As a general rule isotopic compositions show negative ^{18}O values, indicating freshwater conditions or at least a high degree of water dilution. The high-resolution stratigraphic model of the Apennine foredeep made it possible to compare isotopic compositions of colombacci limestones occurring in each cycle in different sub-basins and hence to verify possible areal gradients and stratigraphic trends. The results (Fig. 28; Bassetti et al., 2004) show that the two lower horizons have homogenous, strongly negative isotopic values; the uppermost horizon has less negative values, almost falling in the "normal marine" range. This could either indicate a strong concentration due to evaporation in restricted basins or, on the contrary, a true connection with the Ocean. The latter would be in good agreement with the aggradational stacking pattern of the p-ev_2 unit, suggesting a overall "transgressive" trend heralding the Zanclean flooding.

10 - Marine incursions during the Lago Mare stage?

Besides the above considerations based on isotopic composition of limestone horizons, occasional marine incursions in the Lago Mare deposits have been reported from different Mediterranean basins, especially on the base of nannoplancton assemblages (Blanc-Valleron et al., 1998; Pierre et al., 1998; Spezzaferri et al., 1998; Snel et al., 2001; Clauzon et al., 2005). Isotopic compositions of the typical faunal associations (Keogh and Butler, 1999), suggest the possibility that during the final part of this stage a large water body was present in the Mediterranean. As far as these notes were written, no clear indications of marine incursions have been found in the Apennine foredeep Lago Mare successions.

11 - The Mio/Pliocene boundary

The Mio/Pliocene boundary, marking the sudden return to fully marine conditions, is a synchronous event at a Mediterranean scale (Iaccarino et al., 1999). A particularly interesting feature is that the direct superposition of MPl1 deposits above rocks older than the uppermost

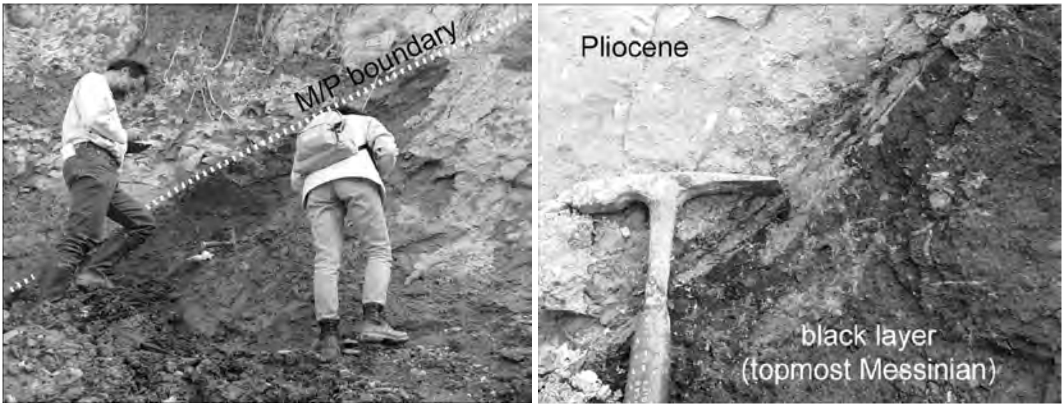


Fig. 29 – The characteristic black layerunderlying the sharp transition to open and deep marine conditions at the Miocene/Pliocene boundary. Riccò section (western Emilia Apennines; from Roveri and Manzi, 2006).

Messinian has never been reported. MPl1 sediments are always associated to Messinian Lago Mare deposits, as part of a longer-term transgressive sequence. This is particularly clear in the Apennine foredeep where such transition occurs in a phase of tectonic quiescence and generalized subsidence that probably led to the almost complete submersion of the Apennine backbone, previously emerged with the intra-Messinian uplift. Significantly, in successions deposited around topographic highs and characterized by the permanent activation of fan-delta systems, the Miocene/Pliocene transition appears to be very gradual and such boundary becomes very difficult to recognize (Gennari, 2003). Elsewhere, a black, organic-rich layer always underlies the lowest deep-marine MPl1 sediments (Fig. 29). Its nature and significance are not clear and its systematic study is currently being carried out. As previously reported (topic 7), in some cases this organic-rich horizon seems to overly a slightly erosional surface and weak paleosoil traces.

The careful re-examination of a large number of sections straddling the Miocene/Pliocene boundary allows us to confirm the Messinian age of the Lagomare deposits (Colombacci Fm.) throughout the Apennine foredeep basin. All the bioevents of the early Zanclean have been recognized in the marine deposits overlying the sharp lithological boundary with the Lagomare unit, documenting its continuous character. As a consequence, the Pliocene age for the Colombacci Fm. suggested by Clauzon et al. (2005) on the base of unpublished data and on its claimed marine character, is here ruled out. The Colombacci/Argille Azzurre boundary lays on the same time line of the Arenazzolo/Trubi boundary of Sicily, i.e. where the GSSP of the Zanclean has been defined. This has no implications on the marine vs continental character of the Lagomare deposits.

According to the above mentioned possible occurrence 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, the Miocene/Pliocene transition would be rather explained by a sudden hydrologic change associated to a bathymetric change of lower amplitude than usually thought. This would point to a less catastrophic character of the Zanclean flooding.

Field-trip itinerary

Roveri M., Lugli S., Manzi V., Gennari R., Iaccarino S.M., Grossi F., Taviani M.

INTRODUCTION TO DAY 1

The first day will be spent in an area between the Santerno and the Lamone valleys (Figs 30-30a). The Santerno Valley that will be visited during the morning surely offers one of the most continuous and spectacular Neogene sections of the Northern Apennines and is particularly famous for the outcrops of the Miocene Marnoso-arenacea Fm, described in great detail in classical papers by Franco Ricci Lucchi and his co-workers in the late 60's and 70's. The local stratigraphic succession that can be observed spans in age from Early Serravallian to Pliocene. The Marnoso-arenacea Formation is overlain by the Messinian evaporites which, in turn, are unconformably overlain by a very thin unit of uppermost Messinian continental deposits which are in turn conformably overlain by marine Pliocene-Pleistocene strata. The geology of the Santerno valley is relatively simple at the surface, where strata form a regular homoclinal gently dipping to the northeast, i.e. down the valley. Moving upstream from Imola, we drop down into progressively older stratigraphic levels.

DAY 1

Stop 1.1 – S. Giovanni (road Tossignano-Fontanelice). This locality offers a wonderful panoramic view over the Santerno valley and the Apennine foothills monocline (see Fig. 11). From SW to NE, the following stratigraphic units can be quickly recognized:

- Marnoso-arenacea Fm, Fontanelice member: coarse sandstone and conglomerate bodies, composed of multiple or individual "channel" fills.

- Marnoso-arenacea Fm., "ghioli di letto" unit: fine-grained thin-bedded turbidites and marls in an overall thinning- and fining-upward trend; this unit represents the fine-grained closure facies of the MA and contains thick intraformational slump (Figs 12, 31); inferred slumping direction to the S-SW can be related to the late Tortonian nucleation of the Riolo Terme high (Fig. 30).

- Marnoso-arenacea Fm, "euxinic shales" unit: marls embedding cyclic intercalations of bituminous clays. The Tortonian-Messinian boundary is situated about 60 m below the unit top.

- Gessoso-solfifera Fm: it is composed of up to 16 evaporite cycles, subdivided into 2 "basal" ones, 3 "major" ones (massive selenite), a very thick 6th one (massive and branching selenite), and up to 10 "minor" ones (mostly branching selenite). A complete gypsum succession comprising the 16 cycles crop out only between the Santerno and Sintria valleys (M. Tondo section, stop 1.4). The gypsum unit is characterized by deformations (normal and reverse faults, shallow thrusts, see figs 32, 33) rooted in a detachment horizon in the underlying euxinic shales and not affecting the overlying deposits. The tectonic vs. gravitative origin of these deformations will be discussed during the field trip.

- Colombacci fm: a thin horizon of continental upper Messinian deposits (p-ev$_2$ sequence), which unconformably cover the Gessoso-solfifera Fm and the pre-evaporite shales. Thickness and facies of this fm are controlled by structural highs and lows of the evaporite unit (Fig. 33). For instance, conglomerates and sandstone pockets are better represented within structural depressions.

- Argille Azzurre Fm: marine silty clays of early Pliocene age. Close to the western divide of the Santerno Valley, clays embed olistostromes and thick bodies of resedimented conglomerates, fed by epi-Ligurian fan-deltas. The well-stratified setting of all Pliocene units is clearly reflected in the landscape morphology (cover photo; Fig. 33).

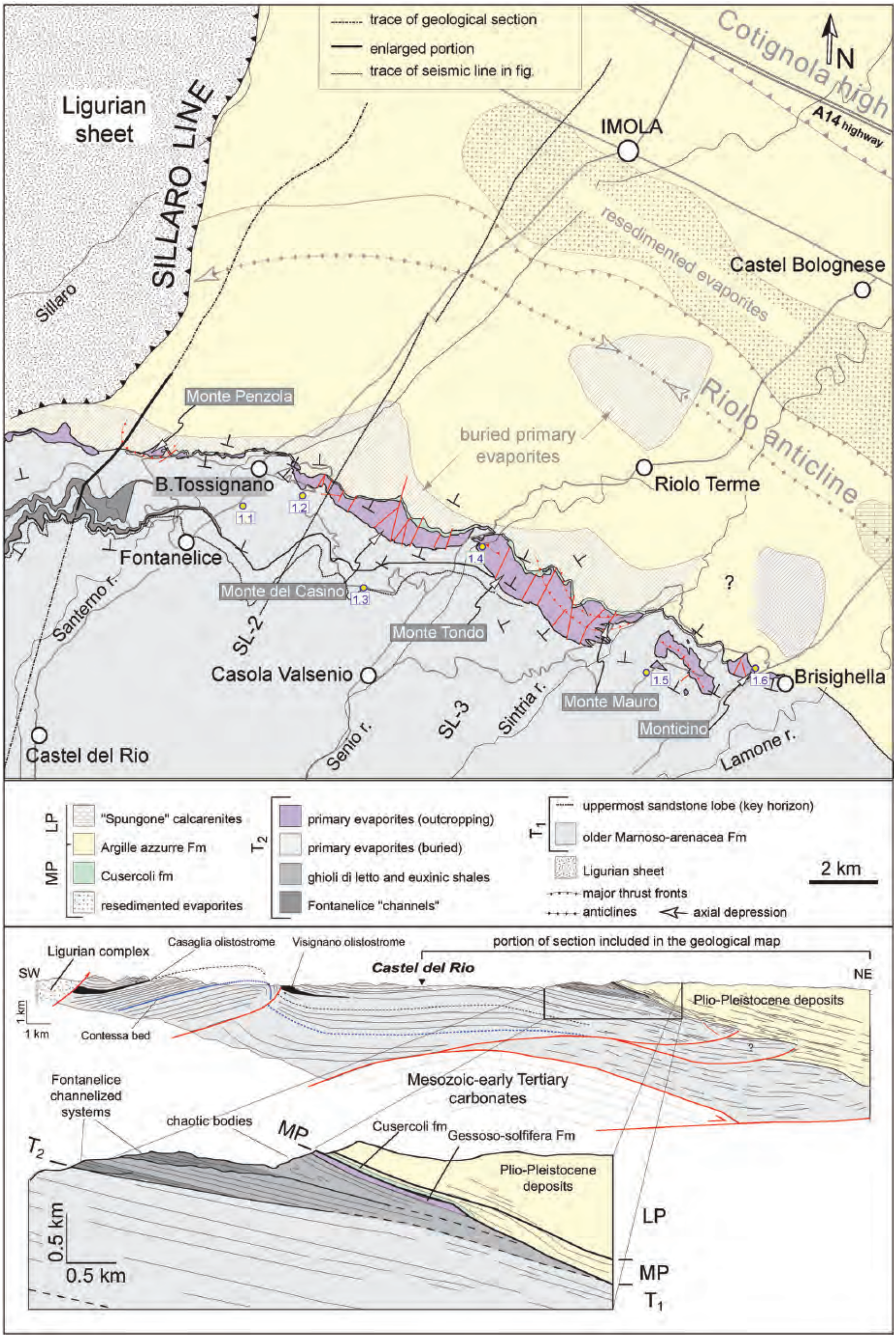


Fig. 30a – Geological map of the western sector.

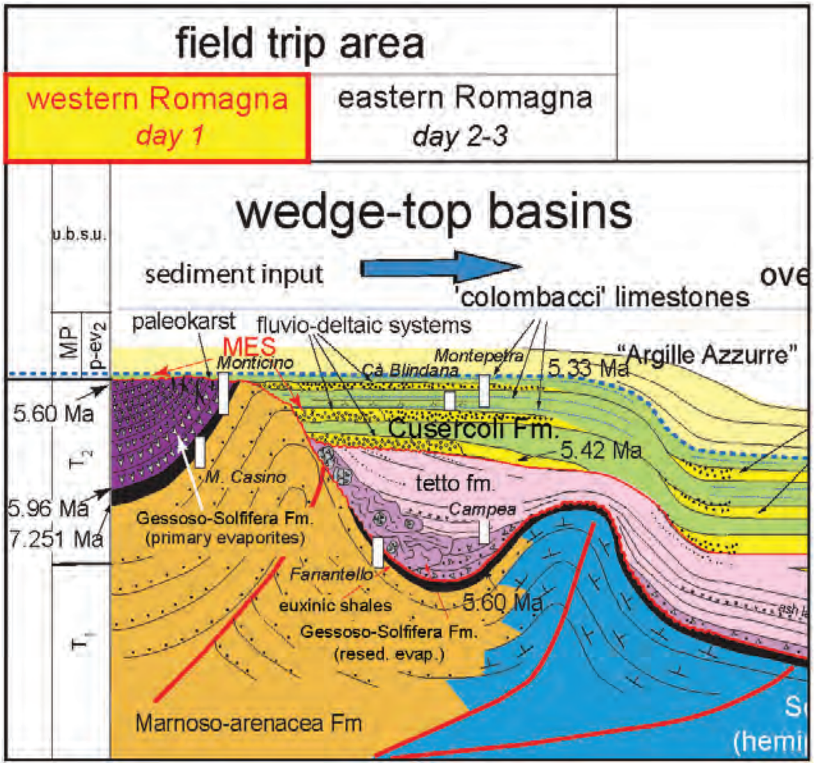


Fig. 30b – Close-up of figure 6 showing the stratigraphic relationships between Messinian units and the location of main outcrop sections and cores visited during the field-trip.

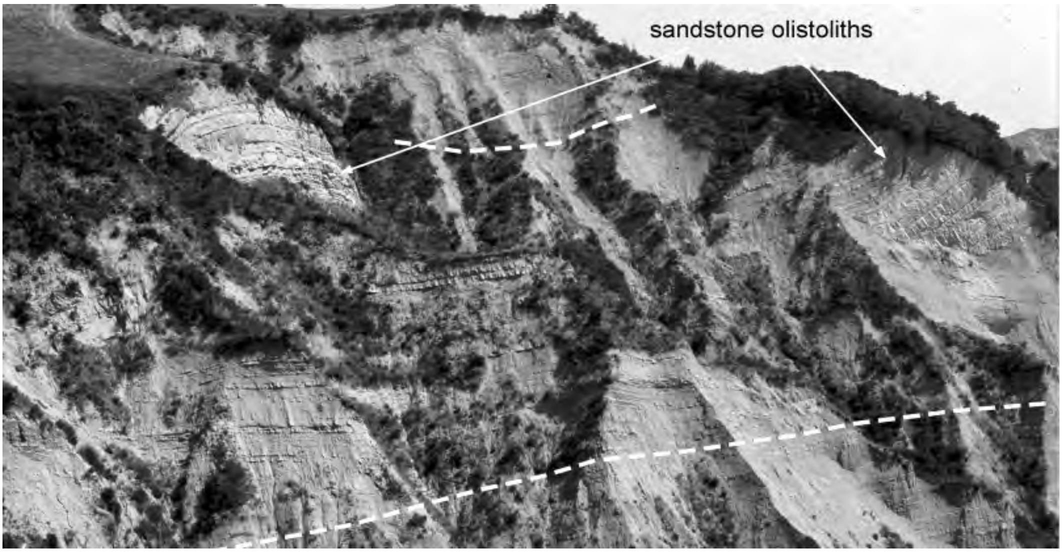


Fig. 31 - Closure facies of the Marnoso-arenacea Fm in the western side of the Santerno Valley: two sandstone olistoliths mark a slump horizon in a fining-upward succession of thin-bedded turbidites.

Fig. 32 - Monte Penzola, western side of the Santerno Valley: a thin-skinned thrust carries the 2nd evaporite cycle over the 5th one. The N-NE vergency of the thrust is contrary to the S-SW transport of all the Vena del Gesso gravity structures.

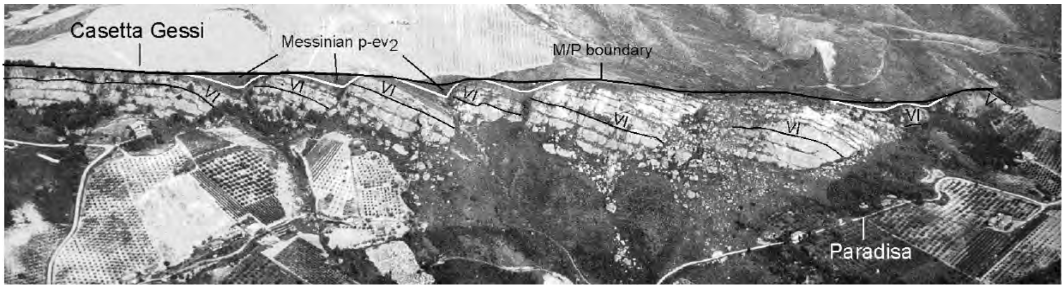


Fig. 33 - Aerial photo of the Vena del Gesso in the western side of the Santerno Valley (M. Astorri). Normal faults and very small reverse faults offset the evaporite cycles, and are sealed by post-evaporite Messinian deposits, which mark a spectacular angular unconformity. The rotational offset of faulted blocks suggests gravity-driven normal faulting, gliding and thrusting on a shallow detachment level within the euxinic shales. Transport was to the S-SW.

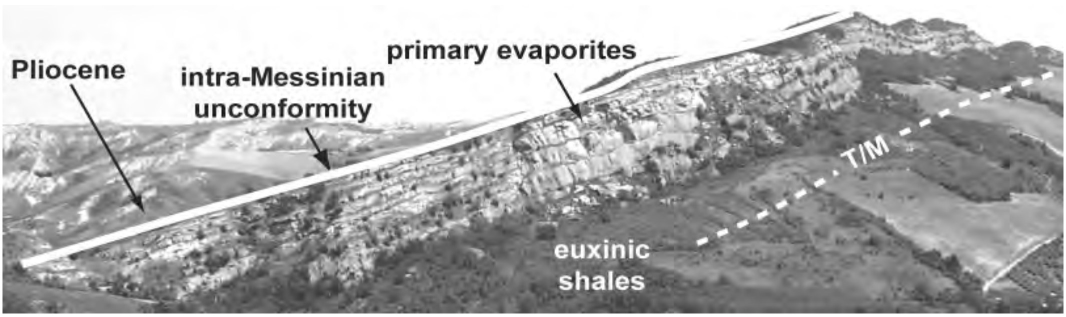


Fig. 34 – Stop 1.2. The spectacular Lower Evaporites outcrop (Rio Sgarba sect.), looking eastward from Tossignano.

Stop 1.2 - Tossignano, Resistance (II World War) Memorial Park. This panoramic view covers the Gessoso-Solfifera Fm from the Riva San Biagio cliff (Fig. 34) to the Rio Sgarba quarry. Basal, major and minor cycles can be easily distinguished and correlated. Two slump horizons embedded in the 8th and 10th evaporite cycles can be used as additional marker beds. The provenance of those slumps is still unknown, but might be an important constraint to the evolution of the Riolo Terme high (Fig. 30). Evaporites are offset by late Messinian normal faults (Fig. 34). Perhaps, those normal faults can be associated to gravity-failure structures, like those documented on the other side of the Santerno valley (Figs 32, 33).
Topics:2.

Stop 1.3 - Road Tossignano – Casola Valsenio. This road offers spectacular panoramic views of the Gessoso-Solfifera Fm. in the area between the Santerno and Senio valleys. Brief stop to observe from distance the location of the Monte del Casino section (Fig. 35); together with the M. Tondo section it represents the most important sampling sites for high-resolution cyclostratigraphy, magnetic calibration and astronomic dating of the main Messinian events in the Vena del Gesso basin (Krijgsman et al., 1997, 1999).
Topics:1,2.

Stop 1.4 – Road Casola Valsenio- Borgo Rivola. **The Monte Tondo section.**

Spectacular view on the 16 cycles of the Vena del Gesso in a fresh cut (Fig. 36). On the eastern

Fig. 35 – Stop 1.3. The Monte del Casino section as seen from the Tossignano-Casola Valsenio road.

Fig. 36 – Panoramic view of the M. Tondo gypsum quarry showing the geometry and stacking pattern of gypsum cycles from the 6th (on the basal platform) up to the 16 th.

side of the quarry we observe the top of 2nd cycle, the shale intercalation and the beginning of the 3rd cycle. The 2nd cycle consists of giant vertically grown selenite (up to 2 m tall, EF 3 facies). At the top of the 2nd cycle, at the contact with the overlying shale (EF 1), a spectacular layer of gypsum crystals up to 1 m across is exposed (Fig. 37). These crystals grew displacively into the shale (EF 6, displacive selenite) from downward seeping brines. The 3rd cycle begins with a carbonate stromatolite (EF 2; Fig. 37) and large selenite crystals (massive selenite, EF 2). On the western side of the quarry we observe the 8th and the 9th cycles: massive selenite at bottom (EF 3), followed by banded selenite (EF 4) and finally by branching selenite (EF 5). Branching selenite terminations project into a gypsum-carbonate matrix (Fig. 15).

Topics: 2

Stop 1.5 – Zattaglia - Brisighella road. In a panoramic view over the western side of the Sintria Valley (Fig. 38), the most prominent tectonic feature is a well-developed imbricate stack of SW-verging late Messinian thrust-sheets, which involve the GS and the upper part of the pre-evaporite succession. In the neighbourhood no similar structure is found, neither in the MA nor in the Argille Azzurre Fm. Indeed, back-thrusts are strictly confined to the evaporite unit. Another important character of this peculiar imbricate stack is that no one of the thrust-sheets has "roots" in the valley-floor, as no gypsum crops out in the river bed. This anomalous setting creates big problems for any cross-section reconstruction, if interpreted as a purely tectonic feature (Fig. 39). Things get simpler if we consider a progressive gravity-driven slope failure. In the upper parts of the slope, the evaporite unit is extended and dismembered by rotational normal faults, while

Fig. 37 –M. Tondo gypsum quarry. The transition between the 2nd (to the right) and the third (to the left) gypsum cycle; note the large flat lying selenite cristals on top of cycle 2 and the carbonate stromatolite at the base of cycle 3.

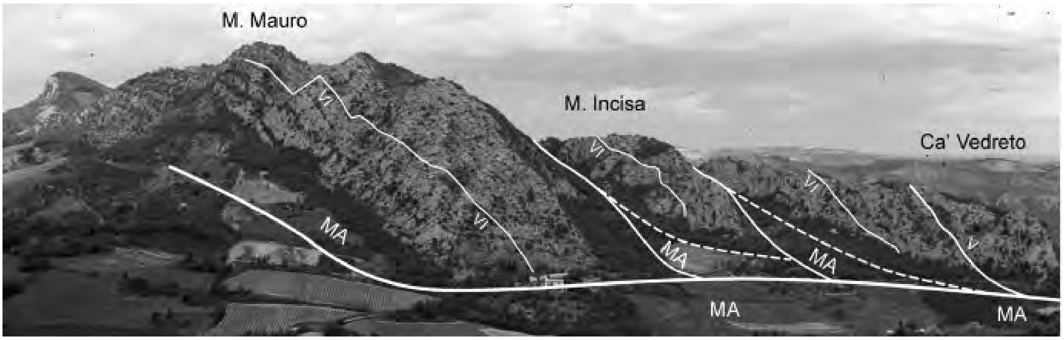


Fig. 38 - Monte Mauro and the western side of the Sintria Valley: the SW-verging thin-skinned thrusts that involve the evaporite unit can be explained by gravity-driven block-gliding, on a shallow detachment level within the euxinic shale unit (MA). As in the Santerno Valley (Fig. 33), the initial effect of gliding was the development of SW-dipping normal faults dismembering the evaporite unit.

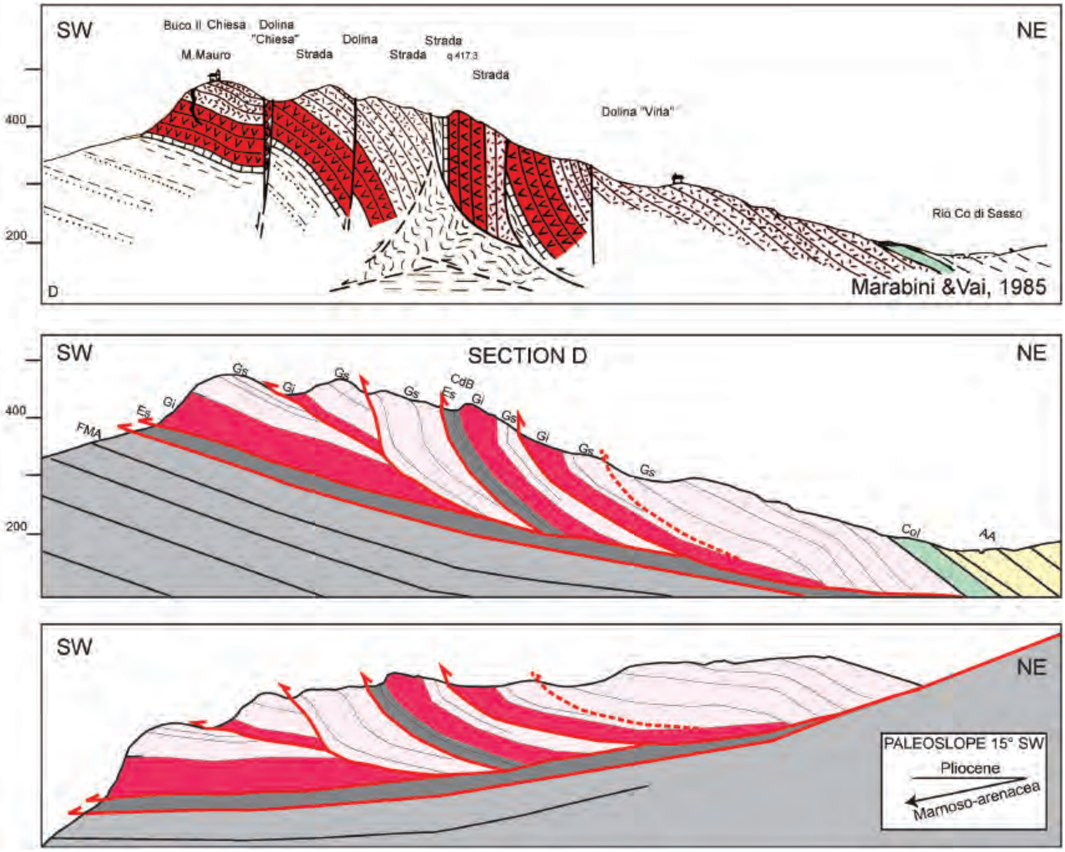
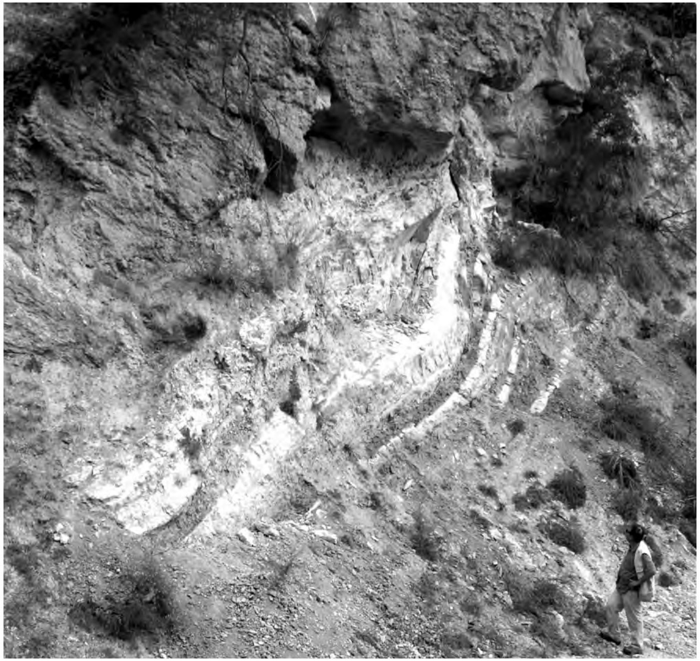


Fig. 39 - (A) Gypsum slide blocks of the Sintria valley (based on Marabini and Vai, 1985, section D). (B) The present-day interpretation; M/P—Miocene/Pliocene unconformity; p-ev2 - postevaporitic unit 2. (C) When removing the Pliocene to Holocene deformation, a southward-dipping late Messinian paleoslope appears. MA - Marnoso-arenacea. The steepening of such a paleoslope during the intra-Messinian tectonic phase triggered large-scale slope instability phenomena and promoted the collapse and accumulation of huge gypsum slabs. After Roveri et al., 2003.



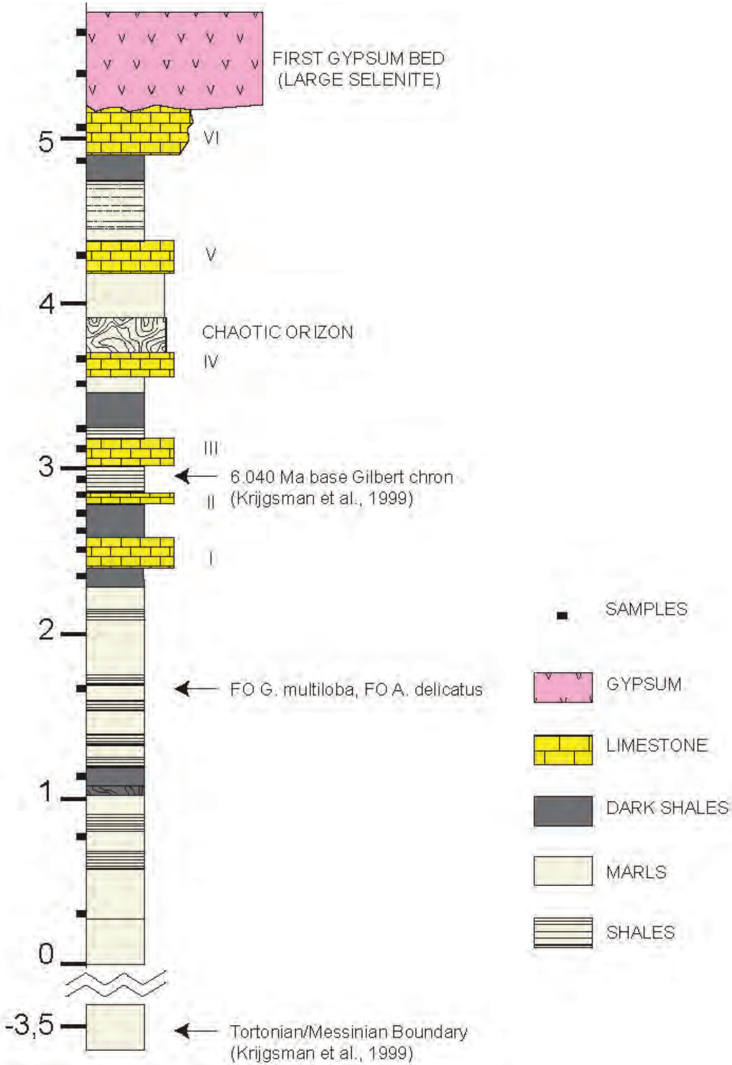


Fig. 40 – Stop 1.6, Monticino open-air museum. The base of gypsum unit; note the cyclically interbedded sapropels and carbonate layer in the uppermost part of the euxinic shales. To the right, sedimentary log of the section (modified from Manzi, 2001). Note the FO of G. multiloba just below the lowermost carbonate bed and the Tortonian-Messinian boundary 8 m below the base of gypsum. Actually the section shows some deformed horizons and shear planes in the euxinic shales, probably explaining in part the reduced thickness of this interval compared to other sections (M. del Casino). However the main bio-magnetostratigraphic markers of this time interval have been observed as a normal stratigraphic order, suggesting that thickness reduction could also have primary, depositional motivations (Manzi, 2001; Roveri et al., 2003).

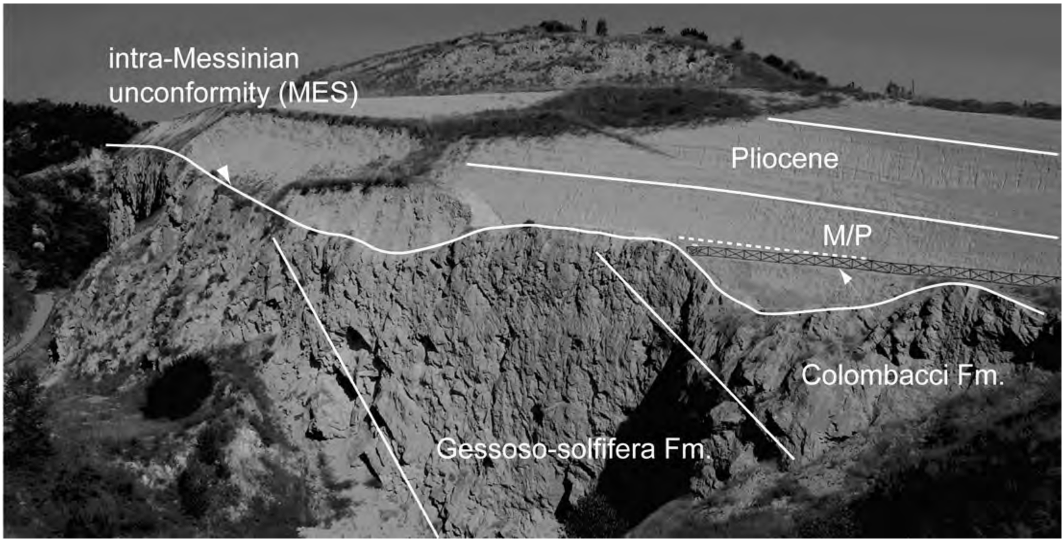


Fig. 41 – Stop 1.6, Monticino Quarry, Brisighella: the mining front represents the best exposure of the angular unconformity between the depositional sequences T2 and p-ev2. Some fractures sealed by the unconformity have been highlighted for their virtual relationship to the famous Vertebrate-bearing upper Messinian sedimentary dykes.

in its lower parts the faulted blocks keep gliding, and thrust over each other. This way, a stack of uprooted rock slices forms in the lower parts of the slope. Summarizing, by a merely structural point of view the back-thrusts cropping out in the Sintria and Lamone valleys are likely to have formed by gravitational failure and gliding. Other valid reasons are reviewed in the introduction of this Guide.

Topics:1, 2

Stop 1.6 - Brisighella: the Monticino Sanctuary and the adjoining gypsum quarry recently converted into an open-air geologic museum. This stop allows to put fingers on three key Messinian surfaces: the base of gypsum, the intra-Messinian unconformity and the Miocene-Pliocene boundary.

The base of gypsum and the uppermost euxinic shale unit, comprising up to six (according to Krijgsman et al., 1999; Fig. 40) carbonate layers cyclically interbedded with sapropels are well exposed in the southern part of the quarry (Cava Li Monti section in Krijgsman et al., 1999); the lower Messinian euxinic shale section is here extremely reduced in thickness and the Tortonian-Messinian boundary has been found only some 8 meters below the base of gypsum (Krijgsman et al., 1999).

Magnetostratigraphic studies showed that gypsum and the uppermost 4 carbonate beds have a inverse polarity (chron C3r), while the two lower ones show normal polarity; thus, a paleomagnetic reversal, aged at 6.04$\pm$0.01 Ma, occurs between the second and the third carbonate bed. These data allowed to date the base of the evaporite unit at 5.96$\pm$0.02 Ma (Krijgsman et al., 1999). Stratigraphic and palaeoenvironmental characteristics and implications of this interval will be discussed.

The 1st and 2nd selenite cycles are visible. These cycles are both composed of giant selenite crystals (massive selenite, EF 3) up to 1,5 m tall. The 2nd selenite cycle sits on top of a thin gypsrudite (EF 6) layer deformed by load.

Deformation and emersion of the evaporite unit in late Messinian times are testified by an impressive angular unconformity between the Gessoso-solfifera Fm and the Colombacci Fm (Fig. 41). The latter in turn is overlain through a sharp, conformable surface, by open marine Zanclean deposits. Subaerial erosion of gypsum is documented by karstic neptunian dikes sealed by post-evaporite Messinian deposits (p-ev$_2$). From 1985 to 1988, a very rich fauna of continental Vertebrates has been found in these paleo-karsts (Marabini & Vai, 1989, Costa et al., 1986; De Giuli et al., 1988).

Topics: 1, 2, 3, 11

Transfer to S. Agata Feltria

Stop 1.7 - Savio valley, panoramic views along the National road to Mercato Saraceno (Fig. 42). The Upper Tortonian-Lower Messinian succession of the Savio valley: correlation with the Santerno valley (Fig. 43).

Topics: *1, 4*.

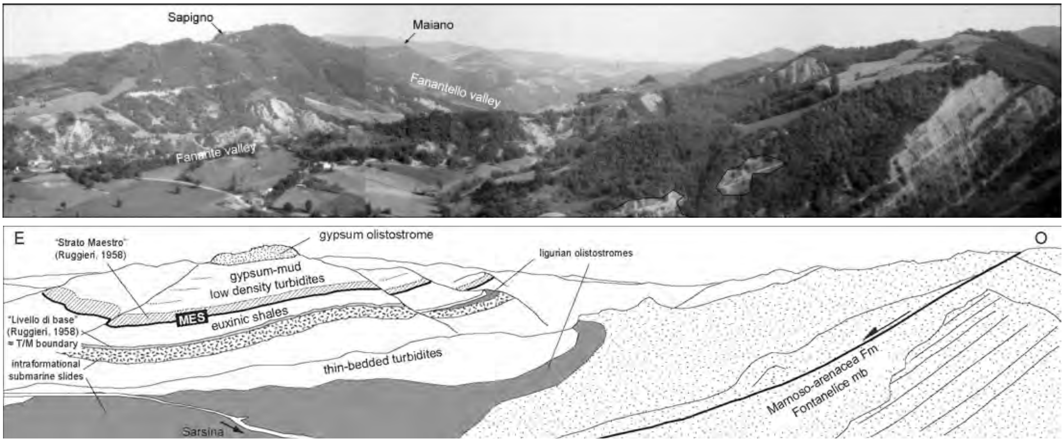


Fig. 42 – Stop 1.7. Savio valley, panoramic views along the National road to Mercato Saraceno. From Roveri et al., 1999).

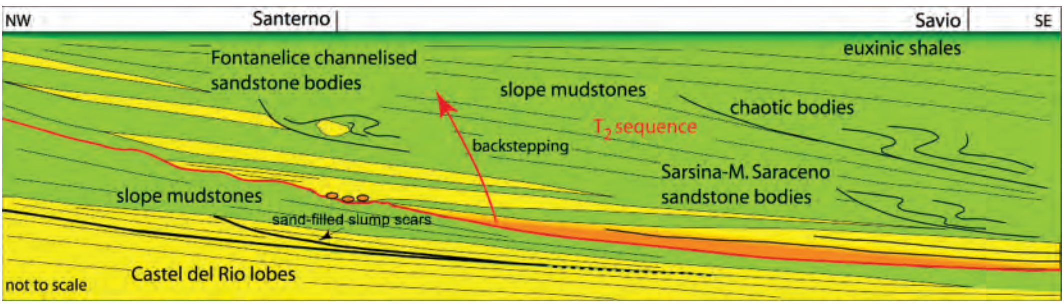


Fig. 43 – Suggested along basin correlation of upper Tortonian deposits between the Santerno and Savio valleys (datum plane: ~ the Tortonian/Messinian boundary; From Roveri et al., 2002).

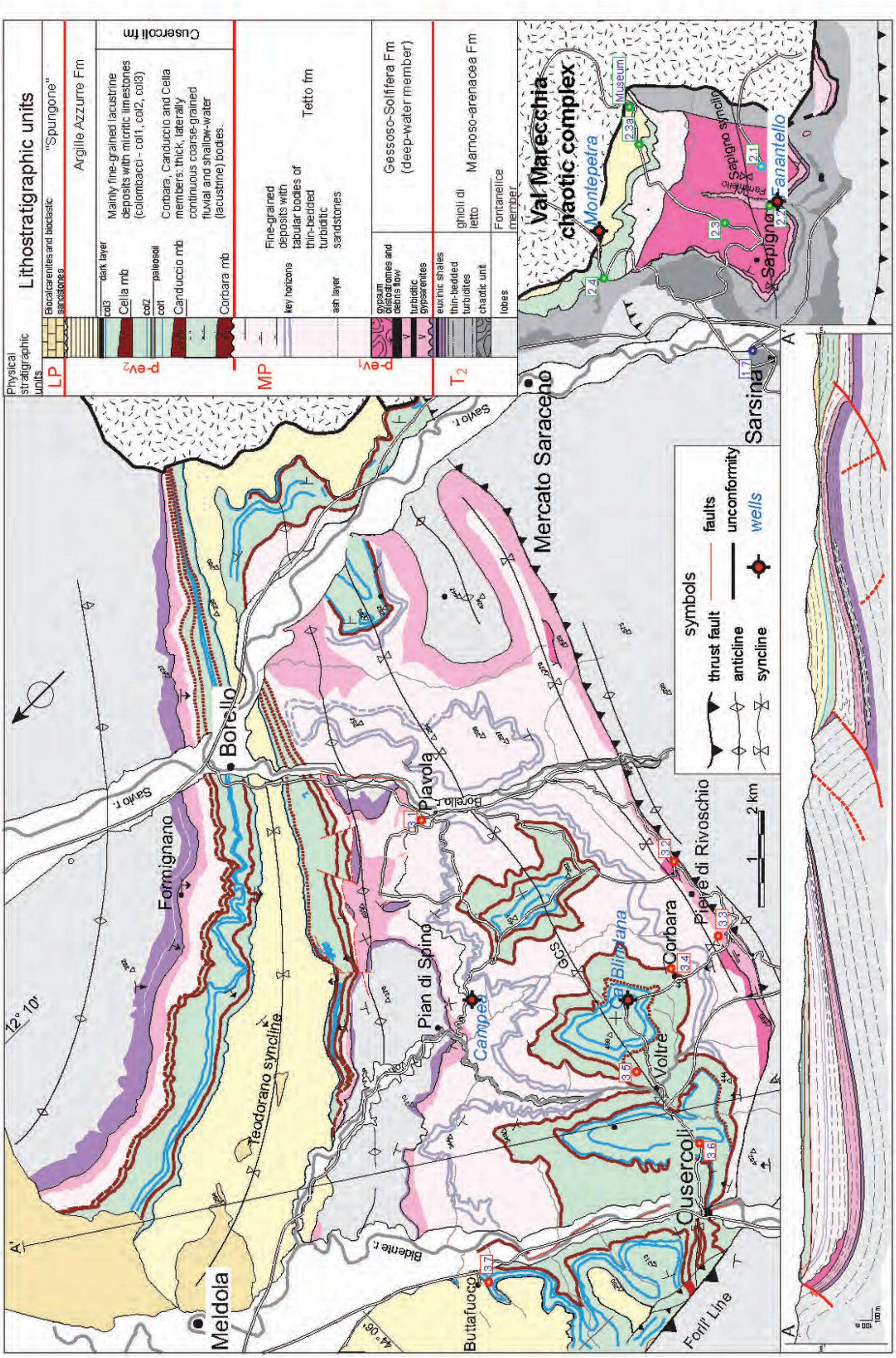


Fig. 44a – Geological map of the eastern sector.

INTRODUCTION TO DAY 2 AND 3

In the Santerno to Lamone sections we examined a reduced, Mediterranean-type Messinian succession, developed above a structural high (Fig. 4). An abrupt facies and thickness change within the successions across the Forlì line that separates the marginal Vena del Gesso basin to the west from the eastern Romagna basins, is the best evidence of the strong structural control on Messinian deposition (Fig.7).

In the Savio valley area, we will examine Messinian deposits cropping out in the Sapigno and Giaggiolo-Cella synclines (see geological map of Fig. 44 and stratigraphic model of Fig. 44a), two wedge-top basin bounded to the west by the Forlì thrust and filled up with more than 600 m of mainly post-evaporitic deposits. Shallow-water primary evaporites are lacking and are replaced by resedimented evaporites (turbiditic gypsarenites, olistostromes, olistoliths and breccias made up of selenitic and alabastrine gypsum). Sedimentary features (graded beds with erosional bases, traction plus fallout structures, sole marks, load casts, climbing ripples, coarse-grained beds deposited by hyperconcentrated flows, debris flow,

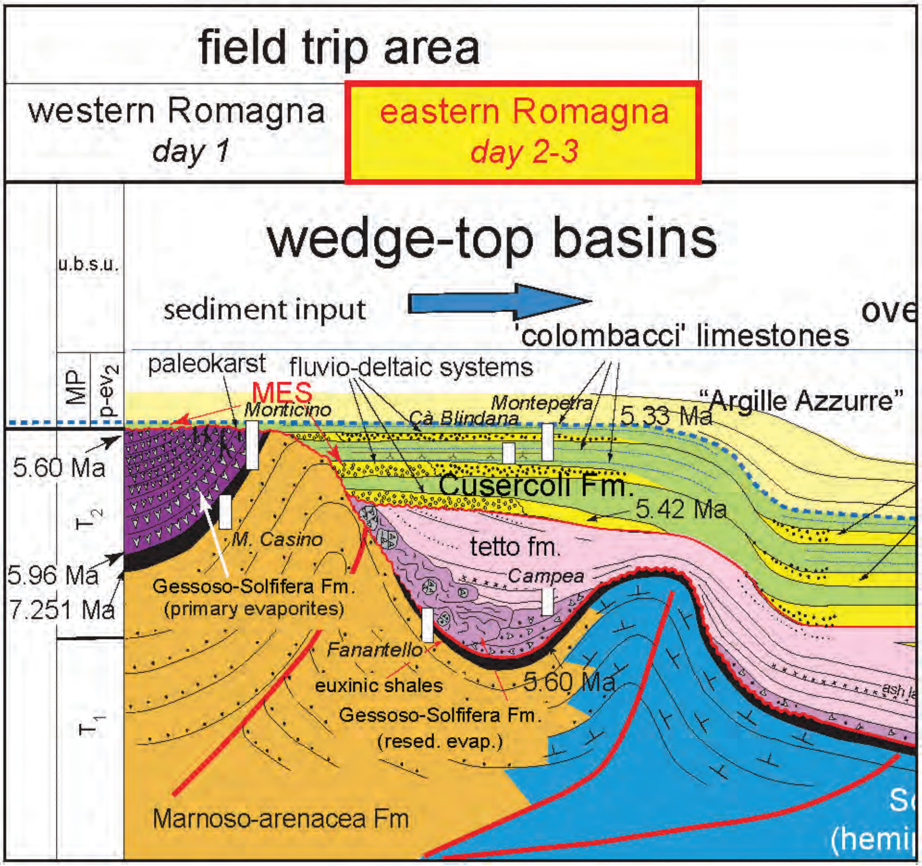


Fig. 44b – Close-up of figure 6, showing the stratigraphic relationships between Messinian units and the ubication of main sections and cores.

small to large-scale intraformational slumpings) shows that these gypsum facies were deposited by gravity flows in a subaqueous setting. Siliciclastic deposits form the bulk of basin fill during the post-evaporitic stage. A very high sedimentation rate of more than 2mm/a reflects the ongoing tectonic uplift and erosion of the Apennine chain following the intra-Messinian phase. Facies characteristics, paleoenvironmental meaning and cyclic stacking pattern of latest Messinian deposits will be also dealt with during these two days.

DAY 2

Stop 2.1 – Road Sarsina - S.Agata Feltria, deviation to Maiano. Panoramic view of the resedimented evaporites complex of the Fanantello section (Fig. 45). Body geometry and stacking pattern.

Topics: *3, 4.*

Stop 2.2 – Road Sarsina-S. Agata Feltria: the Rio Fanantello section (1h walk along the 'Fanantello gorge'). The basal, stratified part of the resedimented evaporite complex crops out along the river bed offering a spectacular chance for a close view of facies characteristics of the clastic gypsum facies (Fig. 46, 48). The stratigraphic and palaeoenvironmental data of the local pre-evaporitic deposits interpreted as coeval of the Vena del Gesso primary evaporites will be presented and discussed. ***Topics:*** *4, 5.*

THE FANANTELLO CORE

The Fanantello core has been drilled on the left side of Fanantello stream valley a few tens of meters distance from a landslide crown which expose a more than 40 m thick succession that has been object of previous studies (Manzi, 2001; Roveri and Manzi, 2006; Manzi, 2005b). Within the Fanantello Section, four main lithological units have been defined; from the bottom they are (Fig. 47):

- Unit A (bottom – 112.8 m), consisting of 26 dm- to m-thick lithological cycles made up of the

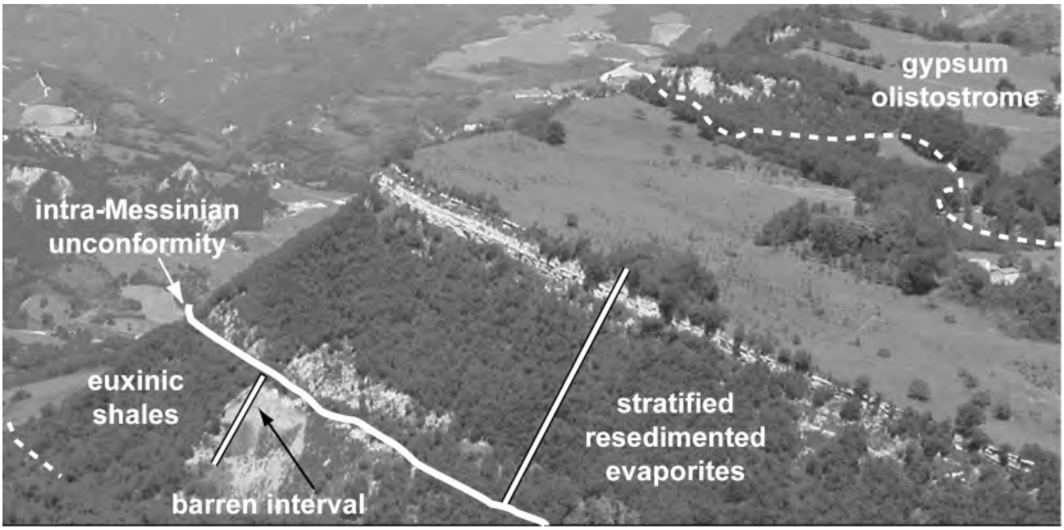


Fig. 45 – Stop 2.1. Panoramic view looking west from Maiano of the Messinian succession of the Sapigno syncline. Note the clear bipartite character of the resedimented evaporite complex overlying the local euxinic shales: a lower gypsarenitic stratified unit is overlain through an irregular surface by a huge chaotic gypsum complex.

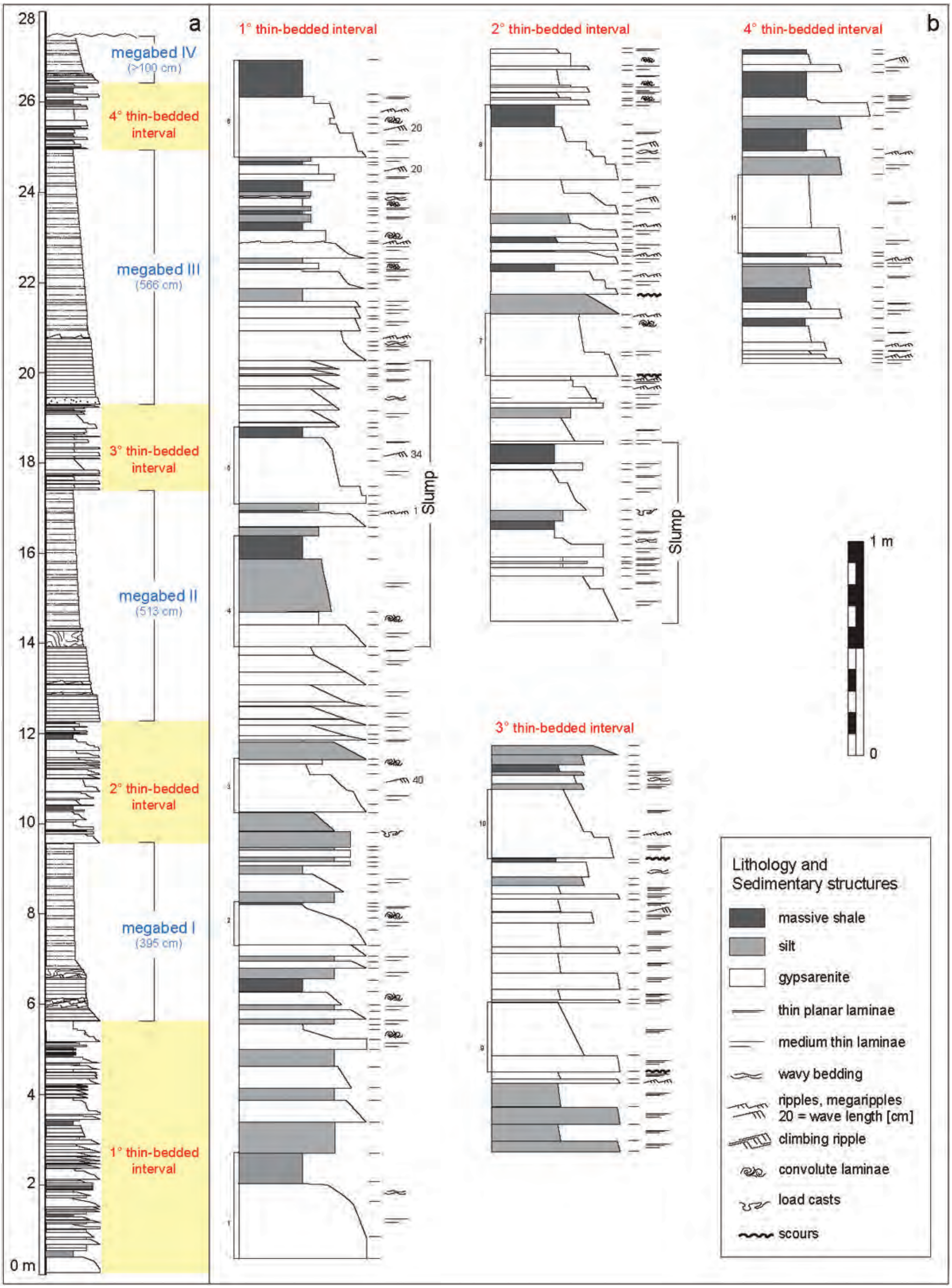


Fig. 46 – Detailed sedimentologic log of the lower part of the clastic evaporitic unit ("strato maestro"). From Manzi et al., 2005.

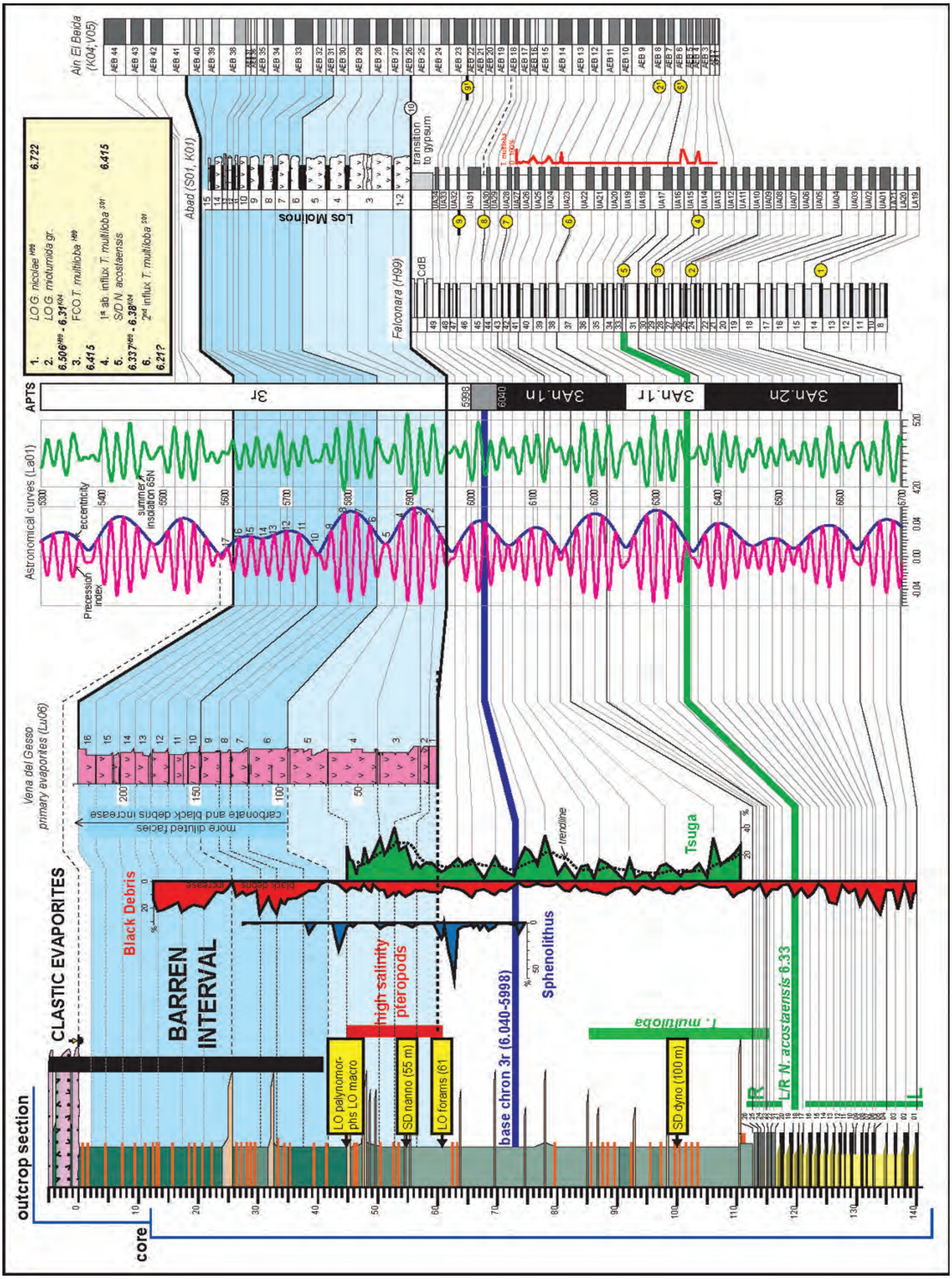


Fig. 47 – Age model of the Fanantello section and correlation with Mediterranean reference sections: Falconara (Hilgen and Krijgsman, 1999; H99); Sorbas including Abad (Sierro et al., 2001; S01) and Los Molinos (Krijgsman et al., 2001; K01), Ain El Beida (Krijgsman et al., 2004; K04; van der Laan et al., 2005; V05); Vena del Gesso (Lugli et al., 2005; Lu05). The astronomical solution of Laskar 2001 (La01) has been adopted.

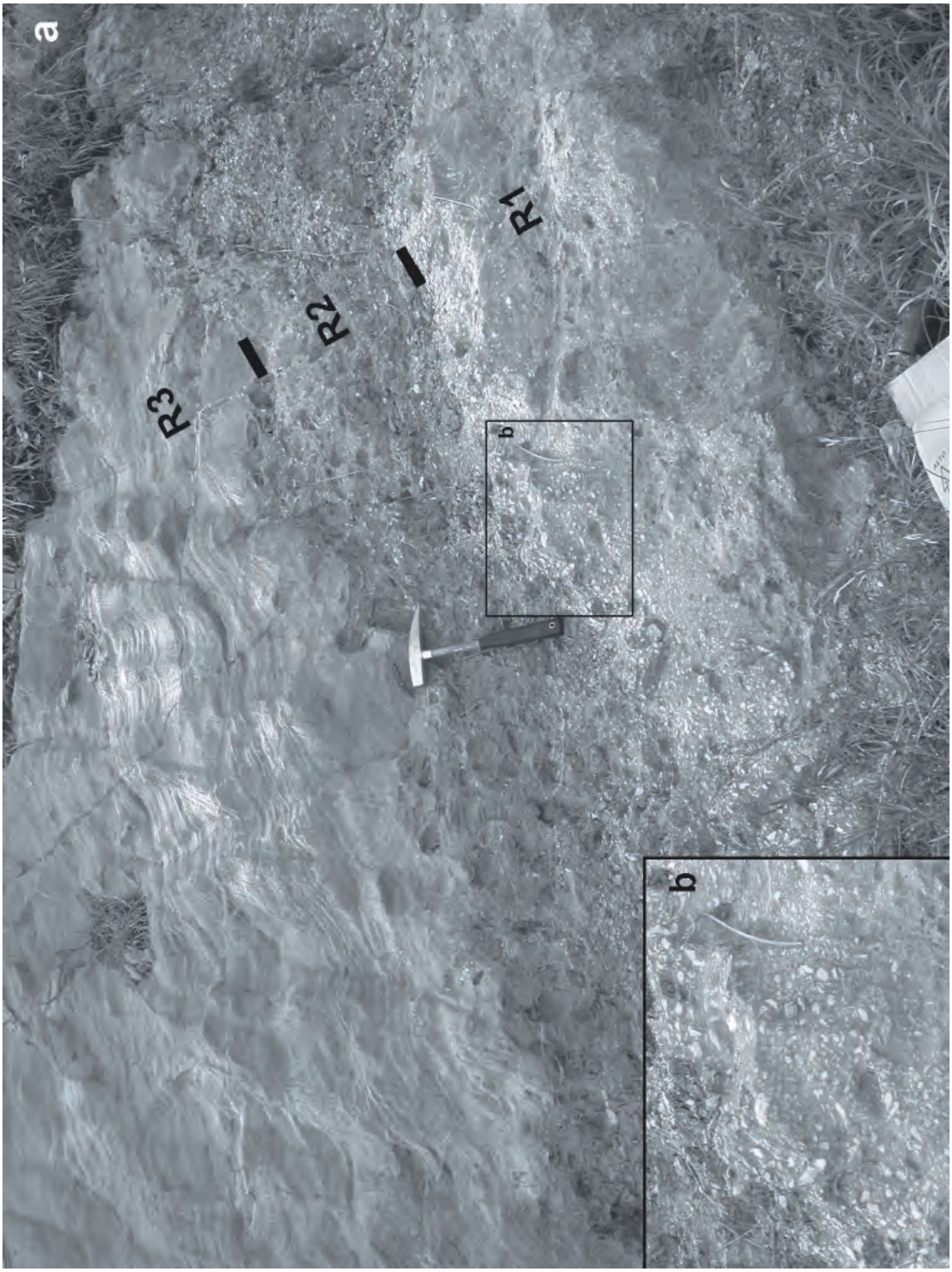


Fig. 48 - Inner basin evaporites. a) Composite graded bed showing a coarser-grained basal portion (R1 facies) consisting of an organic-rich shaly matrix-supported gypsrudite made up of either fragments or preserved twinned selenitic and prismatic gypsum crystals (enlarged in b). A sharp surface separates this "parent flow" deposit from an overlying clay-chip rich massive coarse gypsarenite (R2 facies). In turn this interval is abruptly capped by a thick plane-bedded to low angle cross-bedded gypsarenite interval (R3 facies). This composite bed represents the proximal stage of a single event of evaporite resedimentation; its distal evolution can be considered to be a low-density turbiditic gypsum-bearing flow. Slab enclosed in the upper chaotic member of the resedimented evaporites. Sapigno syncline, northern Marche.

alternation of dark organic matter-rich laminated clays, in the lower portion, and whitish bioturbated marls, in the upper part. The base of the cycles, *i.e.* the base of the sapropel, is commonly sharp whereas the passage between the sapropel and the marls is often transitional; in this case a third grey clay interval can be defined.

- Unit B (112.8 – 45 m), made up of dm- to m-thick thin-bedded turbidite layers mainly referable to t_{b-d} Bouma sequences. This unit show scarce fossil content.

- Unit C (45-top), made up of euxinic shales with rare thin limestone and thin-bedded turbidite beds. This unit, that appear almost barren, is characterised by an increase of dolomite content of clastics, that could be related to evaporite environment in adjacent areas.

- Unit D, consisting of a over 150 m thick succession of clastic evaporites which representi the product of the dismantlement of Lower Evaporites from adjacent uplifted basins, *e.g.* the Vena del Gesso basin (Manzi et al., 2005a).

The pre-evaporitic successions show a well developed lithological cyclicity produced by the alternation of whitish marls and dark euxinic shales that has been recognised and astronomically calibrated and correlated throughout the Mediterranean succession (Krijgsman et al., 2004 with references).

According to this generally accepted bio-magneto-stratigraphic framework, within the Fanantello section, the recognition of a thick reverse magnetic interval below the clastic evaporites lacking evidences of erosion surfaces, led to refer the N/R palaeomagnetic inversion recognised at 73 m depth to the base of the Gilbert Chron (chron 3r) which can be assigned an age ranging between 5.998 and 6.040 Ma (Krijgsman et al., 1999; Krijgsman et al., 2004; van der Laan, 2005).

The main biostratigraphic events identified in the sampled succession, reported in Fig. 47; are the following: *G. miotumida* gr. distribution (bottom - 137.63 m); *N. acostaensis* left coiling distribution (bottom - 121.26); *N. acostaensis* right coiling distribution (115.9 - 110.6); *T. multiloba* distribution (114.63 - 85.3 m). This allows to define a Lower Messinian age for these deposits. Furthermore, using the cyclicity pattern of Unit A, a more accurate age can be defined. The datation of the Fanantello section using an integrated stratigraphy approach indicates between 60 and 65 m the possible base of the deep-water counterpart of the primary evaporites of the peripheral Mediterranean basins. Analysing the main biostratigraphic and palaeoenvironmental events of the Fanantello section, three important events can be identified: 1) the foraminifera last occurrence (61 m); 2) the base of the mollusc biozone c characterised by a pteropods monospecific assemblage (61 m); 3) the first peak of *sphenolithus* sp. (62.77 m). These bioevents could indicate a palaeoenvironmental stress probably imputable to an increase of the water column salinity. It is notable that the disappearance of both benthos and plankton has been never described before in pre-evaporitic successions overlain by primary evaporites (Vena del Gesso basin; Krijgsman et al., 1997; Calieri, 1998; Negri and Vigliotti, 1997; Vai, 1997; Kouwenhowen et al., 1999; Sorbas basin; Baggley, 2000; Sierro et al., 2001; Krijgsman et al., 2001; Sicily; Hilgen et al., 1995; Krijgsman et al., 1995, 1996; Sprovieri, 1996).
Topics: *4.*

Stop 2.3 – Road Sapigno-Perticara. Panoramic view of the gypsum olistostrome and of the post-evaporitic Lago Mare succession of the Sapigno syncline.
Topics: *4, 7.*

Stop 2.3a (*optional*) – Perticara: visit to the local Mine Museum and discussion on the genesis of sulphur mineralisations associated to clastic gypsum deposits.
Topic: *6.*

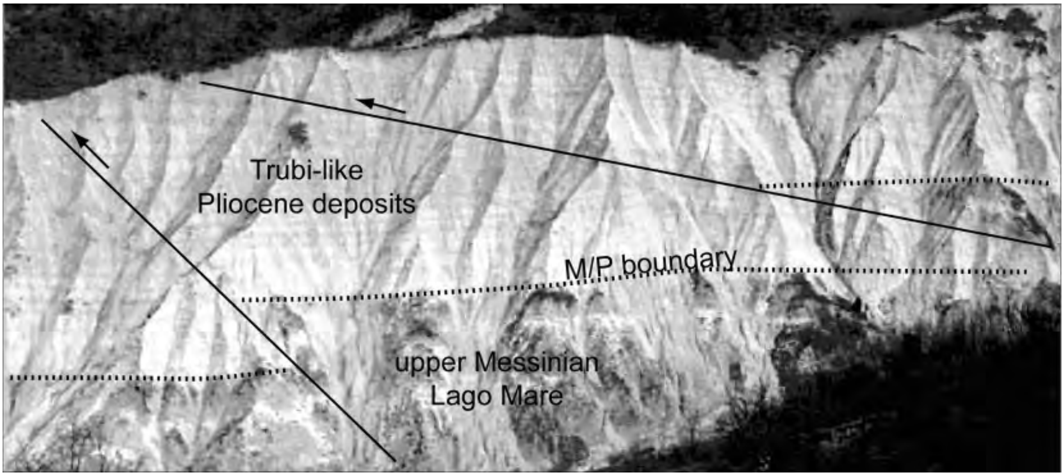


Fig. 49 – Stop 2.4. Park area of Montepetra. The Messinian-Pliocene boundary in the Rio Nasseto section (Sapigno syncline). The Montepetra core was collected just at the right end of the outcrop section. Note the reverse fault offsetting the succession and the well-developed cyclic pattern of the Pliocene marine deposits.

Stop 2.4 - Montepetra. Panoramic views and core data (Montepetra core) of the uppermost Messinian (Lago Mare) deposits and the Miocene/Pliocene transition (Fig. 49).
Topics: *8, 9, 10, 11.*

THE MONTEPETRA CORE

The Montepetra borehole, drilled with the contribution of ENI-AGIP, is located in the Sapigno syncline; the 80 m long sediment-core recovered spans the stratigraphic interval comprised between the upper Messinian *Lago-Mare* and the Lower Zanclean marine deposits.

According to Bassetti et al. (1994, 2004 with refs.) and Roveri et al. (1998, 2001), the cored succession belongs to the p-ev$_2$ unit. These deposits represent the superimposition of at least two lithological fining-upward cycles, each of them showing coarse to medium-grained sandstones bodies at the base and a gradual upward transition to massive and finely laminated clays. The occurrence of a pedogenetic horizon and of a micritic “colombacci” limestone horizon as well as a dark bed at the Messinian/Zanclean boundary are key elements for the reconstruction of the paleoenvironmental evolution and for stratigraphic correlations in the Northern Apennine foredeep. The samples collected approximately every 1 m yielded brackish ostracods with Parathethyan affinity, referable to the *Loxocorniculina djafarovi* Zone (Carbonnel, 1978), together with scarce and partially reworked benthonic foraminifera (only *Ammonia tepida*, *Elphidium* spp. and *Florilus boueanum* are considered in situ); planktonic foraminifera and calcareous nannoplankton are characterized by poor and reworked assemblages (A. Di Stefano, pers. comm.).

The ostracod fauna collected in the Montepetra core contains 19 species referable to 11 genera: *Amnicythere idonea* (Markova), *Amnicythere propinqua* (Livental), *Amnicythere costata* (Olteanu), *Amnicythere palimpsesta* (Livental), *Amnicythere* sp.A Miculan in Bassetti et al., *Amnicythere* sp. D. Miculan in Bassetti et al., *E.* (*Maeotocythere*) *praebaquana* (Livental), *Cyprideis* sp. 5 Gliozzi & Grossi, *Cyprideis agrigentina* (Decima), *Cyprideis anlavauxensis* Carbonnel,

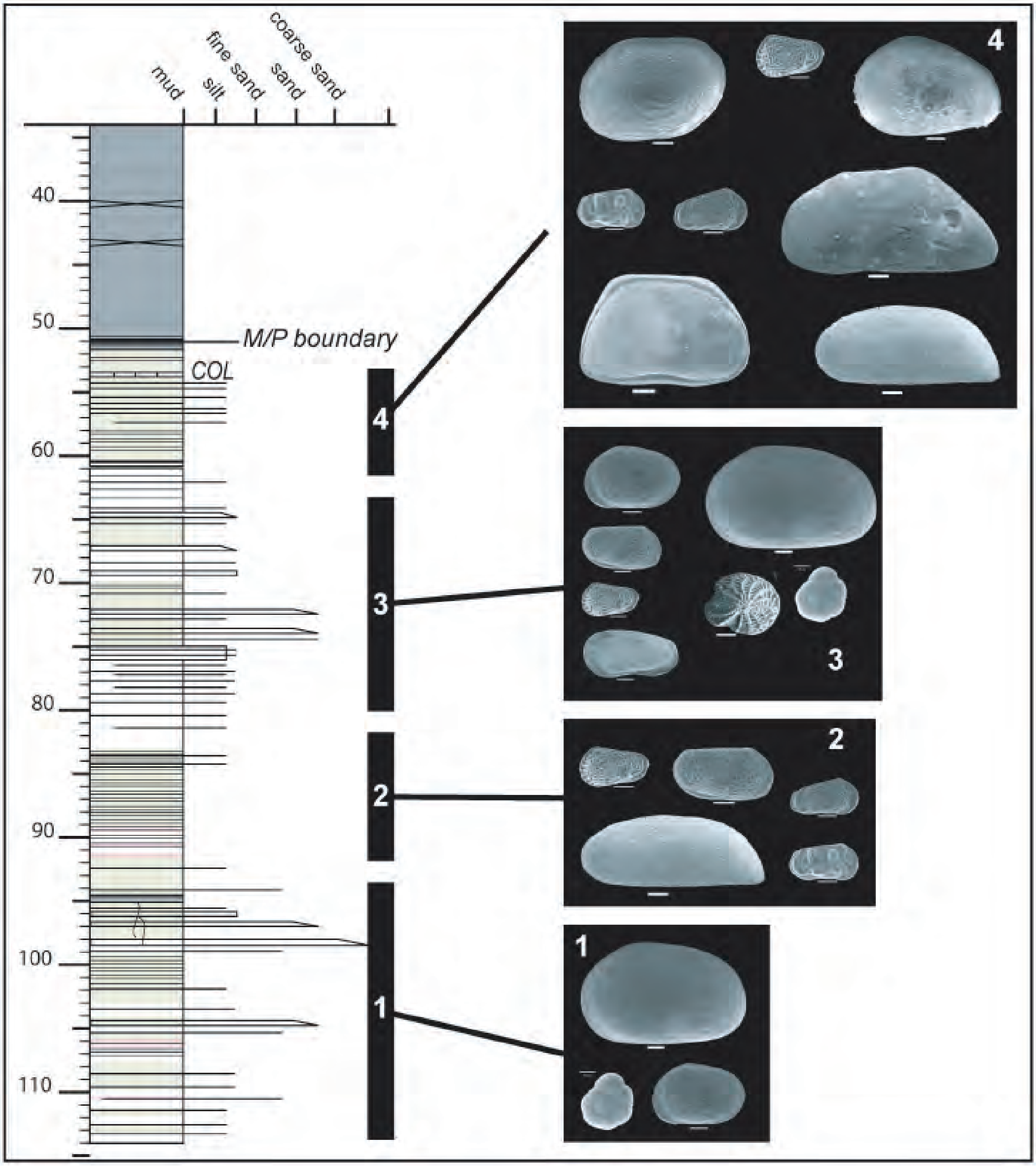


Fig. 50 - Lithology and ostracod assemblages of the Montepetra core.

Loxoconcha mülleri (Mehes), *Loxoconcha eichwaldi* Livental, *Loxocorniculina djafarovi* (Schneider), *Loxoconchissa* (*Loxocaspia*) sp., *Caspiocypris pontica* (Sokac), *Cypria* sp., *Pontoniella pontica* (Agalarova), *Zalanyiella venusta* (Zalanyi), *Tyrrhenocythere ruggierii* Devoto.

Since few of these species are extant, little data exists on the ecology of the recovered ostracod fauna: Leptocytheridae are characteristic of shallow water (down to 100 m depth) and oligo-mesohaline waters (optimum 12.5-13.5‰ (Gofman, 1966; Yassini & Ghahreman, 1976; Boomer et al., 1996). At a generic level, the "pointed Candoninae" (*Pontoniella* and *Zalanyiella*) are characteristic of shallow to deep water (down to some hundreds m) and fresh-oligohaline conditions (Gofman, 1966; Gliozzi & Grossi, 2004), *Cyprideis* is strongly eurihaline and characteristic of very shallow water (optimum < 10 m) (Neale, 1988, with refs.). The late Messinian Lago Mare event, even of short duration, was affected by several climatically driven environmental changes, concerning particularly salinity and depth variations, and the ostracods have shown

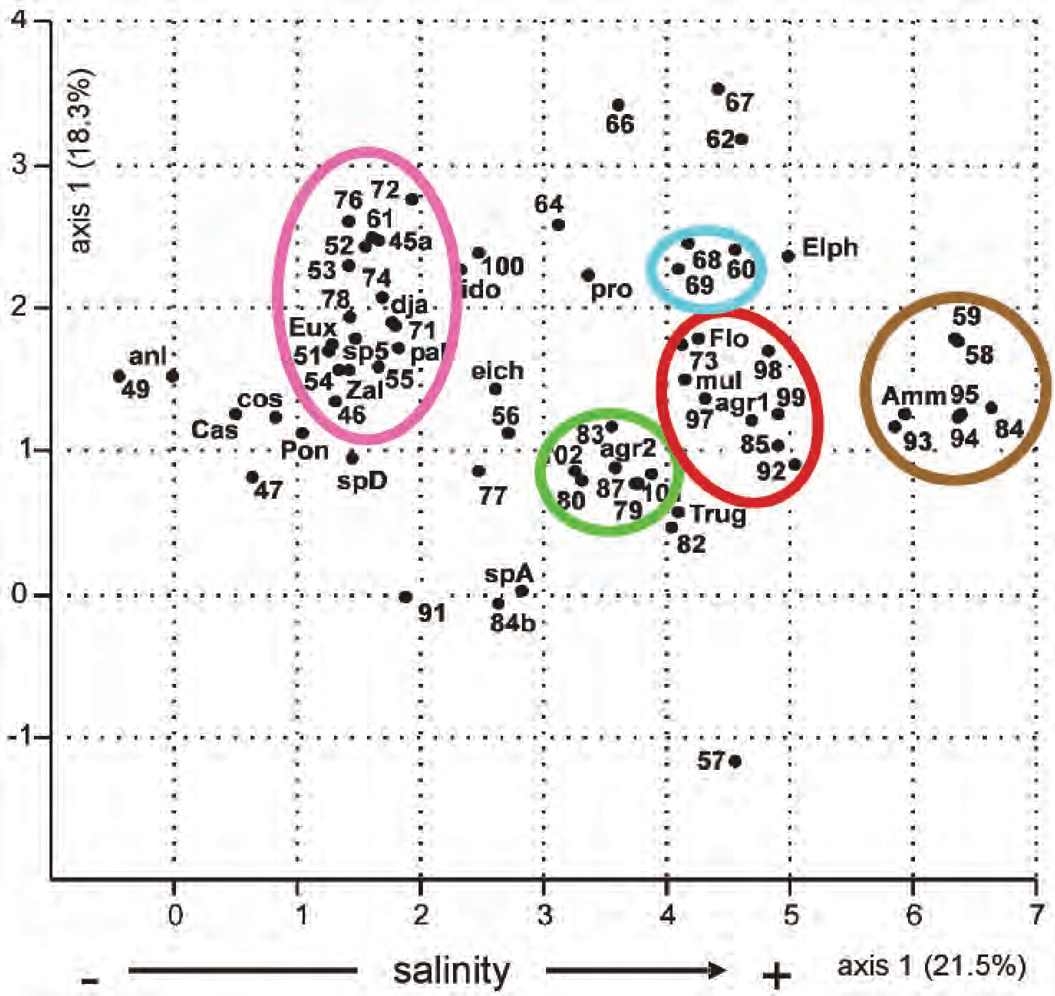


Fig. 51 - DCA ordination plot (Axis 1/Axis 2) of samples and species (Q-mode).

to be a very useful tool to describe in detail these palaeoenvironmental changes. At Montepetra it is possible to recognize the following assemblage clusters (Fig. 50):

1 - from the bottom of the core up to about 93 m (samples 102-83) the low-diversity assemblages are dominated by *Cyprideis agrigentina, Loxoconcha mülleri* and the benthonic foraminifer *Ammonia tepida*

2 - up to 81 m (samples 82-71) an increase in the diversity indexes, with *Zalanyiella*, Loxoconchidae and Leptocytheridae, is observed;

3 - from 80 up to 62 m (samples 70-57) the assemblages are similar to the first cluster, with an increase in the diversity: *Cyprideis agrigentina* and *Loxoconcha mülleri* are prevalent, with *Ammonia tepida, Elphidium* spp., *Tyrrhenocythere ruggierii* and few Loxoconchidae and Leptocytheridae

4 - from 61 up to the top of the Messinian portion of the core (samples 56-45) the high-diversity assemblages contain all the Candoninae species, *Loxocorniculina djafarovi* and other Loxoconchidae, Leptocytheridae and *Cyprideis* sp.5.

Both the *in situ* ostracod and benthic foraminifer assemblages have been studied with a multivariate approach, using the Detrended Correspondence Analysis (DCA) (Fig. 51).

Considering the ecological data and the distribution of both samples and species in different groups in the DCA Q-mode plot, it is possible to suggest that Axis 1, which account for the 21.5% of the relative variance, should represent the ecological parameter "salinity".

Thus, these results show that the salinity was the main parameter that drove the environmental changes, and it spans cyclically from high mesohaline (assemblages dominated by *Ammonia tepida* and *Cyprideis agrigentina*) to low mesohaline in the lower part of the core up to 81.52 m, and from middle mesohaline to oligohaline in the upper part up to 52.8 m. Depth variations within the Messinian deposits are not remarkable, except for two deepening trends around 83.54-81.52 m and 53.91-53.59 m, testified by the occurrence of the "pointed Candoninae" *Zalanyiella* and *Pontoniella*. These deepening events are in agreement with the lithologic cycles and palynological data (Biffi, pers. comm.)

The palaeoenvironmental change at the M/P boundary is marked by a dark, relatively organic rich bed, lacking of any fossil record; no evident sign of paleosoil was found below this horizon, but the above deposits show a sharp change in the fossil content testifying the restoration of open marine conditions. Ostracods disappear and benthic foraminifera become scarce (with P/(P+B) ratio slightly minor then 100%), poorly diversified and indicating deeper bathymetry or unfavourable, anoxic bottom condition, as suggested by the 50 cm laminated clays representing the very base of Zanclean deposits. Above, benthonic foraminifera increase in diversity, but planktonic foraminifera remain dominant in the assemblage. Finally, paleomagnetic, biostratigraphic and cyclostratigraphic evidences indicate for the base of the Zanclean deposits an age very close to 5.33 Ma age, as inferred by the recognition of: a) the *Neogloboquadrina acostaensis* sinistral coiling influx, pre-dating the acme of *Sphaeroidinellopsis* spp.; b) a normal interval starting at 45 m and characterising the overlying Zanclean deposits, that is assumed as the base of the Thvera normal magnetic interval.

Stop 2.5 (*optional*) – Montepetra. Close inspection of the Montepetra "Lucina limestone", a late Tortonian-early Messinian deep-water chemioherm related to cold fluid seepage at the sea-floor. Lucina limestones represent a classic topic for Apennine's geology; their time and space distribution suggest a strong relationships with the structural evolution of the Apennine thrust belt.

DAY 3

Stop 3.1 - Road Piavola - Pian di Spino. Northern limb of the Giaggiolo-Cella syncline.

Panoramic and close views on general facies and physical-stratigraphic characteristics of the basal post-evaporitic succession; the transition to hyposaline conditions - the 5.51 Ma ash layer - sinsedimentary Messinian tectonics. Facies details of the p-ev$_1$ deposits in the Campea core.

Topics: *7.*

The **Campea core** (Fig. 52) was collected on the northern flank of the GCS; it spans the lower part of the p-ev$_1$ unit up to the ash layer. The lowermost 4 meters consists of gypsarenites, passing upward to clayey deposits with thin-bedded and fine-grained sandstones intercalations that represent the dominant lithotype. Sedimentary structures indicate a turbiditic nature, suggesting a relatively deep-water depositional setting (prodelta slope). The ash layer present at the top of the core correlates with the one dated by Odin et al. (1997) in the surrounding outcropping area at 5.51$\pm$0.04 Ma.

Foraminifera and nannoplankton (A. Negri, pers. comm.) are only occasionally abundant and are considered reworked; ostracode are present in just one sample at 55 m, where a few *Cyprideis* sp. was found. According to palinofacies analysis the section can be subdivided in 4 intervals respectively characterised by:

1. brackish water condition, no erosion, arid and scarce vegetation;

2. abundant reworking from cretaceous (ligurian units);

3. presence of *Impagidinium* spp., suggesting brackish water condition (this is the lowermost Lago Mare signal found in the p-ev$_1$ unit);

4. reduced reworked taxa and erosion, anoxic horizons at 49.77 m and 49.89 m.

The absence or scarcity of most of the typical "Lago-Mare" assemblages suggests a very unfavourable paleoenvironment, very common at the base of p-ev$_1$ unit of the Northern Apennine; this aspect is much evident in the horizon at around 50 m where high values of organic matter and pyrite suggest anoxic bottom waters.

Stop 3.2 – Road to Pieve di Rivoschio. Southern limb of the Giaggiolo-Cella syncline. Close view of an exceptionally thick gypsum layer (>12 m) deposited by large-volume, high-density gravity flows (Fig. 53). Like siliciclastic turbiditic beds, this gypsum layer has a lower coarser division with large-size mudstone clasts eroded and incorporated within the flow head, and an upper fine-grained laminated division with possible evidence of flow rebound. Gypsum recrystallization makes it difficult to assess the original textures, but general facies characteristics are still well recognizable.

Topics: *4, 5, 7.*

Stop 3.3 – Road Pieve di Rivoschio – Voltre. Panoramic views of the post-evaporitic succession cropping out in the Giaggiolo-Cella syncline from its southern flank; general depositional characteristics, sedimentary trends and stratigraphic architecture of the p-ev$_2$ unit (Cusercoli fm). This unit is made up of three backstepping fluvio-deltaic coarse-grained bodies separated by lacustrine clays characterized by thin, laterally persistent limestone horizons (*colombacci limestones*).

Topics: *8*

Stop 3.4 – Road Pieve di Rivoschio - Voltre (close view) - Corbara. Flood-dominated, fluvio-deltaic systems of the p-ev$_2$ unit. Close view of the coarse-grained deposits forming the base of small-scale cycles (Fig. 54). They consist of tabular bodies made up of amalgamated massive sandstones and pebbly sandstones, with scoured

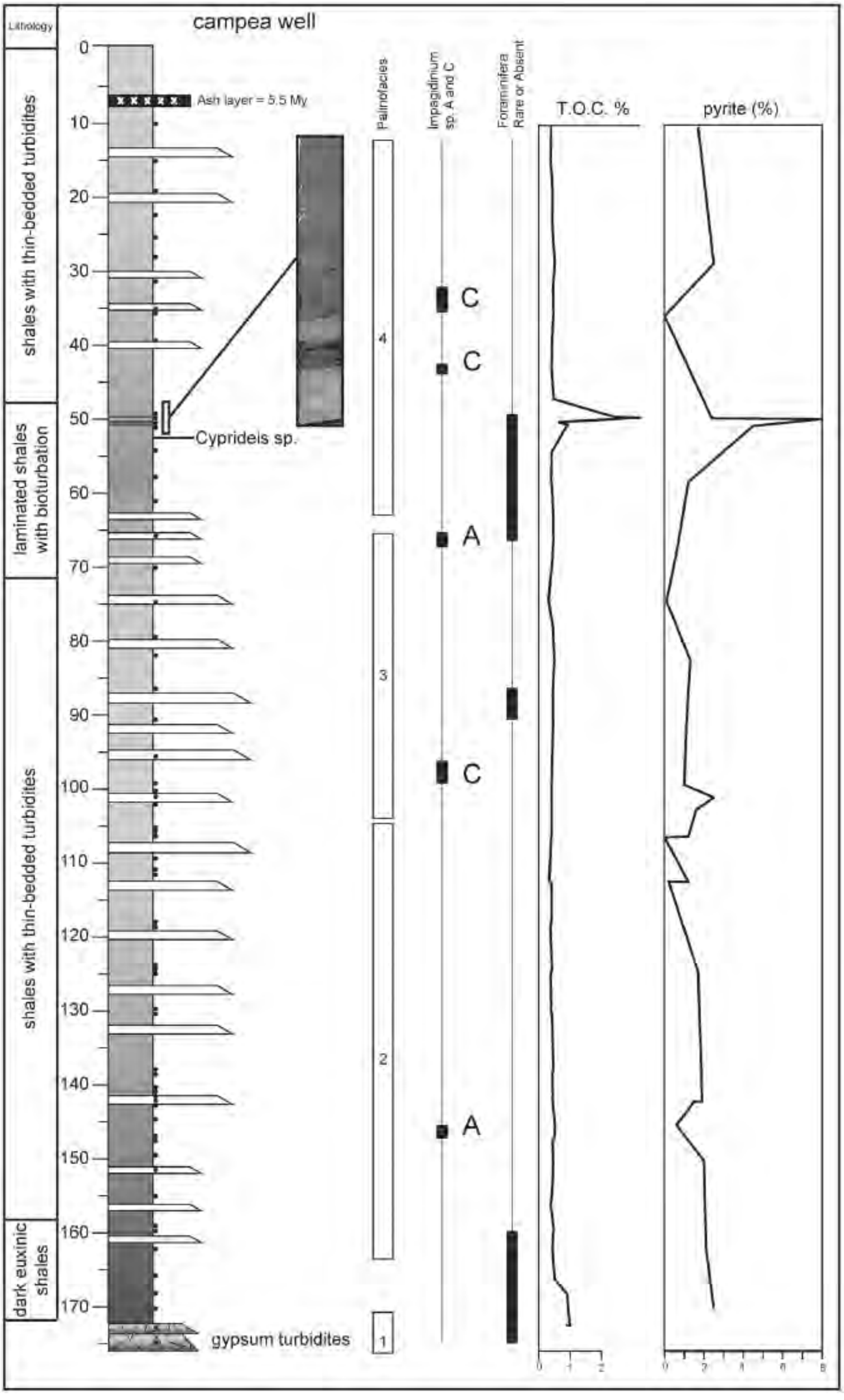


Fig. 52 – Lithology, paleontologic and mineralogical-geochemical data of the Campea core.

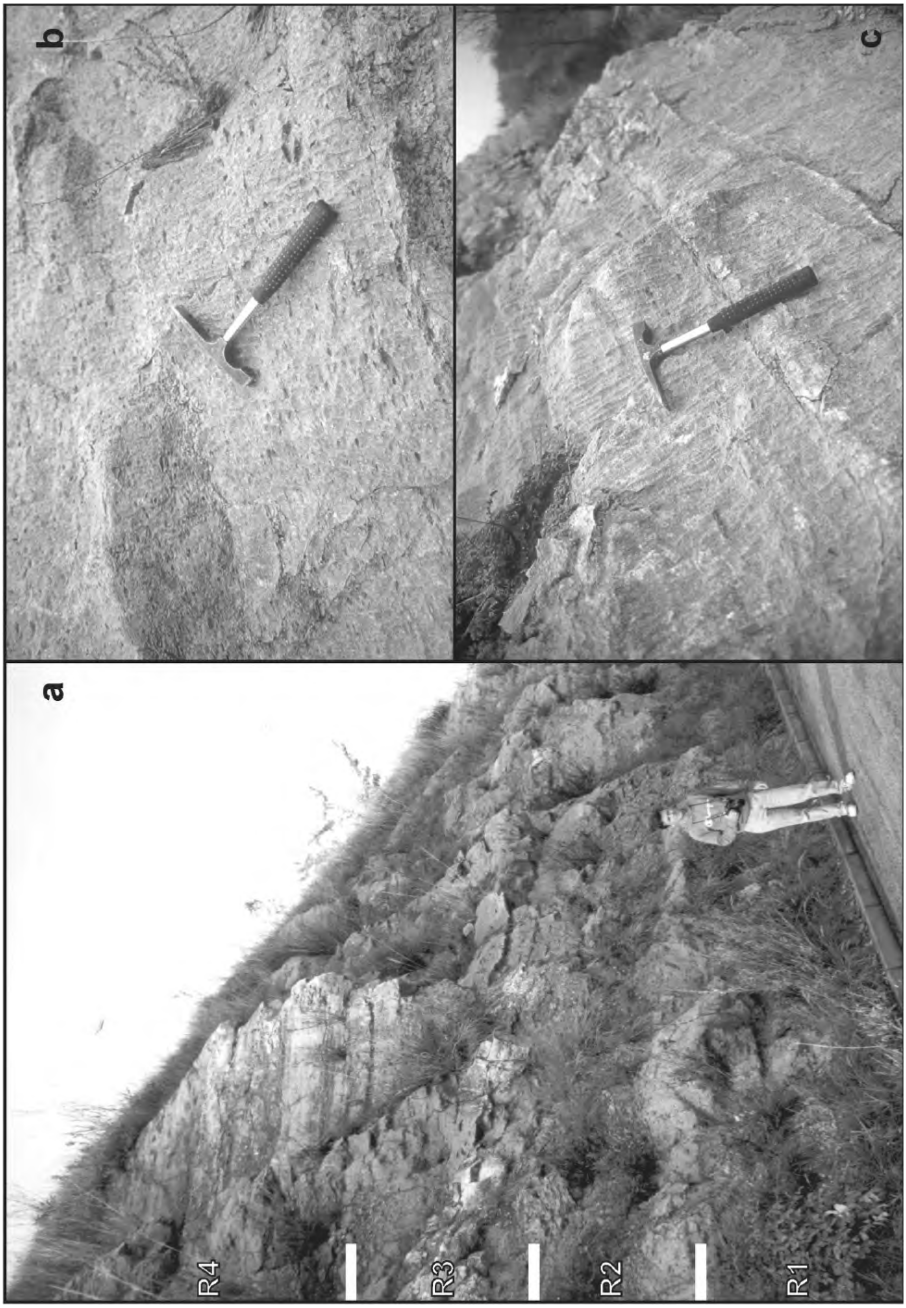


Fig. 53 - Inner basin evaporites. a) Up to 20 m thick composite graded megabed consisting of a basal chaotic division enclosing metric-size clay chip (R1 facies) abruptly overlain by a package of up to five beds of crudely laminated gypsrudite (photo b; R2 facies) and coarse gypsarenites (photo c; R3 facies) with clay chips alignment and traction carpets and capped in turn by plane and cross laminated hybrid medium to fine gypsarenites (R4 facies). These facies are separated by sharp surfaces indicating sediment bypass. Pieve di Rivoschio (Figs 1 and 14 for location), Giaggiolo-Cella syncline southern flank, eastern Romagna.

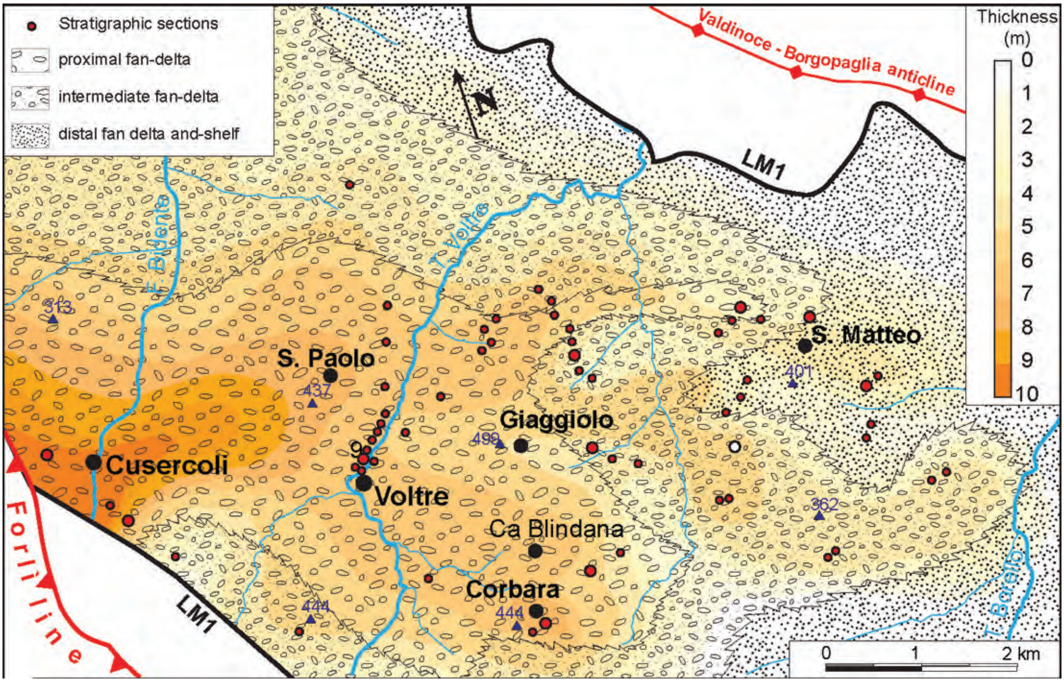


Fig. 54 - Facies and thickness distribution of the lowermost corse-grained body of the Cusercoli fm (Corbara horizon). From Roveri et al. (1998).

erosional bases and clay chips (depositional lobe), passing downcurrent to hummocky cross-stratified sandstones and to thin bedded rippled sandstones; lobes are locally overlain by low-angle inclined conglomerates forming sigmoidal bars. Facies sequence has a regressive character and records the progradation in a shallow lacustrine basin of a small deltaic system dominated by catastrophic floods. Fine-grained deposits on top record the abandonment of the system due to a sudden decrease of flows volume.
Topics: *8*

Stop 3.5 –Voltre. AnatoMa of the upper Lago Mare cycles from outcrop and core data (**Cà Blindana core**). Sedimentology and palaeoenvironmental meaning of fine-grained deposits of the p-ev$_2$ unit. Facies characteristics and origin of the “colombacci” limestones and of intervening black, organic-rich mudstones.
Topics: *8, 9, 10.*

The **Cà Blindana core** (Fig. 55) was collected in the axial zone of the GCS; it is principally made up of claystone with intercalated thin and fine-grained sandstone beds related to low density gravity flows. The recovered succession allowed to better define the anomalously thick and fine interval between the two coarse grained sedimentary bodies at the base of cycle 2 and 4. Within this interval the cyclical sedimentological pattern is provided by the presence of important stratigraphic horizons: two limestone “colombacci” bed (col1) at 45 m and 14 m, and a palesoil (at 34 m) with root and pedogenetic traces underling a dark, palustrine bed and a shell debris horizons.

This palesoil is thought to be the local expression of the base of the 3rd sedimentological cycle of the p-ev$_2$ unit, as confirmed by its occurrence in Montepetra borehole. The second limestone bed at 14 m is of detritic origin, this fact proving that the lateral continuity of the "colombacci" limestone beds is subordinated to erosional processes. Foraminifera are very scarce and dwarfed, thus

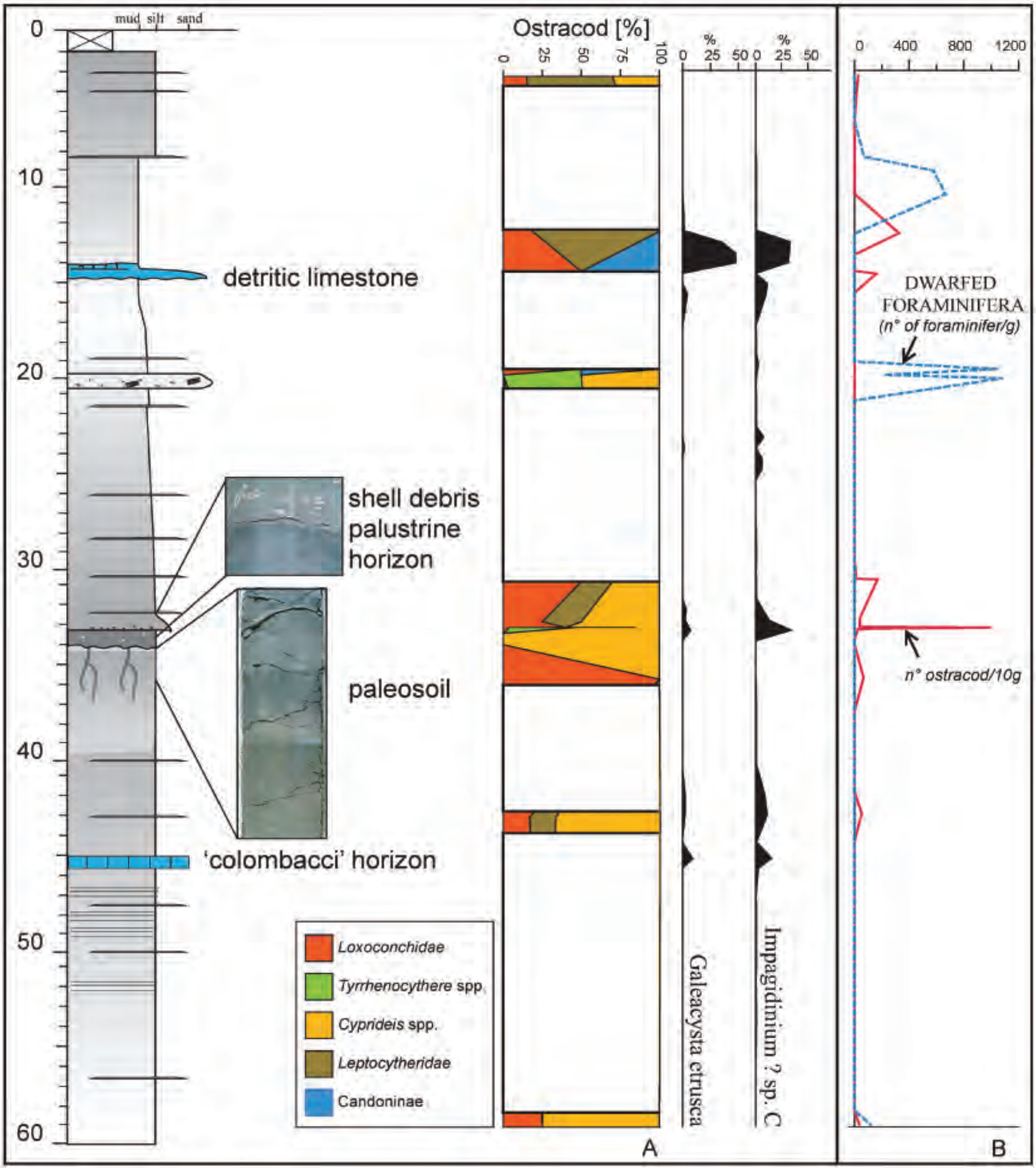


Fig. 55 – Lithology and paleontologic data of the Cà Blindana core.

considered as rewoked; instead, ostracodes and dynocists are present with the typical "Lago-Mare" assemblage. The first group is abundant within the palustrine and debris shell horizons, where *Cyprideis agrigentina* is dominant and below the detritic limestone bed, where *Camptocypria* sp. is the most abundant species together with *L. djaffarovi*; this distribution could suggest a deepening trend, from the palustrine deposits upward. (Dynocists are represented by *G. etrusca* and *Impagidinium* spp.)

Stop 3.6 – Road Voltre - Cusercoli. Panoramic view (Fig. 56) showing the clear stacking pattern of the uppermost Messinian deposits. Climatic vs. tectonic control of high-frequency cyclicity; the latest Messinian 'transgression' and the Pliocene marine flooding.
Topics: *8, 9, 10, 11*

Stop 3.7 – Road Cusercoli-Meldola, Bidente valley. Close view of the Miocene/Pliocene boundary in the Buttafuoco section showing the typical black layer and the abrupt upward transition to open marine deposits.
Topics: *11*

THE BUTTAFUOCO SECTION

The Buttafuoco section (Fig. 57), located on the northwestern flank of the Giaggiolo-Cella syncline allows to observe the characteristics of the local Miocene/Pliocene boundary. From the base to the top the uppermost Messinian interval is composed of several thin sandstone beds and mudstone deposits, laterally passing to a sandstone body interpreted as a mouth bar, intercalated with a reddish horizon and a limestone bed ('*colombacci*'). A black, organic rich horizon overlying a surface with pedogenetic features, occurs immediately below the colombacci limestone horizon.

These deposits deposits are characterized by typical "Lago-Mare" ostracode assemblages and represent the upper part of the local 4th cycle of the pev$_2$ unit. At the top of the Messinian unit a dark, organic rich layer, bearing shell debris, occurs immediately below the Pliocene clays of the "Argille Azzurre" Fm. In the Buttafuoco section two distinct ostracode assemblages occur; the two lowermost samples are related to assemblage 1 of Montepetra borehole (Fig. 50); the upper, ostracode-bearing samples are very similar to assemblage 4, as they show a very diversified fauna.

Due to the higher sedimentation rate in this sector of the basin, the micropaleontological features of the M/P boundary are better defined than in other sites, where the change from ipohaline to marine assemblages seems to be very sudden. Here we can observe

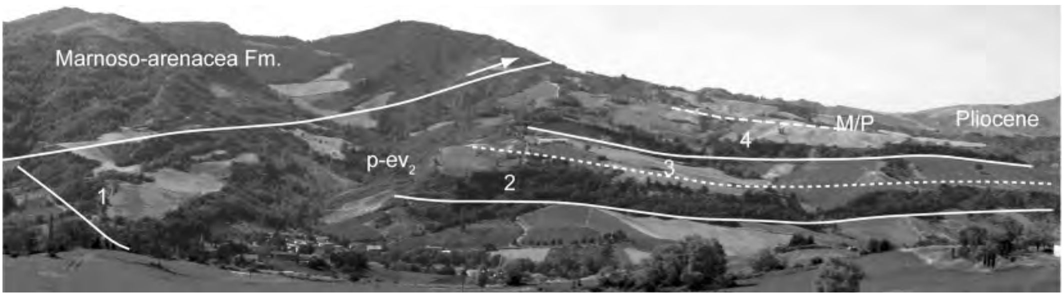


Fig. 56 - Panoramic view showing the clear stacking pattern of the uppermost Messinian deposits. Bidente Valley. Messinian deposits are overthrust by the Tortonian Marnoso-arenacea Fm. turbidites.

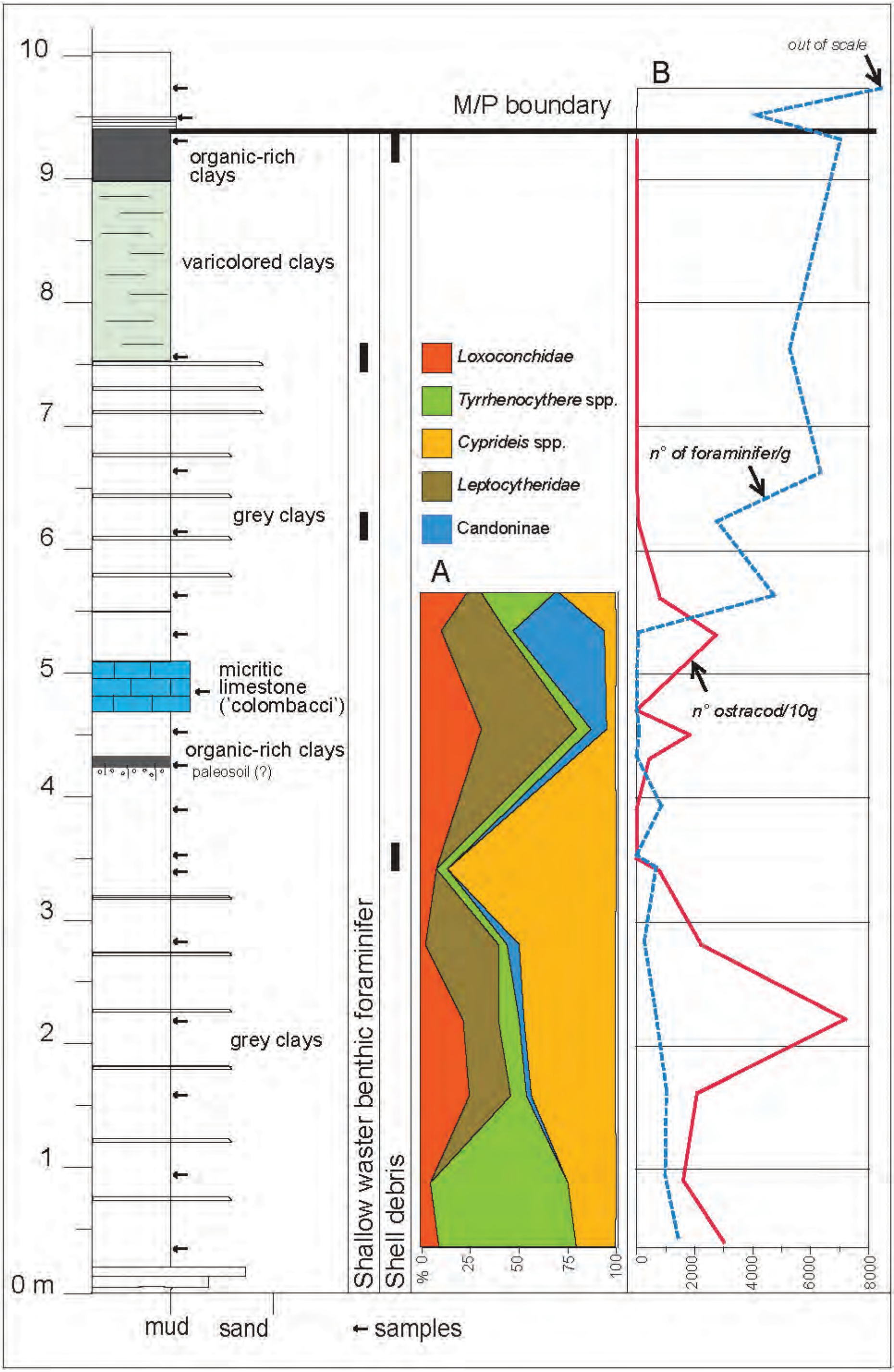


Fig. 57 – Lithology and paleontologic data of the Buttafuoco section.

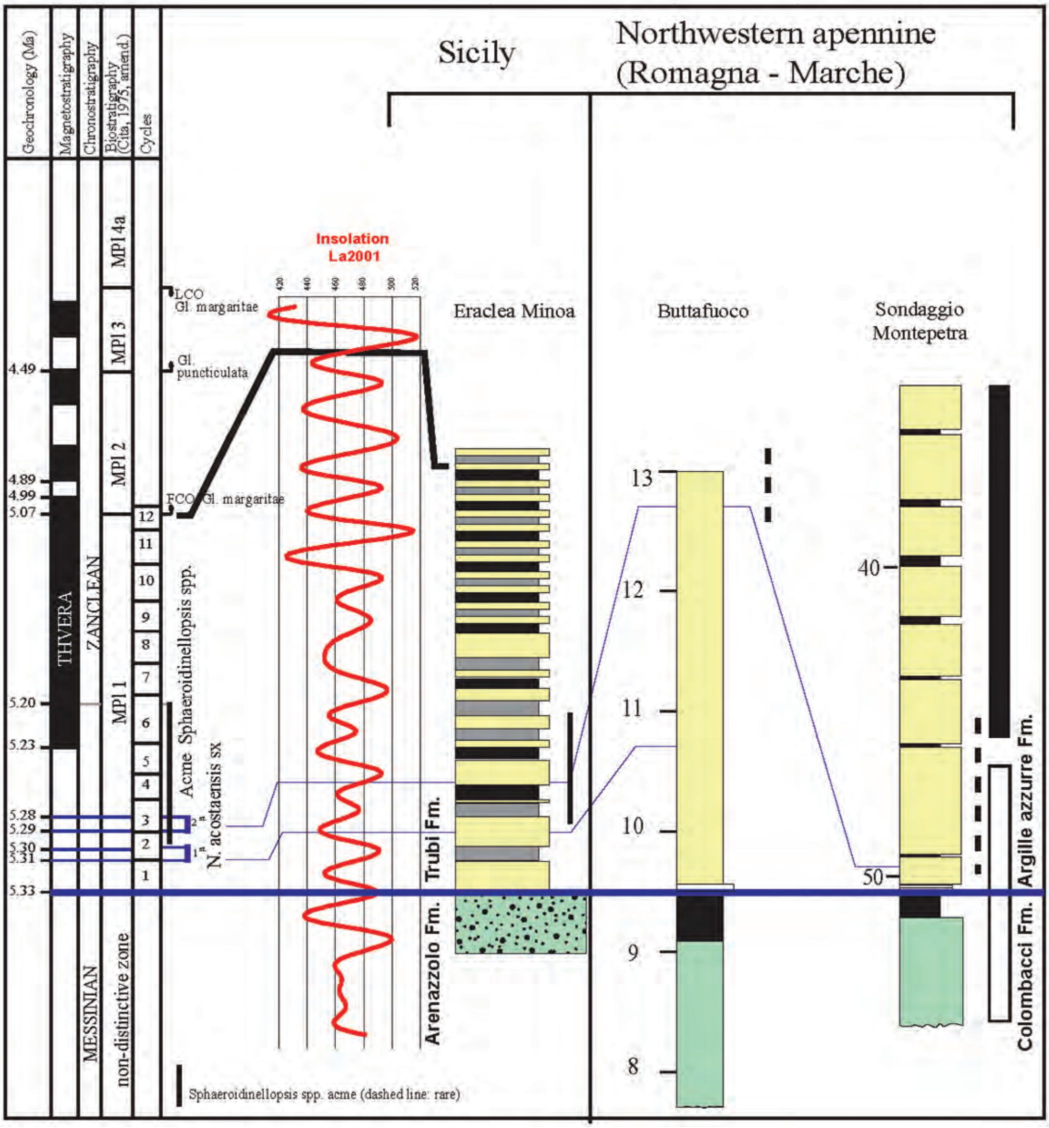


Fig. 58 - The Miocene/Pliocene boundary.

the gradual disappearance of "Lago-Mare" ostracodes several meters below the boundary and a concomitant increase in the number of foraminifera, part of which are reddish and abraded, thus interpreted as reworked. No extinct taxa were noted. Below the M/P boundary the presence of several individuals of *Elphidium* sp., *Cribroelphiduim* sp., *Nonion* sp. and *Neoconorbina* sp. point out for a relatively shallow water environment (Fig. 56). However, as in many others Mediterranean sites, a fully marine paleoenvironment is recorded only above the aforementioned dark bed; here, the low resolution sampling do not allow a precise paleoecological study, but the recognition of two sinistral coiled *Neogloboquadrina acostaensis* influx confirm the presence of the very base of the Zanclean stage, with an age of 5.33 Ma (Fig. 58). As in Montepetra well and in others Northern Apennine sections *Sphaeroidinellopsis* spp. is rare, but its occurrence is correlated with the acme of the Mediterranean sections.

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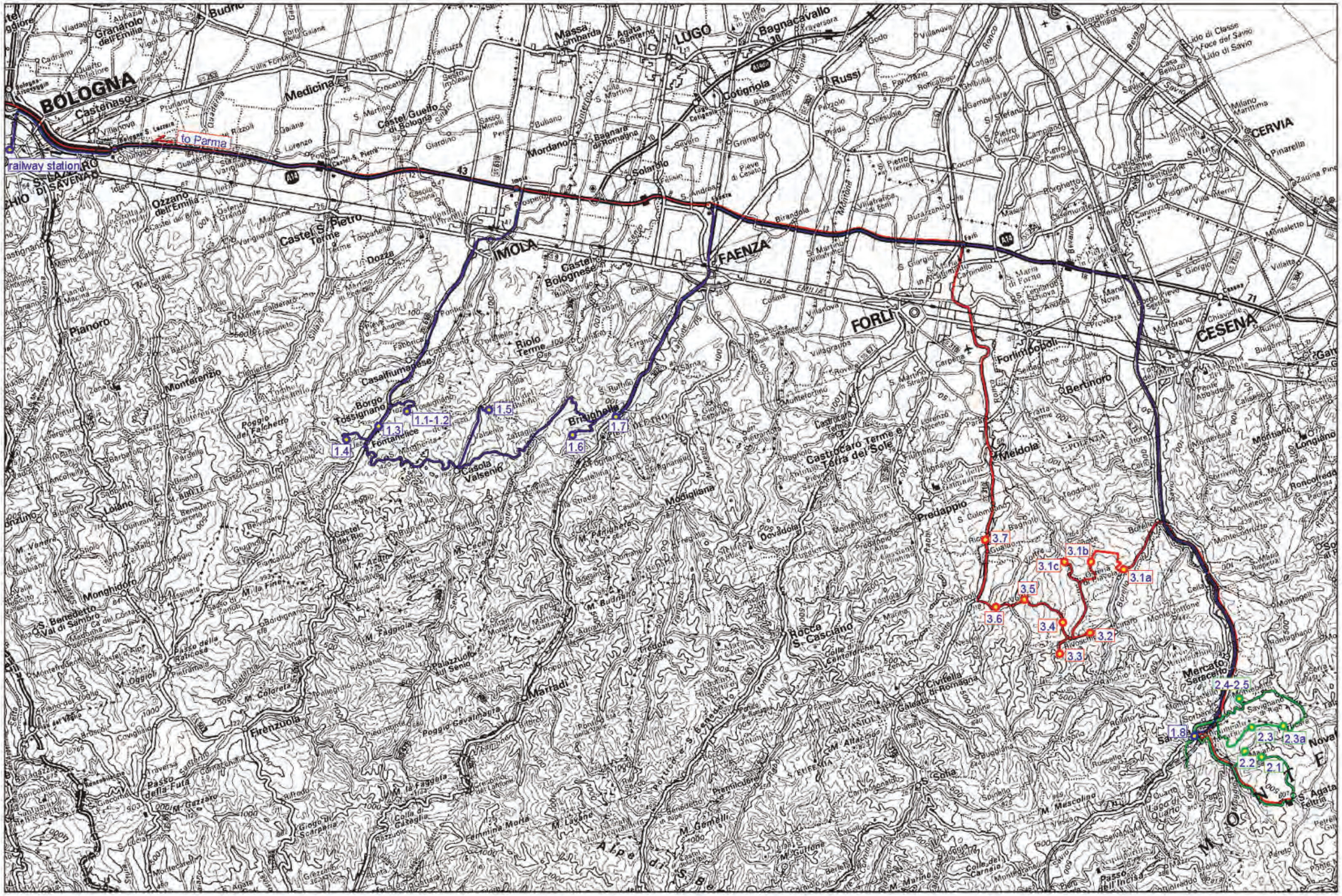
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Fontanelice
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Bertinoro
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The record of Messinian events in the Northern Apennines foredeep basins
PRE-CONGRESS FIELD TRIP, 4th- 6th September 2006

RCMNS Interim Colloquium *"The Messinian salinity crisis revisited - II"*, Parma (Italy) 2006

Participants: Stefano LUGLI (1), Simone PANNIKE (2), Sergej POPOV (3), Marco TAVIANI (4), Rocco GENNARI (5), Berit LEGLER (6), Fabio FABBRI (7), Piet LAMBREGTS (8), Federico ORTI (9), Katarzyna M. BISON (10), Andrea IRACE (11), Yossi MART (12), Silvia IACCARINO (13), Elisabet PLAYÀ (14), Imre MAGYAR (15), Francesco GROSSI (16), Hanna TOMASSI-MORAWIEC (17), Marie-Madeleine BLANC-VALLERON (18), Krzysztof BUKOWSKI (19), Israel ZAK (20), Laura ROSELL (21), Andrea COMELLI (22), Emili CARRILLO (23), Marco ROVERI (24), Vinicio MANZI (25), Antonio CARUSO (26), Cesare PIROZZI (27), Grzegorz CZAPOWSKY (28), Jean Marie ROUCHY (29)

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