Volume n° 2 - from B16 to B33

32nd INTERNATIONAL GEOLOGICAL CONGRESS

Field Trip Guide Book - B19

THE RECORD OF MESSINIAN EVENTS IN THE NORTHERN APENNINES FOREDEEP BASINS

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Associate Leader: A. Landuzzi

Florence - Italy
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Pre-Congress B19

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THE RECORD OF MESSINIAN EVENTS IN THE NORTHERN APENNINES FOREDEEP BASINS

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Front Cover:
Panoramic view of the Vena del Gesso
(Gessoso-Solfiera Formation) along the west side
of the Santerno valley at Borgo Tossignano

Leader: M. Roveri
Associate Leader: A. Landuzzi

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 participants at the end of the field trip will have completed their own list with many others.

Firstly, although not adequately recognized by the scientific community, the Northern Apennines holds the most complete, and probably the best, record 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 7.2 and 5.33 My), and usually referred to as the "Messinian salinity crisis" (**MSC**).

Moreover, in no places of the Mediterranean area has the fascinating history of the Messinian salinity crisis left so many indelible signs on both the physical and cultural landscape as in the Northern Apennines area, which extends from Bologna to Rimini.

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

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 to man for various uses since 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 maybe even before. A short walk downtown in Bologna may quickly substantiate 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 extensively exploited till the early 60s in many small quarries and mines in 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 with 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 third and fourth day of this field trip, we will run over Marsili's outcrops again, which shows how geologic interest in this area has

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

stood the test of 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 was formed through the 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 depositional settings are separated by a tectonic feature oblique to the main Apennine structural trend.

Three centuries after the pioneering work of Marsili, the Messinian outcrops of this area still offer a 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 part of the story that is still missing, is recorded by those huge salt accumulations buried in the deepest Mediterranean basins, whose true nature and stratigraphy still wait to be fully unraveled.

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 will appreciate the strong character of this land, of its people and products, formed and developed through time, in a continuous interlacing of geology, culture, and history of science.

Messinian events, chronology, and modalities

In fact, 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 ever been 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 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 throughout 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 few years, after the adoption of astronomical calibrations and physical-stratigraphic concepts, has certainly improved our general knowledge and chances of understanding these phenomena. The

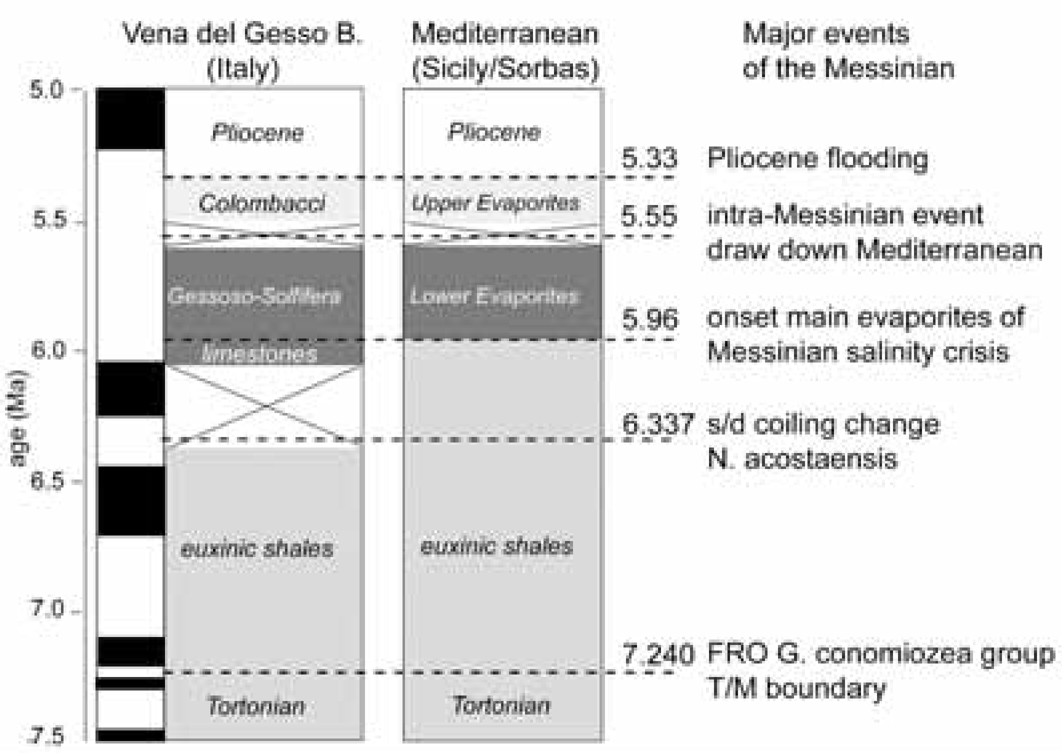


Figure 3 - Chronology of Messinian events according to Krijgsman et al. (1999a-b).

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). Although differing views still exist, in recent years, a growing consensus has been reached about the chronology of Messinian events, as proposed by Krijgsman et al. (1999a-b; Fig. 3). This has been made possible by the well-developed cyclical arrangement of Messinian deposits. According to such a model, 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 shallow-water evaporites precipitation in marginal basins; 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). 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).

Based on astronomic-controlled cyclostratigraphic considerations, the main Messinian events are considered to be synchronous throughout the Mediterranean area, pointing to strong external forcing, tectonic and/or climatic. The duration of the various Messinian 'phases' can thus be estimated: 1.2 My for the pre-evaporitic, 0.35 My for the evaporitic, and 0.35 My for the post-evaporitic phase. This age-model fits quite well with the two-step MSC proposed by Clauzon et al. (1996), which represents an updated version of the Hsü et al. (1972) deep-desiccated basin model. Such a model implies a diachronous deposition of evaporites across marginal and basinal settings at the boundary between the evaporitic and post-evaporitic stages. In marginal settings, this boundary is represented by a subaerial erosional surface, deeply cutting the continental margins, and thought to have been developing during the acme of the MSC, when the Mediterranean sea-level dropped more than 1000 meters, and shallow-water evaporite precipitation was shifted towards the deepest parts. The astronomic polarity time scale (APTS) for the Neogene still shows indeed a gap lasting 90 kyr at the base of the post-evaporitic stage (Krijgsman et al., 1999a-b), related to the deep desiccation of the Mediterranean. 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 (Lago Mare stage). Despite the accurate and unifying chronology of Messinian events, which suggests a homogenous development, it has been recently proposed that the MSC evolved with distinct modalities across the different geotectonic settings involved (Sicily, Apennine foredeep, Andalusia, northwestern Mediterranean; Clauzon et al., 2001). According to this view, the different modalities can be summarized, and translated for simplicity, into two end-member successions: a **Mediterranean-type** and an **Apenninic-type**, the main difference being the non-desiccated character of the Apennine foredeep basin during the whole MSC.

The Apennine foredeep record of Messinian events

With respect to the supposed different Mediterranean and Apenninic modes of the MSC evolution, we now offer a different point of view to the discussion. The end-member successions basically – and very roughly - correspond to the record of distinct morphostructural settings: the Mediterranean-type to marginal, elevated areas, the Apennine type to basinal deeps.

The true "anomaly" of the Apennine foredeep is that, due to its geodynamic setting and post-Messinian evolution, both modalities actually occur and that the stratigraphic and genetic relationships between 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 Apennine-type succession 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; Bassetti et al., 1994; Bassetti, 2000; Roveri et al., 1998; Roveri et al., 2001; Roveri et al., 2003), a geologic and stratigraphic model for the Apennine foredeep Messinian deposits has been reconstructed. Such a model is summarized in Figures 4 and 5, and assumes the development of pre-evaporitic and evaporitic stages that are synchronous with, and with the same modalities as, the other Mediterranean basins. Primary evaporites were deposited only in shallow thrust-top basins whose formation dates back to the Late 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 depocenters toward the foreland. The intra-Messinian unconformity, a perfect equivalent of the erosional surface which cuts Lower Evaporites throughout the Mediterranean, is associated with an angular discordance, and hence it is strictly related to a regional tectonic uplift, leading to the dismantling and resedimentation of Lower

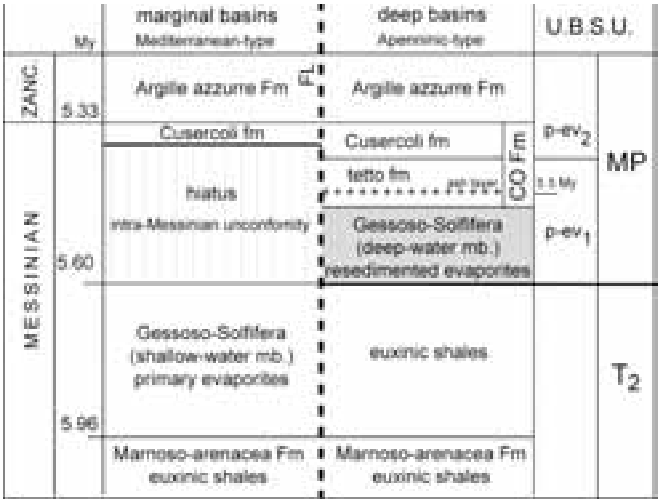


Figure 4 - Chronology of Messinian events in the Apennine foredeep. Modified from Roveri and Manzi (in press).

Evaporites in deep basins through large-scale mass-wasting and gravity flows in shelf and slope areas. By tracing down basin, the intra-Messinian unconformity is a problem solved, and its correlative conformity is placed at the base of the resedimented evaporites complex (Roveri et al., 1998, 2001). This unit accumulated in topographic lows during the subaerial exposure of uplifted basin margins, thus allowing us to bridge the last Messinian gap (Roveri & Manzi, in press). Based on its physical characteristics, a high-resolution stratigraphic framework for the post-evaporitic successions (discontinuities of different hierarchical rank, stacking pattern and cyclic sedimentary succession can be easily correlated to that developed in wedge-top basins through very distinctive physical elements. The distinction between the 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 and second days of the field-trip will be spent in a marginal, Mediterranean-type context, the third and fourth days, 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 features.

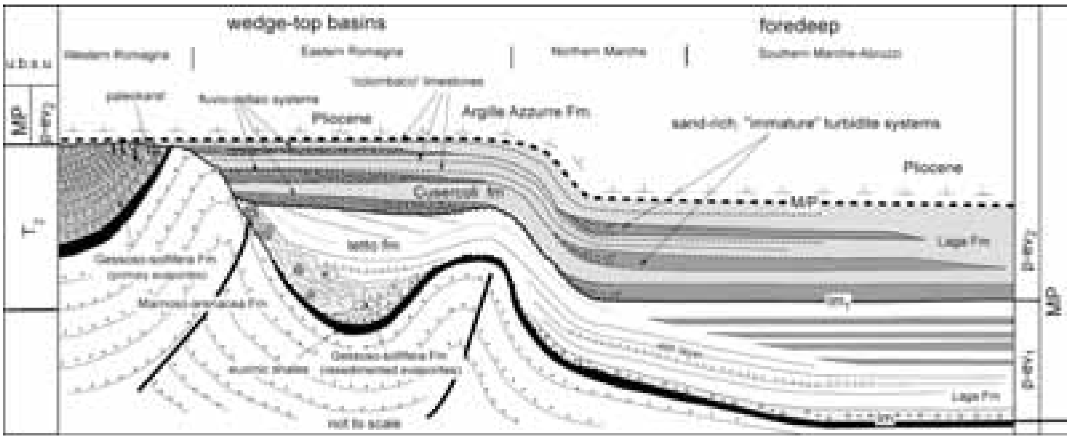


Figure 5 - The geologic-stratigraphic model for the Messinian deposits of the Apennine foredeep (Roveri et al., 2003).

organization of depositional system, key horizons), has been reconstructed. A second, 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 of 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 and generalized subsidence – and/or a base level rise – which preceded the Zanclean flooding.

The relatively small field trip area has the great advantage of being able to sumup all the elements of the larger-scale stratigraphic model. This area corresponds to a series of wedge-top basins (Fig. 5) which are 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 the Southern Marche and Abruzzi (Laga Basin), and their

Regional geologic setting

The Romagna Apennines, extending from the Sillaro valley to the west, to the Marecchia valley to the east (Fig. 6), 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 has been 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 Lower 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

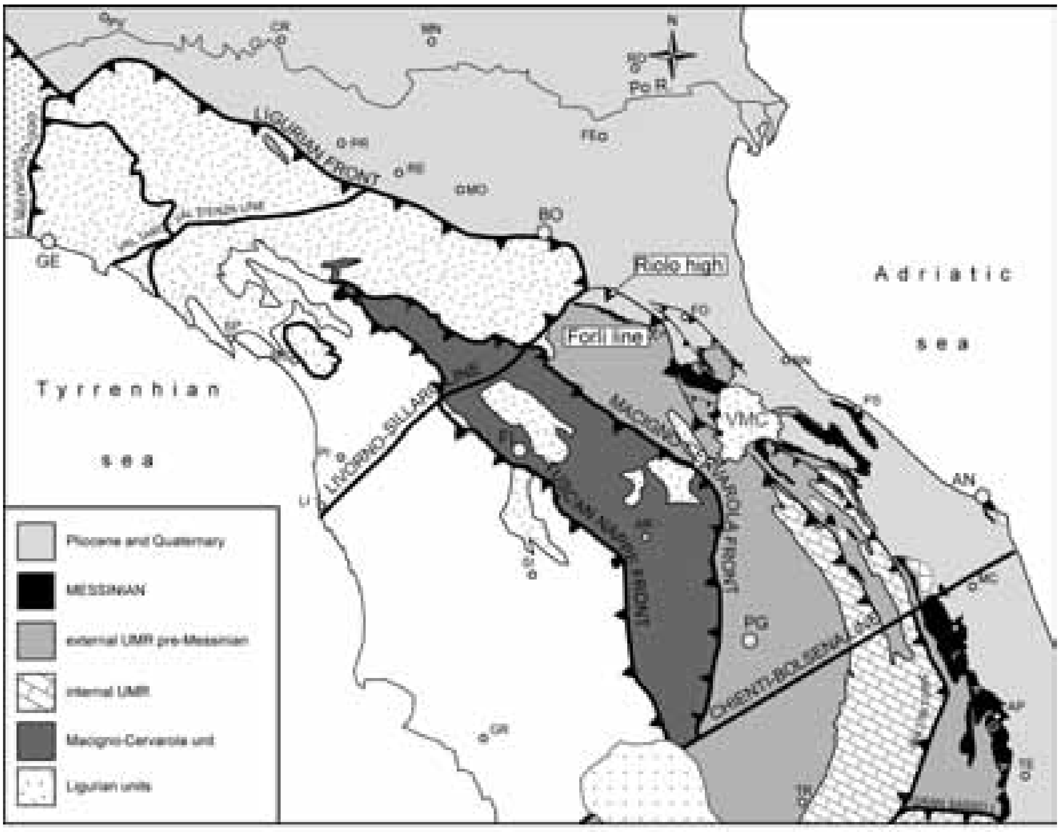


Figure 6 - Simplified structural map of the Northern Apennines.

review of Apennine geology, see Vai and Martini, 2001).

To the west of the Sillaro valley, this unit is covered by the Ligurian nappe (Fig. 6), 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 have a different structural arrangement at the surface; the foothills of the western sector show a gentle N-NE dipping monocline of Messinian to Pleistocene deposits, resting above the Marnoso-arenacea Fm., while the same succession is deformed by several thrust-related anticlines with Apenninic trends 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. 7), dramatic facies and thickness changes within the Messinian succession occur across structural highs 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

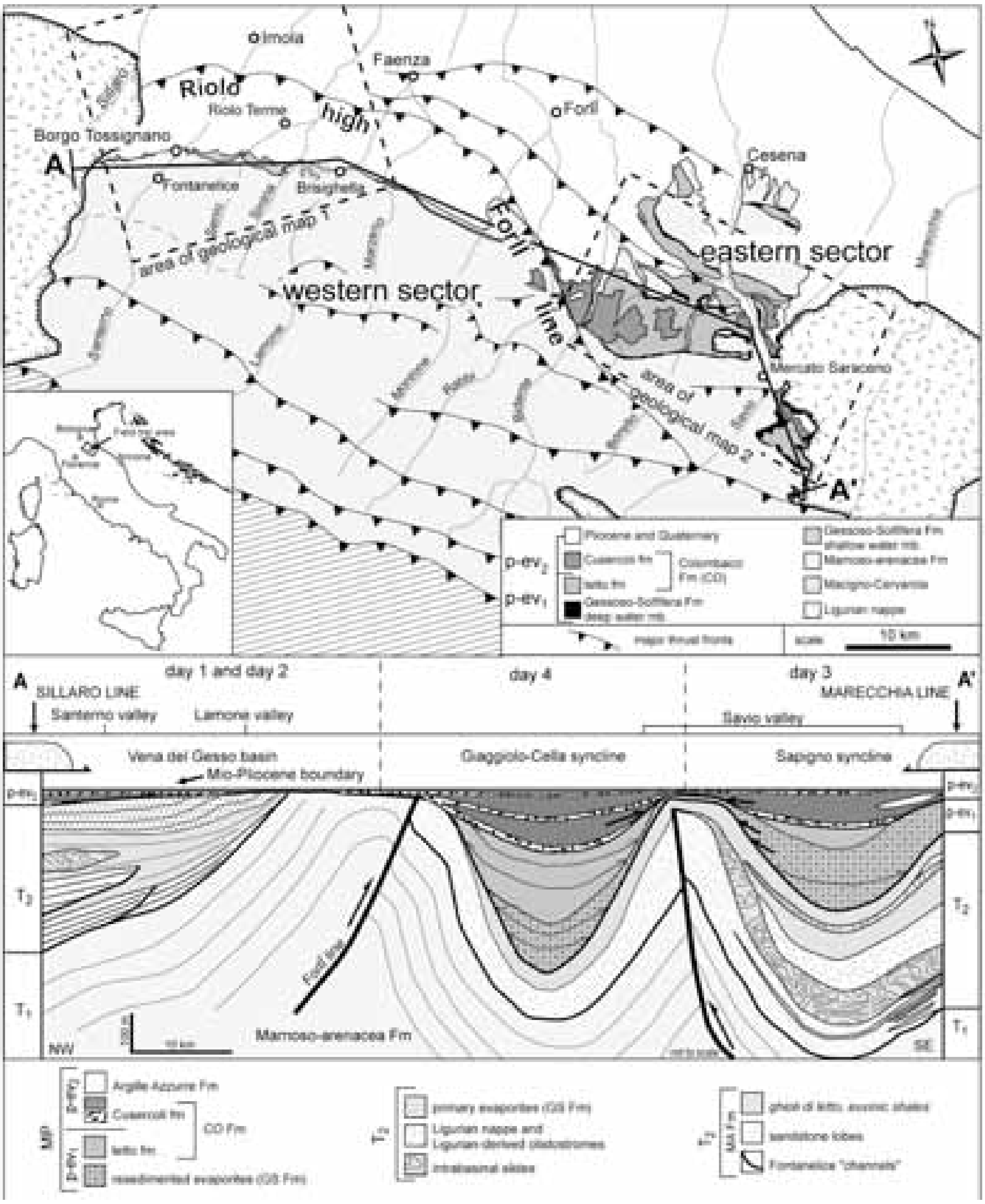


Figure 7 - Simplified geologic map (above) and cross-section (below) of the Romagna Apennines. The cross-section is flattened at the Miocene/Pliocene boundary to better illustrate the great facies and thickness changes characterizing the Messinian succession across main structural elements (modified from Roveri et al., 2003).

field trip.

The lithostratigraphy of the Langhian to Pliocene sedimentary succession of the Romagna Apennines consists of four formations (Vai, 1988; Fig. 8):

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 towards the NE, following the propagation of the compressional front. Towards the top, thick and laterally-continuous turbiditic lobes are replaced by slope mudstones (*ghioli di letto*) which contain 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 with the ensuing MSC.

The euxinic shales span a 1.5 My time

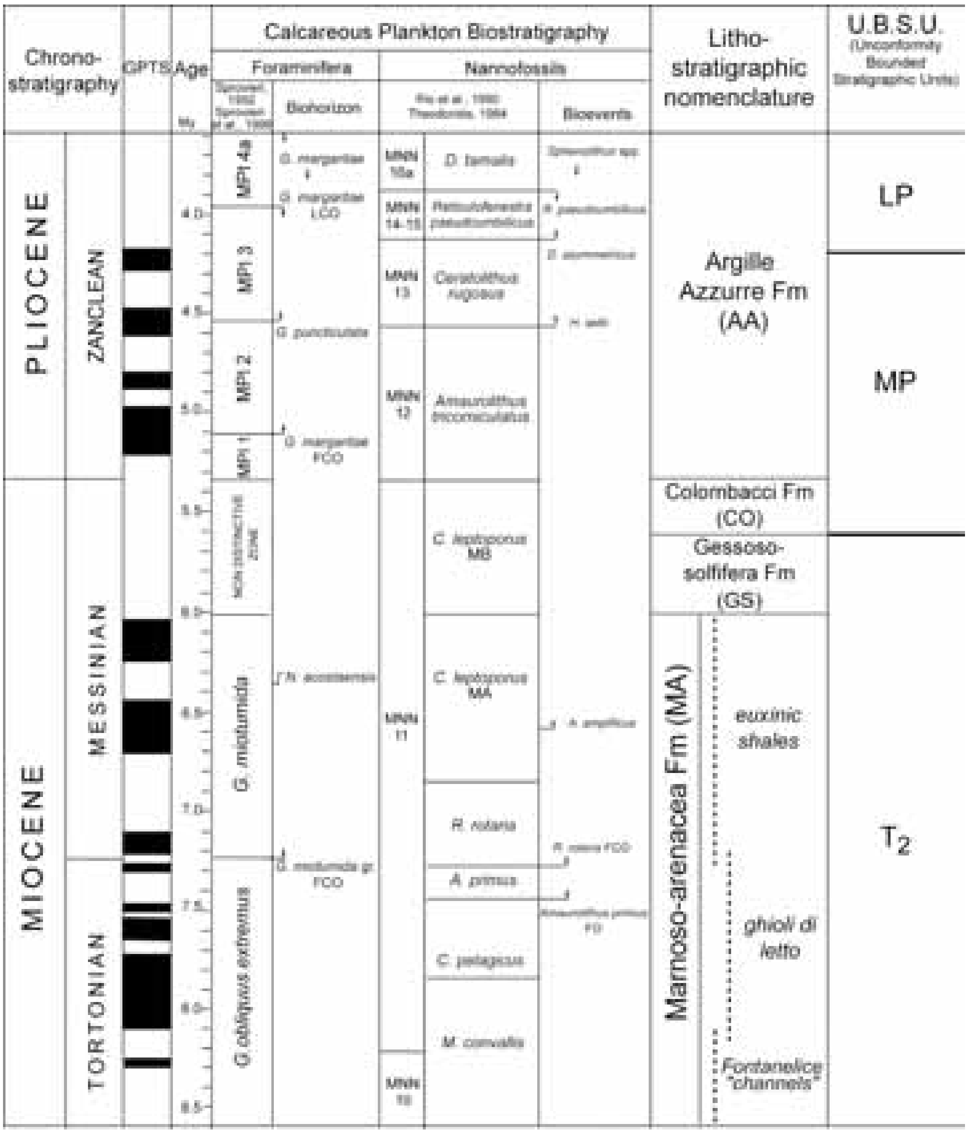
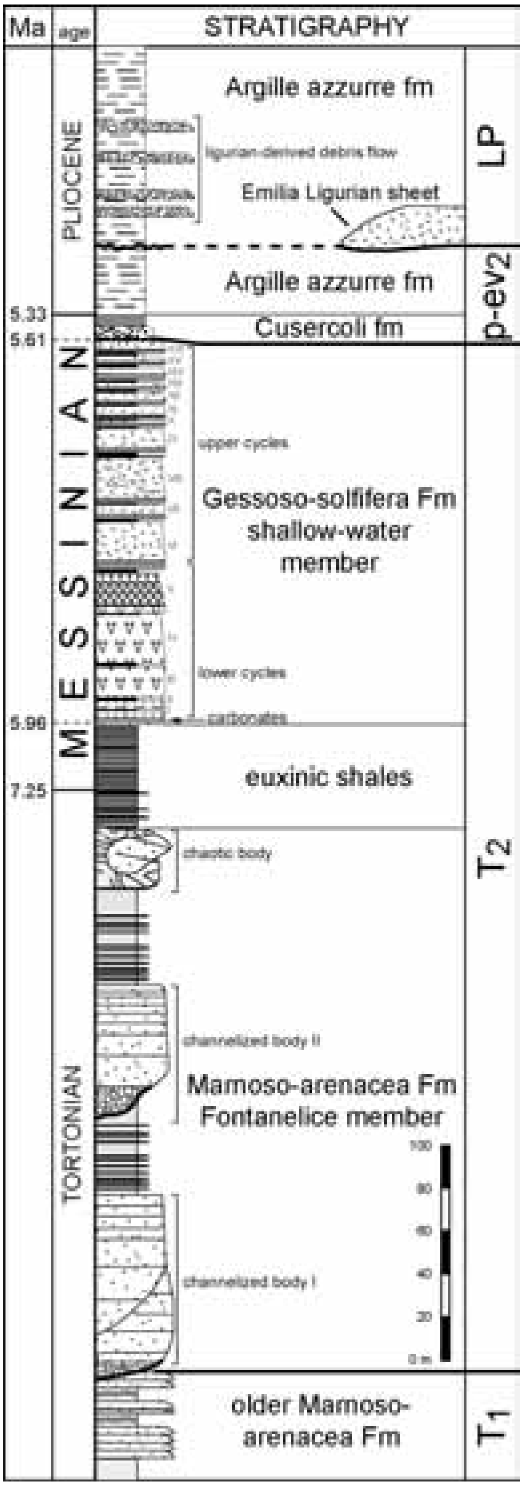


Figure 8 - Stratigraphic scheme of the Apennine foredeep Tortonian to early Pliocene time interval. Note that lithostratigraphy refers to marginal successions, i.e. those characterized by deposition of primary, shallow-water evaporites during the main evaporative event.



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, this unit has been subdivided by Roveri et al., (1998) 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 large-scale unconformities recording important phases of tectonic deformation of the Apennine orogenic wedge. From base to 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 (7.2 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 5.5. My (Odin et al., 1997). Messinian deposits fall in the T_2 (pre- and evaporitic stage) and MP (post-

Figure 9 - Stratigraghy of the western secctor.

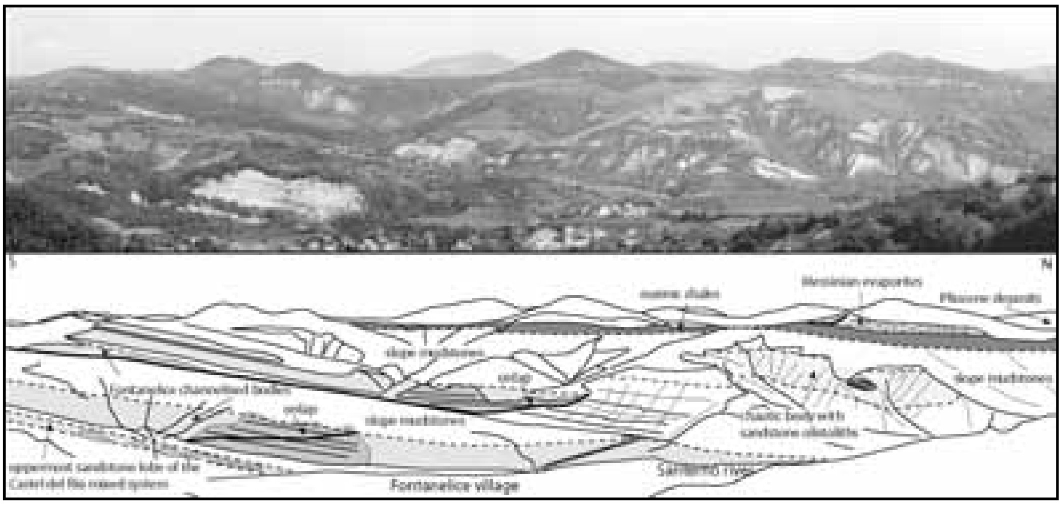


Figure 10 - Panoramic view of the stratigraphic succession cropping our in the Santerno valley.

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. 9, 10), 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 (Upper 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 the 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 usually been 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 the paleocurrents, the basal erosional surface deepens toward the SW, and a spectacular NE-wards onlap of sandstone fill 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 m thick, characterized by sandstone olistoliths, derived from 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. 11; 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 shallow-water evaporites of the Gessoso-solfifera Formation, forming a continuous belt up to 150 m thick, 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 shallow lagoons. These cycles have been interpreted more recently as controlled by periodic changes of orbital parameters (Vai, 1997; Krijgsman et al., 1999b).

The ideal complete cycle consists of the vertical superposition of 6 sedimentary facies (Fig. 12, 13, 14), five of them made up of gypsum and carbonates; it starts with basal organic-rich shales (facies 1), deposited in shallow lagoons below the wave base; these shales are overlain by gypsified limestone stromatolites (facies 2), massive autochthonous selenitic gypsum (facies 3), and well-stratified autochthonous and reworked selenitic gypsum (facies 4). The size of selenite crystals usually decreases upwards; this change is usually thought to be related to the progressive evaporative draw-down, and increasing salt concentration of the lagoon. The upper part of the modal cycles is characterized by nodular gypsum, acicular gypsum, gypsarenites (facies 5), and chaotic selenite breccia (facies 6). These deposits are interpreted as related to subaerial exposure and erosion at the end of an evaporative draw-down cycle, with strong gypsum reworking by waves or torrential streams action (Vai and Ricci Lucchi, 1977).

Progressive upward decrease in thickness and different facies distribution within individual cycles can be observed; upper cycles are thinner, and autochthonous evaporite facies are much less well-developed than the reworked clastic facies.

This suggests the superposition of an overall "regressive" trend on the smaller-scale, higher-frequency cyclicity. This trend provides the guideline for a precise cycle-by-cycle correlation throughout the Vena del Gesso basin, and further to the SE, in the Marecchia valley area (epi-Ligurian evaporites). For correlation purposes, the complete succession of 16 evaporite cycles has been subdivided into 2 thin "basal" cycles (facies 1 and 2 only), 3 thick "major" cycles (facies 5 missing), a very thick 6th cycle (complete sequence), and 10 thin "minor" cycles (complete sequences). The described longer-term

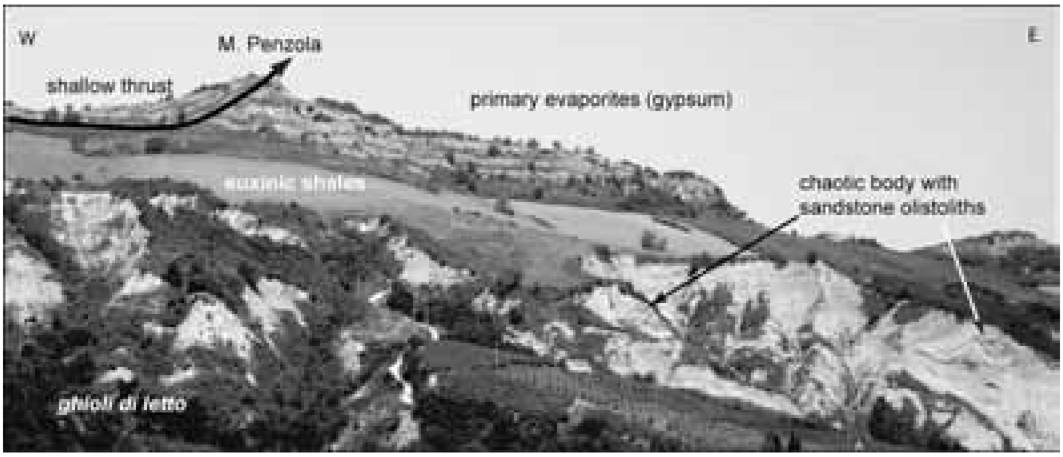


Figure 11 - Panoramic view of the late Tortonian-Messinian succession in the Santerno valley (stop 1.4). Note the chaotic horizon below the euxinic shales and the deformed gypsum unit on top.

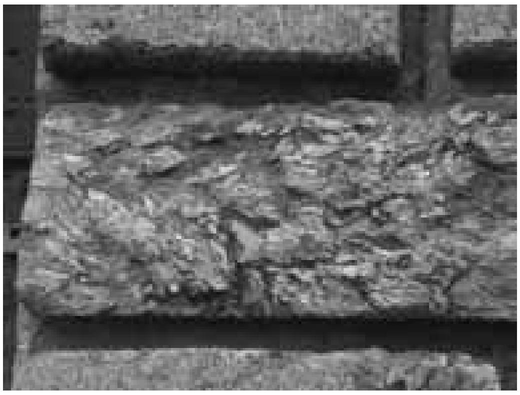


Figure 12 - Facies 3 selenitic gypsum in a block of the Garisenda tower of Bologna.

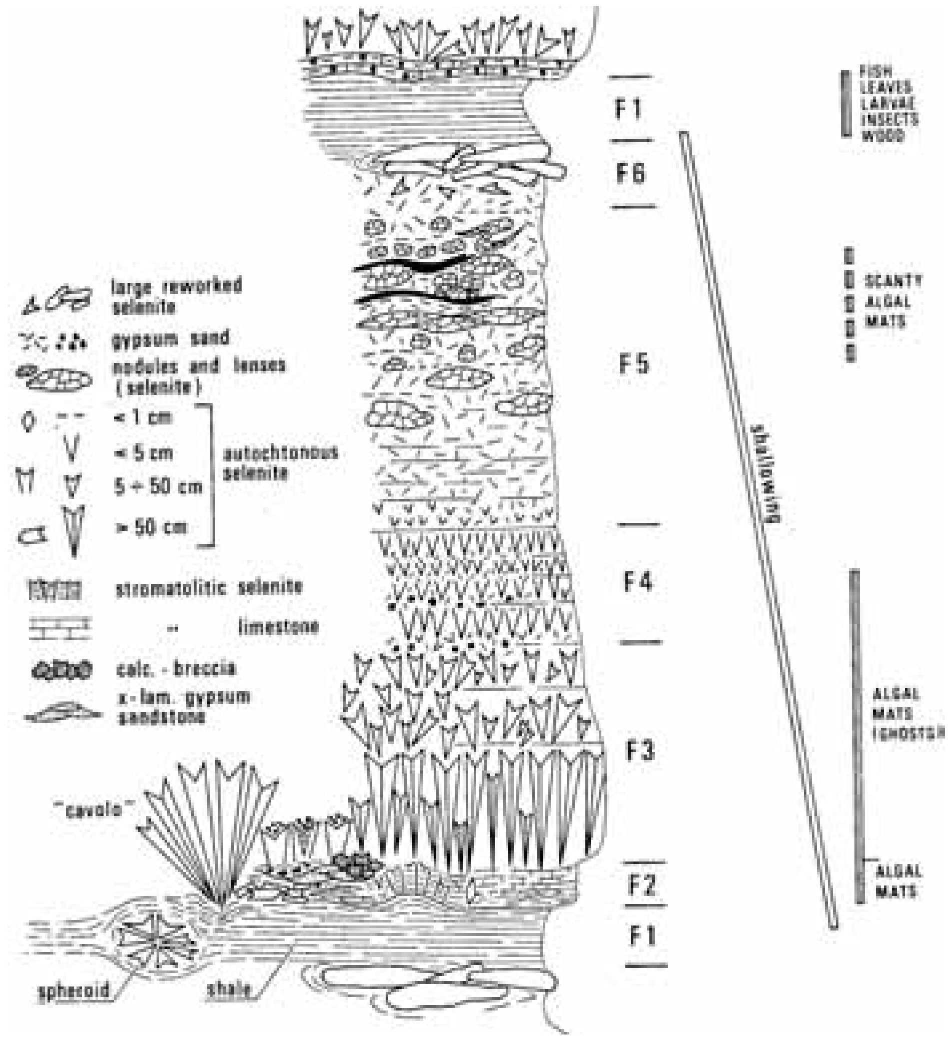


Figure 13 - The ideal depositional cycle of the Vena del Gesso evaporites (Vai and Ricci Lucchi, 1977)

trend culminates with a great erosional unconformity cutting the gypsum unit at its top, and marking the base of the overlying Messinian-Pliocene synthem (MP).

MP synthem (Messinian-Pliocene)

An angular unconformity is associated with the erosional surface (Vai, 1988), marking the T_2/MP boundary, clearly indicating its tectonic nature. This surface preserves spectacular evidence of subaerial exposure (karstic dykes, filled by continental deposits which are rich in mammal fauna, were found in the Monticino section, near Brisighella; Costa et al., 1986; De Giuli et al., 1988). The erosion associated with 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 gray to varicolored clays, containing an hypohaline faunal assemblage (*Melanopsis spp.*, *Limnocardium spp.*). Small lenses of sandstone and pebbly sandstone, and calcareous conglomerate occur locally. In places, a white micritic layer is also found; locally named *colombaccio*, it gives its name to the formation itself. The Miocene/Pliocene boundary is

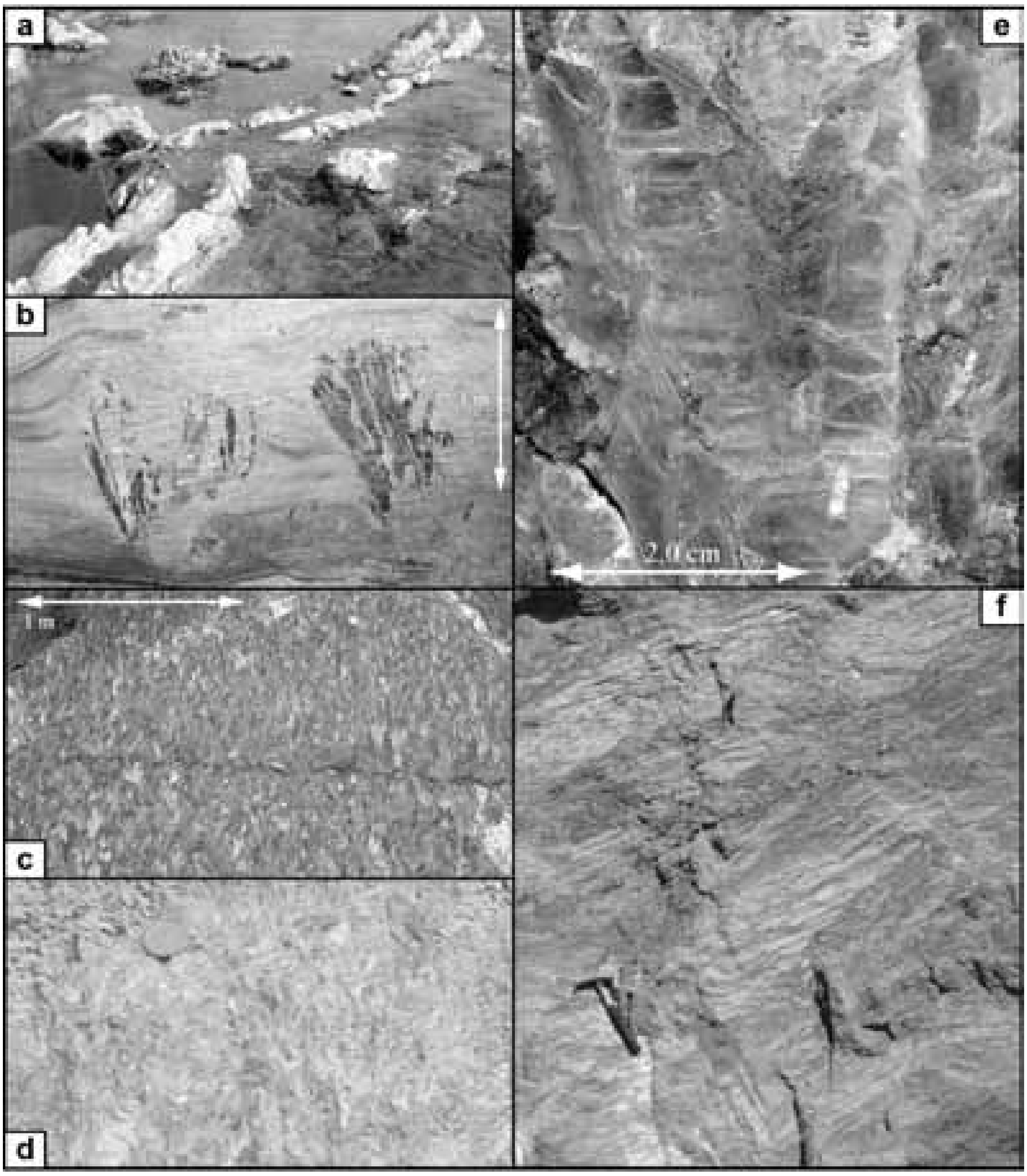
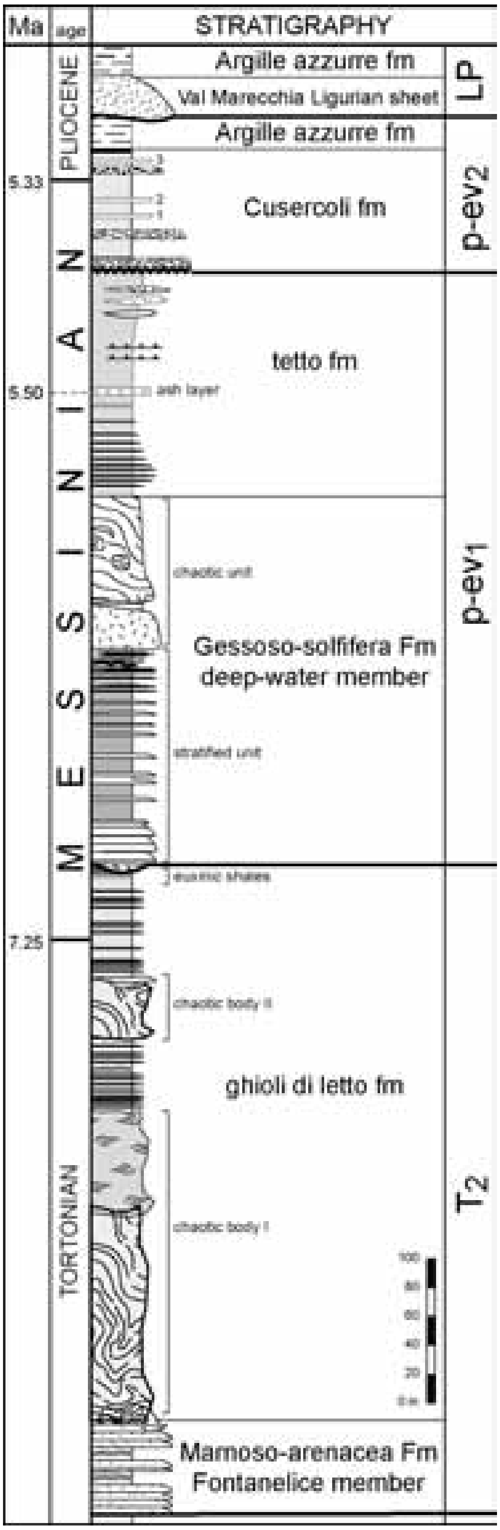


Figure 14 - Vena del Gesso evaporites. A) Santerno river bed. Slumped stromatolitic limestone (F2) and limestone breccia ("calcare di base") embedded in the topmost pre-evaporite mudstones; b) Rio Sgarba Quarry, Borgo Tossignano. GS, cycle II: euxinic shales (F1), and calc-gypsum laminites enclosing meter-sized "palisade"-type crystals of stromatolite-bearing gypsum (F2); c) Montebello Quarry, Marecchia Valley. GS, cycle III: upright and well-packed "swallow-tail" selenite crystals (F3). The evaporite growth is interrupted by an intra-cycle dissolution surface; d) Monte TondoQuarry, cycle VI, reworked selenite (facies F4); e). "Swallow-tail" selenite crystal (F3): an opaque stromatolite-bearing core is surrounded by a transparent diagenetic overgrowth;f) Monte Tondo Quarry, cycle VII, reworked small selenite crystals with nodules and lenses of whitish selenite.



marked by a characteristic dark, organic-rich horizon, whose origin is still poorly understood. Through the boundary, the typically abrupt transition from non-marine to relatively deep-marine waters is observed; such a 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 with 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 shallowness of the Lower Pliocene deposits of the MP synthem in this area is essentially related to the local strong erosion associated with 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. 27), while further to the west (M. Penzola), shallow thrust faults are responsible for the vertical repetition of the lower gypsum cycles (stop 1.8). 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).

Figure 15 - Stratigraphy of the eastern sector.

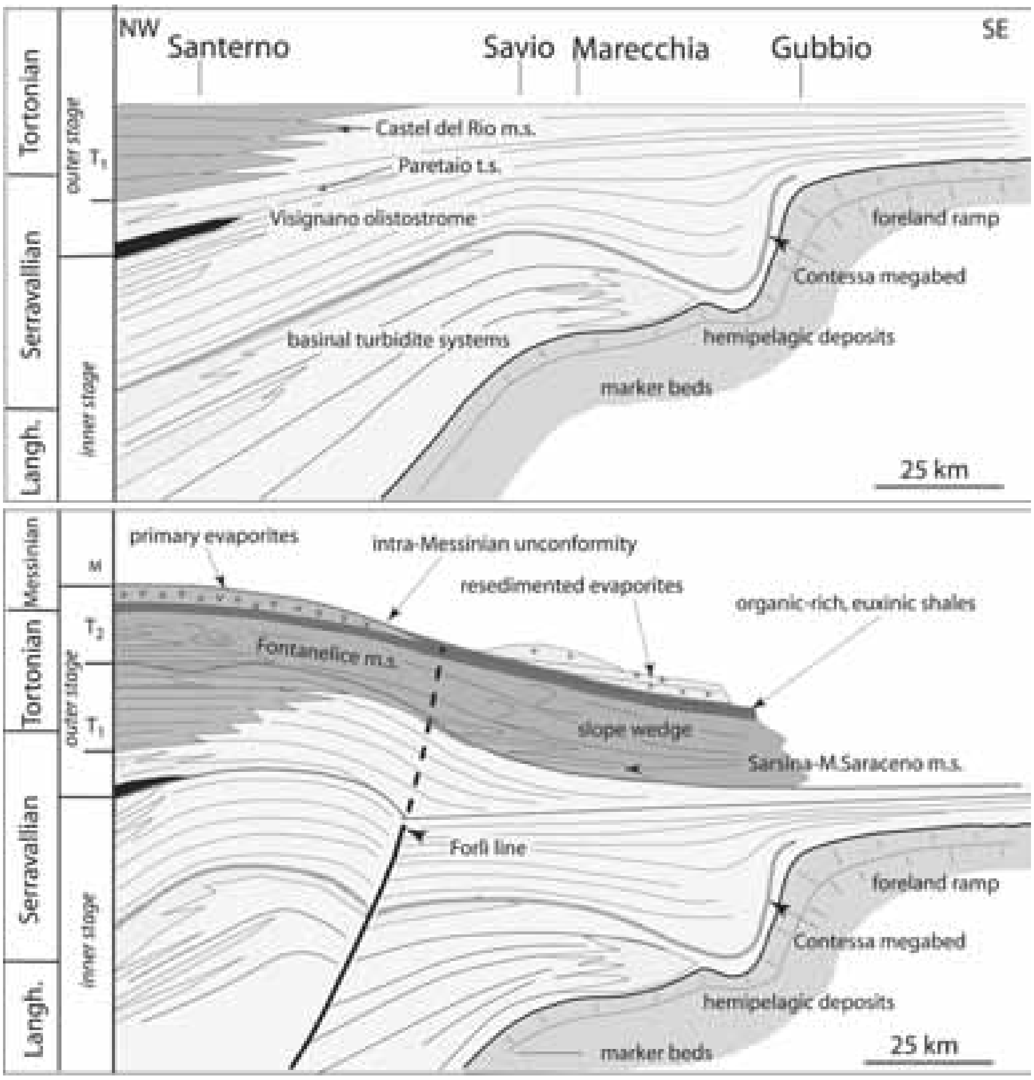


Figure 16 - Tortonian to late Messinian evolution of the Apennine foredeep basin (axial section) showing the longitudinal fragmentation due to the growth of the Forlì line - related structural high (Roveri et al., 2002)

To the east (Sintria valley), the deformation is more severe. Here 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, Fig. 36).

Eastern sector

No obvious unconformities occur in this sector any where in the considered stratigraphic interval. The uppermost Marnoso-arenacea Fm. here consists (Fig. 15) 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, and 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 basis of facies and regional geologic considerations.

As in the western sector, these sandstone bodies are

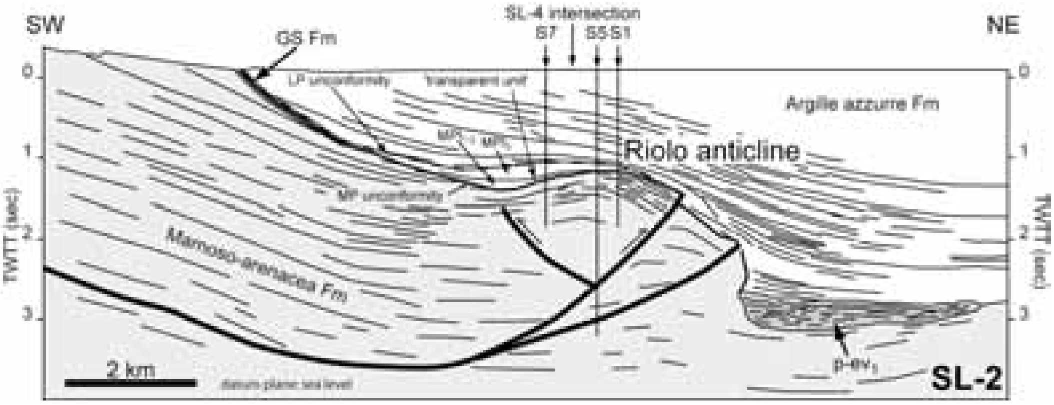


Figure 17 - Line drawing of a seismic profile showing the buried culmination of the Riolo anticline. See location in the geological map of Fig 24 (from Roveri et al., 2003).

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 extra-basinal 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 a 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 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 which contain large blocks of primary selenitic gypsum. These evaporites were deposited in relatively deep-waters, well below the 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 upwards. 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 Colombacci Fm, 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. 7, 15), possibly corresponding to local Messinian depocenters developed above the orogenic wedge. The basal Pliocene deposits have here the same facies characteristics as 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 changes would correspond to large-scale reorganization of basin geometry and drainage patterns 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 tracked 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. 4), separated by a minor unconformity which marks 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, and 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. 5.5 My (Odin et al., 1997), represents an exceptional lithostratigraphic marker throughout the whole Apennine foredeep basin, allowing us 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 towards 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). 3 to 4 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

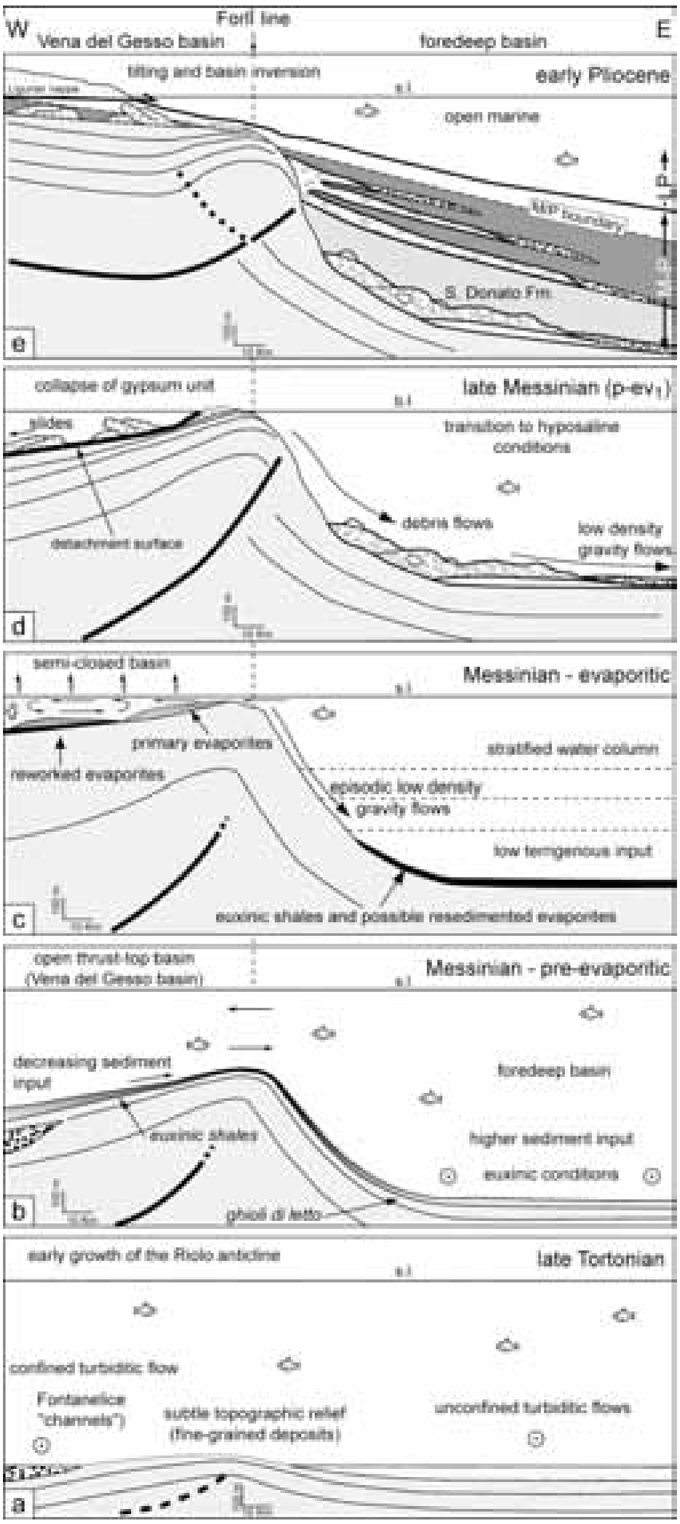


Figure 18 - Evolution of the Riolo anticline during the Upper Tortonian-Lower Pliocene time interval (from Roveri et al., 2003).

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 4 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, as elsewhere in the Apennine foredeep, by a characteristic dark, organic-rich horizon.

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 emergence of the Apennine backbone, and to the development of an embryonic Apenninic drainage system, as witnessed by the abrupt change in sediment composition, and the dramatic increase of the 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. 7 and 16). Seismic data allowed Roveri et al.

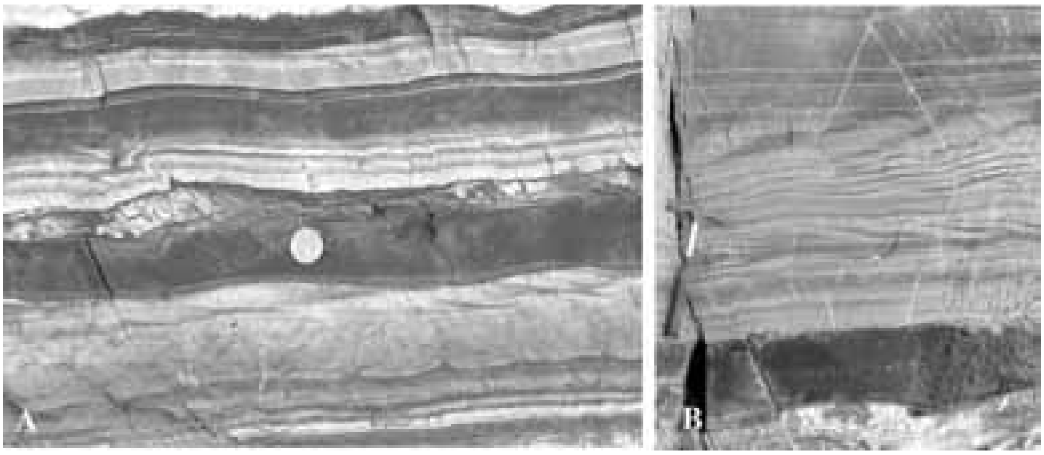


Figure 19 - Graded gypsarenite layers (Fanantello section, stop. 3.3). Each layer is composed by a light -dark couplet related to original grain-size. A) Note load structures at the base of thickest layer and long wavelength climbing ripples at the top of the coarser division. B) thick layer with two climbing ripple divisions showing opposite paleocurrents.

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. 7) allow us 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

(2003) to trace this structure in the subsurface, and to reconstruct a single ENE verging arcuate structure plunging to the west, of which the FL represents the eastern lateral ramp (Fig. 17). The continuous uplift of this structure, starting from the Late Tortonian (Fig. 18), 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

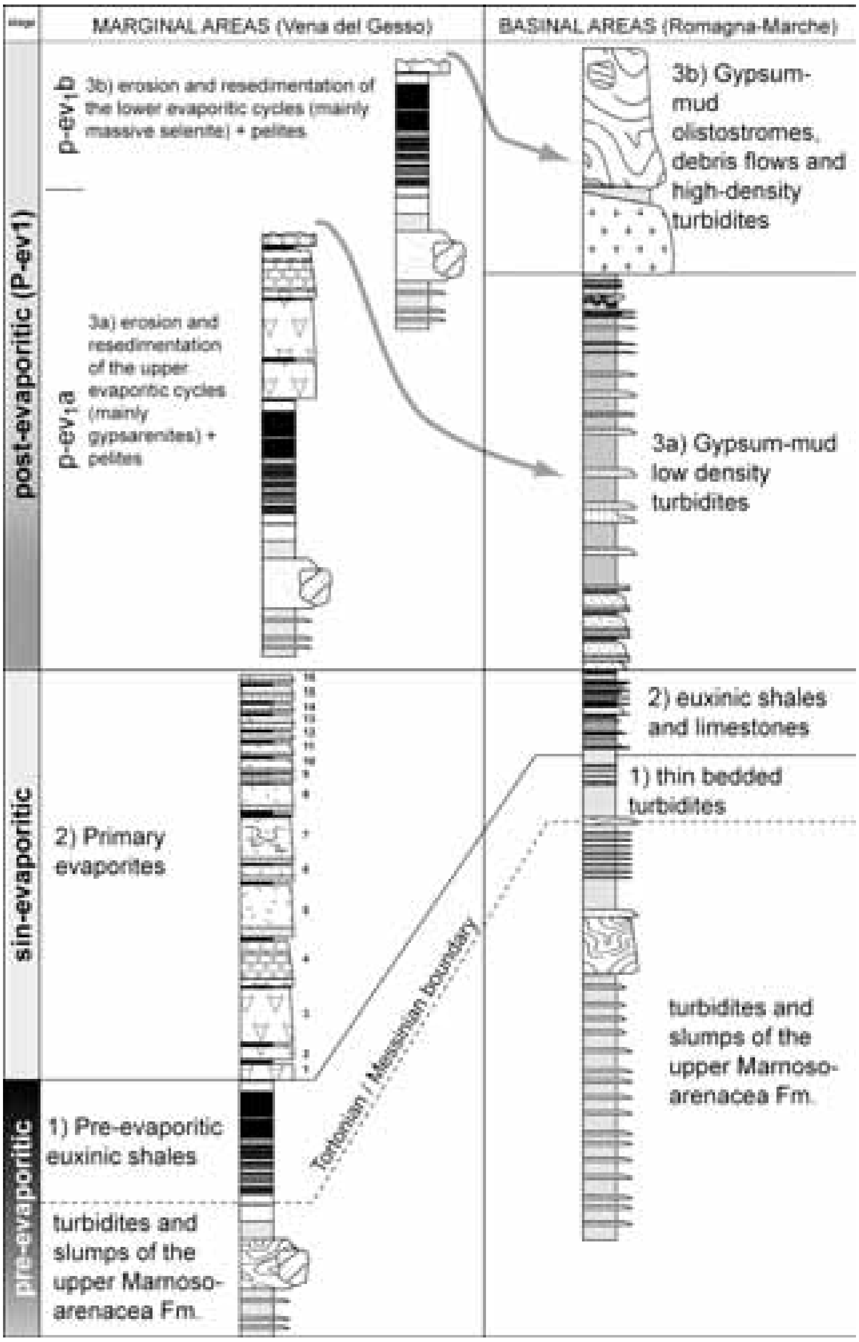


Figure 20 - Genetic and stratigraphic relationships between resedimented and primary evaporites (from Manzi, 2001).

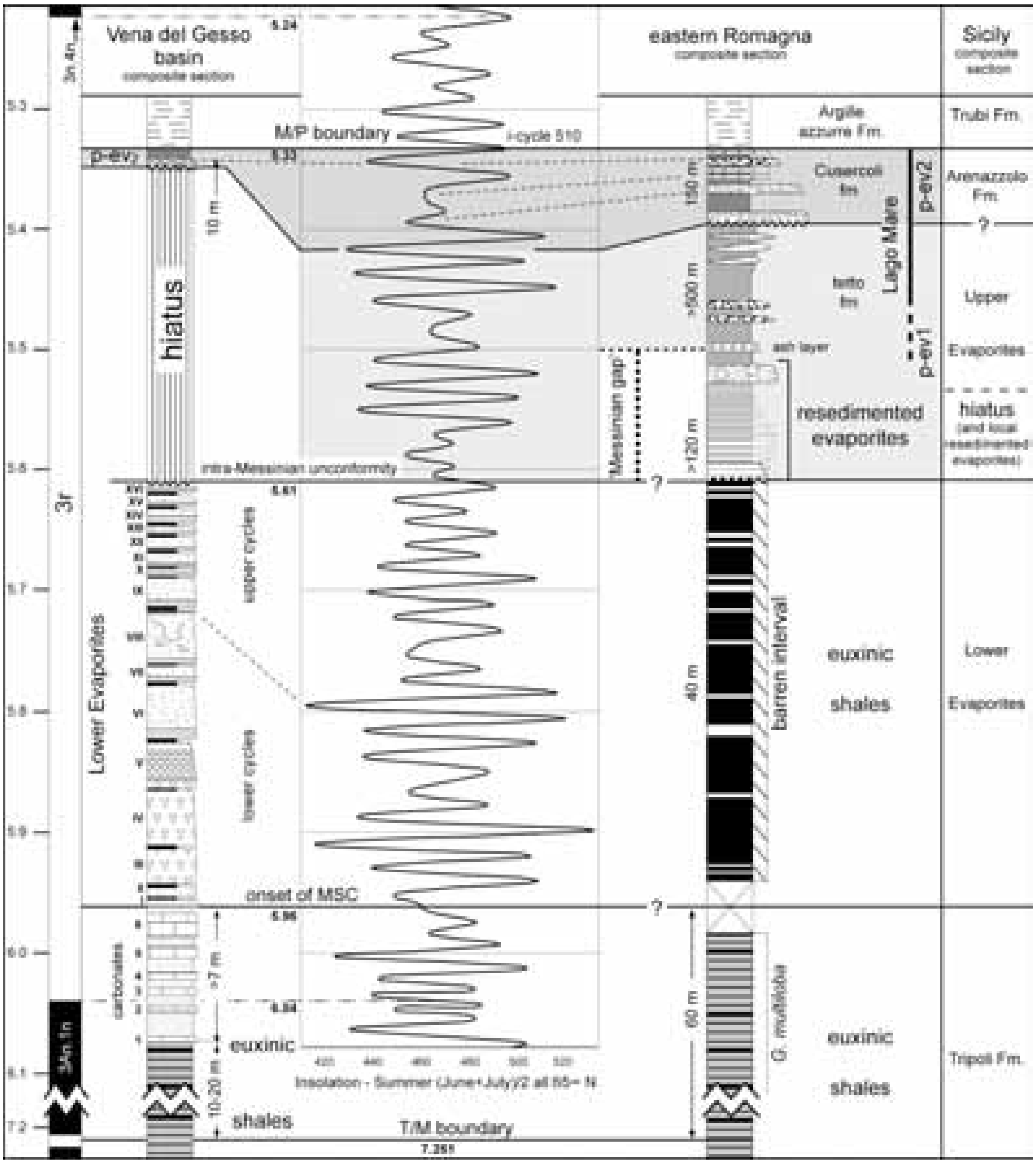


Figure 21 - Correlation of Messinian Apennine foredeep succession with astronomically forced insolation cyclicity. Post-evaporitic deposits show a well-developed cyclic pattern especially in the upper unit (p-ev$_2$).; p-ev$_1$ deposits, having a stronger syntectonic character, show a less-evident cyclicity, especially in the lower part

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 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

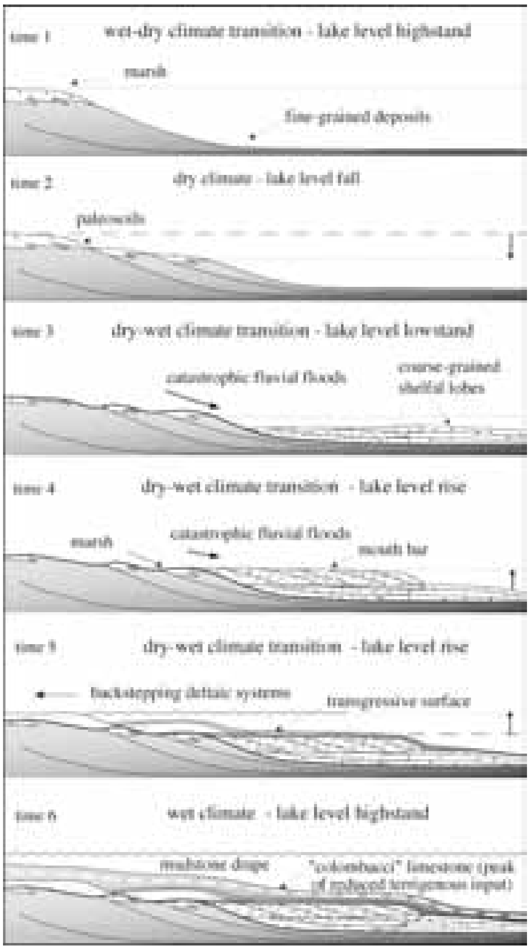
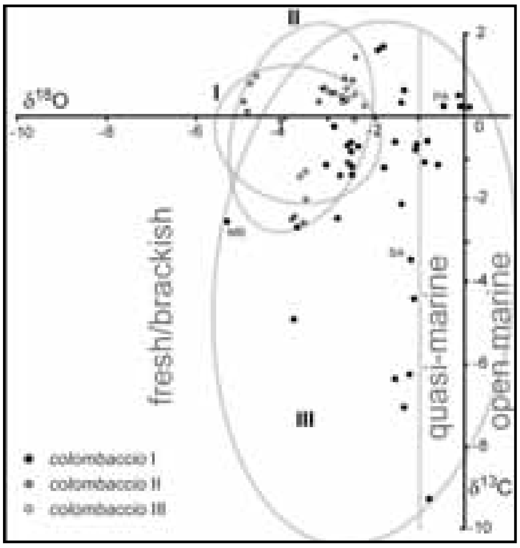


Figure 22 - Ideal evolution of uppermost Lago Mare cyclicity in the Apennine foredeep basins. Modified from Roveri et al. (1998).

instability, leading to huge sediment failures. The deeper and more subsiding character of the eastern sector is demonstrated by the higher thickness of the 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 comes from sediment rates and paleobathymetric reconstruction (Kouvenhowen 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 were 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 with the Forlì line lateral ramp, and to the NE above, the buried anticline crest, which has been revealed by seismic and well data. The unconformity is associated with an angular discordance, and was formed during a paroxysmal phase of tectonic activity. The time elapsed during erosion in marginal uplifting areas, is recorded in topographic depressions by a volume of sediment which corresponds to the lower post-evaporitic unit that occurs 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 a hypersaline to hyposaline basin. Deep-water settings never experienced desiccation, and evaporitic sediments were emplaced by gravity flows, forming a thick unit with tabular

Figure 23 - Isotopic composition of colombacci limestones showing the clear evolution toward the quasi-marine values field, suggesting higher water concentration or true incipient connection with ocean waters (from Bassetti et al., submitted).



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 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 My (LP unconformity), marking a significant propagation of the Apennine thrust front towards 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 with 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 contested 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

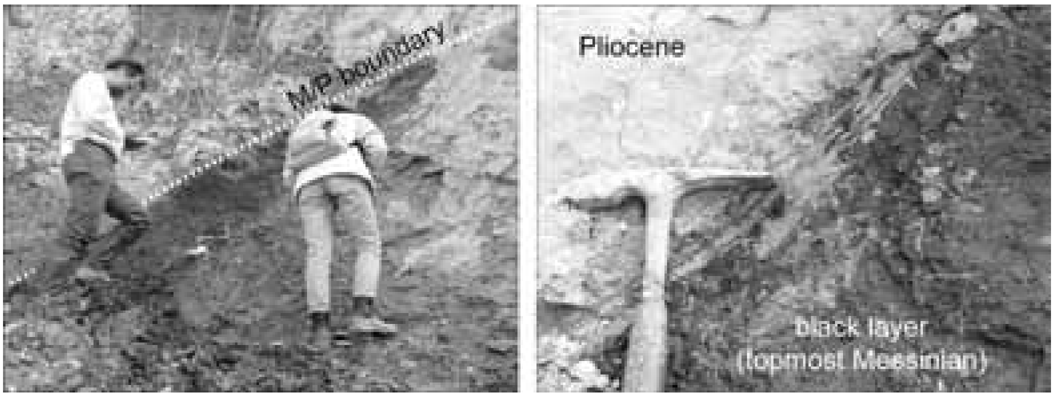


Figure 24 - The characteristic black layerunderlying the sharp transition to open and deep marine conditions at the Miocene/Pliocene boundary. Riccò section (western Emilia Apennines; from Roveri and Manzi, in press).

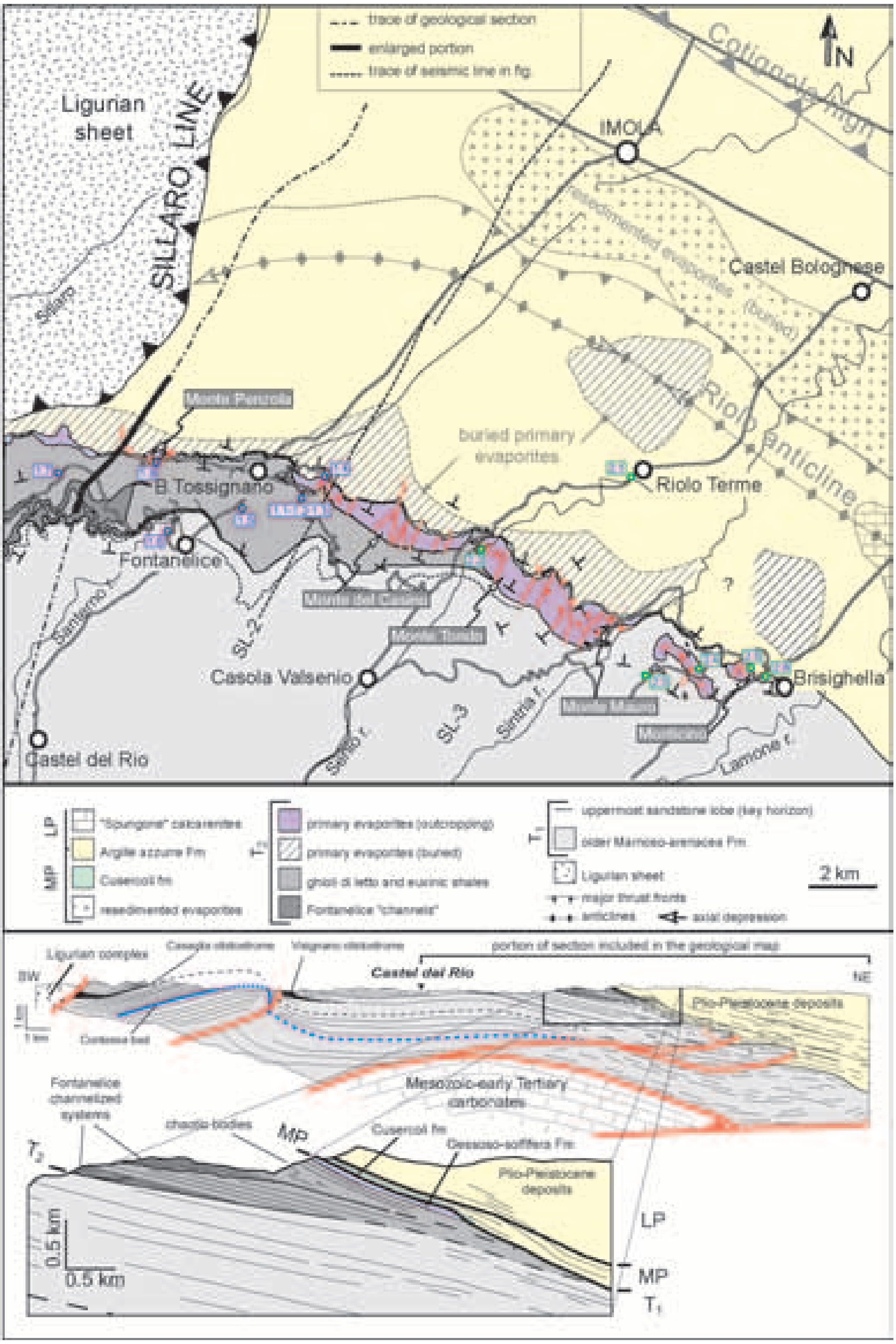


Figure 25 - Geological map of the western sector

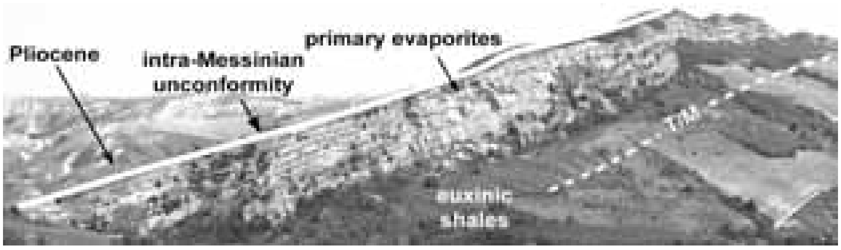


Figure 26 - Stop 1.3. The spectacular Lower Evaporites outcrop (Rio Sgarba sect.), looking eastward from Tossignano.

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

Actually, many differences from the above described ideal cycle of primary evaporites can be observed, especially concerning the regular superposition of facies, with decreasing size of selenite crystals (facies sequence 3-4-5) is concerned; in some cases, inverse facies trends or symmetrical rhythms (4-3-4) occur, and their significance has not been fully understood yet. Such anomalous facies sequences have been observed at the same stratigraphic level (i.e. in the same cycle) in other areas (Marecchia valley), suggesting external forcing factors on facies development.

The aggradational stacking pattern of the Lower Evaporites is a common feature across all the Mediterranean geodynamic settings, and necessarily implies a generalized subsidence or a sea-level rise. The latter hypothesis (Clauzon et al., 2001), would imply a larger water exchange with the Atlantic Ocean, 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.

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 with 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 a 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 the largest rivers (for example, in front of the Nile, Rhone; Clauzon, 1973, 1982; Ryan, 1978; Ryan & Cita, 1978).

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

This suggests an important phase of structural reorganization all along the African-Eurasian 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 with 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 1960s-early 1970s to indicate some "gypsiferous sandstones" cropping out in the Laga basin (the

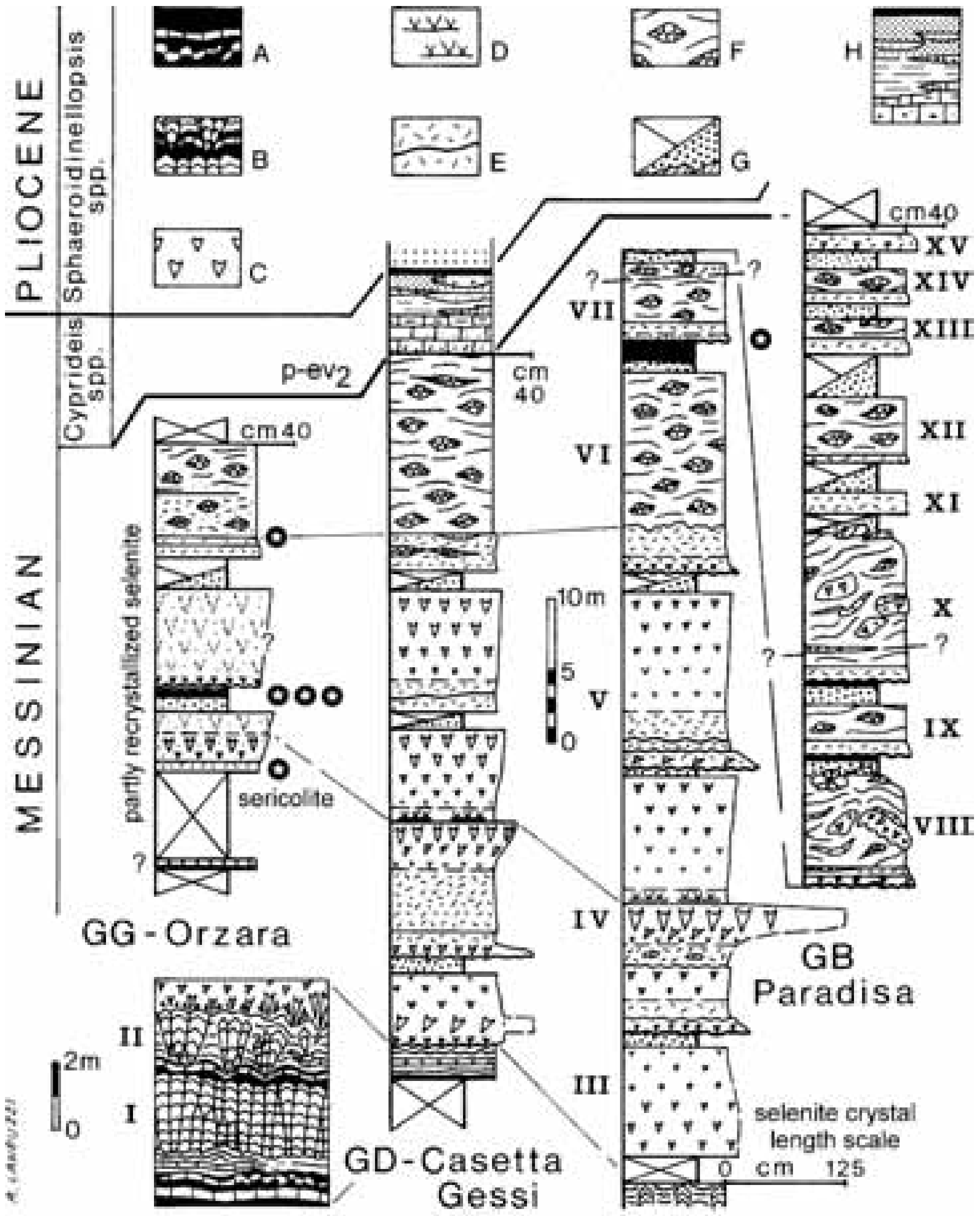


Figure 27 - Stratigraphic columns of the Vena del Gesso in the western side of the Santerno Valley (after Landuzzi, 1985): A= euxinic shales and stromatolitic limestones; B= euxinic shales, calc-gypsum laminites and gypsified stromatolites (facies 1-2); C= massive autochthonous selenite (facies 3); D= interbedded autochthonous and reworked selenite (facies 4); E= entirely reworked selenite (facies 4?); F= clastic, acicular and nodular gypsum (facies 5); G= chaotic gypsum in a clayey matrix (facies 6); H = post-evaporite deposits (see details in Figure28).

southern depocenter of the Messinian Apennine foredeep). These deposits were 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 3.3; Fig. 19), 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 turbidity currents. 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 as the siliciclastic gravity flow deposits are. However, due to the strong diagenetic effects typically undergone 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, 1973; Manzi, 2001; Roveri et al., 2001; Manzi et al., submitted). Despite their common occurrence, they have been virtually ignored until recent times. Based on an integrated sedimentological, petrographic and geochemical study, Manzi et al. (submitted), have proposed a new facies classification, and a genetic model for resedimented evaporates, which implies a close similarity with siliciclastic turbidites. This sedimentological 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.

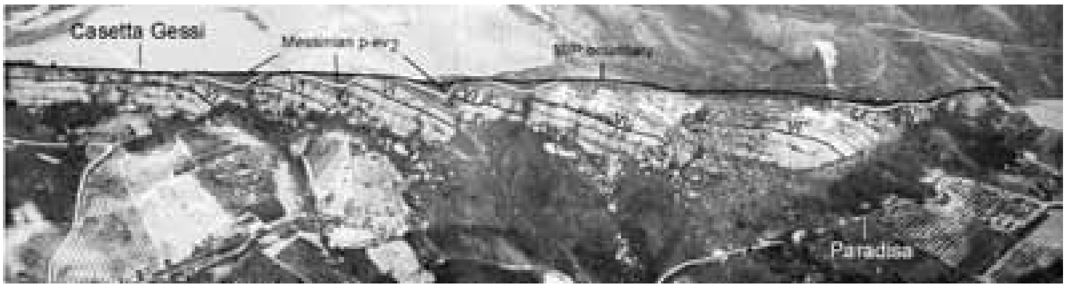


Figure 28 - Air photo of the Vena del Gesso in the western side of the Santerno Valley (M. Astorri). Normal faults and very small reverse faults offset the evaporite cycles, and are sealed by post-evaporite Messinian deposits, which mark a spectacular angular unconformity. The rotational offset of faulted blocks suggests gravity-driven normal faulting, gliding and thrusting on a shallow detachment level within the euxinic shales. Transport was to the S-SW.

One basic problem is the definition of original grain-size of clastic evaporites; in Manzi et al. (submitted), a siliciclastic-derived relationship between grain size and sedimentary structures is proposed in order to indirectly define this important parameter in diagenetically-transformed deposits.

On the basis of 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 which formed in shallow thrust-top basins through large submarine collapses and glides; and these collapses and glides are assumed to have been triggered by tectonic-induced gravitational instability, and were transformed down current into high and low-density turbidity currents. This is clearly evident when considering facies distribution along a NW-SE transect from the Forlì Line to the eastern Romagna and northern Marche basin. Of course, local tectonically-induced topography provides further complications 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 which 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 an upper part made up of disorganized, very coarse clastites, dominated by slumping and olistostromes, often containing large blocks of lithified primary selenite.

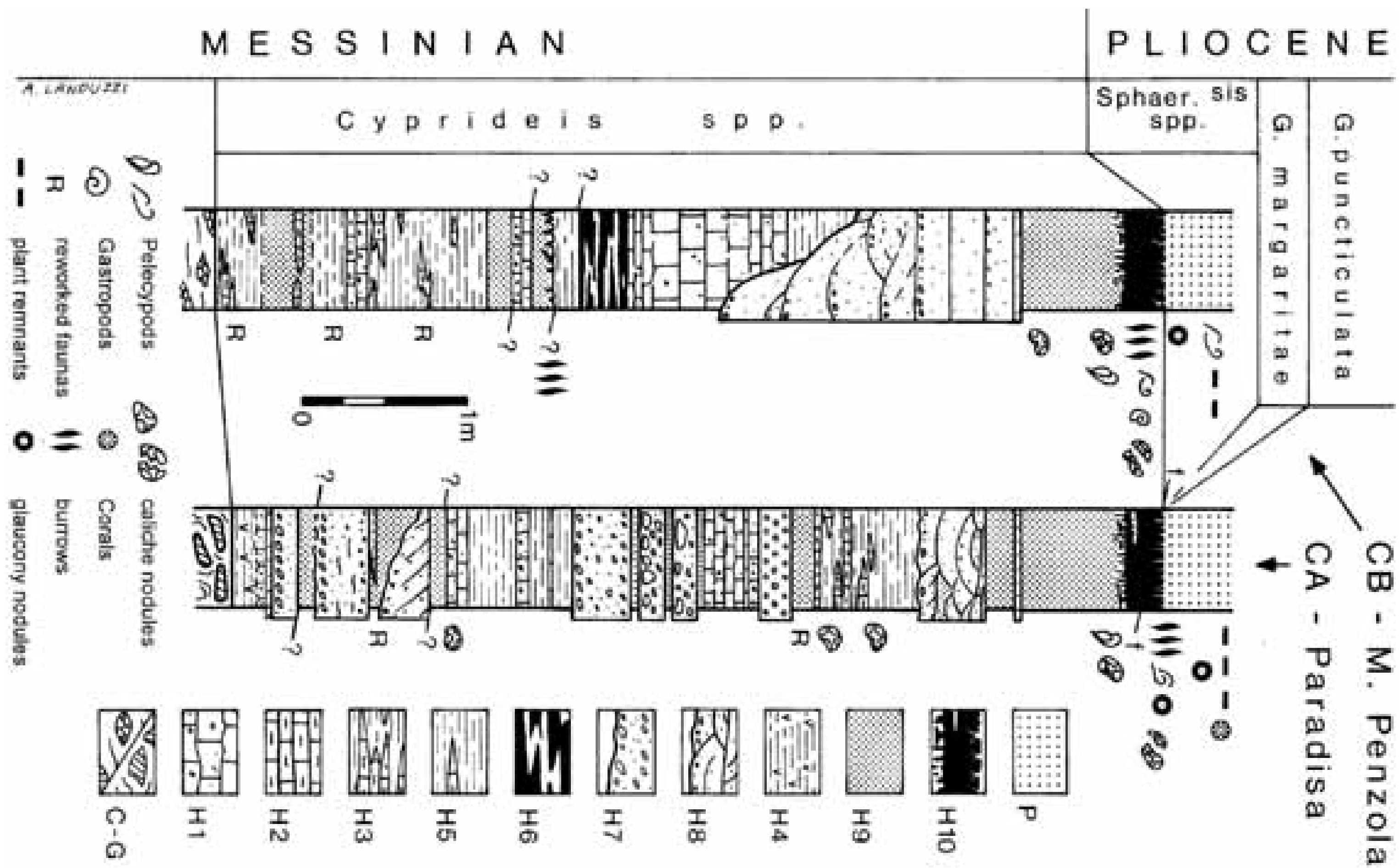


Figure 29 - Stratigraphic columns of the Colombacci fm (upper Messinian p-ev2 unit) in the western side of the Santerno Valley (after Landuzzi, 1985): C-G = GS facies 5-6 (see Figure 27); H1 = limestone breccia with gypsum moulds; H2 = fine-grained clastic limestone; H3 = "varve"-like silty clays with fine-grained limestone lenses; H4 = laminated silty clays; H5 = variegate green and yellow clays; H6 = variegate green and red clays; H7 = poorly sorted calcareous conglomerates in small channel bodies; H8 = festoon-bedded sandstones in small channel bodies; H9 = fossil-rich mudstones; H10 = dark organic-rich pebbly clays; P = Lower Pliocene marine clays (Argille Azzurre Fm).

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 primary evaporitic units formed above or around structural highs (Fig. 20). 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 complex, which could follow up with the muddy deposits of the p-ev1 unit deriving from the euxinic shales and underlying Upper Tortonian slope mudstones. 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 with the intra-Messinian unconformity, would put into discussion the true extent of the Mediterranean deep desiccation.

5 - Gypsum diagenetic transformation and origin of sulphur mineralization

The Gessoso-solfifera Fm. of the Romagna and Marche Apennine contains sulfur deposits that were mined from Roman times until the 1960s (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, in 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 reach 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 with calcite, celestite, barite, bitumen, and emissions of sulfuric acid and methane.

These characteristics indicate that elemental sulfur was 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 most significant aspects is that economically important sulfur concentrations are present only in the clastic sulfate evaporites of the Romagna-Marche area, which 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 through 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 a relatively shallow depth (~ 500-1000 m). Most sulfur deposition possibly occurred through the oxidation of sulfuric acid by dissolved oxygen carried by groundwater during the rehydration of anhydrite.

6 - 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 with 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: that is, the switch from hypersaline to hyposaline waters leading to the Lago Mare stage. The causes, modality, and timing of such a 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 was bridged by the lower part of the p-ev_1 unit, which is made up of resedimented evaporites, and by a thick pile of terrigenous, fine-grained sediments (Figs. 5, 21). This means that the Apennine successions have recorded such events, and for this reason, a detailed study of this interval is being carried out by a multidisciplinary research group. Preliminary observations and analysis carried out on a continuous core (Campea well, stop 4.1) have led to the recognition of the typical Lago Mare ostracod, and 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 their potential as regional lithostratigraphic markers.

7 - 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 Ky, 90 of them recorded by deep Mediterranean evaporites and by the basal p-ev$_1$ unit of the Apennine foredeep (Fig. 21). The bipartite character is an easily-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), is there a well-developed cyclical lithological pattern.

In the Apennine foredeep basins, up to five cycles, defined on the basis of the regular alternation of coarse and fine-grained lithosomes, can be recognized above the ash layer, and can provide an independent, even if not particularly accurate, time calibration.

The upper p-ev$_2$ unit, which is widely recognized on a Mediterranean scale, is characterized by a well-developed, high-frequency cyclical pattern superimposed upon an overall transgressive trend. These two characteristics represent good criteria for high-resolution long-range correlations; 3 to 4 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 uppermost 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 ky interval between the ash-layer and the Miocene/Pliocene boundary.

This is consistent with a precessionally-driven climatic origin of small-scale sedimentary cycles, as occurred during the pre-evaporitic and evaporitic stages. By this way, the p-ev$_2$ unit would span a very short time interval of 60-80 Ky, and a tentative correlation of its small-scale sedimentary cycles with the insolation curve is shown in Fig. 21. 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. 22). During these phases (Fig. 5), small forestepping deltaic systems formed in shallow basins with low gradient shelves; in basins with reduced or steep shelves, fluvial floods could develop hyperpycnal flows which were 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 a rapid rise in the base-level and caused, together with a concomitant climate change towards wetter conditions, the de-activation of flood-dominated deltaic systems, and their landward migration. During wet phases, the base level reached its maximum, but sediment input was drastically lowered for both the reduction of the catchment area, and the possibly lower erosion rate which was due to the increased vegetation cover. In this phase only fine-grained, thinly-laminated mudstones accumulated in the basin. In some places, the 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 with mudstone deposits. According to Bassetti et al. (submitted - see topic 8), they derive from the inorganic precipitation of micrite-size crystals in a relatively deep-water environment which was possibly anoxic and related to permanent water mass stratification events during periods of lake level maxima, and associated peaks of reduced terrigenous input. However, the concomitant occurrence, in the same part of the cycles, of dark, organic-rich clay horizons, rich in specialized Mollusk assemblages (*Congerie*) and interpreted as palustrine deposits, suggests a far more complicated stratigraphic architecture and more complicated evolutionary trends, as tentatively illustrated in the model of Fig. 22. Palustrine horizons, found

at different levels within mudstone units, are not compatible with a simple deepening upward cycle. According to their position within each cycle, the fine-grained lithosome could actually be subdivided 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 could be preserved in the uppermost part of the cycles. However, neither prograding coastal deposits, nor clear evidence of paleosoils, have been clearly recognized so far.
An exception is represented by the uppermost cycle (Roveri et al., unpublished data), where the dark layer marking the Miocene/Pliocene boundary, locally overlies an irregular surface with weak pedogenetic traces (Botteghino section in the Giaggiolo-Cella syncline).
However, the possibly very short time spans encompassed by subaerial exposure phases within each cycle, might not have been sufficient for paleosoil development; moreover, the erosion produced by catastrophic fluvial floods would have removed any trace. According to the model of Fig. 22, palustrine horizons could develop above the subaerial exposure surfaces during initial base-level rises; the *colombacci* limestones would represent a sort of condensed section marking the maximum retreat of clastic sediment sources. Detailed studies of these deposits is being carried out in order to understand better their organization and paleoenvironmental meaning; however, they appear to be analogous with the Lago Mare cycles from the topmost Messinian succession, which have been recently described in Cyprus (Rouchy et al., 2001).

8 - Origin of the colombacci limestones

As previously reported, the colombacci limestones are a typical lithofacies closely associated with the 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. (submitted), 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 the Lago Mare deposits of the Mediterranean basins; their geochemical composition provides 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. 23; Bassetti et al., submitted), 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.

9 - Marine incursions during the Lago Mare stage?

Besides the above considerations based on the isotopic composition of limestone horizons, occasional marine incursions in the Lago Mare deposits have been reported from different Mediterranean basins, especially on the basis of nannoplancton assemblages (Blanc-Valleron et al., 1998; Pierre et al., 1998; Spezzaferri et al., 1998; Snel et al., 2001). Isotopic composition 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. However, the commonly observed foraminifera associations made up of small-size, dwarfed specimens need to be thoroughly investigated.

10 - 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 peculiarly interesting feature is that the direct superposition of MPl1 deposits above rocks older than the uppermost Messinian, has never been reported. MPl1 sediments are always associated with Messinian Lago Mare deposits, as part of a longer-term transgressive sequence. This is particularly clear in the Apennine foredeep, where such a 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 a boundary becomes very difficult to recognize (Roveri and Gennari, unpublished data). Elsewhere, a black, organic-rich layer always underlies the lowest deep-marine MPl1 sediments (Fig. 24). 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 be associated with a slightly erosional surface and weak paleosoil traces.

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 between the different sub-basins, the Miocene/Pliocene transition would be rather explained by a sudden hydrologic change associated with a bathymetric change of lower amplitude than usually thought. This would point to the Zanclean flooding being less catastrophic in character.

Field trip itinerary

Introduction to Days 1 and 2

These two days will be spent in an area between the Sillaro and the Lamone valleys (Fig 25). The Santerno Valley, that will be visited during day 1, 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 1960s and 1970s. The local stratigraphic succession that can be observed spans in age from Lower Serravallian to Pliocene. The Marnoso-arenacea Formation is overlain by the Messinian evaporites which, in turn, are unconformably overlain by uppermost Messinian continental deposits and 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. A packet of vertical to slightly overturned strata interrupts this regular bedding attitude at Coniale; these beds represent the northern limb of the ramp anticline associated with the Mt. Castellaccio thrust, a tectonic feature elongate in a NW-SE direction, that can be traced as far as the Savio valley. In the Santerno valley, the core of the Coniale anticline is where the oldest stratigraphic level of the Marnoso-arenacea Fm is exposed. Further upstream, between S. Pellegrino and Firenzuola, the sand-rich Firenzuola system turbidites crop out in the southern flank of the Coniale anticline.

DAY 1

Stop 1.1:

The reception center of the Vena del Gesso Natural Park, Tossignano. Depending on time availability and weather conditions, this optional stop will be devoted to visiting a small museum exhibiting materials about nature, geology, mining activities, history, and country life in the unusual environment of the Vena del Gesso.

Stop 1.2:

Rocca di Tossignano. The ruins of the medieval castle on the hilltop are a wonderful place for a panoramic view over the Santerno valley and the Apennine foothills monocline (see cover photo and Fig. 26). From SW to NE, the geologist can visually explore up-section the following stratigraphic units, whose details will be dealt with in the next stops:

- 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.
- 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 (not visible), 3 “major” ones (grey selenite), a very thick 6th one (grey selenite and white clastic gypsum), and up to 10 “minor” ones (mostly white clastic gypsum). All 16 cycles crop out only in the eastern side of the Santerno valley (Rio Sgarba quarry, stop 1.4). In the western valley side (Fig. 27), a maximum of 15 cycles is found in the old Paradisa quarry, while 7 cycles crop out at Mt. Penzola, and only 4 ones crop out at Orzara. Near the Santerno river bed, this W-ward reduction of the evaporite succession is clearly explained by a Upper Messinian angular unconformity (Fig. 27), while further to the W, a non-depositional hiatus is also possible. This alternative explanation would be

in agreement with the overall W-ward thinning of the individual evaporite cycles from the Senio valley to the Sillaro valley (Fig. 26).
- Colombacci fm: a hard-to-see 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. 28). For instance, conglomerates and sandstone pockets (facies H7-H8 in Fig. 29) are better represented within structural depressions.
- Argille Azzurre Fm: marine silty clays of Lower 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. 28).

Stop 1.3:

Tossignano, Resistance (II World War) Memorial Park. This panoramic view covers the GS from the Riva San Biagio cliff (Fig. 26), 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. 25). Evaporites are offset by Upper Messinian normal faults belonging to a *Graben* structure symmetrical to the bedding planes (Fig. 30). Perhaps those normal faults can be associated with gravity-failure structures, like those documented on the other side of the Santerno valley.
Topics: 2.

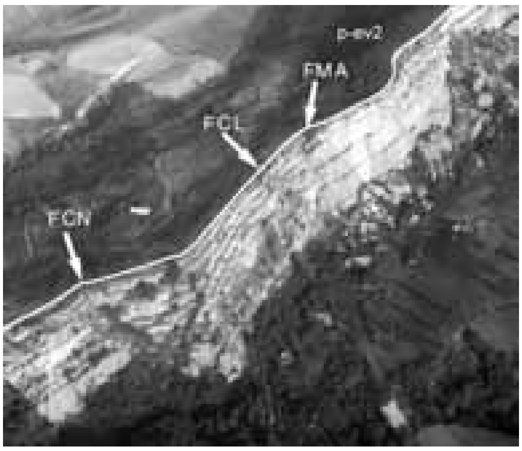


Figure 30 - Air photo of the Vena del Gesso in the eastern side of the Santerno Valley (M. Astorri). Longitudinal (FCN, FMA) and transverse (FCL) normal faults offset the evaporite cycles, and are sealed by post-evaporite Messinian deposits (p-ev2).

Stop 1.4:

Road Tossignano - Borgo Tossignano – Codrignano; deviations to the abandoned quarry in the Rio Sgarba valley, and to the old quarry at Paradisa, on the left bank of the Santerno river. Both sites were deeply investigated when the model of Vai and Ricci Lucchi (1973) was elaborated. The peculiar facies architecture of the modal cycle can be assessed in detail, starting from the 6th cycle, which is the first and thickest example of a complete facies sequence. Smaller scale discrepancies with the basic model represent an interesting subject for debate. For instance, the complex and anomalous crystal size variation in the 3rd, 4th and 5th cycle (Fig. 27), where reverse gradation, dissolution surfaces (Fig. 14 c), and reworked selenite intervals are common. These intra-cycle features, possibly related to brine dilution episodes, have the same impressive correlation potential as the entire modal cycles. Indeed, they can be traced throughout the para-autochthonous Vena del Gesso basin, and from it to the semi-allochthonous evaporite basin of the Marecchia-Conca area (Montebello, Gesso, Sassofeltrio). Another basin-scale problem is represented by the sharp and strongly irregular erosion surface which marks the onset of facies 5 in the 6th cycle. Some of the possible large-scale factors controlling evaporite deposition are summarized in the "hot Messinian topics" chapter.
Topics: 2, 7.

Stop 1.5:

Road Borgo Tossignano - Fontanelice, Molino Campola. A panoramic view from the Santerno river bed towards the western side of the valley allows the framing of a 50-60 m thick intraformational slump within the fine-grained closure facies of the MA (Fig. 31). The inferred slumping direction to the S-SW can be related to the Late Tortonian nucleation of the Riolo Terme high (Fig. 25).
Topics: 2.

Stop 1.6:

Road Fontanelice – Gesso. Other panoramic views illustrate the closure facies and the earliest deformation features of the MA clastic wedge. The uppermost "channel" body of the Fontanelice

member (Figs. 9, 10), the already described slump and the overall thinning- and fining-upward trend, are coherent indications of foredeep fragmentation and basin narrowing.
Topics: 1, 2.

Stop 1.7:

Pieve di Gesso and Sassatello valley. A panoramic view on the so-called "Sillaro line" portraits the synsedimentary overthrust of the Liguride nappe in Messinian times (Fig. 32). Olistostromes coming from the Liguride and epi-Ligurian units have been continuously forerunning the nappe advancement. Many of them were tectonically incorporated in the nappe itself, while others were embedded in the autochthon succession. An example of the second type is the Upper Messinian Sassatello olistostrome, enclosed in the para-autochthonous p-ev_2 unit. Its composition is characterized by Lower-Middle Miocene marls and typical Messinian carbonates, such as pre-evaporite and evaporite-derived limestones. A closer inspection of the olistostrome and the local Gessoso-solfifera Fm, gives us the opportunity to discuss the diagenetic transformations of primary evaporites.
Topics: 1, 2, 5.

Stop 1.8:

The "Mt. Penzola walk" We walk along the Santerno – Sellustra watershed from Mt. la Pieve to Mt. Penzola and Debolezza, then we go down to Casetta Gessi, and reach the nearest bridge on the Santerno River. (Fig. 28) The main subjects that are dealt with

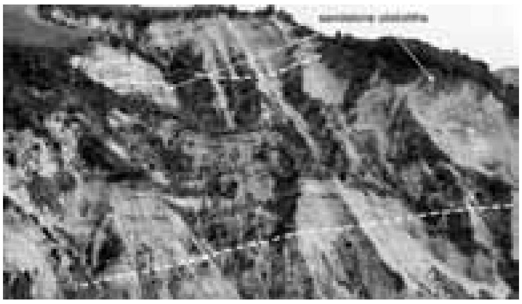


Figure 31 - Closure facies of the Marnoso-arenacea Fm in the western side of the Santerno Valley: two sandstone olistoliths mark a slump horizon in a fining-upward succession of thin-bedded turbidites. Local slumping transport was possibly to the S-SW.

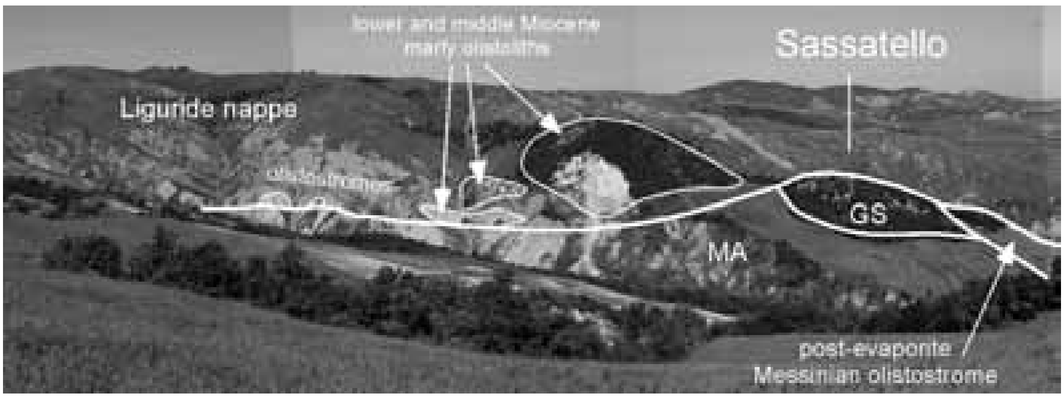
are the Lower Pliocene clays and conglomerates, the angular unconformities in the post-evaporite p-ev_2 sequence, and the Late Messinian tectonics. The most attractive features of this itinerary are the M. Penzola thrust (Fig. 33), and a short but complete section of the Colombacci fm (Fig. 34, Fig. 29), featuring a very good outcrop of the Miocene/Pliocene boundary. Discussion is expected on the role of gravity vs. tectonics in the cortical deformation style of the evaporite unit.
Topics: 1, 2.

DAY 2

Stop 2.1:

Visit to the reception center of the Vena del Gesso Natural Park, Riolo Terme. This is another optional

Figure 32 - The Liguride nappe thrusting over the western Romagna para-autochthon: Messinian pre-evaporite (MA), evaporite(GS) and post-evaporite units are truncated atop by the overthrust surface, a gentle ramp dipping to the W. Olistostromes fed by Liguride and epi-Ligurian units occur both above and below the tectonic contact. Near Sassatello, a peculiar Messinian olistostrome is embedded in the p-ev2 unit of the para-autochthon.



stop about the geological, ecological, historical and socio-economic importance of Vena del Gesso.

Stop 2.2:

Road Riolo Terme - Casola Valsenio, stop at Borgo Rivola: the Mt. Tondo quarry, and the adjoining Messinian outcrops. Monte Tondo and Monte del Casino are respectively situated on the eastern and western divide of the Senio valley. Actually, they are the two most important sampling sites for high-resolution cyclostratigraphy, magnetic calibration and astronomic dating of the main Messinian events in the Vena del Gesso basin. Discussion will mainly focus on the cyclicity of the pre-evaporite unit. If possible, participants will be driven to the site of the Mt. Tondo section, which straddles the Tortonian-Messinian boundary, and extends upwards to the GS base. The typical pre-evaporite Messinian is a dm-scale, dark-light alternation of thin-laminated bituminous shales (anoxic levels), non-laminated organic-rich clays (disoxic levels), and common marly clays (oxic levels).

Topics: 1, 2.

Stop 2.3:

Zattaglia - Brisighella road, near La Torretta. In a panoramic view over the western side of the Sintria Valley (Fig. 35), the most prominent tectonic feature is a well-developed imbricate stack of SW-verging Upper Messinian thrust-sheets, which involve the GS and the upper part of the pre-evaporite succession. In the neighborhood, 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 characteristic of this peculiar imbricate stack is that not 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. 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 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, from a merely structural point of view, the back-thrusts cropping out in the Sintria and Lamone valleys are likely to have been formed by gravitational failure and gliding. Other valid reasons are reviewed in the introduction of this Guide.

Topics: 1, 2.

Figure 33 - 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. This anomaly might result either from complex accommodation of gliding blocks, or from "real" tectonic thrusting.

Figure 34 - Northern slope of Monte Penzola: an about 5 m thick Colombacci fm (see Figure 29) separates the GS (6th cycle, facies 5) from the lower Pliocene clays. The typical dark layer marking the Miocene/Pliocene boundary is slightly offset by normal faults.

Stop 2.4:

Carne' Natural Park and/or Tanaccia cave entrance. A short off-road walk gives the participants the opportunity to see recent karstic morphologies superimposed on Upper Messinian thrust-faults and sub-vertical gypsum strata.

Topics: 1, 2, 3.

Stop 2.5:

Brisighella: the Monticino Sanctuary and the adjoining gypsum quarry. 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. 36). Subaerial erosion of gypsum is documented by karstic Neptunian dikes sealed by post-evaporite

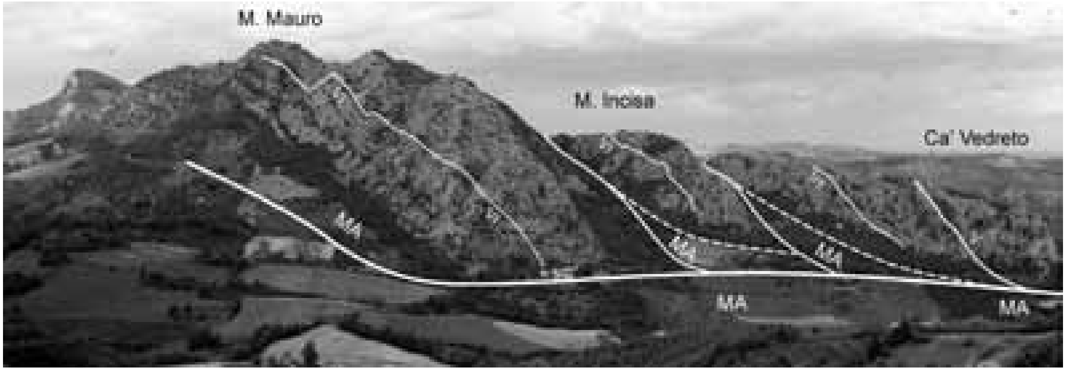


Figure 35 Monte Mauro and the western side of the Sintria Valley, from the S: the SW-verging thin-skinned thrusts that involve the evaporite unit can be explained by gravity-driven block-gliding, on a shallow detachment level within the euxinic shale unit (MA). As in the Santerno Valley example (Figure 28), the initial effect of gliding was the development of SW-dipping normal faults dismembering the evaporite unit. During the subsequent gliding progression, the same faults were rotated and partly reactivated as thrusts (dashed lines).

Messinian deposits (p-ev$_2$). From 1985 to 1988, a very rich fauna of continental vertebrates was found in those paleo-karsts (Marabini & Vai, 1988). Panoramic and close views point out the present-day state of the quarry, which is being converted into an open-air geological museum.

Topics: 1, 2, 3, 10.

Stop 2.6:

Brisighella: participants will be offered a leisurely walk from the medieval castle to the Clock Tower, along faulted, vertical-bedded and karstified gypsum ridges.

Topics: 2.

Introduction to Day 3 and 4

In the Santerno section 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. 38), two wedge-top basins bounded to the west by the Forlì

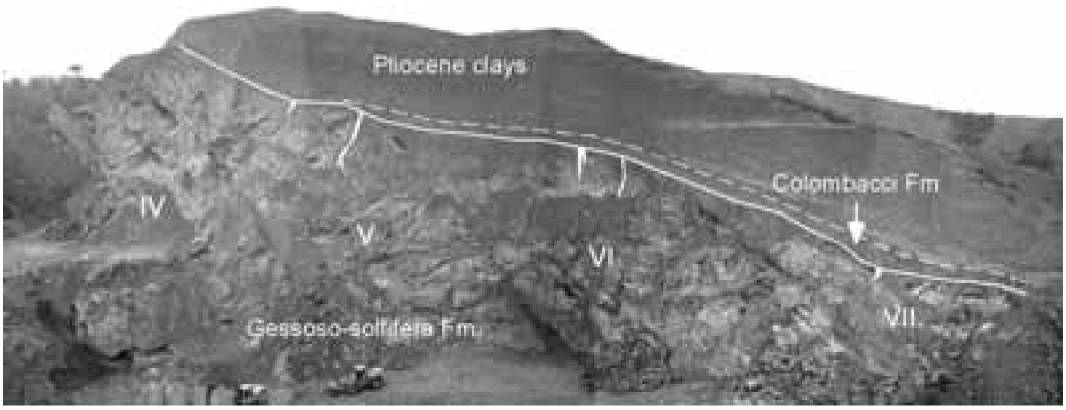


Figure 36 - Monticino Quarry, Brisighella: the mining front represents the best possible exposure of the angular unconformity between the depositional sequences T2 and p-ev2. Some fractures sealed by the unconformity have been highlighted for their virtual relationship to the famous Vertebrate-bearing upper Messinian sedimentary dykes.
Figure 38 – Stop 3.1. 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).

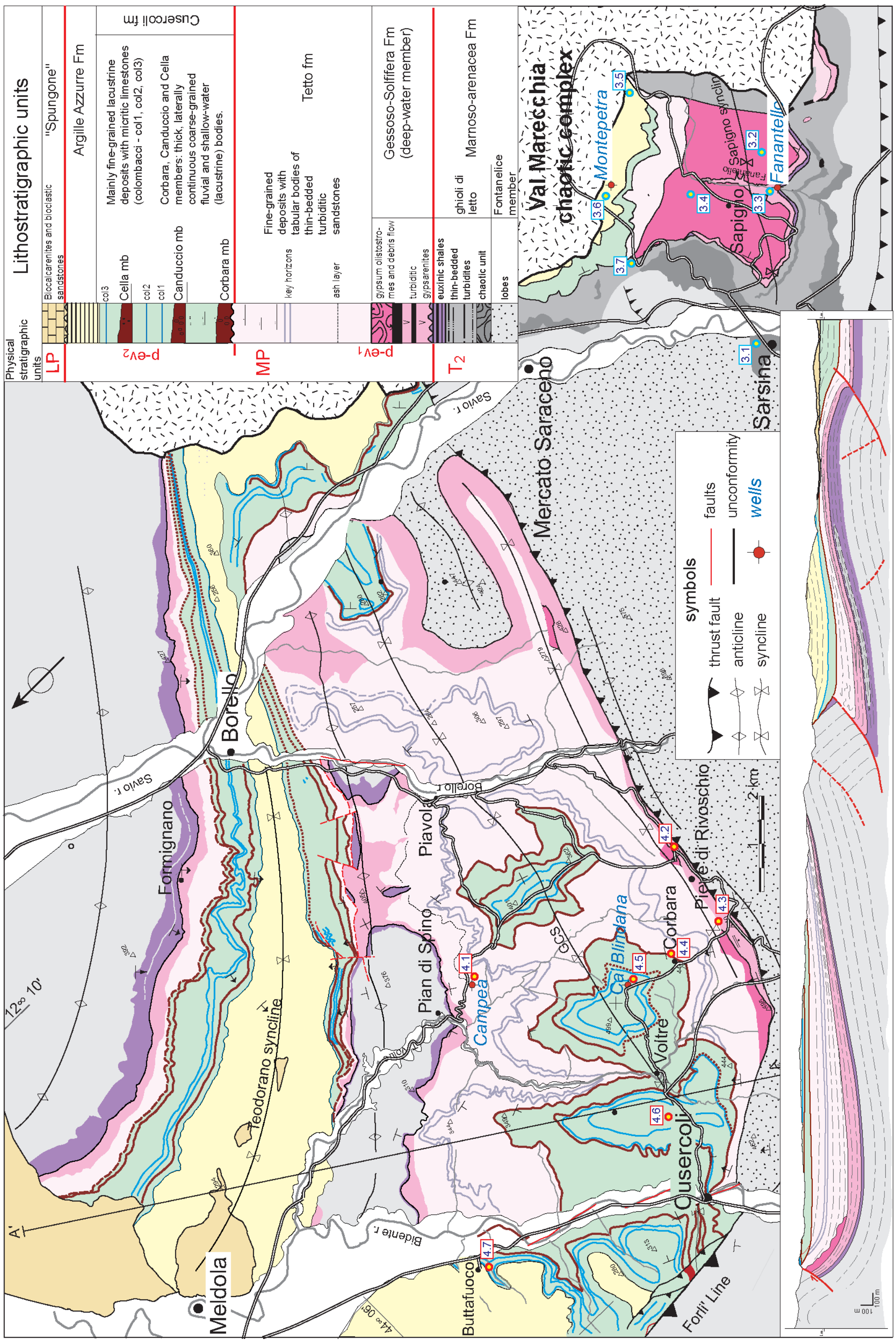


Figure 37 - Geological map of the eastern sector

Figure 38 - Stop 3.1. 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).

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, small to large-scale intraformational slumpings), show 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/yr 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 uppermost Messinian deposits will be also dealt with during these two days.

DAY 3

Stop 3.1:

Savio valley, panoramic views along the National road to Mercato Saraceno. The Upper Tortonian-Lower Messinian succession of the Savio valley: correlation with the Santerno valley (Fig. 38).
Topics: 1, 4.

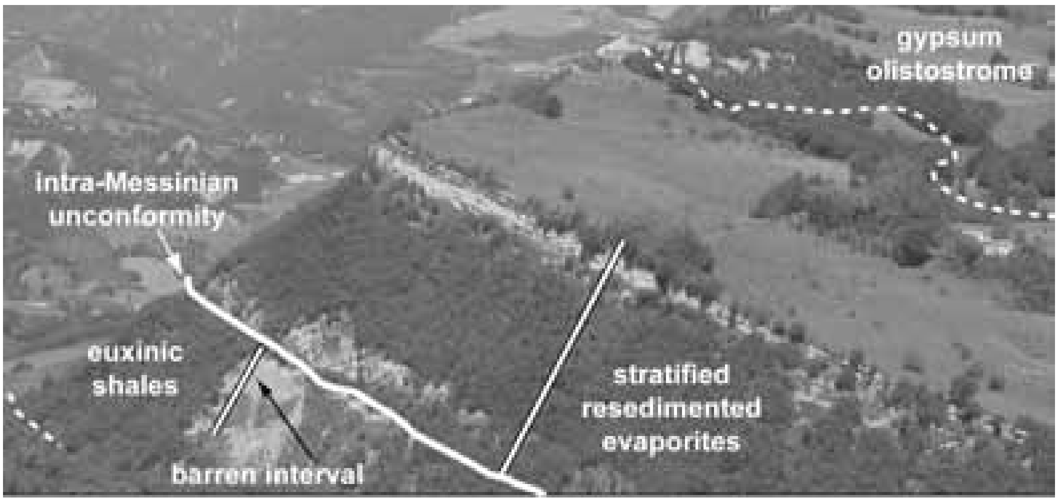


Figure 39 - Stop 3.2. Panoramic view looking west from Maiano of the Messinian succession of the Sapigno syncline. Note the clear bipartite character of the resedimented evaporite complex overlying the local euxinic shales, also well detectable from slope morphology: the tabular gypsarenitic bodies of the lower part are overlain through an irregular surface by a huge chaotic gypsum complex.

Stop 3.2:
Road Sarsina - S.Agata Feltria, deviation to Maiano. Panoramic view of the resedimented evaporites complex of the Fanantello section (Fig. 39). Body geometry and stacking pattern.
Topics: 3, 4.

Stop 3.3:
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 the facies characteristics of the *balatino* gypsum facies.
Topics: 4.

Stop 3.4:
Road Sapigno-Perticara. Panoramic view of the gypsum olistostrome, and of the post-evaporitic Lago Mare succession of the Sapigno syncline.
Topics: 4, 6.

Stop 3.5:
Perticara: visit to the local Mine Museum.
Topic: 5.

Stop 3.6:
Road Perticara-Montepetra. Panoramic views and core data (Montepetra well) of the uppermost post-evaporitic (Lago Mare) deposits, and the Miocene/Pliocene transition (Fig. 24).
Topics: 7. 8, 9, 10.

Stop 3.7: (optional)
Montepetra. Close inspection of the Montepetra "Lucina limestone", an Upper Tortonian-Lower Messinian deep-water chemioherm related to cold fluid seepage on the sea-floor. The Lucina limestones represent a classic topic for Apennine geology; their time and space distribution suggest a strong relationship with the structural evolution of the Apennine thrust belt.

DAY 4

Stop 4.1:
Road Piavola - Pian di Spino. Northern limb of the Giaggiolo-Cella syncline.
Panoramic and close-up views on general facies and the physical-stratigraphic characteristics of the basal post-evaporitic succession; the transition to hyposaline conditions - the 5.5 Ma ash layer - synsedimentary Messinian tectonics. Facies details of the p-ev$_1$ deposits in the cores of the Campea well.
Topics: 6.

Stop 4.2:
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. As with 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 easily recognizable.
Topics: 4.

Stop 4.3:
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: 7.

Stop 4.4:
Road Pieve di Rivoschio - Voltre (close view) - Corbara. Flood-dominated, fluvio-deltaic systems of the p-ev$_2$ unit. Close-up view of the coarse-grained deposits forming the base of small-scale cycles (Fig. 40). They consist of tabular bodies made up of amalgamated massive sandstones and pebbly sandstones, with scoured erosional bases and clay chips (depositional lobe), passing down-current to hummocky, cross-stratified sandstones, and to thin-bedded, rippled sandstones; lobes are locally overlain by low-angle-inclined conglomerates forming sigmoidal bars. The 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 flow volume.
Topics: 7

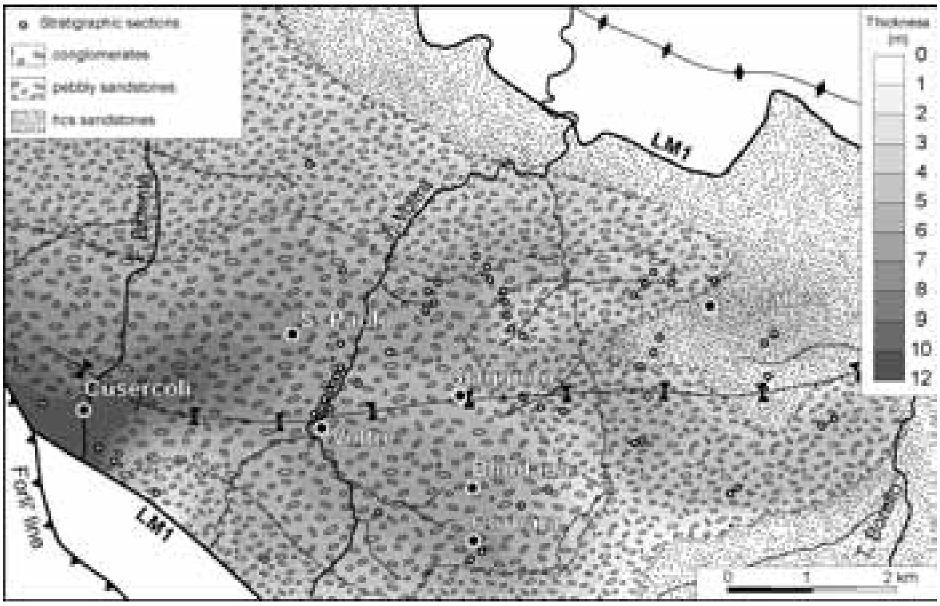


Figure 40 - Facies and thickness distribution of the lowermost corse-grained body of the Cusercoli fm (Corbara hzn)

Stop 4.5:

Road Voltre - Pian di Spino. Anatomy of the upper Lago Mare cycles from outcrop and core data (Cà Blindana well). The sedimentological and palaeoenvironmental meaning of fine grained deposits of the p-ev_2 unit. Facies characteristics and the origin of the "colombacci" limestones and of intervening black, organic-rich mudstones.

Topics: 7, 8, 9.

Stop 4.6:

Road Voltre - Cusercoli. Panoramic view, showing the clear stacking pattern of the uppermost Messinian deposits. Climatic vs. tectonic control of high-frequency cyclicity; the uppermost Messinian 'transgression' and the Pliocene marine flooding.

Topics: 7

Stop 4.7: (optional)

Road Cusercoli-Meldola, Bidente valley. Close-up view of the Miocene/Pliocene boundary in the Buttafuoco section.

Topics: 10.

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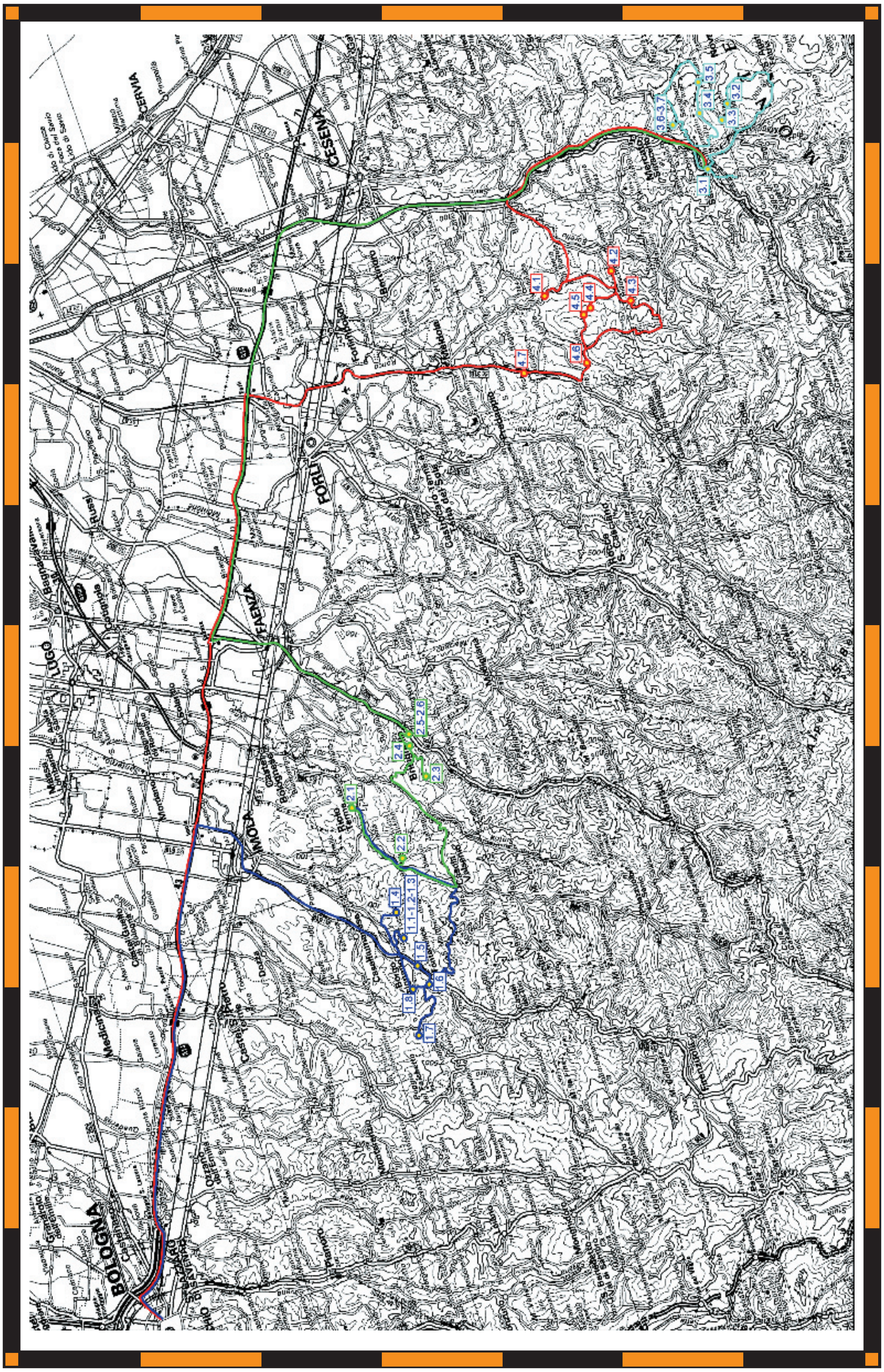
Back Cover:
field trip itinerary

FIELD TRIP MAP



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