# Sedimentary and tectonic evolution of the Vena del Gesso basin (Northern Apennines, Italy): Implications for the onset of the Messinian salinity crisis

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## ABSTRACT

**The integration of field and subsurface data permits a substantial revision of the sedimentary evolution of the Vena del Gesso basin, a thrust-top basin in the Northern Apennines where shallow-water primary gypsum deposits related to the Messinian salinity crisis were well developed and preserved. As inferred from lateral and vertical facies changes within the underlying deep-marine turbidites of the Marnoso-arenacea Formation, evaporite precipitation occurred in a basin bounded to the north and to the east by a thrust-related anticline actively growing since the late Tortonian. Both gypsum deposition and subsequent deformation were strongly controlled by evolving paleobathymetry driven by tectonics. Primary gypsum precipitated in a shallow, silled basin, while in the adjacent deeper and larger foredeep basin, organic-rich shales were deposited. Gypsum deposits underwent severe postdepositional deformation related to large-scale gravitational collapse, as a result of a regional uplift event, also coincident with the end of the evaporitic phase. Along the inner, shallower-dipping limb of the anticline bounding the basin, large-scale, poorly deformed gypsum slabs moved downslope along a detachment surface developed at the contact with the underlying euxinic shales, forming both extensional and compressional features and showing an overall southwestern vergence. The identification of a southwest–dipping paleoslope, here pointed out for the first time, suggests that the deformational features affecting the gypsum unit were probably driven by gravity and not by active thrusting, as thought up to now. The steeper frontal limb of the anticline promoted the transformation of gypsum slides into debris flows and turbidite currents that deposited their load in the adjacent deeper basin. This gravitational deformation was sealed by postevaporitic upper Messinian Lagomare deposits. The sedimentary history of the Vena del Gesso basin suggests that the Messinian salinity crisis in the Apennine foredeep, as well as in the Balearic, Tyrrhenian, Sicily, and Eastern Mediterranean Basins, was tightly linked to tectonic processes. The large-scale, postdepositional collapse of primary evaporitic deposits is a widespread feature in the Mediterranean basins, and it may have altered the original stratigraphic relationships in some places. This finding has potentially important implications for a correct paleoenvironmental reconstruction of the onset of the Messinian salinity crisis.**

**Keywords: Messinian salinity crisis, Apennine foredeep, thrust-top basins, evaporites, slope instability, physical stratigraphy.**

## INTRODUCTION

The Tortonian–Messinian succession of the Apennine orogenic wedge records the fragmentation and closure of the Marnoso-arenacea foredeep basin during the longer-term thrust-front propagation and concurrent depocenter migration toward the foreland (Ricci Lucchi, 1986). This process implied the formation of small thrust-top basins; some of them were characterized during the Messinian by the deposition of shallow-water, primary evaporites (mainly selenitic gypsum), coeval with the Lower Evaporites of Mediterranean marginal basins (Krijgsman et al., 1999a, 1999b). However, because of subsequent tectonic deformation, these basins are rarely preserved; the Vena del Gesso basin is a valuable exception. It is worth noting that most of the Messinian evaporitic rocks occurring in the Apennine foredeep are actually deep-water clastic deposits derived from the dismantling of primary evaporites and their resedimentation through gravity flows (Parea and Ricci Lucchi, 1972; Ricci Lucchi, 1973; Roveri et al., 2001; Manzi, 2001).

The name ''Vena del Gesso'' indicates a continuously outcropping gypsum belt elongated in a northwest-southeast direction for some 15 km in the western Romagna Apennines (Fig. 1). This area offers spectacular and impressive outcrops of selenitic gypsum. Extensive studies carried out in the 1970s led to the formulation of the sedimentary model for the cyclical deposition of primary selenitic gypsum (Vai and Ricci Lucchi, 1977). Subsequent work focused on related topics concerning the origin of postdepositional deformation affecting the gypsum unit (Marabini and Vai, 1985), the late Messinian mammalian fauna found in karstic dikes cutting the unit's

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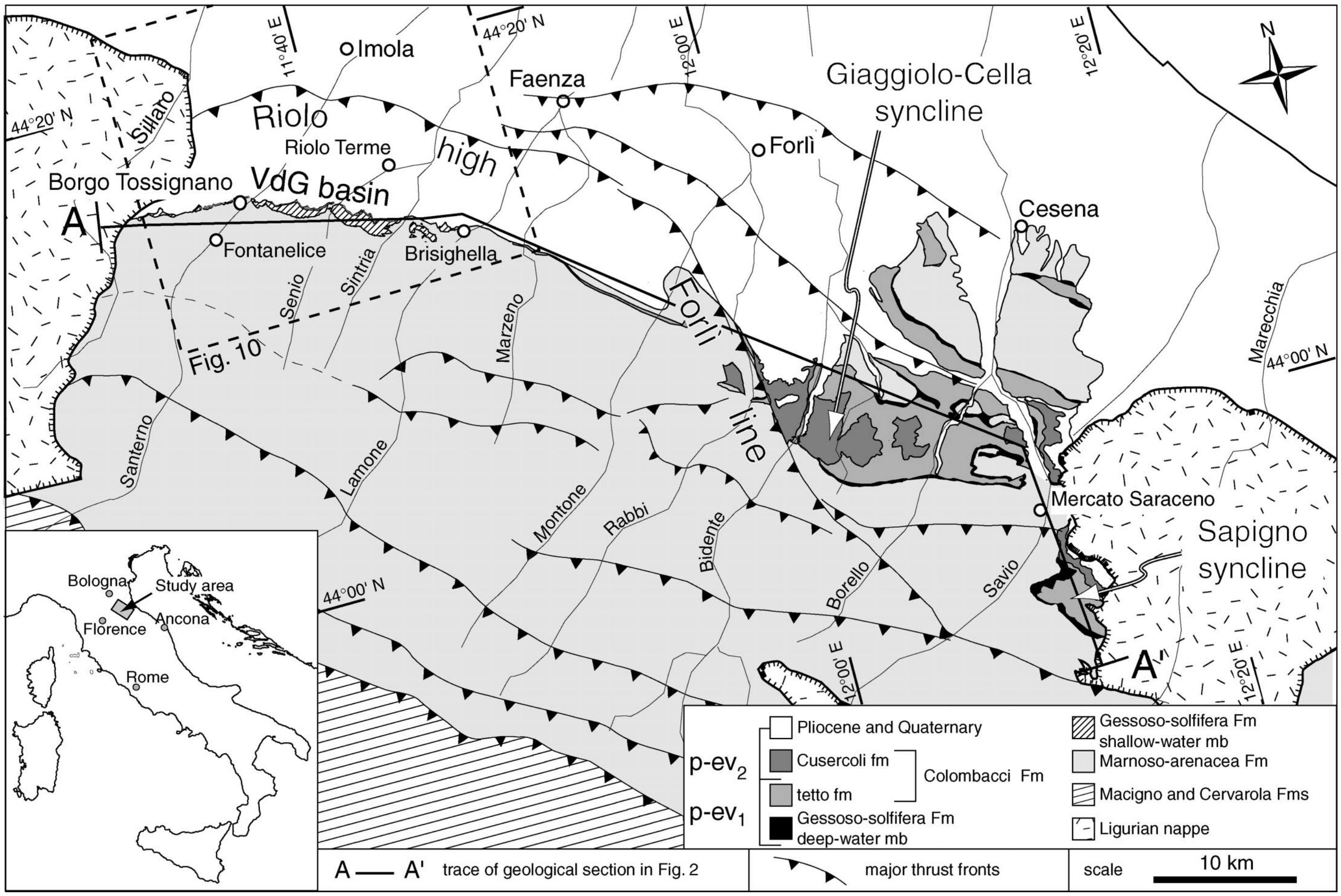


**Figure 1. Schematic geologic map of the Romagna Apennines with the reported main stratigraphic and tectonic features of the study area. The Cusercoli and tetto formations are informal units easily recognizable in the field throughout the Apennine foredeep; their use has been proposed by Roveri et al. (1998) to replace the less specific Colombacci Formation. The Gessoso-solfifera Formation is informally subdivided into lower-rank lithostratigraphic units (shallow- and deep-water members [mb]), following Roveri et al. (1998). VdG—Vena del Gesso basin. Abbreviations of unconformity-bounded stratigraphic units: p-ev$_2$—postevaporitic unit 2; p-ev$_1$—postevaporitic unit 1.**

upper part (Costa et al., 1986; De Giuli et al., 1988; Marabini and Vai, 1988; Landuzzi and Castellari, 1988), and the cyclostratigraphy of lower Messinian euxinic shales underlying the evaporites (Vigliotti, 1988; Krijgsman et al., 1999a, 1999b; Vai, 1997; Negri and Vigliotti, 1997; Negri et al., 1999).

Despite these valuable contributions, the tectonic and sedimentary history of the Vena del Gesso basin, as well as its relationships with the adjacent areas, were not investigated in detail and still remain poorly understood. In this paper, based on new field observations integrated with subsurface data (wells and seismic profiles), we propose a new geologic model for the Vena del Gesso basin that provides a unifying explanation for the complex of sedimentary and deformational features characterizing the upper Tortonian to lower Pliocene successions. Besides some obvious local implications, this model provides some thoughtful insights into the general geologic problems related to the Messinian salinity crisis at a Mediterranean scale.

Many still-open problems in the big Messinian puzzle are related to the virtually unknown nature of evaporitic and preevaporitic deposits lying below the deepest Mediterranean basins (McKenzie, 1999). Primary evaporites occur in many marginal, shallow-water basins, but both the sedimentary processes involving evaporite deposits and their stratigraphic relationships with deeper depositional settings are poorly understood, mainly because of (1) the poor preservation of many Messinian successions that often makes regional geologic reconstructions very difficult, and (2) the fact that some areas (like the Apennine foredeep) have been overlooked in the past, as a result of their ‘‘anomalous’’ stratigraphic characteristics, thought to be not fully representative of the Messinian salinity crisis.

The most puzzling feature of the Messinian evaporites is that these shallow-water deposits are sandwiched between deeper-water sediments through apparently continuous contacts. This fact has been very attractive for the geologic scientific community; the studies of the early 1970s led to the reconstruction of one of the most fascinating geologic histories. Several lines of evidence led to the formulation of the successful ‘‘deep desiccated basin model’’ of Hsü et al. (1972). The initial model and its subsequent modifications (Muller and Hsü, 1987; Hsü, 2001) envisage the total desiccation of the Mediterranean basin, considered to have a physiography similar to the present-day configuration, as a result of the closure of the Atlantic gateways (the Betic-Rifian corridors). Evaporite precipitation (Lower Evaporites) followed a long phase of progressively reduced deep-water circulation and consequent development of dysaerobic seafloor conditions in the Mediterranean Sea, responsible for the widespread deposition during the early Messinian of organic-rich laminites (Tripoli Formation, euxinic shales).

The main controversies around this model involved the timing of Messinian events and the stratigraphic relationships between marginal and basinal evaporites at a Mediterranean scale. These actually form two distinct evaporitic bodies separated by a great erosional unconformity, deeply cutting the marginal evaporites. In deeper basins, such a surface was traced to the base of a very thick evaporitic suite. On the basis of such observations, a two-step model for the Messinian salinity crisis has been proposed (Clauzon et al., 1996): evaporite deposition started in the marginal basins and progressed only later into the deepest Mediterranean basins, following the complete closure of the Atlantic connections that caused a dramatic sea-level drop of 1500–2000 m. This huge sea-level fall led to the development of the great intra-Messinian erosional surface, mainly through subaerial, fluvial processes (Ryan and Cita, 1978); the main rivers cut deep canyons along the shelves and slopes of the desiccated Mediterranean Sea (Rhone, Nile, Ebro; Clauzon, 1982). The already-mentioned Apennine foredeep ''anomaly'' is due to the fact that its deepest part did not undergo total desiccation; this anomaly has usually been explained by invoking its complete isolation from the Mediterranean and the consequent development of its own positive hydrologic budget (Cita and Corselli, 1990).

Before the connections with the Atlantic were catastrophically reestablished at the base of the Pliocene, the Mediterranean was partially refilled with brackish to fresh waters coming from the Paratethys, a large nonmarine basin placed to the east, in the present-day Black Sea area (postevaporitic Lagomare phase). During this final phase of the Messinian salinity crisis, some minor, nonmarine evaporites locally developed (Upper Evaporites).

The timing of Messinian events proposed by Krijgsman et al. (1999a), on the basis of a detailed astronomically calibrated cyclostratigraphy, pointed out their remarkably synchronous character throughout the Mediterranean, despite the different geodynamic and depositional settings represented in the studied sections (Sicily, Spain, Apennines). In particular, the onset of Lower Evaporite deposition has been dated at ca. 5.96 Ma and its end at 5.6 Ma. These dates raise important questions about the nature of the Lower Evaporites, especially concerning the actual paleodepth of evaporites formed in the deepest basins (Krijgsman et al., 1999a). Moreover, this study does not support the hypothesis shared by many authors that the connections between the Atlantic and Mediterranean were ultimately controlled by eustasy (Kastens, 1992; Clauzon et al., 1996). The obliquity-driven, glacioeustatic sea-level falls of oxygen isotope stages TG22 and TG20, thought to have played an important role in the Messinian salinity crisis, postdate and predate, respectively, the base of the Lower Evaporites and the intra-Messinian unconformity related to the isolation and desiccation of the Mediterranean. Instead, a complex interplay between precession-induced climatic changes superposed on longer-term tectonic processes in the Mediterranean area has been suggested by these authors as the main factors controlling the Messinian salinity crisis (Krijgsman et al., 1999a).

A complete discussion of all the open problems related to the Messinian salinity crisis is well beyond the scope of this paper. We limit this paper to the possible larger-scale implications of our interpretation of the Vena del Gesso basin succession as far as the onset of the evaporite phase and the relationships between shallow- and deep-water settings are concerned.

## GEOLOGIC SETTING

The Romagna Apennines, extending from the Sillaro valley to the west to the Marecchia valley to the east (Fig. 1), are part of the northeast-verging Northern Apennine arc and is characterized by an exposed belt of siliciclastic deposits of early Miocene to Pleistocene age, overlying buried Mesozoic to Cenozoic carbonates, only reached by commercial exploration wells. This sedimentary succession formed above the Adria plate, representing the lowest structural unit of the Apennine orogenic wedge (for an updated review of the Apennine geology, see Vai and Martini, 2001).

To the west of the Sillaro valley, this tectonostratigraphic unit is covered by the Ligurian nappe (Fig. 2), a chaotic complex of Jurassic to Eocene deep-marine sedimentary rocks and slabs of their oceanic crustal basement (Castellarin and Pini, 1989). This mélange formed during the Late Cretaceous Alpine compressional phases and was subsequently (during the Apennine orogeny, in post-Oligocene time) thrust over the Adria plate (Kligfield, 1979; Boccaletti et al., 1990). During its movement, deep- to shallow-water sediments also accumulated above the Ligurian complex, forming the so-called Epiligurian units.

The uppermost structural unit cropping out along the Po Plain side of the Romagna Apennines consists of the Langhian to Tortonian Marnoso-arenacea Formation turbiditic complex (Ricci Lucchi, 1975, 1981). This unit, >3500 m thick, is detached from its lower Miocene carbonate basement along a flat basal thrust and shows a deformational style dominated by fault-propagation folds, forming imbricated structures in some places (Capozzi et al., 1991; Benini et al., 1991; Farabegoli et al., 1991). The inner part of the Marnoso-arenacea Formation has been overridden by a stack of older turbiditic units (Macigno, Cervarola, and Modino Formations) along a thrust front approximately corresponding to the present-day watershed (Fig. 1). Northeast-verging thrusts in the southern belt of the chain are rectilinear features elongated in a northwest-southeast direction (Fig. 1). The axes of the thrust folds plunge toward the northwest and the southeast approaching the Sillaro and Marecchia valleys, respectively. These two valleys roughly correspond to the axis of tectonic depressions occupied since the late Miocene by the advancing Ligurian nappe.

The Apennine foothills consist of a gentle north-northeast–dipping monocline of Messinian to Pleistocene deposits resting above the Marnoso-arenacea Formation. Seismic data show that the outermost front of the Apennine thrust belt lies in the subsurface of the Po Plain (Pieri and Groppi, 1981; Castellarin et al., 1986, Castellarin, 2001), where several ramp anticlines are buried by a thick succession of marine Pliocene–Pleistocene deposits.

The Romagna Apennines are split into two sectors (western and eastern) by the Forlì line (Fig. 1), a deformational zone characterized by reverse faults oriented obliquely to the Apenninic trend (north-northeast–south-southwest). This tectonic feature played a primary role in the geologic evolution of the area, at least since the late Tortonian (Ricci Lucchi, 1986). In a northwest-southeast cross section, flattened at the Miocene/Pliocene boundary (Fig. 2), dramatic facies and thickness changes can be observed particularly within the Messinian succession, caused by the structural high related to the Forlì line.

Subsurface data permit a better definition of the tectonic framework of the area. One of the buried ramp anticlines of the western sector (Riolo anticline, Fig. 1) turns its axis from a northwest-southeast to a north-south direction and merges with the outcropping structural high associated with the Forlì line. As a con-

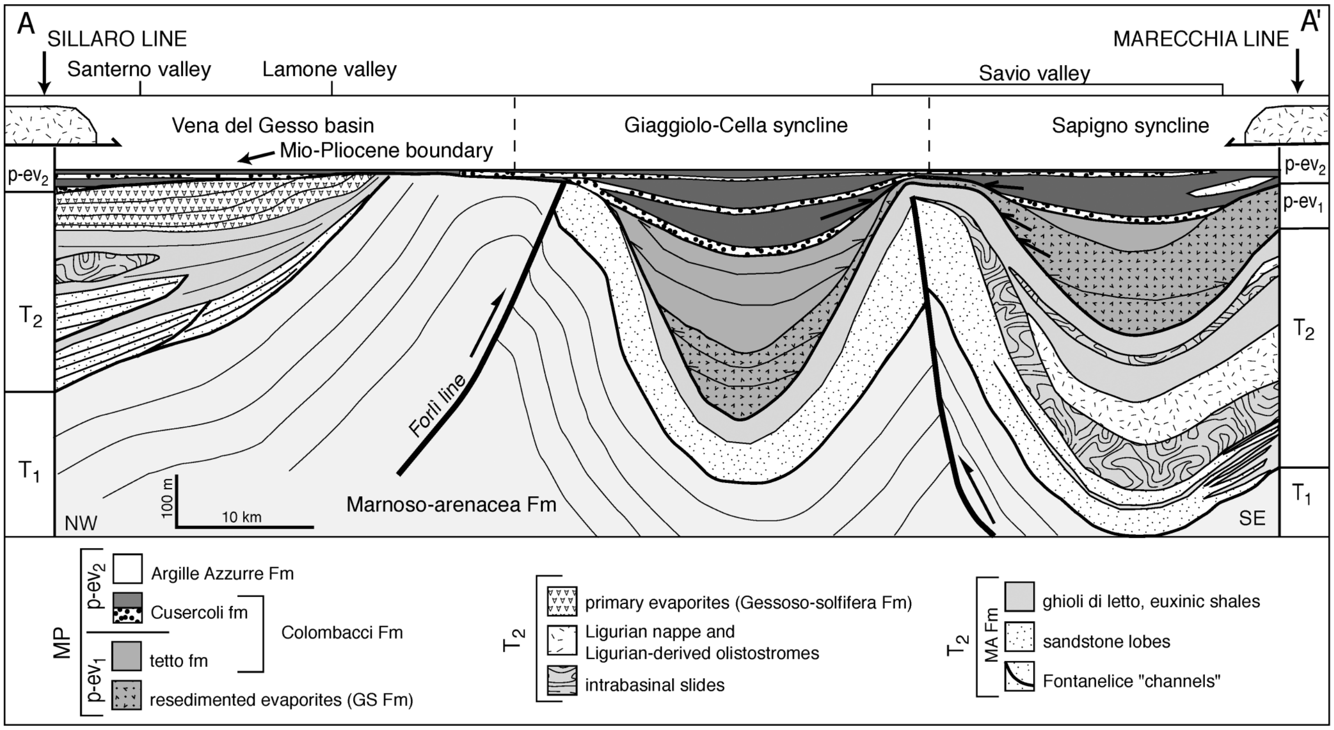


**Figure 2. Schematic geologic cross section roughly parallel to the Apennine front (see location in Fig. 1) and connecting the main Messinian depocenters; the section is flattened at the Miocene/Pliocene boundary. Note the strong thickness change of the Messinian succession across the Forlì line. Abbreviated formations: GS—Gessoso-solfifera; MA—Marnoso-arenacea. Abbreviations of unconformity-bounded stratigraphic units (synthems): p-ev$_2$—postevaporitic unit 2; p-ev$_1$—postevaporitic unit 1; T2—Tortonian–Messinian; MP—Messinian–Pliocene.**

sequence, a single east-northeast–verging arcuate structure, of which the Forlì line represents the eastern lateral ramp, can be reconstructed (Fig. 1). This anticline, plunging westward below the Ligurian nappe along the Sillaro valley, bounds the Vena del Gesso basin to the north and to the east. The original basin extension to the west and to the south cannot be reconstructed owing to the Ligurian nappe cover and the post-Messinian erosion.

## STRATIGRAPHY

From a lithostratigraphic point of view (Fig. 3), the Langhian to Pliocene sedimentary succession of the Romagna Apennines is classically subdivided into four formations (Vai, 1988):

1. The Marnoso-arenacea Formation (Langhian–Messinian), made up of deep-water siliciclastic turbidites mainly derived from Alpine sources, is the infill of a large foredeep basin elongated in a northwest-southeast direction, whose depocenter shifted through time, following the northeastward propagation of the compressional front. The upper part of this unit mainly consists of slope mudstones (informally named ''ghioli di letto'' by older authors) containing minor turbiditic sandstones and chaotic bodies; these rocks are in turn overlain by a thin horizon characterized by cyclically interbedded organic-rich laminites and mudstones, informally referred to as ''euxinic shales'' (upper Tortonian–lower Messinian). Like the coeval Tripoli Formation in Sicily and Spain, such deposits, consisting of organic- and diatomite-rich laminites (Pedley and Grasso, 1993; Sprovieri et al., 1996b; Sierro et al., 1999; Bellanca et al., 2001), record the paleoceanographic changes that heralded the Messinian salinity crisis. The euxinic shale unit, straddling the Tortonian/Messinian boundary, spans a 1.5 m.y. time interval, characterized by well-defined biomagnetostratigraphic events; their calibration with astronomical cyclicity allowed a detailed chronostratigraphy to be established (Krijgsman et al., 1999a, 1999b; Vai, 1997).

2. The Gessoso-solfifera Formation (Messinian), is made up of both primary and clastic, resedimented evaporites with interbedded organic-rich shales, deposited during the evaporitic and postevaporitic stages of the Messinian salinity crisis.

3. The Colombacci Formation (upper Messinian), consisting of siliciclastic sediments derived from Apenninic sources, was deposited in both shallow and deep, brackish or freshwater basins developed during the final phase of the Messinian salinity crisis (Lagomare stage).

4. The Argille Azzurre Formation (lower Pliocene) is made up of mudstones deposited in a relatively deep marine environment. They locally encase conglomerate and sandstone bodies and small, isolated carbonate platforms (locally named Spungone).

A few attempts to establish a physical-stratigraphic framework of the study area have been carried out so far. The most complete stratigraphic scheme has been provided by Ricci Lucchi and Ori (1985) and Ricci Lucchi (1986), within a general synthesis of the sedimentary evolution of the Apennine thrust belt, taking into account both tectonism and eustasy as controlling factors. Creation of this physical-stratigraphic framework resulted in the definition of several large-scale, unconformity-bounded units (called depositional sequences) recognizable in different domains of the Apennine Chain and thus led to a unifying picture of Apennine evolution (Fig. 3).

The stratigraphic framework has subsequently been slightly revised (Roveri et al.,

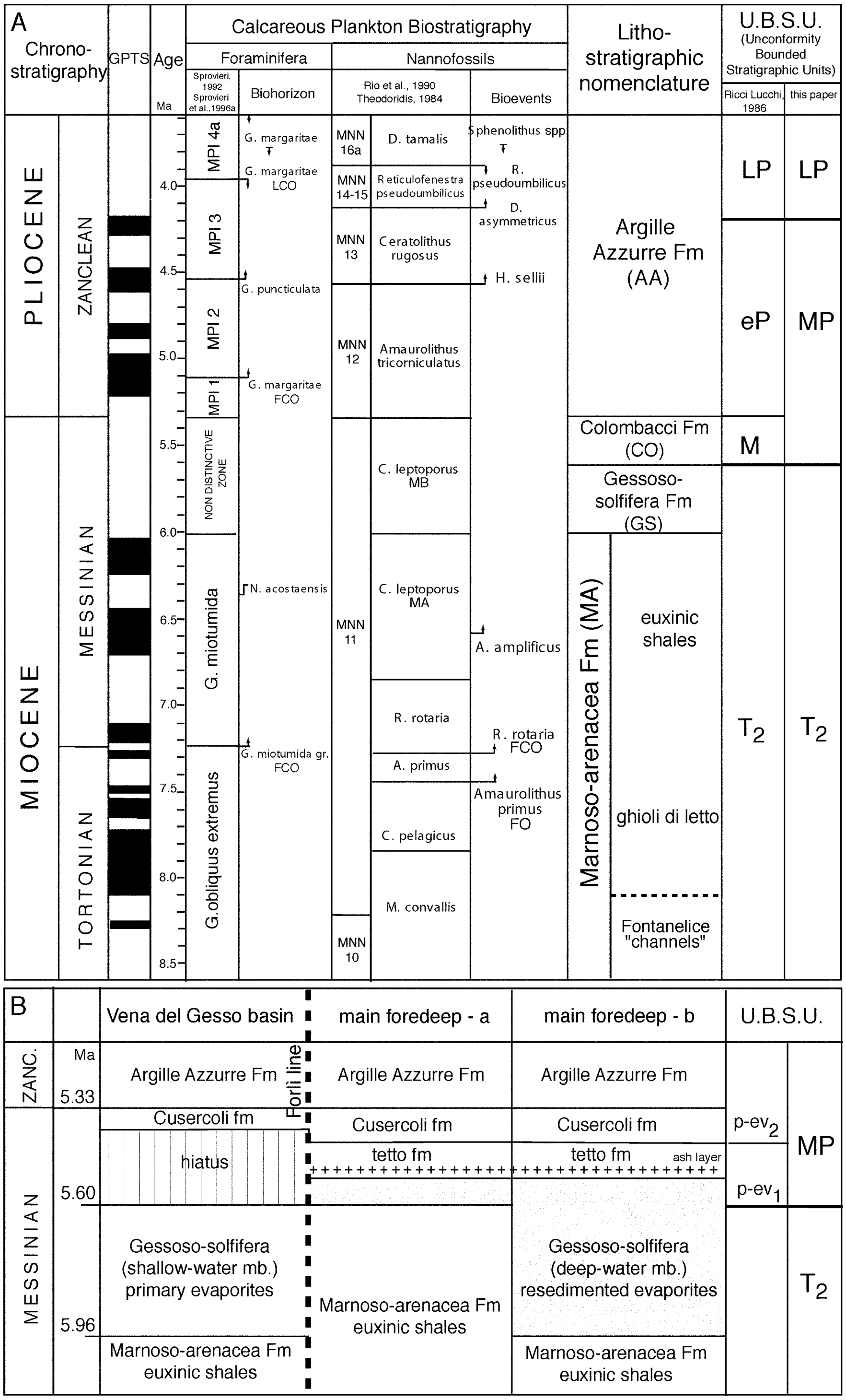


**Figure 3. Stratigraphic scheme (A) adopted in this work, and (B) a more detailed framework for the Messinian deposits showing the possible stratigraphic relationships between marginal and basinal settings of the Apennine foredeep (based on Roveri et al., 1998, 2001; chronology of Messinian events from Krijgsman et al., 1999a). Abbreviations of unconformity-bounded stratigraphic units (synthems) are explained in Figure 2, except for the following: LP—lower Pliocene; eP—early Pliocene; M—Messinian. GPTS—geomagnetic polarity time scale. Hypotheses a and b are discussed in the text (see columns labeled "main foredeep a" and "main foredeep b").**

1998, 2001; Manzi, 2001), particularly for the Messinian interval. In this paper we adopt a physical-stratigraphic scheme that substantially derives from these studies (Fig. 3). The Tortonian to lower Pliocene succession is subdivided into three main large-scale synthems that record regional-scale phases of tectonic deformation of the Apennine orogenic wedge. From base to top, they are the $T_2$ (upper Tortonian–lower Messinian) synthem (termed a "sequence" in Ricci Lucchi, 1986), the MP (upper Messinian–lower Pliocene) synthem, and the LP (lower Pliocene) synthem; the names adopted for such units derive from those of their basal unconformities. These large-scale units can be further subdivided into lower-rank unconformity-bounded stratigraphic units and lithohorizons of regional significance delimited by minor unconformities and flooding surfaces (Roveri et al., 1998; Fig. 3).

In the next sections, the stratigraphic units are described. The depositional characters of the western and eastern sectors of the Romagna Apennines separated by the Forlì line are compared as well.

### $T_2$ Synthem (Late Tortonian–Messinian)

The base of the $T_2$ synthem corresponds to a sharp vertical change in the sedimentary features (facies character, sandstone-body geometries, and overall stacking pattern) of the Marnoso-arenacea Formation turbiditic systems. During the previous stages ($T_1$ sequence of Ricci Lucchi, 1986), turbiditic deposits were characterized by tabular geometries, high lateral continuity, and transitional bases, suggesting deposition by unconfined flows running parallel to the basin axis (i.e., in a northwest-southeast direction) along a nearly flat sea bottom (Ricci Lucchi, 1981, 1986). In the $T_2$ synthem, sandstone bodies show erosional bases, poor lateral continuity, coarser mean grain size, and various sedimentary structures (e.g., basal scours, cut-and-fill, and water-escape structures; Ricci Lucchi, 1981) that suggest rapid deposition from low-efficiency flow, i.e., flows that were not able to fully segregate their grain populations as a result of topographic constriction (Mutti et al., 1999). Such change of geometry and facies characters of turbidites implies the creation of erosional depressions cut by large-volume turbiditic flows and subsequently filled by smaller-volume, confined flows forced to rapidly deposit their sediment load. This scenario has usually been related to a regional phase of uplift and basin narrowing (Ricci Lucchi, 1981, 1986), but the tectonic structures involved in the generation

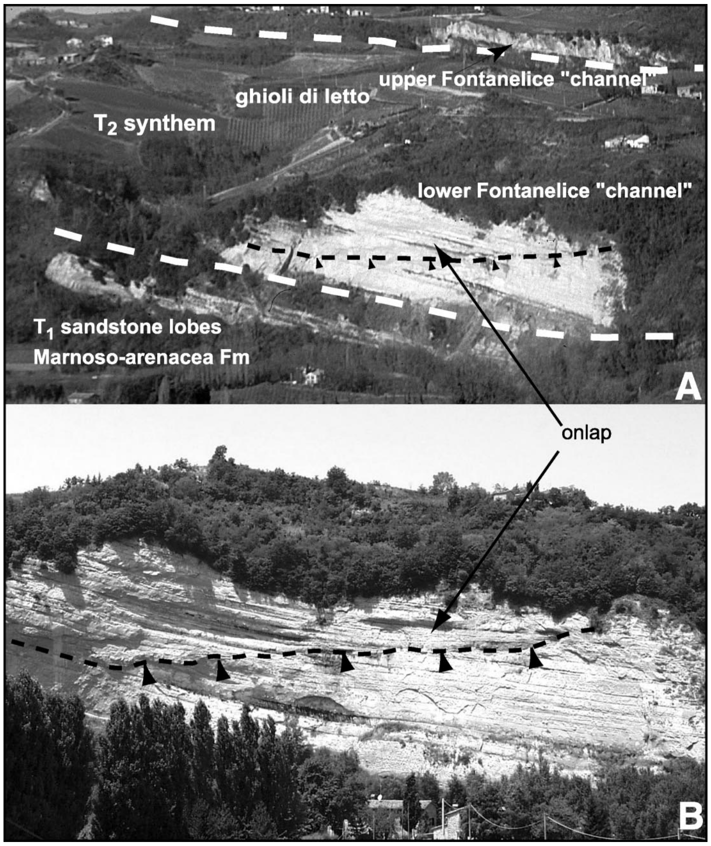


**Figure 4. (A) Panoramic and (B) closer view of the lower Fontanelice channelized system, Santerno valley. (A) The thickness and geometry of the lower Fontanelice ‘‘channel’’ contrast with those characteristics of the underlying sandstone lobes of the $T_1$ group. (B) Cut-and-fill feature within the lower ‘‘channel’’; note the abrupt onlap of thick to very thick sandstone beds above the scour wall.**

of the observed sedimentary features have never been identified.

### *Western Sector*

$T_2$ synthem deposits show some differences across the Forlì line. In the western sector, they crop out only in the Santerno-Sillaro area. They are represented by the well-known Fontanelice ‘‘channels,’’ two turbiditic sandstone bodies confined within large-scale erosional depressions and separated by a mudstone horizon (Ricci Lucchi, 1968, 1969, 1975, 1981; Figs. 4A, 4B). The lower body (Fig. 4A) has a slightly concave-upward, erosional base and a thickness of ~30 m. The first fill is cut by a second erosional surface (Fig. 4B), which forms a depression filled by thick sandstone beds, characterized by erosional bases, massive to crudely horizontally laminated divisions and rippled, commonly climbing, tops. Mudstone divisions are either very thin or absent, and amalgamated beds are common, especially in the lower part of the scour fills. The upper erosional surface deepens toward the southwest, i.e., normal to the main paleocurrents. As a result of the exposure, the control in a downcurrent direction is poor, but these bodies disappear within a few kilometers.

The upper channelized body (Figs. 5A, 5B) is completely encased in mudstones (ghioli di letto) and is larger and thicker than the lower one. Like the lower body, its basal surface deepens toward the southwest, and a spectacular onlap toward the northeast of sandstone fill can be observed in the section almost normal to the paleocurrent direction (Fig. 5A). The erosional surface is much deeper than that of the lower system, almost reaching its top. The composite fill consists of clean, fairly well sorted conglomerates that form small bars at the bottom and at least two distinct sandstone bodies in the upper part (Fig. 5B). Pebble composition indicates an Alpine provenance (Ricci Lucchi, 1969), and the conglomerates’ facies character (degree of organization, etc.) suggests that they represent the coarser-grained load laid down by large-volume gravity flows bypassing this area and depositing the bulk of their sediment load more downstream (i.e., to the southeast). Sandstone beds of the upper part of the ‘‘channel’’ fill show facies characters similar to those of the lower system.

The upper Fontanelice system is overlain by a prevailing mudstone unit (ghioli di letto) with interbedded minor turbiditic sandstone bodies, more preserved to the west and forming an overall thinning-upward sequence (Fig. 5B). Toward the southeast, minor bodies disappear; in the Santerno river section, the mudstone unit instead contains a chaotic slumped horizon, up to 50 m thick, characterized by sandstone olistoliths, likely derived by minor turbiditic bodies (Fig. 6). The slumped horizon is capped by an ~50 m thickness of the organic-rich euxinic shales, here attaining a thickness of ~50 m. Sedimentation rates through the euxinic shales are plotted in Figure 7 and are discussed subsequently.

The $T_2$ synthem is topped by the primary in situ Messinian evaporites of the Gessoso-solfifera Formation, which form a continuous belt from the Sillaro to the Lamone valleys (Fig. 1). A maximum thickness of 150 m is attained in the central area of the sector (Fig. 8). Like the underlying euxinic shales, gypsum deposition was cyclical, probably controlled by periodic changes of orbital parameters (Vai, 1997; Krijgsman et al., 1999b). Up to 16 small, decameter-scale-thick, shallowing-upward cycles—each recording the progressive evaporation of shallow lagoons (Vai and Ricci Lucchi, 1977)—have been recognized. The typical cycles are characterized by the vertical superposition of six main sedimentary facies, five of them made up of gypsum; each cycle starts with basal organic-rich shales, deposited in shallow lagoons below the wave base; these shales are overlain by stromatolites replaced by gypsum and, in turn, by well-stratified selenitic gypsum. The size of selenite crystals usually decreases upward; this change is thought to be related to the progressive evaporative drawdown and increasing salt concentration of the lagoon. The upper part of each cycle is characterized by clastic gypsum deposits (gypsarenites, chaotic selenitic breccia). These deposits are thought to be related to a phase of subaerial exposure and erosion, leading to strong gypsum reworking by waves or torrential streams action (Vai and Ricci Lucchi, 1977).

A progressive vertical change in the thickness and facies distribution within the individual cycles can be observed; the upper cycles are thinner than those at the base, and the relatively deeper-water facies units are signifi-

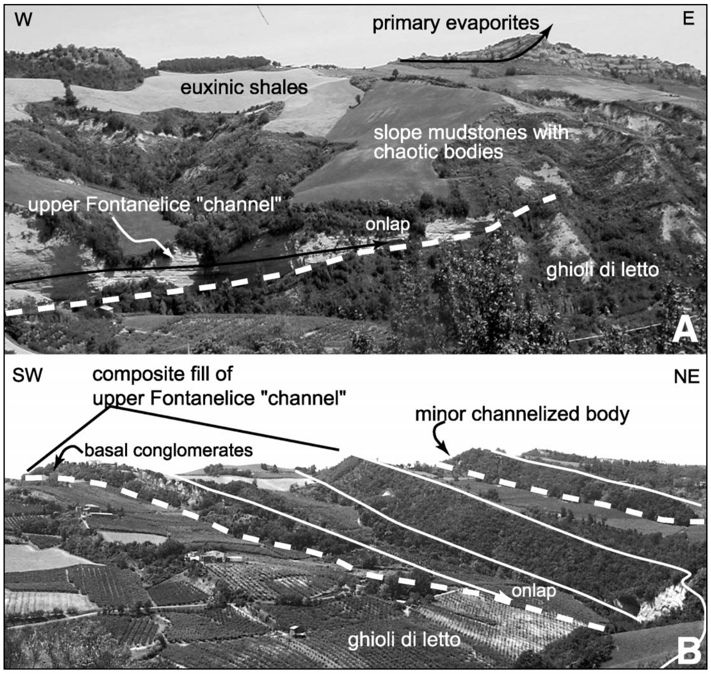


**Figure 5. The upper Fontanelice ''channel.'' (A) The classical view looking north with the clear onlap of sandstone beds against the basal erosional surface. The sandstone body is encased in slope mudstones containing an intrabasinal slump (see also Fig. 6); (B) General view of the upper ''channel'' looking west from the east side of the Santerno valley. The basal erosional surface deepens toward the southwest, and the channel fill is composite with alternating sand- and mud-rich bodies onlapping toward the northeast.**

cantly less well developed than the clastic facies. This change suggests that an overall ''regressive'' trend is superposed on the smaller-scale, higher-frequency cyclicity; this longer-term trend culminates with the great erosional unconformity that cuts the uppermost gypsum unit and marks the base of the overlying MP synthem. An angular unconformity is associated with this surface (Vai, 1988), clearly indicating its tectonic nature. It is well known from regional geologic studies that the intra-Messinian event is one of the most important in the evolution of the Apenninic orogenic wedge, marking a significant migration of the whole compressive front and associated foredeep basin toward the foreland, i.e., the Po Plain.

Along this surface, evidence of prolonged subaerial exposure (karstic dikes filled by continental deposits rich in mammal fossils) has been found in the Monticino section, near Brisighella (Costa et al., 1986; De Giuli et al., 1988). The erosion associated with the Messinian/Pliocene unconformity increases toward the southeastern end of this sector (Lamone valley), where the evaporitic and preevaporitic Messinian deposits are completely missing.

### *Deformation of the Primary Evaporites of the Vena del Gesso Basin*

The gypsum unit is characterized in the western sector by extensional and compressional deformations (Marabini and Vai, 1985), with rotated blocks (Fig. 9A) and shallow thrust faults (Fig. 9B), partially also affecting the top of the underlying euxinic shales (shear planes observed by Krijgsman et al., 1999b). All these deformational features emanate from a detachment surface in the upper part of the euxinic shales (Marabini and Vai, 1985). The gypsum deformation processes, not involving either the overlying or underlying units, have usually been referred to as thin-skinned tectonics related to strike-slip movements along northeast-trending faults, leading to the formation during the latest Messinian of a complex framework of structural highs and depressions (Marabini and Vai, 1985).

From west to east, the deformation shows different characteristics. To the west (Santerno-Sillaro sector, Fig. 10), the gypsum unit is greatly reduced in thickness and more discontinuous and is characterized by both compressive and extensional deformations. Rotational listric faults affect the gypsum unit on the left bank of the Santerno River (Borgo Tossignano; Fig. 9A), whereas farther to the west (Monte Penzola), a shallow thrust fault is responsible for the vertical repetition of the lower gypsum cycles (Figs. 5, 6). All these structures indicate a west-southwest vergence (Fig. 9B). Traces of transformation of gypsum to anhydrite (due to higher lithostatic loading during burial) and subsequent rehydration have been observed in the westernmost edge (Sillaro-Santerno valleys, S. Lugli, 2001, personal commun.).

To the east (Sintria valley, Fig. 10), the deformation is more severe. Here the gypsum unit forms a complex tectonic structure made up of at least three thrust sheets with a southwest vergence (Fig. 9B; Marabini and Vai, 1985). Thrust faults emanate from a flat detachment surface in the upper part of the underlying euxinic shales. The latter contain scattered blocks of chemosynthetic carbonates whose origin is related to methane-rich fluid venting (informally referred to as ''calcari a Lucina'' by older authors; see Ricci Lucchi and Vai, 1994; Taviani, 1994, 2001; Conti and Fontana, 1998).

The central sector shows a minor degree of deformation. The gypsum unit is only cut by subvertical normal faults (Fig. 8). The Monte del Casino section, where the upper part of the euxinic shales is characterized by abundant shear planes (see Krijgsman et al., 1999b), belongs to this sector.

### *Eastern Sector*

The $T_2$ synthem in the eastern sector of the Romagna Apennines is significantly different, especially in its upper part. The basal unconformity, here only slightly erosional, is traced along the base of a thick pile of tabular turbiditic sandstone bodies, made up of thick-bedded, coarse to very coarse and pebbly sandstones, with common amalgamated beds and basal scours. Mud-draped scours and water-escape structures are also common. The Savio turbidite system, cropping out discontinuously in the Savio valley (Fig. 2), has a composite nature with up to five sandstone bodies vertically stacked to form an overall fining-upward sequence with a maximum thickness of some 200 m. Although not easy to assess because of the exposure conditions, the close physical and genetical relationship of such turbiditic deposits with the channelized bodies of the western sector (Fontanelice systems) is here suggested on the base of facies and regional geologic considerations.

As in the western sector, these sandstone bodies are overlain by a mudstone unit, but in the eastern sector, they are more developed and contain two huge chaotic bodies separated

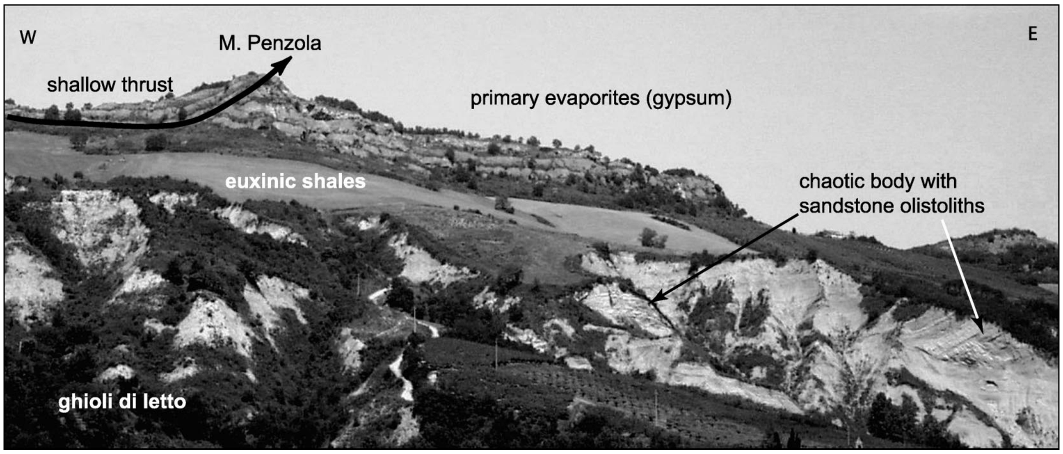


**Figure 6. Panoramic view of the upper part of the $T_2$ strata along the west side of the Santerno valley. The intrabasinal chaotic body with sandstone olistoliths is overlain by the upper Tortonian–lower Messinian euxinic shales. On top is the deformed gypsum of the Gessoso-solfifera Formation; note the lateral ramp of a shallowly northeast-dipping thrust cutting gypsum unit at Monte (M.) Penzola.**

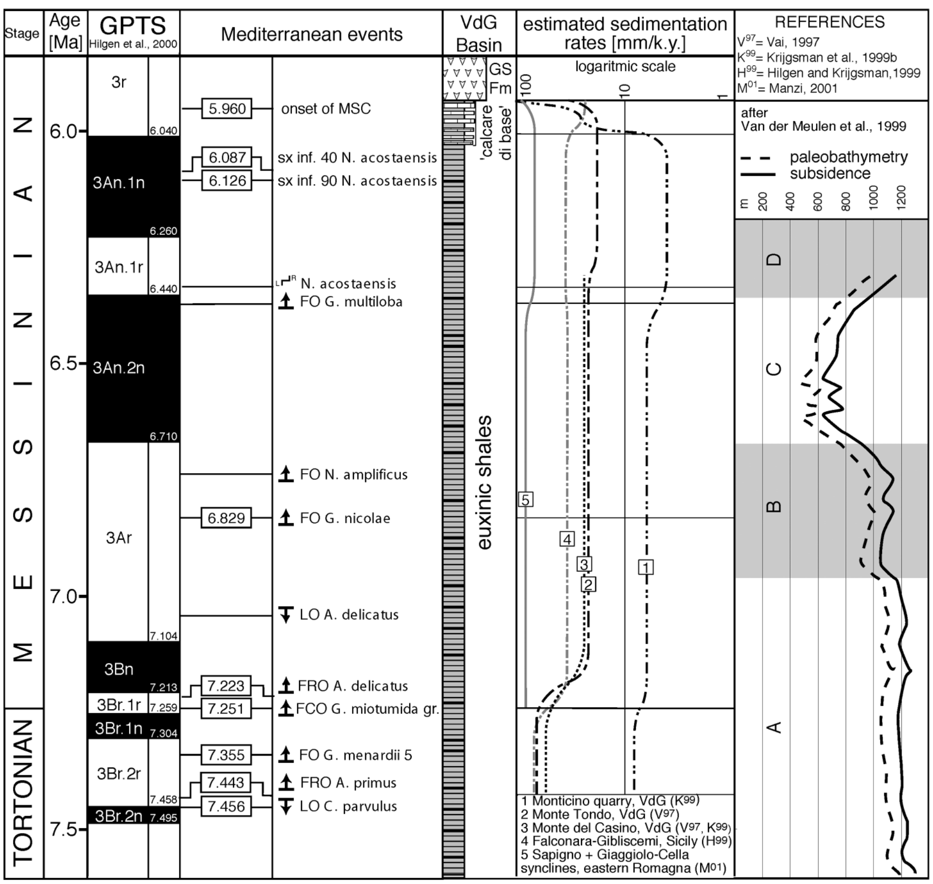


**Figure 7. Sedimentation rates and subsidence trends in the euxinic shales from different sections of the Romagna Apennines (names of locations 1–5 labeled in Fig. 10) compared with the coeval Tripoli Formation of the Falconara-Gibliscemi sections of Sicily; the uniform upward decrease of sedimentation rate matched with paleobathymetric data suggests an overall uplift during the preevaporitic phase; note also that beside this general vertical trend, absolute values also decrease from west to east in the Vena del Gesso basin, suggesting larger uplift to the southeast (Monticino section).**

by an undisturbed muddy horizon, 400 m thick. The chaotic bodies are made up of both intra- and extrabasinal deposits (Lucente et al., 2002), and their thickness reaches ~300 m.

Also in this sector the $T_2$ synthem is topped by an organic-rich unit corresponding to the euxinic shales of the western area; the unit here is thicker (100 m) but with a less evident lithologic cyclicity owing to a higher terrigenous content. As in the western sector, the Tortonian/Messinian boundary lies at the base of this unit, just above the upper chaotic body.

Primary evaporites are totally absent in the eastern sector. Instead, a thick complex of resedimented evaporites made up of a complete suite of gravity-flow deposits—ranging from thin-bedded, gypsum turbidites to huge olistostromes containing large blocks of primary selenitic gypsum—is preserved. 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; for deep-water evaporite sedimentation, see also Schlager and Bolz, 1977). Interbedded mudstones have a moderate organic content, decreasing upward. No evidence of subaerial exposure or any angular unconformities has been found in this unit. Moreover, despite the fact that these deposits are well stratified, a clear cyclical pattern cannot be recognized, pointing to a more random style of sedimentation, strongly different from that of the primary evaporites. All these characteristics make the detailed correlation with the Messinian succession of the western sector a quite difficult task.

In order to better define the genetic relationships between primary and resedimented

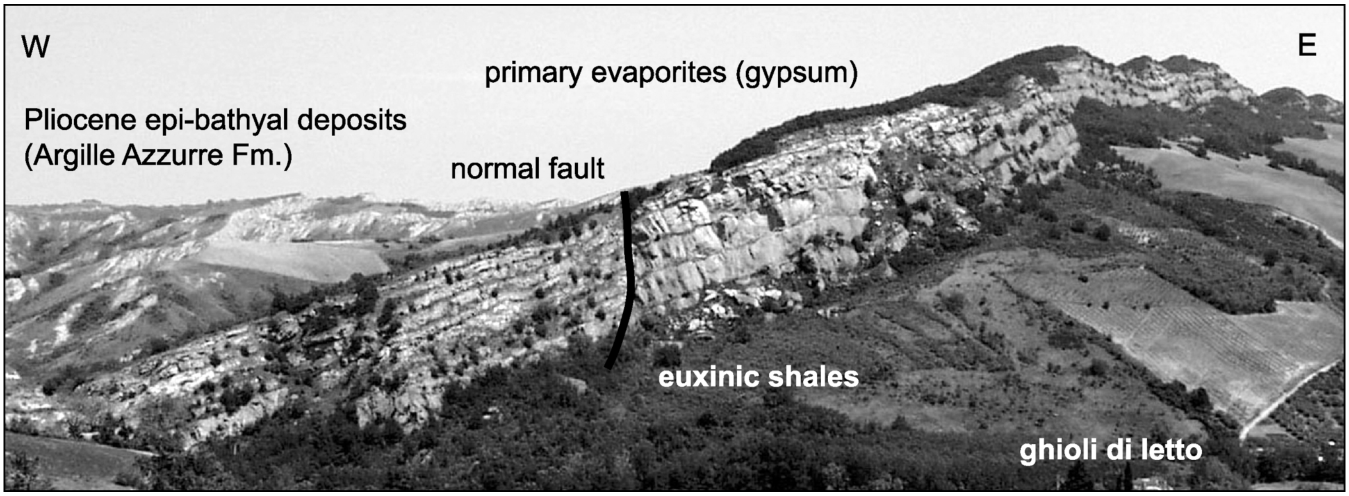


**Figure 8. Panoramic view of the Gessoso-solfifera Formation in the central, less deformed sector, of the Vena del Gesso basin. Gypsum beds are cut by small normal faults leading to the lateral juxtaposition of upper, thinner cycles and lower, thicker ones (looking north from Tossignano; location in Fig. 10).**

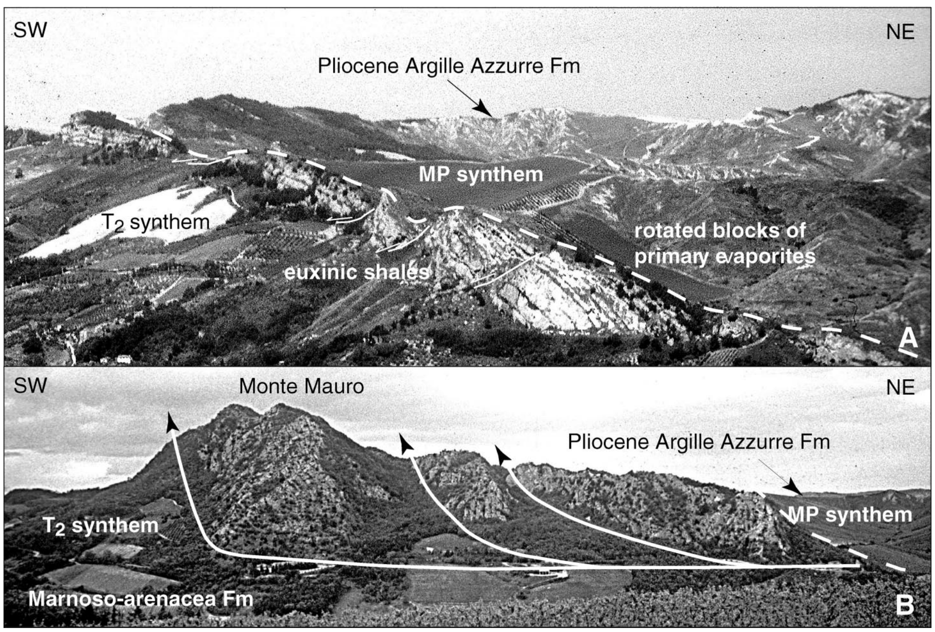


**Figure 9. Panoramic view showing two contrasting examples of deformation affecting the Gessoso-solfifera Formation. (A) Rotated blocks along the west side of the Santerno valley at Borgo Tossignano (location in Fig. 10). (B) The three small northeast-dipping thrust sheets of Monte Mauro (Sintria valley; see location in Fig. 10). Abbreviations of unconformity-bounded stratigraphic units (synthems): TM—Tortonian–Messinian; MP—Messinian–Pliocene.**

gypsum facies, Roveri et al. (1998, 2001) and Manzi (2001) suggested that the erosional unconformity of the western sector could be traced into a correlative conformity either at the base or within the resedimented evaporitic complex of the eastern sector. As a consequence of this interpretation, the whole Gessoso-solfifera Formation of the eastern sector (or at least part of it) belongs to the postevaporitic phase and can be included in the overlying MP synthem as in the ''main foredeep a'' column of Figure 3 (see hypotheses illustrated by columns labeled ''main foredeep a'' and ''main foredeep b'' in the stratigraphic diagram of Fig. 3).

According to hypothesis a of Figure 3, the time equivalent of primary evaporites in the eastern area is to be found in the upper part of the local euxinic shales. As a general rule, no stratigraphic studies have ever been carried out on deep basinal Messinian successions of the Mediterranean, either because they are buried at great depths below the seafloor or because they are not recognized in the field. The Apennine foredeep offers such a unique opportunity to observe both the shallow and relatively deep Messinian depositional settings and compare them in field-based studies. In the upper part of the euxinic shales of the eastern sector, preliminary biomagnetostratigraphic data (Manzi, 2001) indicate the presence of a very organic rich, barren horizon that does not occur below the primary gypsum unit of the western sector (and also not below the Lower Evaporites of Sicily and Spain). We think that this horizon represents a good candidate for being correlated to the primary evaporites, as their deeper-water counterpart.

The implications at Mediterranean scale for the Messinian salinity crisis of such a stratigraphic model will not be discussed in more detail here. What we would emphasize is the strong tectonic component superposed to the Apennine foredeep intra-Messinian unconformity.

### MP Synthem (late Messinian–Early Pliocene)

This synthem shows the most dramatic facies and thickness changes across the Forlì line. Its general characters will be only briefly summarized here; for more detailed descriptions the reader can refer to Roveri et al.

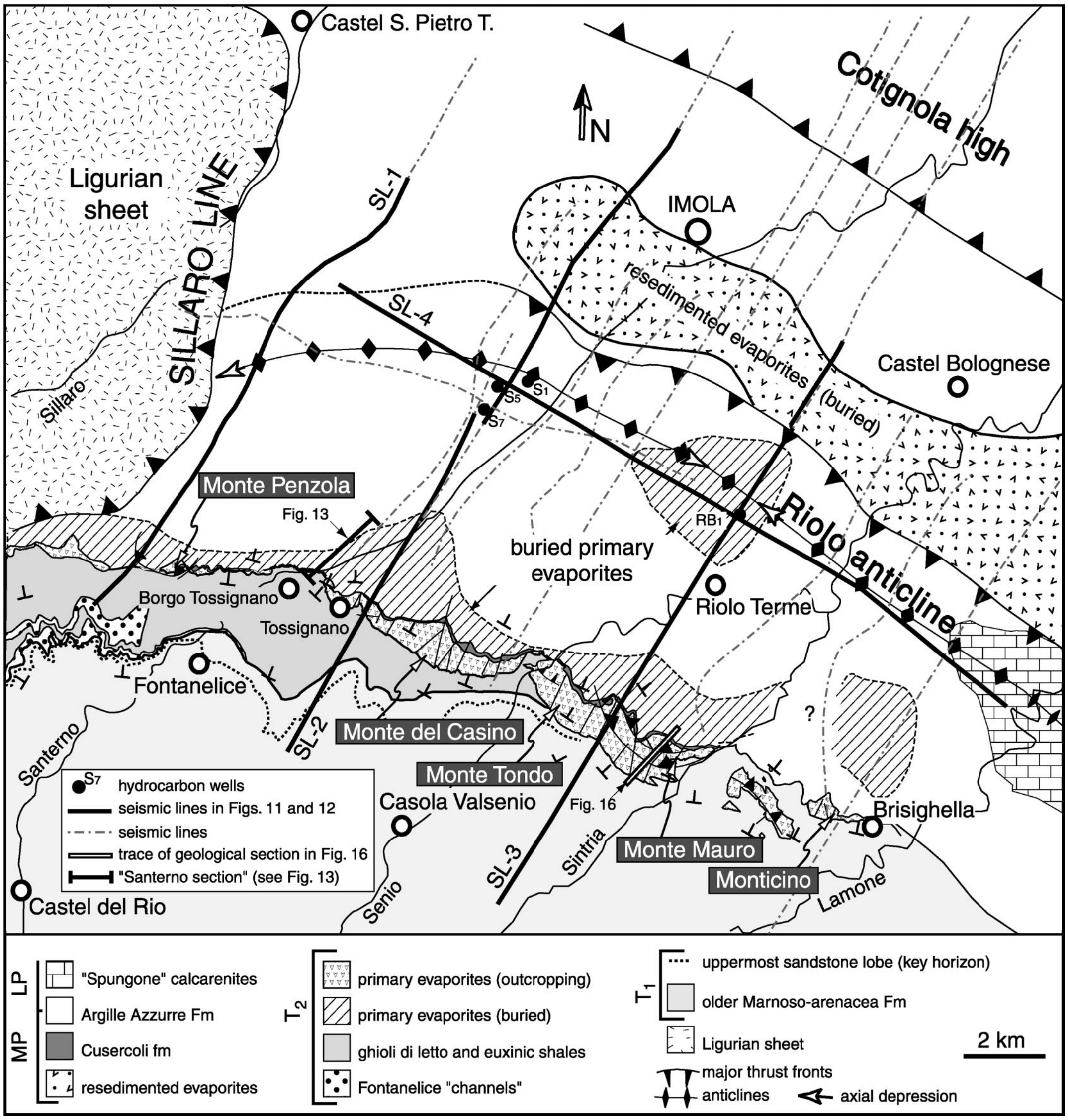


**Figure 10. Detailed geologic map of the Vena del Gesso basin with indications of the main subsurface features. The locations of wells and seismic lines are also shown. Abbreviations of unconformity-bounded stratigraphic units (synthems): LP—lower Pliocene; MP—Messinian–Pliocene; TM—Tortonian–Messinian. RB1—Riolo Bagni 1 well.**

(1998, 2001), Bassetti (2000), and Bassetti et al. (1994). We emphasize here that this group contains the Miocene/Pliocene boundary, a supraregional synchronous surface marking the sudden reestablishment of fully marine conditions in the Mediterranean (Hsü et al., 1972; Iaccarino et al., 1999).

***Western Sector***

Deposits of this unit are very thin and can be separated in two minor lithohorizons by the Miocene/Pliocene boundary. The uppermost Messinian deposits consist of clays containing a hypohaline faunal assemblage of para-Tethyan affinity (Lagomare fauna). Small lenses of sandstones occur locally, and near the top a micritic horizon, locally named ''colombaccio,'' is commonly present. As in many other areas of the Apennine foredeep where the succession is continuous, the Miocene/Pliocene boundary is generally heralded by a characteristic dark, organic-rich horizon, whose origin is still poorly understood.

Lower Pliocene deposits of this synthem consist of a thin unit (only 2 m in the Santerno section, according to Colalongo et al. [1982] and Cremonini et al. [1969]) of deep-marine mudstones draping the entire area. Detailed biostratigraphic studies carried out in the Santerno and Monticino sections show that a large hiatus is associated with the LP regional unconformity marking the top of this synthem; the LP unconformity occurs in the upper part of the Gilbert Chron (Fig. 3A) 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 flows) derived from the Ligurian units (Cremonini and Ricci Lucchi, 1982). The small thickness of lower Pliocene deposits of the MP synthem in this area is essentially related to the strong erosion associated with the LP unconformity.

### *Eastern Sector*

The main outcrops of the upper Messinian–lower Pliocene synthem occur in two large synclines (Giaggiolo-Cella and Sapigno synclines in Fig. 1), possibly corresponding to former basins separated by topographic highs related to minor tectonic structures. From a lithostratigraphic point of view, this synthem, according to Roveri et al. (1998, 2001; Fig. 3B, hypothesis a) consists of a basal complex of resedimented evaporites and organic-rich shales (deep-water member of the Gessoso-solfifera Formation in Fig. 3B). This complex is overlain by a thick (up to 600 m) succession of upper Messinian Lagomare deposits (Colombacci Formation), made up of terrigenous sediments derived from Apenninic sources; these in turn are overlain by the Pliocene fully marine Argille Azzurre Formation.

Physical features (minor unconformities, key beds, cyclical stacking pattern) define a detailed stratigraphic framework, useful for regional correlations (Roveri et al., 1998). The succession can be subdivided into two units (p-$ev_1$ and p-$ev_2$ in Fig. 3; see Roveri et al., 2001) separated by a minor unconformity marking important paleogeographic and structural changes.

The lower unit (p-$ev_1$) only occurs in structural depressions and consists of resedimented evaporites overlain by a thick, monotonous muddy section containing minor sandstone bodies and showing an overall coarsening-upward trend. An ash layer, dated at ca. 5.5 Ma (Odin et al., 1997), represents an exceptional lithostratigraphic marker throughout the whole Apennine foredeep basin that allows us to trace the unit across different subbasins (Bassetti et al., 1994; Ricci Lucchi et al., 2002).

The upper unit (p-$ev_2$) consists of cyclically stacked coarse-grained fluviodeltaic systems, vertically arranged in a backstepping sequence. This unit is thicker in structural depressions but also overlies and seals all the previously uplifted and subaerially exposed areas. Geologic cross sections clearly show the onlap of this unit against the Forlì high and the progressive upward decrease of thickness and grain size of the fluviodeltaic sediments (see Figs. 2 and 3). Paleocurrents and facies changes (Manzi, 1997; Roveri et al., 1998) show that the entry points of such fluviodeltaic systems were located along the Forlì line. Coarse-grained bodies are regularly interbedded with muddy units containing three limestone horizons (locally named "colombacci"); the upper one, as in the western sector, lies just below the Miocene/Pliocene boundary, also here marked by a dark, organic-rich horizon. The basal Pliocene deposits here have the same facies character as in the western sector (epibathyal mudstones), but their thickness is greater because of the less-developed erosional character of the overlying LP unconformity.

## SUBSURFACE DATA

The assessment of northeast to southwest facies changes and geometrical relationships among the different stratigraphic units is normally prevented by the limited width of the outcrop belt in the western sector. Seismic profiles and well data made available by ENI-Agip Division overcome this problem. A grid of dip and strike seismic profiles of good quality, shot in the lower reaches of the valleys, has been studied in detail (Fig. 10). Some profiles reach the outcrop area of the Marnoso-arenacea Formation and Gessoso-solfifera Formation, allowing integration of field and subsurface data.

The gently northeast-dipping, outcropping monocline is clearly imaged in seismic profiles. The unconformity separating the $T_2$ and the MP synthems is easily recognizable, as a result of the high-amplitude reflector associated with the gypsum and angular relationships between the underlying and overlying units (Figs. 11, 12). A thrust-related anticline interrupts the regular monoclinal attitude of the $T_2$ synthem and older Marnoso-arenacea Formation deposits (Fig. 11, SL-2 and SL-3). The northwest-trending anticlinal axis lies ~6 km northeast of the gypsum outcrop belt. The Messinian/Pliocene unconformity has a strongly erosional character (e.g., Fig. 11, SL-2 and SL-3), and the gypsum reflector disappears along the southern flank of the anticline approaching the crest (e.g., Fig. 11, SL-1, SL-2 and SL-3). The unconformity lies at ~1500 m depth at the crest of the anticline and is overlain by a seismically transparent unit thinning toward both to the southwest (the outcrop zone) and the northeast, with maximum thickness along the southwest flank of the structure. The upper boundary of this transparent unit, erosional along the monoclinal ramp, becomes more conformable above the anticline core. The seismic unit above this upper unconformity is characterized by high-amplitude reflections regularly dipping toward the northeast; they can be traced to the outcrop zone into Pliocene deposits.

The northeast limb of the anticline is characterized by a highly deformed belt, corresponding to the thrust-fault zone (Fig. 11, SL-1, SL-2 and SL-3). The seismic succession in the footwall consists of parallel, regular reflectors, subhorizontal or gently dipping toward the southwest (Fig. 12).

The anticline has been drilled in the past for hydrocarbon exploration; wells are distributed along its axis and are particularly abundant in the Santerno valley (Fig. 10), where the flanks of the structure have also been explored (Fig. 13). The anticlinal crest consists of Tortonian turbiditic sandstones of the Marnoso-arenacea Formation (Fig. 11, SL-2; Fig. 13). Although the available stratigraphic data from wells do not allow an accurate age determination of these deposits, the absence of a thick mudstone interval equivalent to the upper Tortonian–lower Messinian interval occurring in the outcrop belt indicates that these turbiditic deposits could be older than the $T_2$ synthem. However, this sandstone unit is abruptly overlain by lower Pliocene clays, corresponding to the transparent unit recognized on seismic profiles (Fig. 11, SL-2). Detailed biostratigraphic studies carried out on these wells show that the Pliocene deposits overlying the MP unconformity still belong to the MP synthem (Fig. 3); well correlations also show that these deposits onlap the southern flank of the anticline (Fig. 11, SL-2; Fig. 13). The upper erosional surface is the LP unconformity; its erosive character increases away from the anticlinal crest toward the southwest, i.e., the outcrop belt. As a consequence, the Pliocene deposits of the MP synthem are much thicker above the anticline than in outcrop. Significantly, no trace of either primary selenitic gypsum or postevaporitic deposits of the MP synthem have been found in the anticline crest or in the upper part of its flanks (Fig. 11, SL-2; Fig. 13).

Primary gypsum has been encountered in the Riolo Bagni 1 well (RB1 in Figs. 10, 11, 12), drilled in an axial depression of the anticline. Seismic profiles indeed show in this area a strong reflector draping the anticlinal crest (Fig. 11); this reflector is discontinuous, and the extension of gypsum above the anticline is limited to a small area that is aligned with the segment of the outcrop belt where gypsum deposits show the lowest degree of deformation.

## DISCUSSION—THE TECTONIC AND SEDIMENTARY EVOLUTION OF THE VENA DEL GESSO BASIN

The data just presented permit a reconstruction of the sedimentary and tectonic history of the Vena del Gesso basin, whose general stratigraphic framework is schematically shown along a west-northwest–east-southeast section in Figure 14. Basin evolution can be

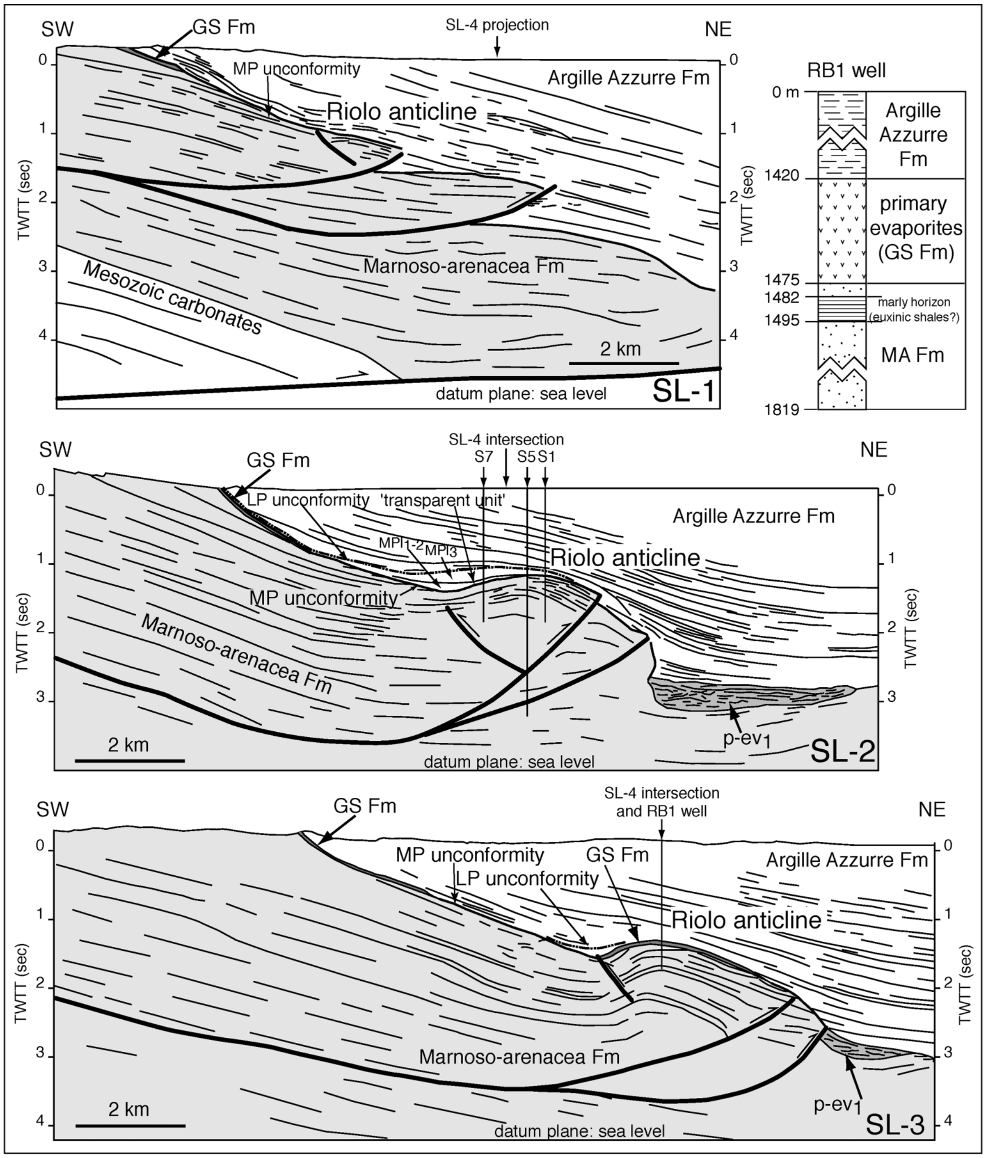


**Figure 11. Line drawings of dip-parallel seismic profiles in the Vena del Gesso basin (see traces in Fig. 10) showing a buried thrust-related anticline (Riolo anticline). In SL-1, note in the lower left, the deep thrust involving the Mesozoic carbonate succession. Note also the deeply eroded Marnoso-arenacea Formation on the southwest limb of the anticline and the occurrence of gypsum above its crest only in profile SL-3. A synthetic stratigraphy of the Riolo Bagni 1 well (RB1; see location in Fig. 10) is shown in the upper right. Formations: GS—Gessoso-solfifera; MA—Marnoso-arenacea. MP—Miocene–Pliocene; LP—lower Pliocene; p-ev$_1$—postevaporitic unit 1. TWTT—two-way traveltime.**

subdivided in several steps related to discrete time slices (see Fig. 15).

### Late Tortonian: First Evidence for Subtle Topographic Relief

Facies and geometry characteristics of sandstone bodies of the Fontanelice channelized systems imply the lateral confinement of turbiditic flows running from the northwest to the southeast in a progressively narrowing basin. The geometry of the erosional surfaces suggests the creation of limited topographic relief to the northeast, possibly elongated in a direction parallel to the basin axis. We argue that such subtle seafloor topography is the first evidence of the growth of the Riolo anticline (Fig. 15A). The early growth of this structure is not substantiated by clear wedging of strata in the outcropping succession; however, slightly converging seismic reflectors characterize this unit in the subsurface (Fig. 11). Such weak geometric evidence for uplift is likely related to very slow and subtle movements compensated by high sedimentation rates (for more on this item, see Argnani and Ricci Lucchi, 2001). Nevertheless, the ongoing modifications of seafloor topography left a strong imprint on the facies characters of turbidite systems. The larger-volume flows, accelerated by lateral constriction, increased their erosional power and cut large-scale erosional features; we expect their sediment load to be deposited farther downcurrent, i.e., to the southeast, to feed the Savio turbidite system. The thick, often amalgamated and structure-

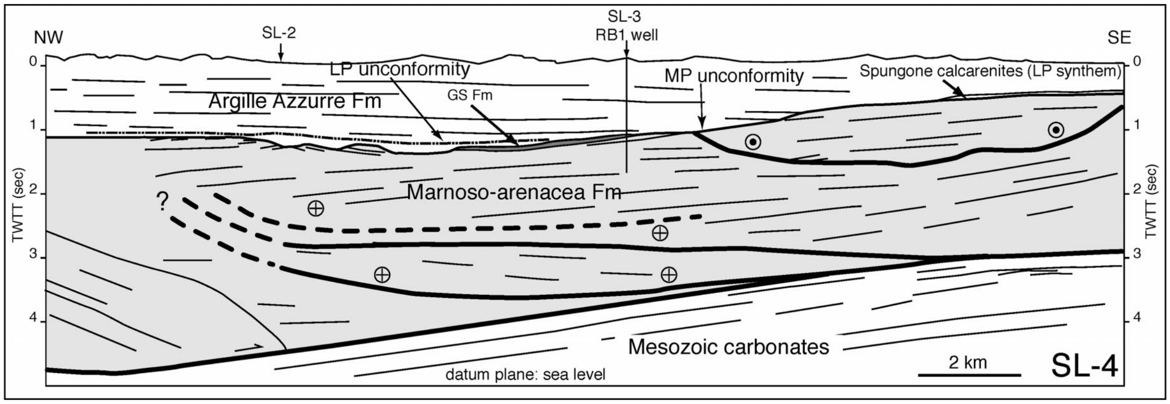


**Figure 12. Line drawing of a strike-parallel seismic profile (see trace in Fig. 10) along the anticlinal axis. The strong reflectors associated with Mesozoic carbonates clearly show the overall westward plunge of the structure. TWTT—two-way traveltime.**

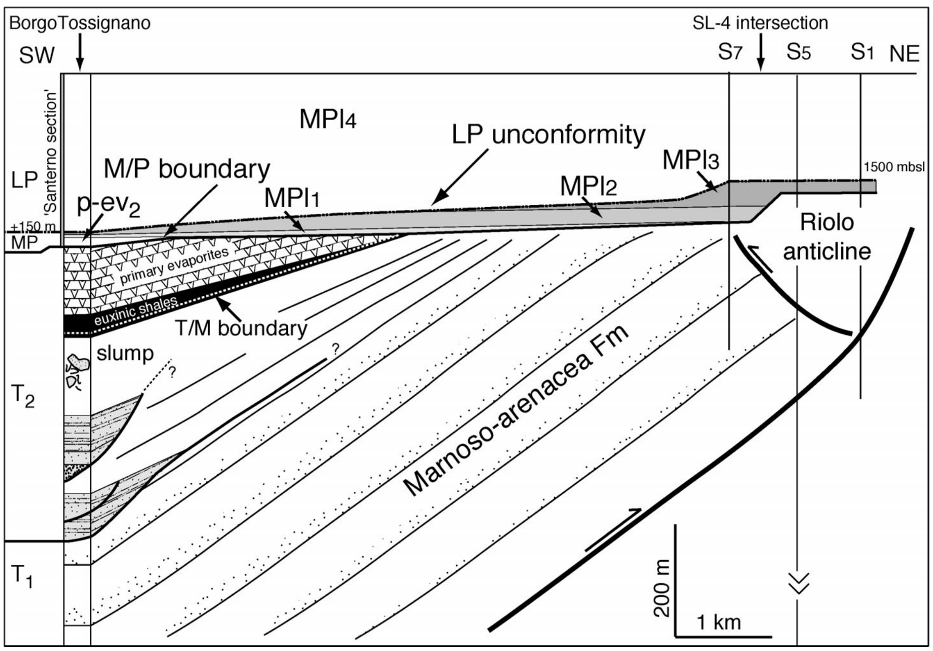


**Figure 13. Schematic cross section, flattened at the $MPl_2/MPl_3$ boundary (early Pliocene), along the Santerno valley from the outcrop area (Santerno section, see location in Fig. 10) to the crest of the Riolo anticline, e.g., along the SL-2 profile up to the intersection with SL-4 (Fig. 11). This section clearly shows the paleotopography just before the early Pliocene tilting (LP unconformity); thickness and stratal relationships of upper Tortonian and Messinian units suggest a paleoslope dipping toward the southwest. Abbreviations: LP—lower Pliocene; p-$ev_2$—postevaporitic unit 2; M/P—Miocene–Pliocene; T/M—Tortonian–Messinian; mbsl—meters below sea level.**

less sandstone beds of ''channel'' fills were deposited by smaller volume flows during the subsequent recessional phase of the system; they can actually be considered as depositional lobes formed in a confined basin.

Several sandstone bodies (up to four with upward-decreasing thickness) are vertically stacked to form a clear backstepping sequence (Fig. 5B). This trend is probably due to the growth of the anticline, but changes in the volume of sediment delivered by the source area (i.e., the Alps) cannot be ruled out. The progressive growth of the anticline along the frontal and lateral ramp (i.e., the Forlì line) split the former foredeep into two different subbasins: an uplifting basin to the west (the future Vena del Gesso basin), gradually disconnected from the main foredeep and cut off from the main pathway of turbidite flows, and a subsiding basin to the north and to the east, still reached in the late Tortonian by turbidity currents fed by Alpine sources.

### Independent Evidence for Uplift During the Late Tortonian and Early Messinian

Paleobathymetric reconstructions based on benthic foraminifera from the Monte del Casino section (Kouwenhoven et al., 1999; Van der Meulen et al., 1998, 1999) provide independent evidence for the uplift of the western sector during the late Tortonian and early Messinian. Calculations show a steadily decreasing sedimentation rate associated with a progressive shallowing-upward trend (Fig. 7).

Early Messinian sedimentation rates from three sections aligned in a northwest-southeast direction show absolute values regularly decreasing toward the southeast (Monticino section; Figs. 14, 15B), indicating an additional, more local effect to the general trend. The latter is common to other basins of the Mediterranean area and is usually related to the changing paleoceanographic conditions heralding the Messinian salinity crisis, promoting the widespread development of organic-rich deposits in deep-water settings. Setting apart the meaning of such a regional trend, still far from being fully understood, we concentrate here on the specific depositional setting of this study area. Euxinic shales formed through the slow settling of biogenic and very fine-grained terrigenous particles from (1) hemipelagic ''rain'' and (2) low-density, turbiditic currents. The observed decrease of sedimentation rate is essentially due to the suppression of the terrigenous component; this change can be best related to the deactivation of sediment sources due to large-scale climatic or eustatic events, but also to the progressive cutoff of an uplift-

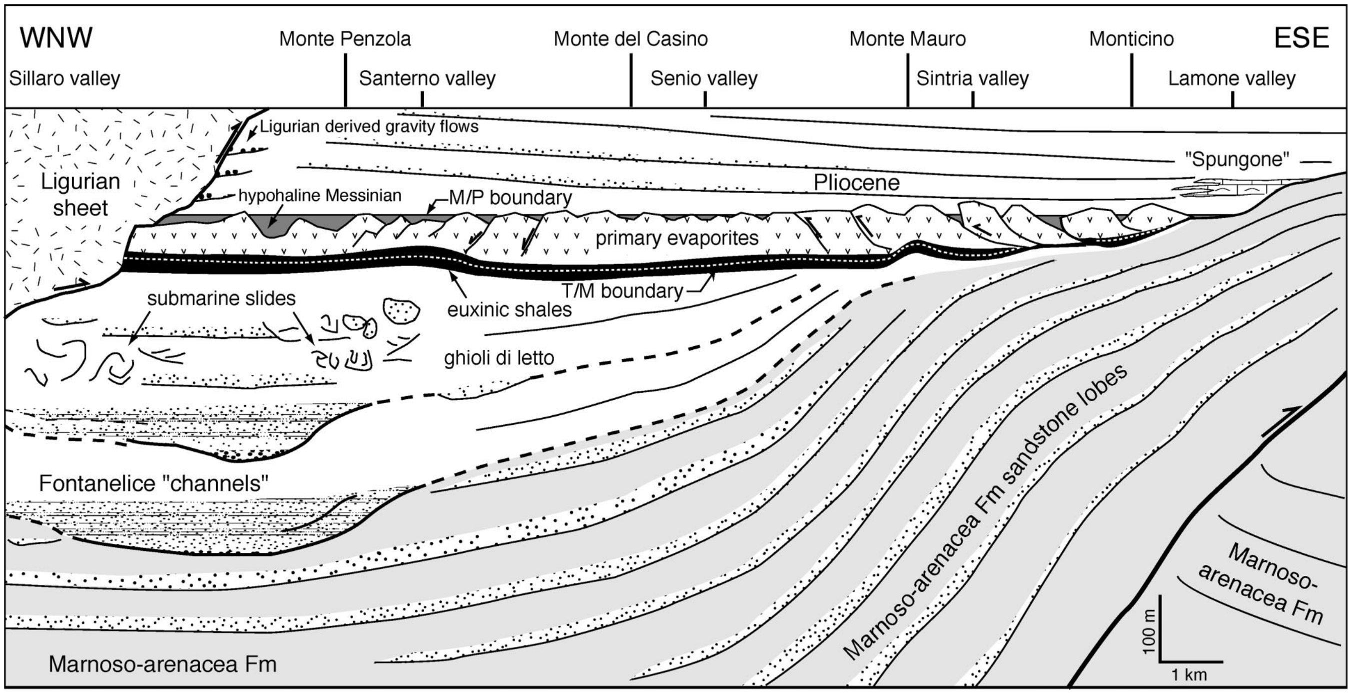


**Figure 14. General geologic and stratigraphic model of the Tortonian–Pliocene succession of the Vena del Gesso basin along a west-northwest–east-southeast section, flattened at the lower Pliocene and showing all the depositional and deformational features described in the text. M/P—Miocene/Pliocene boundary; T/M—Tortonian/Messinian boundary.**

ing seafloor area from bottom-seeking turbidity currents; the two hypotheses are not mutually exclusive, and their combination is more than likely, especially considering the paleobathymetric data based on foraminifera (Kouwenhoven et al., 1999).

Such considerations and the reconstructed late Tortonian–early Messinian paleogeographic setting imply that the observed additional southeastward decrease in the sediment rate is due to a topographically more elevated southeastern area, corresponding to the culmination of the ramp anticline related to the Forlì line, developed during the Messinian. To the east of the Forlì line, both the thickness and sandstone/shale ratio of upper Tortonian–lower Messinian deposits are much greater than in the western area, suggesting higher subsidence and sediment input (Fig. 15B).

## Evaporite Deposition

During the evaporitic phase of the Messinian, the role of the Riolo anticline is clearly defined. Primary, shallow-water evaporites (selenitic gypsum) deposited in a barred basin (Vai and Ricci Lucchi, 1977) only occur to the west of the Forlì line (Fig. 15C).

The abrupt vertical facies changes from the euxinic shales to the overlying shallow-water evaporites implies a dramatic relative sea-level fall, on the order of several hundreds of meters, occurring in a very short time span (according to Krijgsman et al., 1999a). However, its amplitude cannot be easily determined in the Vena del Gesso basin because of the absence of reliable paleodepth indicators in the uppermost euxinic shales.

The overall aggradational stacking pattern of shallow-water primary gypsum cycles clearly indicates that climatically forced, cyclic evaporite deposition occurred during a relative sea-level rise. The longer-term shallowing-upward trend superposed on small-scale cycles suggests a gradual upward reduction in the amount of accommodation space created. The evaporites are cut by an erosion surface showing evidence for subaerial exposure. This unconformity can be traced to the southeast on the culmination of the structural high associated with the Forlì line lateral ramp, where lower Pliocene sediments directly overlie the Marnoso-arenacea Formation or the Tortonian mudstones. The same situation can be reconstructed in a southwest-northeast direction from seismic and well data; the latter show that above the anticline culmination, gypsum is normally absent, with the notable exception of a small area (below the Riolo Terme village, Fig. 10), coinciding with an axial depression.

Whether these vertical trends were mainly controlled by eustasy or by tectonics is very difficult to assess. We are well aware that, according to most models, Messinian events are thought to imply dramatic eustatic changes, far exceeding the amplitude and velocity of local tectonic movements. As far as the Apennine foredeep succession is concerned and taking into account the fact that the main Messinian events were not coincident with global sea-level cycles (Krijgsman et al., 1999a), the observed stratigraphic evolution appears to be fully consistent with the regional tectonic history.

## Thickness and Facies Distribution of Postevaporitic Deposits

Messinian postevaporitic deposits show dramatic thickness differences across the Forlì line (Fig. 2). To the west, above the uplifted and subaerially eroded gypsum, only a thin, mainly fine-grained unit occurs; this unit of latest Messinian age is conformably overlain by the lower Pliocene deep-marine deposits. To the east of the Forlì line, postevaporitic deposits occur in different subbasins with thicknesses of >600 m. Two units with different

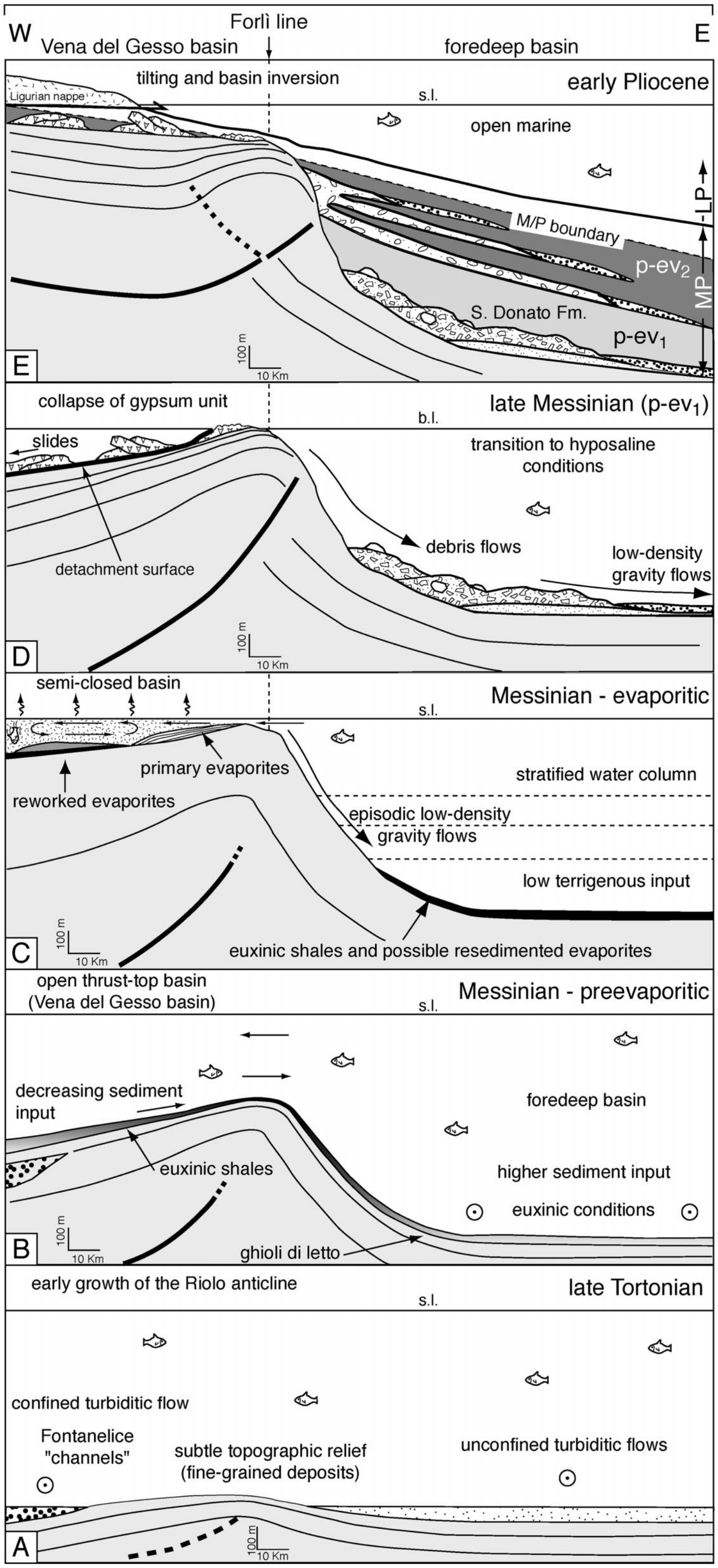


**Figure 15. Sketches showing the evolution of Vena del Gesso basin from the late Tortonian to early Pliocene. See text for explanation; s.l.—sea level; b.l.—base level; M/P—Miocene/Pliocene boundary; M–P—Miocene–Pliocene strata; LP—lower Pliocene strata; p-ev$_1$—postevaporitic unit 1.**

stacking patterns can be recognized: (1) the lower unit (p-ev$_1$) comprises the resedimented evaporites (Figs. 15D, 15E) at its base and is mainly made up of fine-grained terrigenous deposits. It has an overall progradational stacking pattern and a shallowing-upward trend. This unit only occurs in structural depressions and was deposited during the uplift phase, as suggested by minor unconformities and evidence for slope instability. (2) The upper unit (p-ev$_2$; Fig. 15E) is made up of cyclically stacked fluviodeltaic systems, showing an overall backstepping pattern. This unit onlaps the basin margins and tends to cover all the previously uplifted structures (Fig. 2). Its uppermost part lies above the culmination of the Forlì line and extends all over the Vena del Gesso basin. The geometric characteristics of the unit point to the unit's deposition during a phase of relative base-level rise (at that time, the Mediterranean area was disconnected from the ocean and a complex array of endorheic lakes occupied the more depressed areas), more likely controlled by tectonic quiescence and generalized subsidence that lasted until the early Pliocene. As an alternative to explain the observed vertical facies trends, a mechanism must be envisaged for the progressive refill of the basin with fresh to brackish water prior to the earliest Pliocene marine flooding.

Southwest-northeast seismic profiles show that the thin p-ev$_2$ occurring in the Vena del Gesso basin onlaps toward the northeast against the southern limb of the Riolo anticline and is absent on its crest (Fig. 11). After the emergence following the evaporitic phase, the structural high bounding the basin was progressively submerged and leveled in the late Messinian; it ceased to be a topographic high during the early Pliocene, when mainly fine-grained, deep-water sediments again accumulated above its culmination, as clearly demonstrated in both the outcrop area and in the subsurface (Santerno river wells).

### Early Pliocene Tilting

Lower Pliocene deposits of the MP synthem are very thin in the outcrop area of Vena del Gesso basin and thicker above the buried Riolo anticline. Well data also show that the hiatus associated with the overlying LP unconformity decreases along the southern limb of the anticline and disappears above its culmination (Fig. 13). This geometry means that lower Pliocene deposits preserved below the unconformity are progressively thicker in a northeast direction.

Moreover, a careful evaluation of outcrop and subsurface data shows that within the northeast-dipping monocline, lower Pliocene deposits have higher dip angles than those of the Marnoso-arenacea Formation (Figs. 10, 16). This finding can only be explained by admitting the existence of a Messinian–early Pliocene paleoslope dipping toward the west and the southwest that was subsequently tilted and inverted during the early Pliocene. The south and western sectors of the Vena del Gesso basin, topographically more depressed during the Messinian, were uplifted and eroded, while the northern sector was contemporaneously affected by higher subsidence. A possible explanation for such northeastward tilting is the movement of a deeper thrust fault, detached along the base of Mesozoic carbonates (Fig. 11, SL-1) and possibly also involving the basement. This important tectonic event, dated at 4.2 Ma (and represented by the LP unconformity), marks a significant propagation of the Apennine thrust front toward the Po Plain area and a concomitant generalized advance of the allochthonous Ligurian nappe (Ricci Lucchi, 1986).

### The Gravity vs. Tectonic Nature of Evaporite Deformation in the Vena del Gesso Basin

We think that the existence of a paleoslope dipping toward the west and southwest during the late Tortonian–early Pliocene interval, here suggested for the first time, is well substantiated by the sedimentary history of the Vena del Gesso basin and could explain the deformational features affecting the primary evaporites as being mainly related to largecale gravity processes. Cross sections modified from Marabini and Vai (1985) show the geometry of the deformation (Fig. 16), and their close relationship to the southwest-dipping paleoslope that can be easily reconstructed by removing post-Messinian deformation through the flattening of lower Pliocene deposits. The strong mechanical contrast between the rigid gypsum and the underlying, more plastic, organic-rich euxinic shales created the conditions for the development of a weak layer at their boundary, which acted as a very efficient detachment surface. Renewed uplift during the intra-Messinian phase triggered gliding of large gypsum slabs along this surface on the southern, shallower-dipping limb of the anticline. On the frontal limb, characterized by a steeper profile, movement of gypsum slabs was accelerated, and they were transformed by breaking up along the slope, leading to more evolved deposits (debris flows, turbidites). The observed change in type and degree of deformation along the outcrop belt can be related to a different magnitude of translation of gypsum slabs along the paleoslope; in this respect, it is worth noting that in the central, less deformed sector of the Vena del Gesso basin, gypsum layers are preserved in an axial depression of the anticline. The gravity-driven downslope translation of primary gypsum slabs also implies a somewhat important vertical-movement component; rough and prudent calculations based on the reconstructed paleoslope show that such vertical displacement could be ~150–200 m for a translation in the order of 1–2 km.

As a consequence, a word of caution is needed when interpreting in terms of dramatic paleobathymetric changes the ‘‘abrupt’’ vertical transition from euxinic shales to primary evaporites observed in the Vena del Gesso basin. The amplitude of the relative sea-level fall, if any occurred, associated with the onset of evaporite deposition, could have been far less important than usually thought. At a larger scale, this observation could resolve the apparent contradiction deriving from the synchronous development of Lower Evaporites above sediments of greatly variable paleodepth, as implied by the cyclostratigraphic models (Krijgsman et al., 1999a). This synchronous development represents one of the most puzzling problems of the Messinian salinity crisis, as previously discussed; however, considering the peculiar mechanical properties of Messinian rocks and the high tectonic mobility of the Mediterranean area during this time interval (Meulenkamp and Sissingh, 2001), large-scale, gravity-driven gypsum-slab sliding and related gravity-flow deposits could be widespread features in other Mediterranean basins (Roveri et al., 2001). Many other Mediterranean basins, tectonically active during the Messinian (Tertiary Piedmont Basin, Sicily, Tuscany, Greece, Spain), are characterized by the common occurrence of collapse features affecting the Messinian evaporites at a variable scale (Ghibaudo et al., 1985; Decima and Wezel, 1971; Kontopoulos et al., 1997; Michalzik, 1996; Testa and Lugli, 2000). Nevertheless, the larger-scale implications of such deposits have not been thoroughly investigated yet. Besides the correct paleodepth estimate of the local base of Lower Evaporites successions, the experience derived from the Apennine foredeep supports the hypothesis that evaporitic deposits occurring in deepest subbasins of the Mediterranean could actually have been deposited in deep waters (Krijgsman et al., 1999a) through precipitation from deep brines and/or, we suggest, through clastic resedimentation processes.

Pierre et al. (2002) have suggested that the huge sea-level drop related to the Mediterranean desiccation caused gas hydrate dissociation in late Tortonian reservoirs of the Lorca Basin (Spain), thus triggering large-scale failure processes. This mechanism is undoubtedly plausible and can explain sedimentary instability without the need for tectonic processes; however, in the example of Pierre et al., no Messinian evaporites were apparently involved in failures and this missing feature caused some problems in the correct determination of the age of such events. In the Apennine foredeep, carbonate bodies related to methane-rich fluid venting are largely diffused at several stratigraphic levels throughout the whole Miocene succession (Ricci Lucchi and Vai, 1994; Conti and Fontana, 1998). As in the Lorca Basin, chemosynthetic carbonate bodies also occur in the euxinic shales of the Vena del Gesso basin, just below the deformed gypsum unit. A specialized mollusk fauna is often associated with these bodies, indicating that fluid venting at the sea bottom was already active during the early Messinian (Taviani, 1994, 2001). The areal distribution of the carbonate bodies is revealing: In the Vena del Gesso basin, they only occur in the southeastern sector (Sintria valley); like similar bodies occurring at other stratigraphic levels, they are most commonly associated with structural culminations. Gas hydrate could well have played a role in triggering mass movements of gypsum slabs in the Vena del Gesso basin; however, the distribution of the carbonate bodies suggests that tectonic uplift likely provided the conditions for their dissociation.

## CONCLUSIONS: IMPLICATIONS FOR THE ONSET OF THE MESSINIAN SALINITY CRISIS

The sedimentary and tectonic history of the Vena del Gesso basin clearly illustrates the complex evolution of a thrust-top basin, from the early growth of its bounding thrust to the final tectonic uplift. In such a geologic context, the deposition of Messinian primary evaporites—which occurred during the final stage of a long-lasting uplift phase affecting the whole Apennine thrust front—seems to have been intimately controlled by the tectonic history of the region and not merely—or, at least, not only—the result of the superposition of remote events (closure and reopening of the Atlantic gateways).

Evaporite deposition and subsequent deformation were both locally controlled by tectonics and the evolving basin morphology. The growth of a structural high led to the forma-

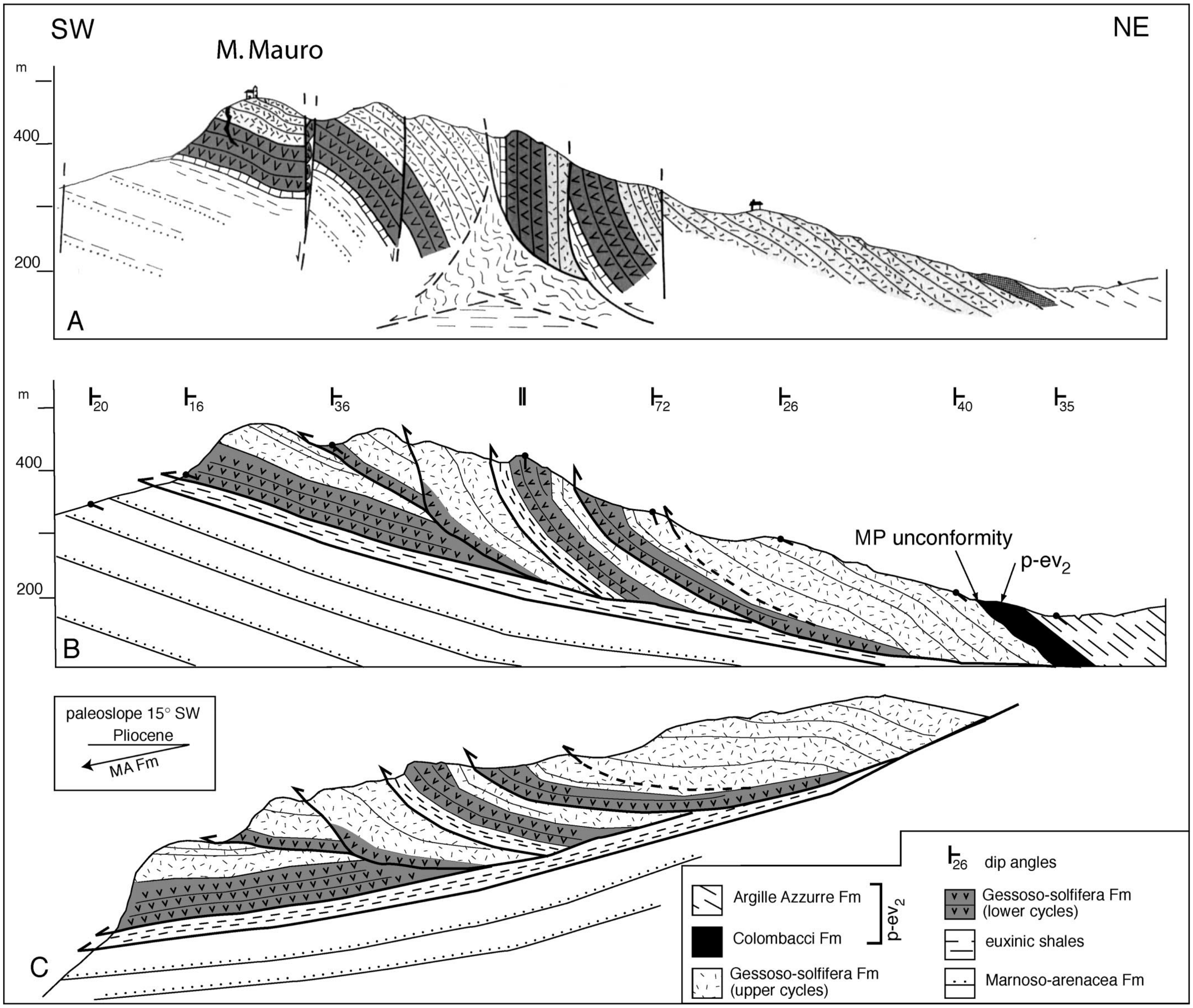


**Figure 16. (A) Gypsum slide blocks of the Sintria valley (based on Marabini and Vai, 1985, section D). (B) The present-day interpretation; M/P—Miocene/Pliocene unconformity; p-ev$_2$—postevaporitic unit 2. (C) When removing the Pliocene to Holocene deformation, a southward-dipping late Messinian paleoslope appears. MA—Marnoso-arenacea. The steepening of such a paleoslope during the intra-Messinian tectonic phase triggered large-scale slope instability phenomena and promoted the collapse and accumulation of huge gypsum slabs.**

tion of a small basin, isolated from the mainland and with reduced connections with the main basin. Evaporites were deposited within this shallow basin; the deeper and wider foredeep basin was characterized by deposition of organic-rich shales. Subsequent uplift and tilting led to the collapse of the gypsum unit in the late Messinian.

A point that we want to stress here is the tectonic nature of the base of the local Lower Evaporites; this fact probably has negligible effects on the chronostratigraphy, as the intrastratal deformation does not produce significant stratigraphic elisions or duplications. This interpretation could have a far-reaching effect on paleoenvironmental reconstructions, as primary gypsum deposits were fragmented and eradicated from their original substratum and translated downslope. As previously discussed, depending on the extent of translation, gypsum might be superposed onto sediments somewhat bathymetrically deeper than those on which they were deposited; the estimated vertical displacements are in the order of 150–200 m. This result implies that the amplitude of sea-level drop at the onset of the Messinian salinity crisis, as inferred from the abrupt superposition of the Lower Evaporites to the euxinic shales, could be considerably smaller than generally thought.

As for the ultimate processes triggering large-scale slope instability and mass movements, we think that, also taking into account the possible role of other factors—for example, the gas hydrate dissociation related to high-amplitude sea-level falls (see Pierre et al., 2002)—the contribution of the Mediterranean structural evolution in controlling the Messinian stratigraphy has been somewhat overlooked in the past and should be reconsidered.


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