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Deep-water clastic evaporites deposition in the Messinian Adriatic foredeep (northern Apennines, Italy): did the Mediterranean ever dry out?

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ABSTRACT

A new genetic facies model for deep-water clastic evaporites is presented, based on work carried out on the Messinian Gessoso-solfifera Formation of the northern Apennines during the last 15 years. This model is derived from the most recent siliciclastic turbidite models and describes the downcurrent transformations of a parent flow mainly composed of gypsum clasts. The model allows clearer comprehension of processes controlling the production and deposition of clastic evaporites, representing the most common evaporite facies of the northern Apennines, and the definition of the genetic and stratigraphic relationship with primary shallow-water evaporites formed and preserved in marginal settings. Due to the severe recrystallization processes usually affecting these deposits, petrographic and geochemical analyses are needed for a more accurate interpretation of the large spectrum of recognized gravity-driven deposits ranging from debrisflow to low-density turbidites. Almost all the laminar 'balatino' gypsum, previously considered a deep-water primary deposit, is here reinterpreted as the fine-grained product of high to low-density gravity flows. Facies associations permit the framing of the distribution of clastic evaporites into the complex tectonically controlled depositional settings of the Apennine foredeep basin. The Messinian Salinity Crisis occurred during an intense phase of geodynamic reorganization of the Mediterranean area that also produced the fragmentation of the former Miocene Apennine foredeep basin. In this area, primary shallow-water evaporites equivalent to the Mediterranean Lower Evaporites, apparently only formed in semi-closed thrust-top basins like the Vena del Gesso Basin. The subsequent uplift and subaerial exposure of such basins ended the evaporite precipitation and promoted a widespread phase of collapse leading to the resedimentation of the evaporites into deeper basins. Vertical facies sequences of clastic evaporites can be interpreted in terms of the complex interplay between the Messinian tectonic evolution of the Apennine thrust belt and related exhumation–erosional processes. The facies model here proposed could be helpful also for better comprehension of other different depositional and geodynamic contexts; the importance of clastic evaporites deposits has been overlooked in the study of other Mediterranean areas. Based on the Apennine basins experience, it is suggested here that evaporites diffused into the deeper portions of the Mediterranean basin may consist mainly of deep-water resedimented deposits rather than shallow-water to supratidal primary evaporites indicative of a complete basin desiccation.

Keywords Apennines, clastic evaporites, facies analysis, Messinian Salinity Crisis, sulphate evaporites.

INTRODUCTION

The Messinian Salinity Crisis affecting the Mediterranean area was marked by a widespread deposition of evaporites. In the Apennine foredeep basins, Messinian evaporites consist of shallow-water primary evaporites (Vena del Gesso sequence; Vai & Ricci Lucchi, 1976, 1977) and, to a much larger extent, deeper water, resedimented clastic evaporites; both these deposits, without distinction, have been historically included within the Gessoso-solfifera Formation.

The term 'clastic evaporites' was used during the late 1960s–early 1970s to describe some 'gypsiferous sandstones' of the Laga Basin (LB in Fig. 1) strictly associated with the 'balatino gypsum', a laminar alternation of gypsum and bituminous shales that were considered to be the products of primary deep-water sedimentation (Parea & Ricci Lucchi, 1972; Ricci Lucchi, 1973). After these preliminary studies, no further investigations were carried out on these deposits. Due to the overwhelming popularity of the Mediterranean desiccated deep basin model (Hsü *et al.*, 1972, 1973) and the lack of modern analogues of deep-water clastic evaporites (Schreiber, 1973; Schreiber *et al.*, 1976; Kendall & Harwood, 1996; Warren, 1999; Schreiber & El Tabakh, 2000) most attention in sedimentological facies models has been mainly focussed on primary shallow-water depositional settings.

Nevertheless, clastic evaporites, both shallow and deep-water facies, have been described in the last years from Cyprus (Polemi basin, Robertson *et al.*, 1995), Egypt (Red Sea, Rouchy *et al.*, 1995), Greece (Zakynthos basin, Kontopoulos *et al.*, 1997), Poland (Carpathian foredeep, Peryt, 2000) and Spain (Balearic basin, Martinez del Olmo, 1996; Teruel Basin, Ortì *et al.*, 2003; Nijar Basin, Fortuin & Krijgsman, 2003), but a well-developed genetic model for clastic sulphate deposition is still lacking.

The main aim of this work is to fill the gap in the study of clastic evaporitic rocks by proposing a new facies model for resedimented evaporites in order to: (i) explain the production process of evaporitic detritus, (ii) describe their genetic relationships with the primary evaporites, and (iii) provide a useful tool to 'remove' the diagenetic effects characterizing ancient sulphatic evaporitic rocks. To this purpose the same approach of recently proposed siliciclastic turbidites genetic facies models (Mutti, 1992; Mutti *et al.*, 1999) is adopted.

The genetic facies model for clastic evaporites here proposed has been developed from the Apennine foredeep Messinian successions and proved to be fundamental in reconstructing the palaeogeographical framework of this area. It also might prove a powerful tool for physical stratigraphy-based regional-scale studies in different geodynamic contexts, especially those characterized by a complex, tectonically induced basin topography. Furthermore, this facies model pointing out the common occurrence of clastic evaporites in deep-water settings during Messinian time, may have strong implications for several aspects concerning the salinity crisis on a broader Mediterranean-wide scale; some of them are discussed in the final section of this paper.

GEOLOGICAL SETTING

The northern Apennines (Fig. 1), a collisional orogenic wedge formed since the Late Eocene after the closure of the Ligurian-Piedmont Ocean, consist of the superposition of tectonic units becoming progressively younger towards the east. These tectonic units are traditionally considered to represent former juxtaposed Mesozoic palaeogeographical domains and are characterized by different sedimentary successions: Ligurian (internal and external), Subligurian, Tuscan and Umbro-Marchean-Romagna.

The Umbro-Marchean-Romagna tectonic unit (Fig. 1), cropping out from the Sillaro Valley in the north-west up to the Gran Sasso Massif in the south-east, forms the more external part of the northern Apennines. This unit can be subdivided into two minor basement-detached units affected by thrust-and-fold structures (Barchi *et al.*, 1998): (1) a lower and older one composed of Mesozoic to Cenozoic carbonates and (2) an upper one, up to 3500 m thick, consisting of a Lower Miocene to Quaternary siliciclastic wedge representing the deep-water to continental infill of successive foredeep basins formed and progressively migrating ahead, i.e. towards the north-east, of the

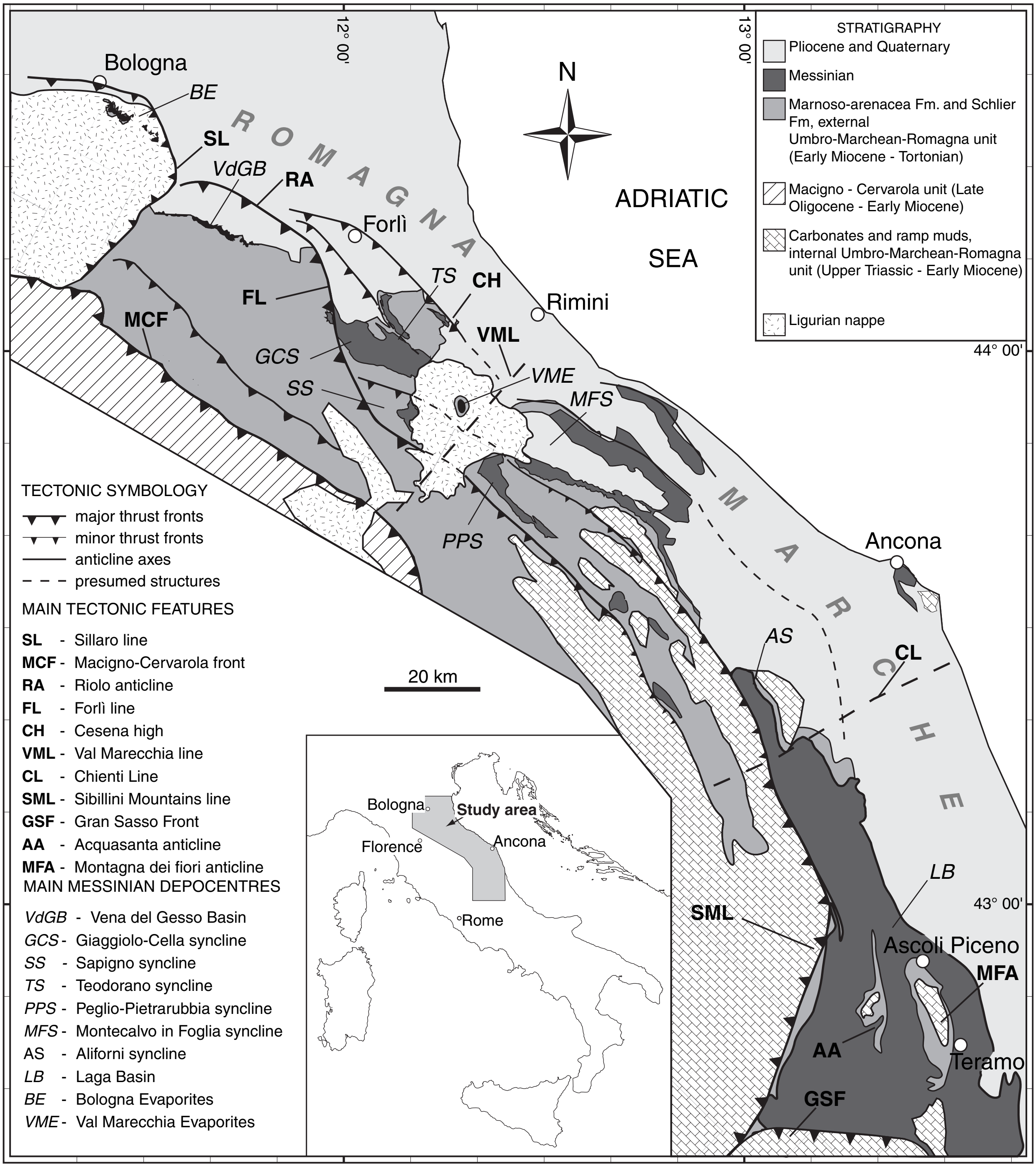


Fig. 1. Geological map of Romagna-Marche Apennines (modified after Manzi, 2001; Roveri *et al.*, 2003).

advancing Apennines thrust belt (Ricci Lucchi, 1975, 1986). The upper unit contains the Messinian deposits that were the object of this study; their facies characteristics and thickness distribution were closely related to a tectonically controlled basin topography which started to develop well before Messinian time and whose reconstruction represents a fundamental step for the comprehension of the Apennines record of Messinian events.

STRATIGRAPHY

The external Umbro-Marchean-Romagna succession can be divided into four main lithostratigraphic units: (i) the Marnoso-arenacea Formation (Langhian-Messinian) made up of deep-water mainly Alpine-derived siliciclastic turbidites, (ii) the Gessoso-solfifera Formation (Messinian) recording the evaporitic event, (iii) the hypohaline Colombacci Formation (grouping the Tetto, San Donato and Cusercoli formations, Late Messinian), and (iv) the open marine Argille Azzurre Formation (Early Pliocene).

This simple lithostratigraphic subdivision actually does not take into consideration the relationships that occurred between tectonics and sedimentation during the Apennine evolution. Here a more effective physical stratigraphic framework is adopted (Fig. 2) based on field and subsurface recognition of unconformity-bounded units (Ricci Lucchi, 1981, 1986; Ricci Lucchi & Ori, 1985; Bassetti *et al.*, 1994; Roveri *et al.*, 1998, 2001, 2002, 2003, 2004; Ricci Lucchi *et al.*, 2002; Roveri & Manzi, 2005). In this scheme, the Tortonian to Early Pliocene succession is subdivided into two main synthems, T_2 (Ricci Lucchi, 1986) and MP, bounded by unconformities related to regional-scale phases of tectonic deformation (Fig. 2). According to Krijgsman *et al.* (1999) the main Messinian Salinity Crisis events recorded in the Apennine foredeep basins, despite the strong tectonic overprint, developed synchronously to that of the rest of the Mediterranean area.

T_2 synthem (Late Tortonian–Messinian)

This unit comprises the Upper Tortonian Marnoso-arenacea Formation, the Lower Messinian organic-rich euxinic shales, a local equivalent of the Tripoli Formation of Sicily, and the primary evaporites of the Gessoso-solfifera Formation (shallow-water member of Roveri *et al.*, 1998, corresponding to the Mediterranean 'Lower evaporites'). The onset of the evaporitic stage is dated at 5·96 Myr (Krijgsman *et al.*, 1999). The T_2 synthem is bounded at the top by a regional scale angular unconformity (Fig. 2) associated with a phase of subaerial exposure of the primary evaporites with the development of palaeokarsts (Costa *et al.*, 1986; De Giuli *et al.*, 1988). This erosional surface is a perfect equivalent of the Messinian erosional surface (Mes), well developed along the Mediterranean margins and is usually related to the huge sea-level drop leading to the desiccation of deepest basins (Hsü *et al.*, 1973). Based on cyclostratigraphic considerations, the oldest age for this surface can be tentatively placed at 5·60 Myr (Fig. 2).

MP synthem (Late Messinian–Early Pliocene)

The MP synthem comprises, from the bottom, a complex of resedimented clastic evaporites belonging to the Gessoso-solfifera Formation (deep-water member of Roveri *et al.*, 1998), a

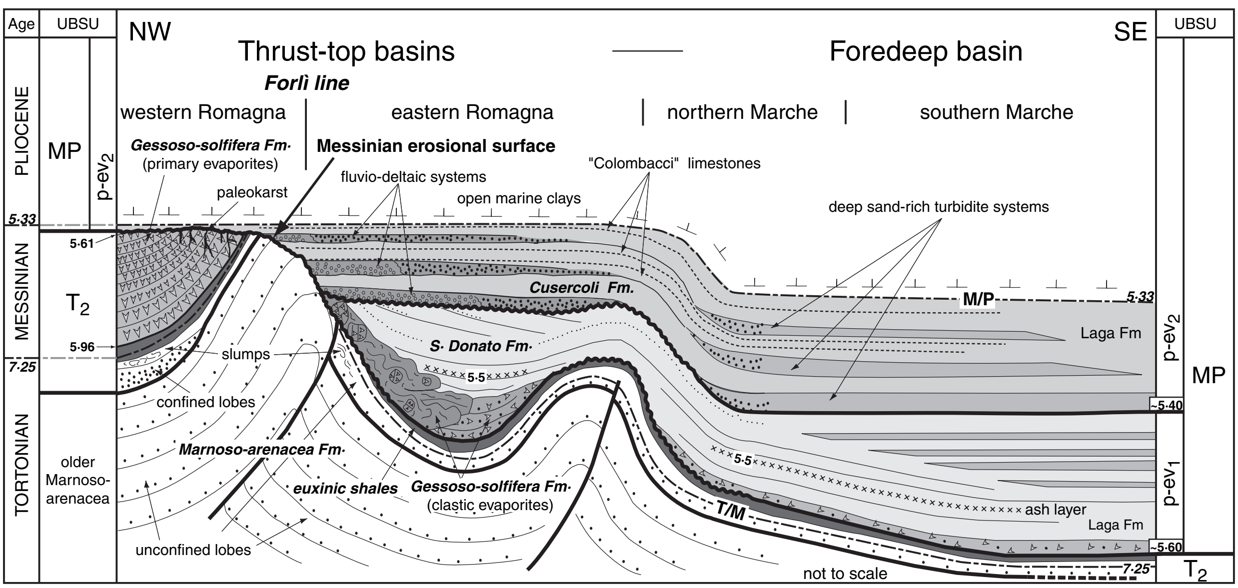


Fig. 2. Schematic geological setting of the northern Apennines during Late Messinian (Pliocene base as datum plane) and relationships between marginal (the Vena del Gesso Basin) and basinal settings (eastern Romagna – northern Marche basins and Laga Basin). After Roveri & Manzi (2005).

fine-grained siliciclastic unit with thin-bedded turbidites (S. Donato and Tetto formations), a unit consisting of a rhythmic alternation of coarse and fine-grained fluvio-deltaic deposits (Cusercoli Formation) and the open marine Lower Pliocene Argille Azzurre Formation, whose base coincides with the Miocene/Pliocene boundary (5·33 Myr). This synthem can be split into two subunits (p-ev$_1$, p-ev$_2$) separated by a minor unconformity at the base of the Cusercoli Formation (5·4 Myr). An ash layer dated at 5·5 Myr (Odin *et al.*, 1997) occurs in the upper part of the p-ev$_1$ unit and represents an excellent basin-wide marker. The MP synthem shows dramatic facies and thickness changes related to the morphostructural setting. A complete sedimentary succession only occurs in structural depressions, where the correlative conformity of the Messinian erosional surface can be traced at the base of the clastic evaporite complex. On the contrary, above the eroded primary evaporites of the T$_2$ synthem, only uppermost p-ev$_2$ deposits are found. These deposits, as well as the uppermost part of the p-ev$_1$ unit, are characterized by the typical Mollusc and Ostracod assemblages with paratethyan affinities representing the so-called Lagomare stage of the Messinian Salinity Crisis.

TECTONIC AND SEDIMENTARY EVOLUTION

Since Late Tortonian time (base of T$_2$ synthem) the relatively wide foredeep basin filled by the Langhian to Lower Tortonian deep-water turbiditic deposits of the *inner*, i.e. lower, Marnoso-arenacea Formation was progressively tightened and separated into areas that underwent different tectonic evolution (Ricci Lucchi, 1986; Roveri *et al.*, 2002, 2003). During this tectonic phase, that continued throughout the Lower Messinian (Van der Meulen *et al.*, 1999), the rise of isolated highs within the foredeep was responsible for: (i) the 'closure stage' of the Marnoso-arenacea, i.e. the accretion of older foredeep deposits into the orogenic wedge, characterized by the progressive reduction of sediment input (shifted to a new developing depocenter to the NE) and the widespread occurrence of chaotic deposits emplaced during the Late Tortonian (Ricci Lucchi & D'Onofrio, 1967; Roveri *et al.*, 1999; Lucente *et al.*, 2002); (ii) the precipitation of primary evaporites at the onset of the Messinian Salinity Crisis within shallow, semi-closed thrust-top basins; (iii) the subsequent uplift, subaerial exposure and dismantlement of these basins; and (iv) the resedimentation of primary evaporites and underlying deposits within adjacent structural and topographic depressions (Roveri *et al.*, 1998, 2001, 2003, 2004).

As a result of this, Messinian primary evaporites rarely crop out in the Apennine chain, because they were either eroded from uplifted basins or deeply buried below sedimentary or tectonic covers. However, the northern Apennines offer a good opportunity to observe one of the best developed successions of primary evaporites (in the Vena del Gesso Basin) and to study their stratigraphic relationships with resedimented clastic evaporites, cropping out in adjacent areas.

The progressive growth of the 'Riolo anticline – Forlì line' (Fig. 1) structure, since the Late Tortonian (T$_2$ synthem), caused the progressive isolation of the Vena del Gesso thrust-top basin from the main foredeep leading to the formation of two distinct depositional areas (Roveri *et al.*, 2003). As a consequence, while the precipitation of primary evaporites was going on within uplifted shallow-water basins (Messinian evaporitic stage), only barren bituminous shales were deposited in deeper settings (Roveri & Manzi, 2005). In the Late Messinian (MP synthem, p-ev$_1$ subsynthem), following an important tectonic pulse that brought the Apennine to emersion, the Vena del Gesso basin primary shallow-water evaporites were eroded and resedimented in structural lows of the Romagna-Marche area (see main depocenters in Fig. 1). During this phase, the Messinian erosional surface developed in subaerially exposed areas. The p-ev$_2$ unit marks the transition to a phase of tectonic quiescence and more generalized subsidence leading to the development of a transgressive succession heralding the Zanclean flooding.

The Plio-Pleistocene tectonic phases essentially caused the deformation of the main tectonic features already developed during the Late Tortonian–Messinian phase. As a consequence, the main Messinian depocentres correspond to the present-day structural lows and synclines.

RESEDIMENTED EVAPORITES FACIES

The recognition of the existence of resedimented clastic evaporites within the Apennine Messinian deposits was pointed out 35 years ago (Bernardini, 1969; Parea & Ricci Lucchi, 1972; Ricci Lucchi, 1973). Founded on the deep-water evaporite depositional models of Schmalz (1969) and Sloss (1969), these deposits were interpreted as indicators of slope instability and deep-basin conditions in the Adriatic foredeep. This interpretation was based mainly on the presence of: (i) laminar or 'balatino' gypsum, i.e. a thin-laminated alternation of gypsum and bituminous shales originally thought to be a primary deposition during annual rhythms (Ogniben, 1957); (ii) clastic evaporites made up of chaotic deposits; and (iii) a less-common facies composed of gypsiferous sandstones, cropping out in the Laga Basin. A shallow-water mechanical origin for the 'balatino' gypsum was considered in contradiction with the great lateral continuity of the gypsum layers, the almost complete absence of terrigenous sand division and the mostly euxinic conditions that characterize the evaporitic stage. Moreover, due to the close association with deep-water clastic deposits and its confinement to the deepest parts of the Adriatic trough, the laminar 'balatino' gypsum was considered to be a deep-water primary evaporitic facies. This hypothesis was somewhat contradicted by the recognition of convex-up sedimentary structures interpretable as megaripples (Fanantello river, northern Marche; Schreiber, 1973). Subsequently, also in Sicily (Gibellina basin) the occurrence of graded and cross-laminated gypsum beds associated with slumps and mass flows was referred to as primary shallow deposits reworked into a deep-water environment (Schreiber *et al.*, 1976; Schreiber & El Tabakh, 2000). Although these studies were considered a good analogue for the interpretation of the evaporite-bearing turbidites of the Permian Zechstein (Schlager & Bolz, 1977), after the proposal of the desiccated deep basin model (Hsü *et al.*, 1972) many efforts were devoted to the recognition of shallow-water primary evaporites as they were considered fundamental proof of Mediterranean desiccation.

Recent studies (Roveri *et al.*, 1998, 2001, 2003; Manzi, 2001; Ricci Lucchi *et al.*, 2002) have stressed the importance of resedimented evaporites in the northern Apennines Messinian deposits. Based on the pioneer studies of Bernardini (1969), Parea & Ricci Lucchi (1972) and Ricci Lucchi (1973), the term 'resedimented evaporites', previously limited to the Laga gypsiferous sandstones, has been extended to most of the gypsum deposits of the northern Apennines. In particular, due to the recognition of very distinctive sedimentary structures (load casts, fluid-escape structures, bed gradation, cross lamination and traction-plus-fallout structures), the 'balatino' gypsum of the Apennines has been reinterpreted as sediments largely deposited from turbidity currents. Furthermore, as discussed later, the almost complete absence of terrigenous sand within these deposits is not indicative of primary origin as postulated in former papers. The term 'balatino' was used in the past to describe indistinctly, primary deep water, secondary (i.e. diagenetic) and clastic (resedimented) evaporites (Ogniben, 1957; Schmalz, 1969; Parea & Ricci Lucchi, 1972; Nesteroff, 1973; Rouchy, 1976; Kendall, 1992). The abandonment of its use is suggested in order to separate the rock description from its genetic significance.

Facies description

The main sedimentary facies recognized in the resedimented clastic evaporites of the northern Apennines are reported in Table 1 and Fig. 3. These facies are genetically organized following the theoretical downcurrent transformations of an ideal, gypsum clast, bearing gravity flow. This organization has been observed in the Apennines. A siliciclastic-approach is adopted here according to modern turbidite genetic models (Mutti, 1992; Mutti *et al.*, 1999). This model applies to deposits where gypsum is the main component, whereas other gypsum-bearing deposits containing lower amounts of gypsum can be more properly described with classic siliciclastic facies models. In Table 1 clastic evaporite facies are subdivided into four distinct groups based on the mean grain size.

Genesis and evolution of evaporite-bearing flows

As described in many deposits, clastic sulphates may show all ranges of sedimentary features, indicating that gypsum can be eroded, transported and re-deposited in the same fashion as other clastic sediments (Hardie & Eugster, 1971; Parea & Ricci Lucchi, 1972; Ricci Lucchi, 1973; Schreiber, 1973; Schreiber *et al.*, 1976; Schlager & Bolz, 1977; Kendall, 1992; Kendall & Harwood, 1996; Warren, 1999). What remains relatively obscure is the hydraulic behaviour of low-density mineral grains, such as gypsum, in a fluid that was probably denser than seawater. Possibly, the transporting fluid was already hypersaline or was progressively gaining salinity by partial dissolution of its load of sediments. The classic hydrodynamics of sediments is calculated on the basis of the densities of a quartz-water system, but gypsum is less dense than quartz and any

Table 1. Facies of resedimented evaporites.

Facies groups	Facies	Description	Processes
(a) Very-coarse-grained clastic gypsum Chaotic or crudely stratified deposits	R0 (submarine glides, slides and slumps)	Large gypsum blocks and shales. Depending on the prevailing lithology they may appear as imbricated (Fig. 4B and C) or slide blocks (Fig. 4A) rather than as gypsum blocks included within a chaotic shaly matrix.	Slide, glides
	R1 (gypsrudites)	Disorganized gypsum blocks supported by a shaly or shaly gypsarenitic matrix (Fig. 5A). Inverse gradations rarely appear at the top. This facies forms thick lenticular bodies (up to tens of meters), enclosing metric-sized clay chips.	Cohesive flows, the finer-grained division abruptly capping these deposits indicate sediment by-pass.
(b) Coarse-grained clastic gypsum Well stratified deposits graded beds with basal erosional surfaces	Facies R2 (pebbly gypsarenites)	Massive pebbly gypsarenites, micro-gypsrudites or coarse gypsarenites (Fig. 5B) with rip-up mudstone clasts forming medium (dm to m thick) beds.	Hyper-concentrated flows
	Facies R3 (coarse gypsarenites)	Massive or crudely laminated gypsarenites (Fig. 5B) with aligned clay chips and traction carpets forming medium graded beds (dm to m thick).	Gravel-rich high-density turbidity currents.
(c) Fine-grained clastic gypsum ('balatino' facies) Well stratified deposits graded beds with basal erosional surfaces	Facies R4 (plane laminated gypsarenites)	Medium to fine-grained plane laminated gypsarenites (Fig. 5C). Generally these deposits appear either as single thin tabular beds or as the basal portion of composite R5 beds. Load casts, flames and pillows are common.	Traction and traction-plus-fallout sedimentary structures indicate emplacement by flows with lower density than in R1, R2 and R3 facies.
	Facies R5 (megarippled gypsarenites)	Fine-medium megarippled (Fig. 5C) and cross-bedded gypsarenites overlying R4 deposits and generally abruptly capped by massive shales forming thin wavy beds with metric-spaced megaripples.	Residual deposits of by-passing high density turbiditic flows (Mutti, 1992). Palaeocurrents mainly parallel to the basin axis; flow reflection are also observed.
	Facies R6 (fine-grained gypsarenites, gypsiltites and shales)	Commonly indicated as 'balatino' gypsum, these deposits form composite dm to m thick graded beds made up of plane laminated, cross-laminated and convolute fine gypsarenites and gypsum siltites (Fig. 5D).	Base-missing Bouma sequences (Mutti *et al.*, 1999). Well-developed climbing ripple laminations indicate traction-plus-fallout within low-density turbiditic currents (Fig. 5D). Changes in palaeocurrent directions indicate rebounds and reflections on the flanks of structural depressions.
(d) Very fine-grained clastic gypsum ('balatino' facies) Stratified deposits massive or faintly laminated	Facies R7 (gypsiltites and limestone)	Gypsiferous silty laminae interbedded within bituminous shales and limestones. Different from the R6 facies, consist exclusively of the finer-grained divisions (Fig. 5E).	Very low-density organic- or carbonate-rich 'tails' of gypsum-saturated density flows deposited on intrabasinal highs. The presence of diatomaceous-like marly horizons and varved shales in association with R7 deposits may indicate hemipelagic sedimentation.

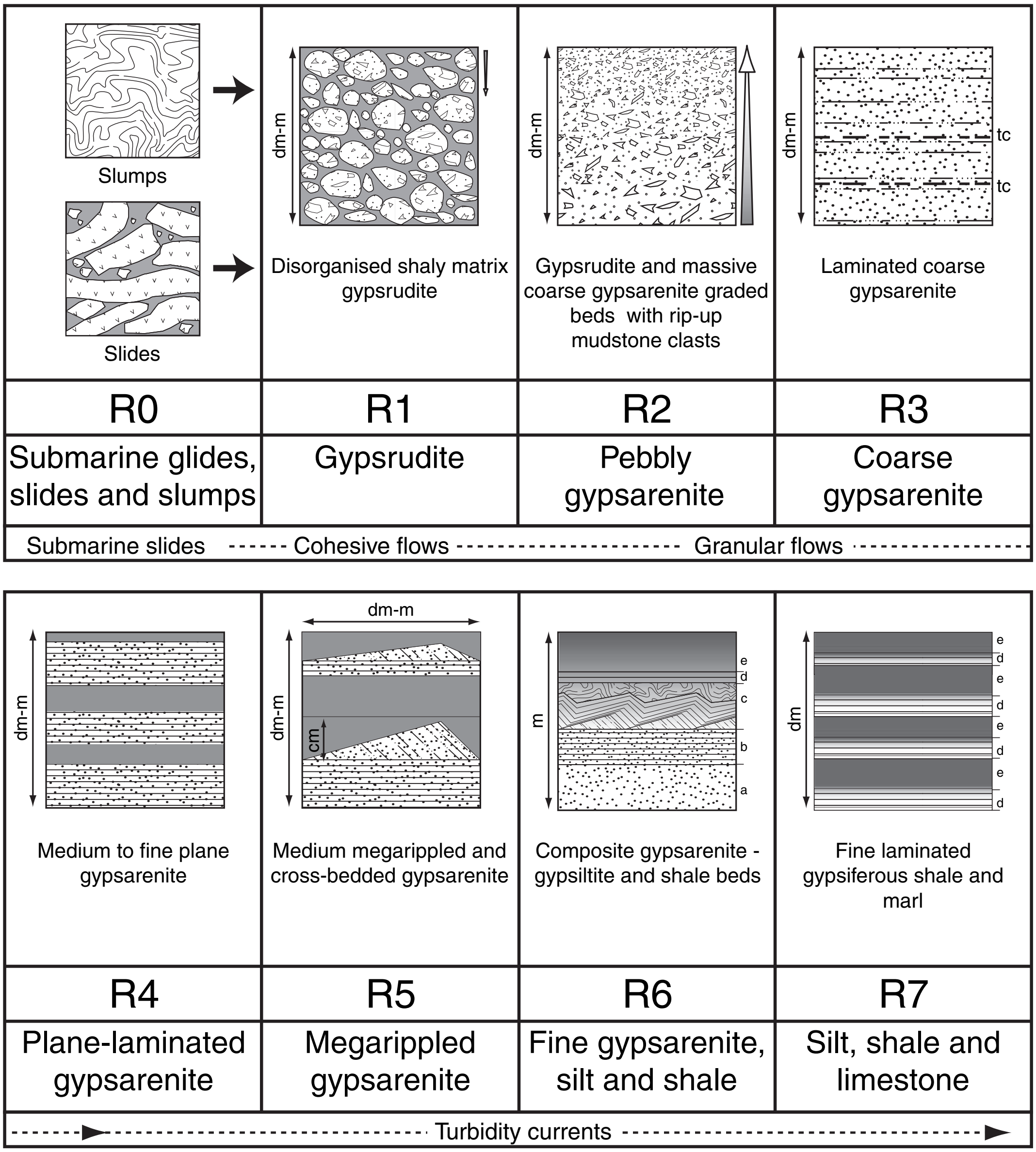


Fig. 3. Scheme of the main facies recognized in the gypsumclastites of the northern Apennines. They are genetically organized following a theoretical downcurrent evolution of a hypothetical gypsumclastites-bearing flow.

gypsum-saturated solution is denser than pure water. Would it then be appropriate to compare the sedimentary features produced in siliciclastic and clastic gypsum? Should a different significance be expected when the same sedimentary features are looked at in clastic gypsum or in 'normal' siliciclastic sediments? If this approximation is justified for halite which can form ripples and megaripples (Karcz & Zak, 1987), then it must be correct also for gypsum that is more dense than halite, provided that some adjustments are adopted.

So, the use of a siliciclastic depositional model to describe clastic evaporites requires some considerations concerning the different properties of clasts and flows involved in the resedimentation process:

1. The behaviour of a flow strictly depends on the ratio between inertial and viscous strength and can be defined using the Reynolds number:

$$\mathrm{Re} = \mathrm{F_R}/\tau \quad \text{where} \quad \mathrm{F_R} = C\cdot(\rho\cdot u^2\cdot d^2) \quad or$$
$$\mathrm{F_R} = 3\cdot\pi\cdot u\cdot d\cdot\mu \quad \text{and} \quad \tau = \mu\cdot \mathrm{d}u/\mathrm{d}y$$

The inertial strength $\mathrm{F_R}$ that promotes turbulent flow conditions depends on three main factors: fluid density (ρ), flow speed (u) and solid parti-

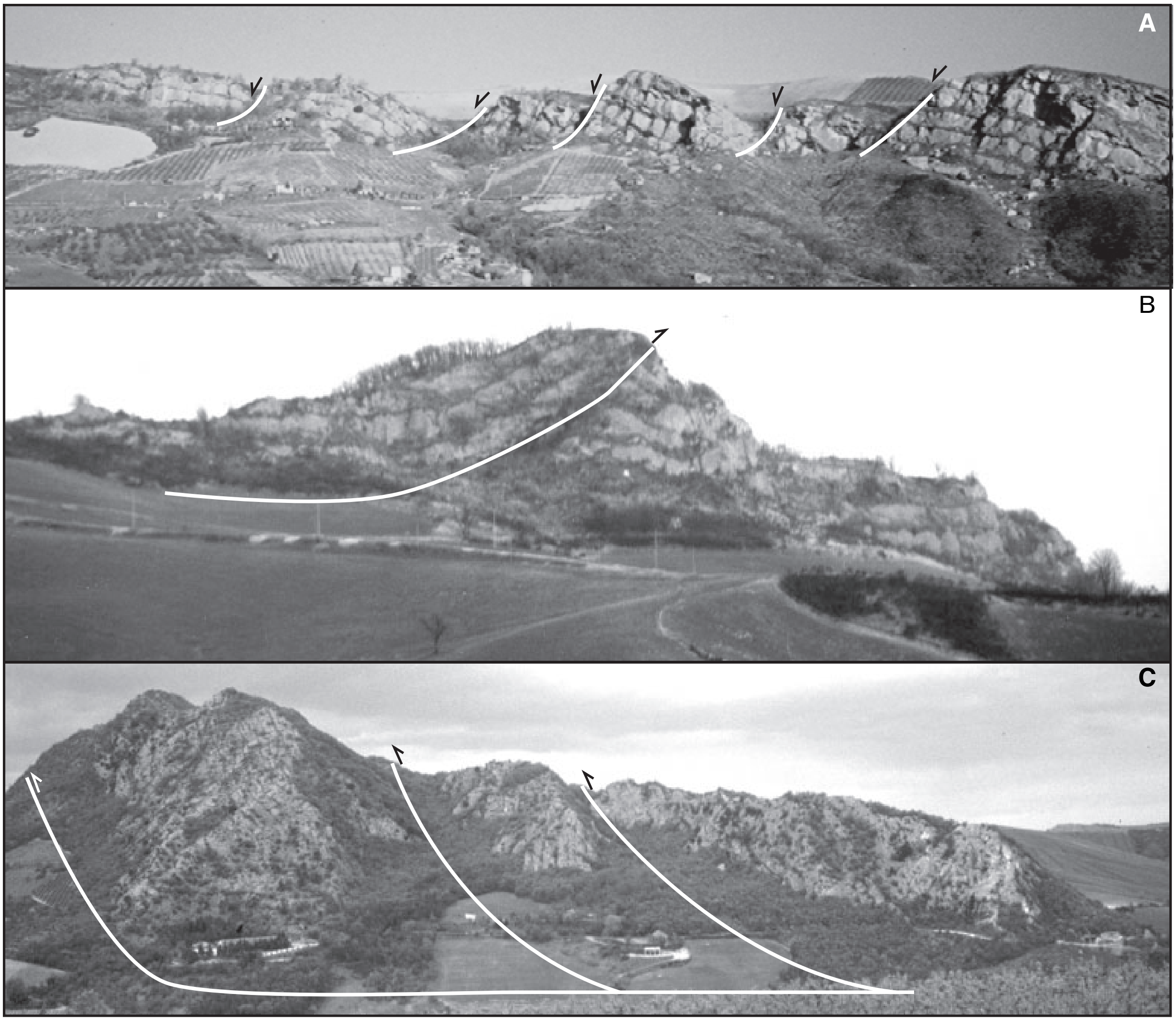


Fig. 4. *Facies R0* (*residual deposits*) – The Monte Penzola thrust and the Santerno rotated blocks belonging to a large-scale glide complex, affecting the entire Vena del Gesso Basin during the post-evaporitic stage, representing the residual deposits of the evaporite resedimentation. Santerno Valley, Vena del Gesso Basin, western Romagna.

cles diameter (d). With respect to a theoretic siliciclastic gravity flow, the following considerations must be borne in mind for a gypsum-bearing flow.

- *Fluid density* – Due to the presence of brine sinking or flowing from the shallow water evaporitic environments to topographic lows, the water column during the evaporitic and early post-evaporitic stage could have been characterized by higher density (ρ) than normal marine water both near the surface and the bottom. An increased salinity could also have played an important role in the preservation of the gypsum-bearing flow deposits.
- *Grain population* – As with many primary evaporites in Messinian Mediterranean marginal basins, the Vena del Gesso evaporites consist of a lower part (major cycles) made up of very coarse (cm- to dm-sized) selenite crystals, minor carbonates interbedded by thin organic-rich layers, and an upper finer-grained part mainly consisting of mm- to cm-sized prismatic and selenitic gypsum crystals reworked within a micritic carbonate or shaly matrix. As a consequence, the final product obtained by the erosion, transport and resedimentation of such evaporitic rocks may be lacking in some grain populations (namely fine sand and silt), implying that the mean size of the solid particles (d) is larger in the case of resedimented evaporites. This will produce a higher inertial strength that could maintain the flow turbulence with lower flow velocity, thus

promoting the formation of lower regime structures, even with larger clasts.

• *Shape* – The Reynolds number is calculated using a theoretic spherical grain of quartz. With respect to quartz clasts, the shape of the gypsum detritus can be more or less elongated, depending on the original evaporitic sediment. This is because the clasts originate mainly from primary gypsum ranging from small prismatic (several mm to cm in size) to large selenite crystals (up to 2 m in size).

2. The geometry of the sedimentary structures forming in the flow bottom is regulated by the Froude number:

$$\mathrm{Fr} = u/(g \cdot d)^{0{\cdot}5} \quad \text{where} \quad g = \text{gravitational constant}$$

The higher inertial strength produced by the increase of both fluid density and mean grain size may also increase the Froude number. This would imply that larger and lighter clasts floating in a denser flow might form sedimentary structures even with lower inertial strength or larger bedforms.

Diagenetic effects: tools and calibration

Evaporite rocks are strongly affected by burial (under lithostatic load) and exhumation processes. The associated changes of thermal regime can cause diagenetic transformations of sulphate evaporites. The Gessoso-solfifera Formation consists of a great variety of evaporite facies that were deposited in different depositional environments, from shallow- to deep-water according to the structural setting. For this reason, whereas the original texture of primary evaporites deposited above structural highs is quite well preserved, resedimented evaporites largely underwent the gypsum–anhydrite–gypsum diagenetic cycle during Late Messinian–Early Pliocene burial and subsequent exhumation. The secondary gypsum (diagenetic) resulting from these transformations is commonly microcrystalline and the original rock texture is almost completely obliterated.

Petrographic characterization of the resedimented evaporites

Grain-size, texture, sedimentary structures, stratal patterns and geometries are basic tools to reconstruct the depositional processes that lead to formation of sedimentary rocks. In order to overcome the problems caused by diagenetic effects, that can permanently obliterate either the grain size or the rock texture, it is suggested that when the grain size of resedimented evaporites cannot be directly observed, e.g. when crystal pseudomorphs or terrigenous clasts are not visible, these sedimentary properties must be inferred, when possible, from the preserved sedimentary structures, adopting a siliciclastic perspective.

Anhydrite rocks

Anhydrite has been observed as rare nodules or scattered patches within gypsum rocks (Fig. 6A and B). The nodules are up to a few dm in size, light grey in colour and may show a scanty lamination, which can be followed into the adjacent gypsum. The anhydrite in the nodules ranges from felted to microcrystalline.

Anhydrite patches within the gypsum rocks are a few mm in size and consist of concentrations of corroded crystals surrounded by zones of cloudy amoeboid gypsum. The crystals range from microcrystalline to prismatic aligned, and may reach 1·5 mm in size. Elongation of the largest anhydrite crystals is generally parallel or forms a small angle with bedding. In rare cases, the anhydrite patches show contorted lamination.

Gypsum rocks (C)

The gypsum rocks consist mostly of massive white microcrystalline secondary gypsum (Fig. 6A). This petrofacies is made of xenotopic, cloudy-amoeboid gypsum crystals. Corroded anhydrite relics are rare and concentrated mostly within rosettes of gypsum crystals consisting of cloudy radial aggregates up to a few mm in size. The massive gypsum rocks also contain larger idiotopic gypsum crystals showing competitive boundaries and including patches of the host cloudy-amoeboid gypsum, suggesting a late growth stage at its expense (Lugli & Testa, 1993).

The less pure gypsum rocks also display cloudy-amoeboid gypsum but contain mud laminations. The mud laminae drape and isolate polygonal domains with angular shapes consisting of aggregates made up of cloudy-amoeboid gypsum crystals (Fig. 6C). These polygonal shapes can be clearly seen only in plane polarized light and form layers showing normal gradation.

In areas where the mud layers are thicker, less common aggregates of cloudy-amoeboid gypsum may display prismatic and hexagonal shapes (Fig. 6E and F). These regular shapes are up to a few mm in size and are not draped by mud. These shapes are irregularly scattered and show no gradation, suggesting that they grew displacively into the mud.

Interpretation of petrographic features

The characteristics of the anhydrite nodules and the petrography of the gypsum rocks reveal that most of the gypsum formed by hydration of precursor anhydrite. The reconstruction of original sedimentary features is complicated by various factors: (i) the anhydrite–gypsum transition, which partially obliterated the original grain size of the gypsum, (ii) the presence of satin-spar veins, which in part altered the spatial relationships among the original components, and (iii) the lack of stratification in the pure, massive secondary gypsum rocks.

Despite these difficulties a series of useful observations that allows the reconstruction of the original nature and grain size of the sediments can be made for the mud-laminated rocks. The mud drapes outline aggregates of microcrystalline secondary gypsum after anhydrite that have polygonal and angular shapes and are graded too. These characteristics clearly indicate that the aggregates represent former angular clasts. Only the hexagonal shapes cannot be interpreted as clasts but apparently formed as post-depositional displacive crystals. Although previously consisting of anhydrite, these crystals were not originally anhydrite because their shape clearly points to even earlier gypsum crystalline features. The hexagonal crystals were originally gypsum that was dehydrated to form microcrystalline anhydrite, which was then rehydrated back to cloudy-amoeboid gypsum.

If this explanation is correct then it applies also to the clastic polygonal shapes that were made up of anhydrite at one stage of their evolution, but formed at the expenses of gypsum. This interpretation is also supported by the polygonal and angular shape of the clasts, because microcrystalline and felted anhydrite rocks normally form rounded clasts. On the contrary, resedimentation of monocrystalline gypsum (selenite) is known to form angular clasts (Fig. 8 of Lugli & Testa, 1993). Two different processes may explain the dehydration of subaqueous detrital gypsum to anhydrite: (i) burial diagenesis; (ii) increased salinity of the interstitial brines (decrease of activity of water, a_{H_2O}). Geothermal temperature rise by increasing depth of burial accounts for the dehydration of gypsum to form anhydrite at depths >600 m (Murray, 1964). As inferred from the geology of the area under study, most of the evaporite deposits of the Adriatic foredeep were buried by 500–1000 m of sediments.

A decrease in the activity of water (a_{H_2O}) of the interstitial solutions also can shift the mineral stability towards the anhydrite field at low temperatures (Hardie, 1967). In this case, the increase of fluid salinity by dissolution of halite could induce the replacement of gypsum by anhydrite under syndepositional or early diagenetic conditions (Shearman, 1985). However, there is no evidence of halite-saturation conditions in the interstitial fluids. The interstitial fluids were gypsum-saturated as demonstrated by the growth of displacive gypsum crystals in the mud, but no halite pseudomorphs were observed. Moreover, no evidence of significant halite deposits in the northern Apennines evaporite deposits is available. It follows that the most probable cause responsible for the dehydration of clastic gypsum is burial diagenesis. The dehydration of the original clastic gypsum sediments released a large volume of water that was possibly responsible for the formation of fluid escape structures that cut and deformed the newly formed anhydrite (Fig. 6D).

In summary, a complete gypsum–anhydrite–gypsum cycle can be envisioned for the clastic evaporite deposits of the Adriatic foredeep: the secondary gypsum rocks formed by hydration of diagenetic anhydrite rocks derived from the burial-induced dehydration of clastic gypsum.

Stable isotopes

Methodology

For strontium isotopic analyses, 100 mg of ground sample and 1 g of Na_2CO_3 were treated with 40 ml H_2O for 6 h at 70°C to obtain pure $CaCO_3$ which was subsequently dissolved with 2·7 N HCl. After evaporation to dryness, the resulting $CaCl_2$ was dissolved in HCl and the solution passed through a cation exchange resin to separate strontium. The strontium was then eluted and analysed for $^{87}Sr/^{86}Sr$ using a VG Isomass 54E mass spectrometer.

Some secondary gypsum samples collected in the Sapigno olistostrome (facies R0 and R1) have values of $^{87}Sr/^{86}Sr$ ranging from 0·708887 to 0·708950 (Bassetti *et al.*, 2004). These values fall within the range of both the Lower Evaporites in the Mediterranean (0·708838–0·709034, Müller & Mueller, 1991; and 0·70892–0·70900, Keogh & Butler, 1999) and in the Vena del Gesso Basin (0·708904–0·708928 Aharon *et al.*, 1993, values from the third bed; and 0·708890–0·709024 results of the whole Vena del Gesso section (Bassetti *et al.*, 2004). These data are compatible with a source area for the evaporite resedimentation located in the Vena del Gesso Basin or in equivalent topset, shallow-water sites, now dismembered.

Facies associations

All the clastic gypsum facies discussed in the previous paragraphs have been grouped in three main interpretative facies associations ranging from the coarser-grained to the finer-grained:

1. *Chaotic deposits*, representing the 'proximal' poorly evolved gypsum-shale flow deposit, mainly consist of chaotic complexes including primary evaporite slabs, boulders and blocks (facies R0), debrisflow and hyper-concentrated flow deposits (facies R1, R2 and R3).

2. *Lobe deposits* representing the product of high to low-density gravity flows, are made up of medium to fine-grained gypsarenites, silt and shales (facies R4, R5 and R6) forming tabular or lenticular bodies interbedded with thin-bedded fine-grained gypsarenites; these deposits are commonly called 'balatino gypsum' in this region.

3. *Drape deposits* representing the ultimate products of flow evolution, consist of thin parallel gypsum laminae interbedded with bituminous shales (facies R7). Due to the lack of obvious transport evidence, as cross-laminations or convolutions, these deposits were traditionally considered primary deep-water evaporites ('balatino' gypsum, Ogniben, 1957; Bernardini, 1969; Parea & Ricci Lucchi, 1972). A less common variation of these facies is represented by massive composite layers consisting of a lower marly interval with displacive lenticular gypsum (Fig. 5E) overlain by massive limestone. The close association of R7 facies with clastic deposits (R5 and R6) indicates that they also belong to the resedimented evaporites class, representing the products of more dilute flows draping intrabasinal topographic highs.

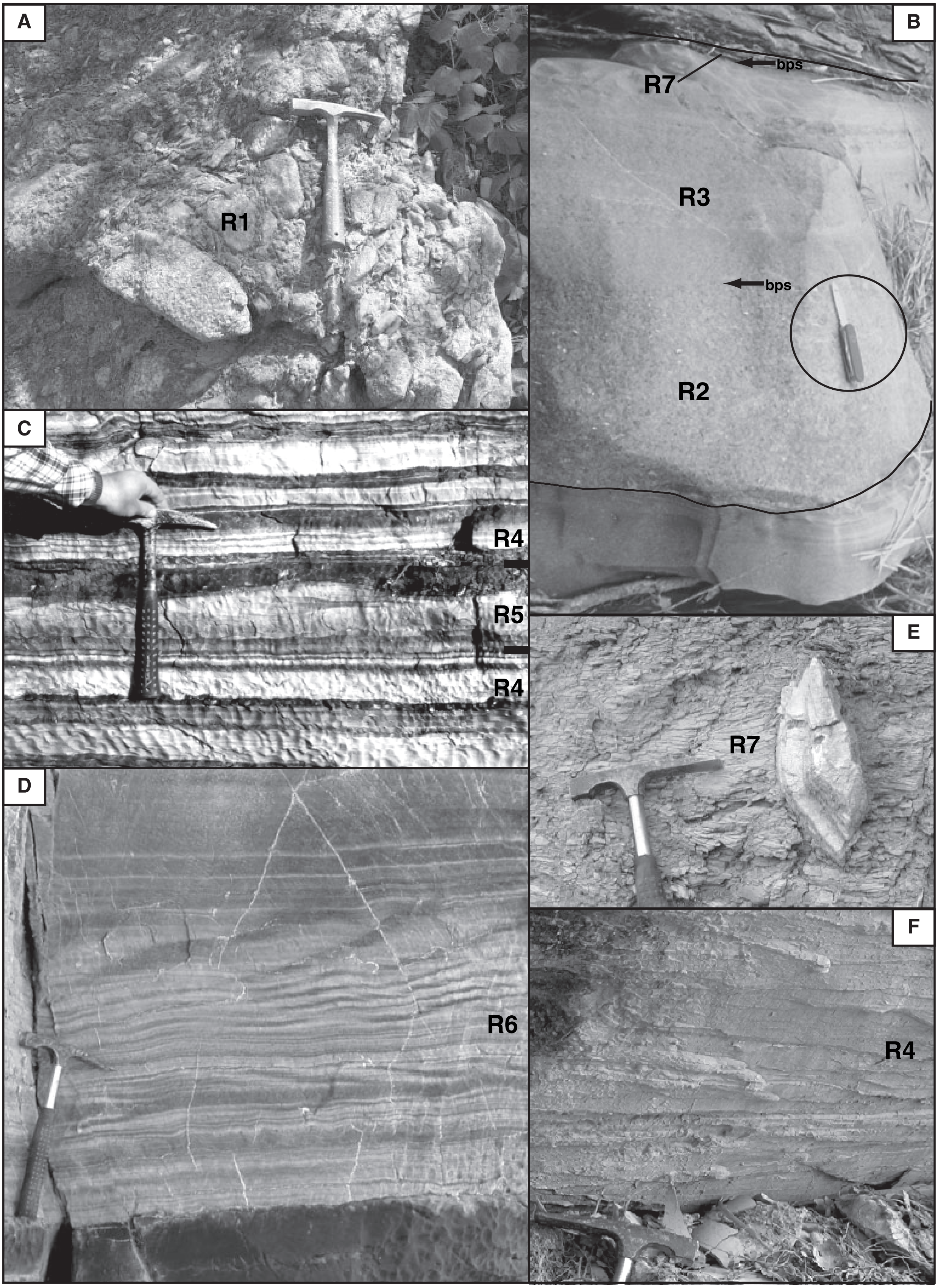
Depositional settings of the resedimented evaporite

Due to the present-day structural setting of the northern Apennines, genetic relationships between the previously described facies of resedimented evaporites have been inferred from the correlation of single vertical sequences rather than from the observations of individual lateral bed transitions. However, a general organization can be clearly outlined (Figs 7 and 8). Moving south-east from the Vena del Gesso basin towards the eastern Romagna and Marche regions, a complete facies transition can be recognized from chaotic deposits, to lobe, and to drape deposits.

Based on their position with respect to the general structural framework, three main depositional areas can be distinguished in the northern Apennine Messinian foredeep: (i) the inner basin; (ii) the central basin, and (iii) the uplifted and starved intrabasinal areas.

The *inner basin* is the part of the basin closest to the active thrust fronts; in this specific case it coincides with the main sediment source areas, i.e. the thrust-top basins, from which it received a large amount of reworked detritus of primary evaporites. Deposits here mainly consist of chaotic masses that, due to the short travel distance from the source area, are not able to evolve into low-density flows. The chaotic deposits generally form thick, wedge-shaped bodies confined close to the structural highs or enclosed in erosional depressions (Roveri *et al.*, 2003); the external

Fig. 5. (A) *Facies R1* (*gypsrudites*) – disorganized gypsum blocks (made both by crystal fragments and by gypsarenite blocks) supported by a shaly matrix. Idice riverbed, Bologna evaporites, eastern Emilia. (B) *Facies R2* (*pebbly gypsarenites*), *R3* (*coarse gypsarenites*) and *R7* (*gypsiltite*) – composite graded bed with erosional base made up of three divisions of massive gypsrudites, laminated gypsarenite and gypsiltite separated by by-pass surfaces (bps). Encircled hand pocket knife for scale. Idice riverbed, Bologna evaporites, eastern Emilia. (C) *Facies R4* (*plane laminated gypsarenites*) and *R5* (*megarippled gypsarenites*) – alternation of plane laminated (facies R4) and cross bedded (R5) thin bedded fine-grained gypsarenites and pelite. Note the megaripple (facies R5) abruptly capped by dark euxinic shales. These deposits were often termed as 'balatino' gypsum. Fanantello riverbed, Sapigno syncline, northern Marche. (D) *Facies R6* (*fine-grained gypsarenites, gypsumsiltites and shales*) – coarser-grained lower portion of a 4 m thick composite graded bed (megabed I, Fig. 13) made up of plane laminated, cross-laminated and convolute fine gypsarenites and gypsum siltites. Fanantello riverbed, Sapigno syncline, northern Marche. (E) *Facies R7* (*gypsum siltites and limestone*) – large lenticular gypsum crystals that grew within grey massive or lightly laminated marls. The crystal was transformed into anhydrite and rehydrated back into microcrystalline gypsum. The growth of gypsum crystals into the mud indicates that the tails of low density gravity flows were sulphate-saturated. Palazzo section, Giaggiolo-Cella syncline northern flank, eastern Romagna. (F) Flute casts at the base of a gypsarenitic bed indicating palaeocurrent towards north. Montorio al Vomano, Laga Basin.


A
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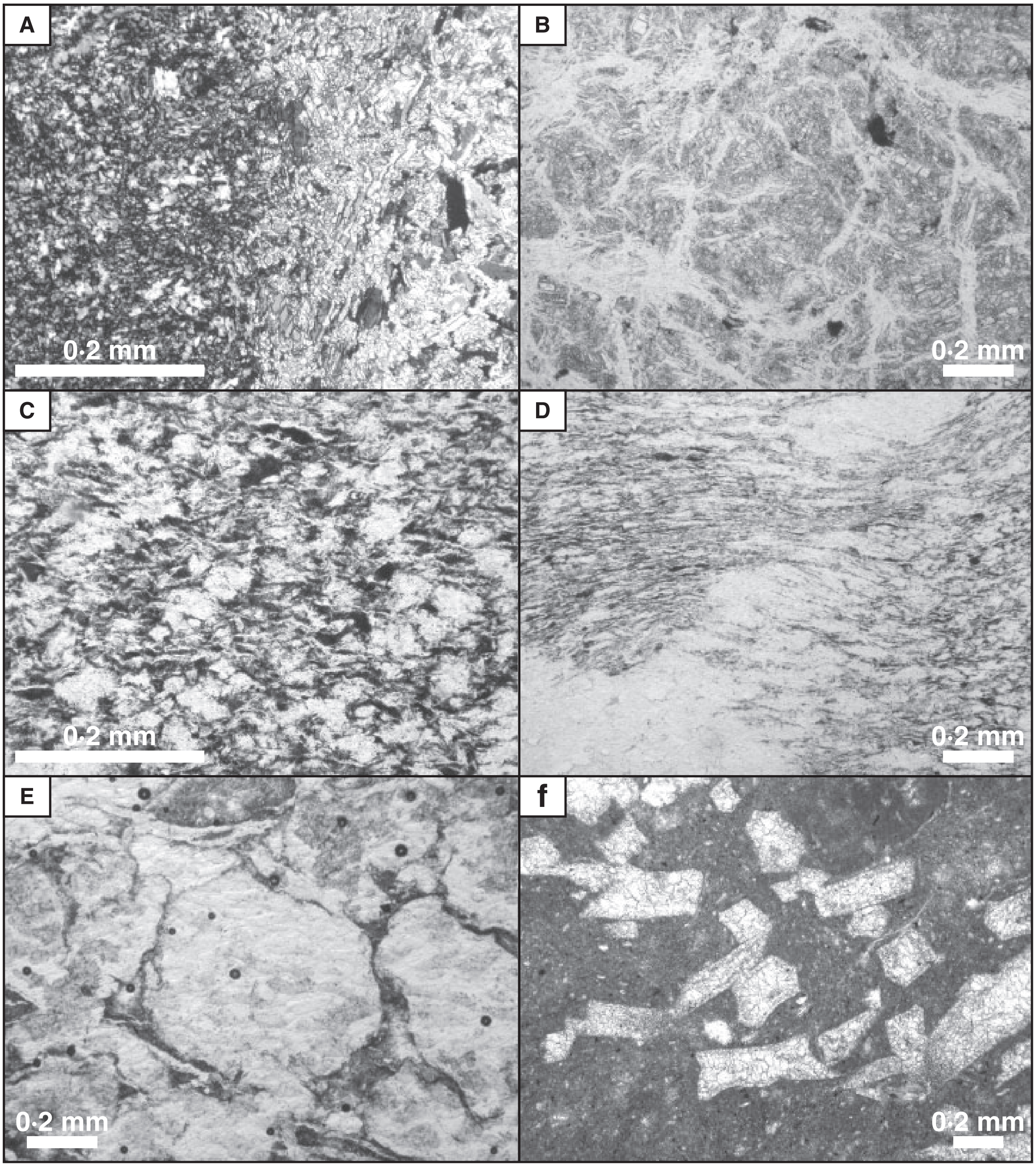

Fig. 6. Photomicrographs of northern Apennines evaporites. (A) Sharp hydration front between an anhydrite nodule consisting of felted crystals (right) and a cloudy amoeboid gypsum rock (left). Crossed polars. (B) Anhydrite patches into a cloudy amoeboid gypsum rock. The anhydrite crystals (grey) are corroded and are surrounded by gypsum veins (white), suggesting they represent remnants of a massive rock which almost completely hydrated to form gypsum. Sapigno. Plane-polarized light. (C) Polygonal domains with angular shapes (white) consisting of aggregates of cloudy amoeboid gypsum crystals outlined and draped by mud laminae (black). These polygonal shapes represent former clasts of gypsum (selenite fragments) which were dehydrated into felted anhydrite and then rehydrated back to form cloudy amoeboid gypsum. Sapigno *Facies R6*. Plane-polarized light. (D) Irregular vein filled with cloudy amoeboid gypsum (white) cutting through the same rock illustrated in 'A'. Note that the polygonal domains of cloudy amoeboid gypsum outlined by the mud show soft deformation in the area adjacent to the vein. The vein represents a possible fluid escape structure originally filled by anhydrite. Sapigno, *Facies R6*. Plane-polarized light. (E) Hexagonal shapes (white) irregularly scattered into a mud rock. The shapes consist of aggregates of cloudy amoeboid gypsum (white) after anhydrite. Sapigno, *Facies R6*. Plane-polarized light. (F) Hexagonal and prismatic shapes that grew displacively into a mud rock. The shapes consist of cloudy amoeboid gypsum (white) after anhydrite. Sapigno, *Facies R6*. Plane-polarized light.

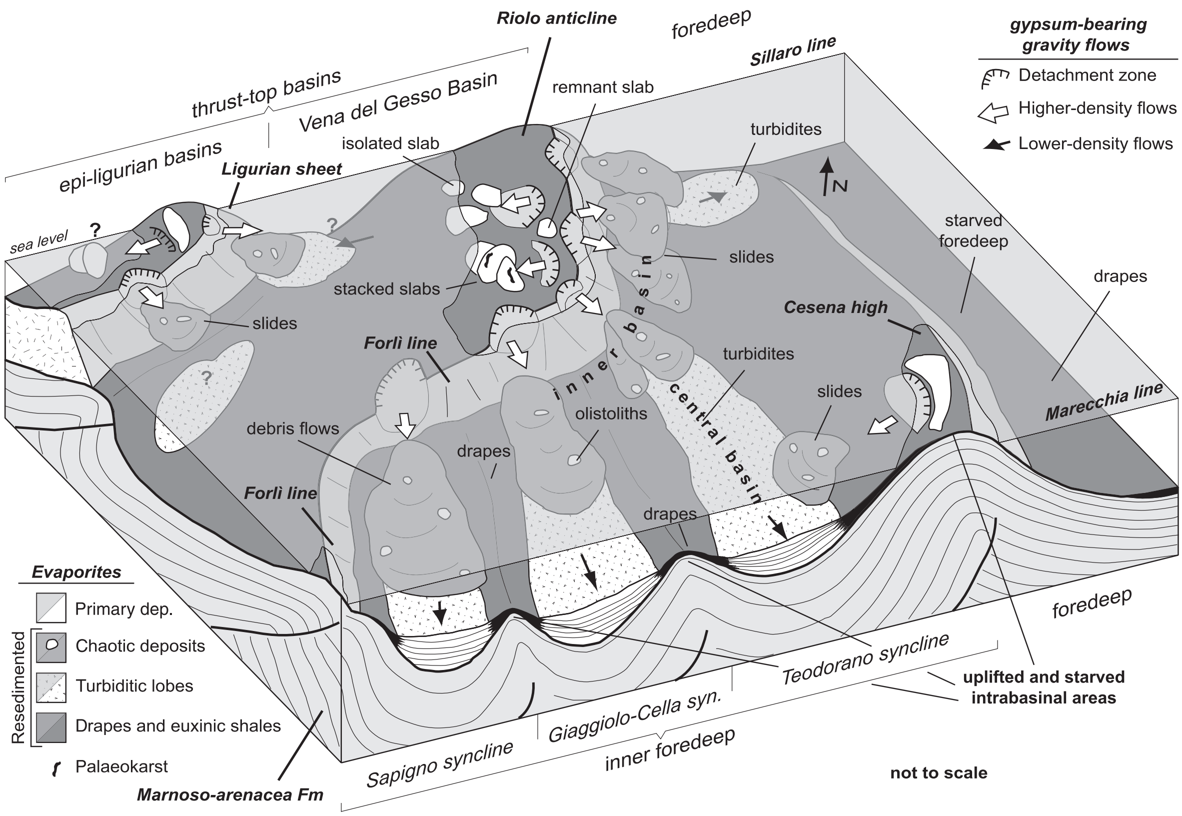

Fig. 7. Three-dimensional reconstruction of the Romagna sector of the Adriatic foredeep during the Messinian. Clastic evaporites, mainly discharged by structural culminations, were accumulated in structurally controlled topographic lows, finer-grained deposits occurred on intrabasinal highs and in the undeformed foredeep, tectonically isolated from the gypsum-bearing flows.

flank of the Vena del Gesso Basin-edge structure (the Riolo anticline – Forlì Line system; see Fig. 1) is bordered by a great volume of deposits including slides, slump and debrisflows both to the east (outcropping) and to the north (now buried). This distribution of chaotic bodies close to the main structural high is also a common feature in the buried sector of the Emilia Apennine (Rossi *et al.*, 2002). The most representative examples are observed in the Sapigno, Giaggiolo-Cella syncline and Peglio-Pietrarubbia synclines.

The chaotic unit of the Sapigno syncline (p-ev$_{1b}$; Figs 1 and 9) is made up of gypsiferous debris-flow deposits (df) in the lower portion, and of fine-grained deformed deposit with floating blocks and boulders of alabastrine (microcrystalline secondary gypsum either massive or with selenite pseudomorphs) and stratified gypsum in the upper portion (ol). Even slabs of the proximal equivalent of the gypsarenitic lobes are enclosed in this chaotic unit (Fig. 10). Other representative examples of inner basin resedimented evaporites have been recognized in the Giaggiolo-Cella syncline (Figs 11 and 12).

The *central basin* is the deeper and larger portion of the foredeep system. With respect to the older Marnoso-arenacea, central basins are much narrower and less connected features due to the strong articulation of the Messinian foredeep related to the ensuing deformation. The relatively greater distance from the source areas, with respect to the inner basin, permitted the full downcurrent evolution of flows from high to low-density turbidity currents. Lobe deposits are the main depositional products, widely distributed within the main structural lows of the Romagna-Marche Apennines. The best representative outcrops are located in the Sapigno, Giaggiolo-Cella and Peglio-Pietrarubbia synclines as well as in the Marchean basins (Fig. 1).

These deposits crop out spectacularly in the Fanantello riverbed (Sapigno syncline, Fig. 9) where three gypsum turbidites units (units l1, l2 and l3 of Fig. 9) have been recognized in the lowermost part of the p-ev$_1$ unit ('Strato Maestro' *sensu* Ruggieri, 1958). Unit l1 consists of thin-bedded alternation of gypsiferous and shaly

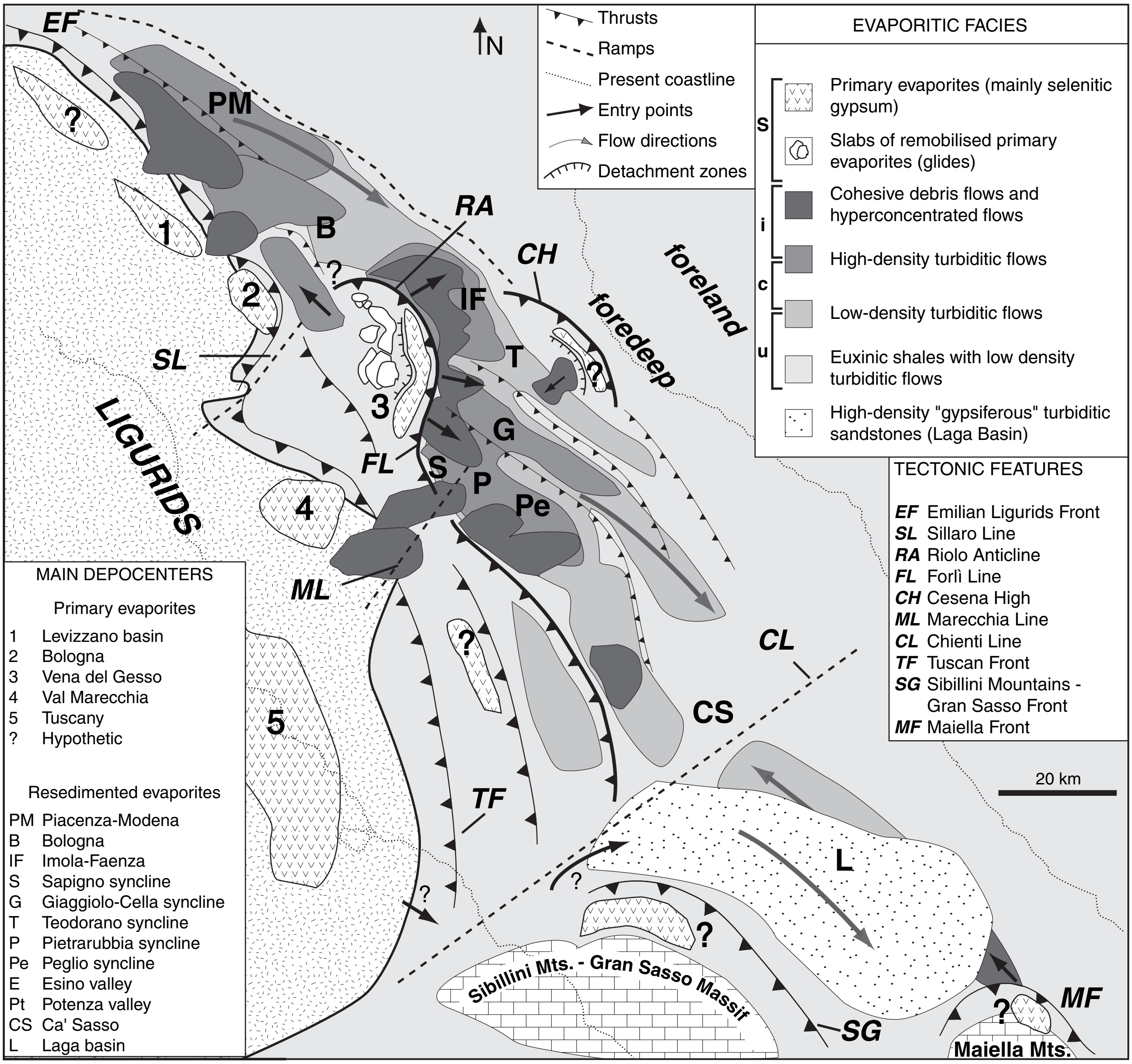

Fig. 8. Schematic distribution of the main clastic evaporite facies in the northern Apennines. Coarser-grained deposits accumulated close to the main structural highs, whereas finer-grained deposits were widely distributed. The depositional settings of the main facies are also indicated: i, inner basin; c, central basin; u, uplifted and starved intrabasinal areas. S: source areas.

layers, forming a 30 m thick tabular body shown in Fig. 13.

Also the Laga Basin deposits accumulated in a central basin setting (Figs 8 and 15), probably larger and less affected by synsedimentary deformations than the Romagna and Northern Marche basins. These deposits (Figs 5F and 14), show a greater siliciclastic content than the others previously described. Petrographic analyses (Dronkert, 1985) indicate an average gypsum content of about 23% for the Venarotta section instead of the 78% measured in the Ca' Sasso section. As a consequence, these coarse-grained massive or faintly laminated sandstones must be classified as siliciclastic gravity flow deposits rather than gypsum turbidites as previously defined by Parea & Ricci Lucchi (1972). The gypsum now occurring only as cement may represent the diagenetic effect of fluid migration within the sandstone. Originally it could have been incorporated by siliciclastic gravity flows eroding previously clastic gypsum clastites (Fig. 8).

The uplifted and starved intrabasinal areas, located both on top of structural intrabasinal highs within the central basin or in the more external part of the main basin (uplifted or

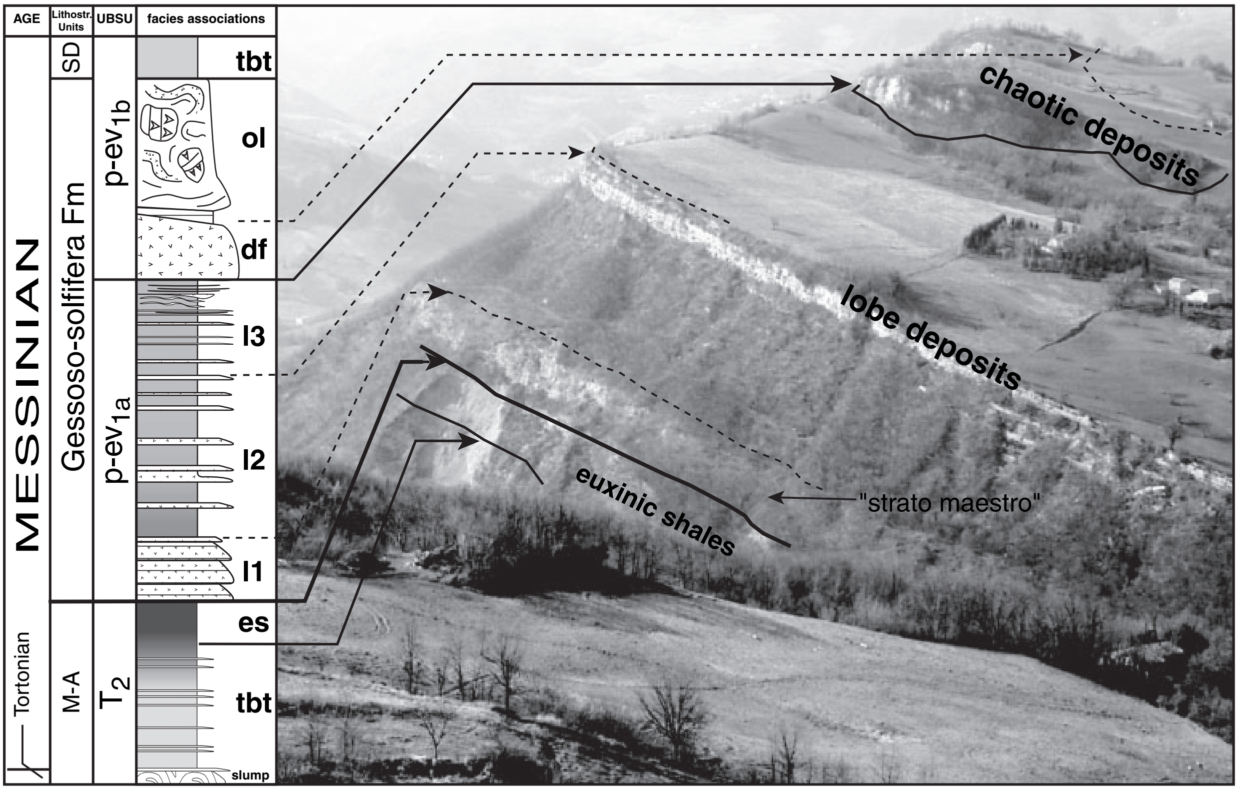

Fig. 9. Panoramic view of the Inner and Central basin resedimented evaporites in the Sapigno syncline (Fanantello Valley, Northern Marche). Note the bi-partition of the clastic evaporite unit. The lower part p-ev$_{1a}$ (see Fig. 13) is made up of lobe deposits (units l1, l2, l3 made of *facies R4*, *R5* and *R6*) separated by thick intervals of dark bituminous clays (up to 10 m). The upper part p-ev$_{1b}$ consists of debrisflow (df) and olistostromes (ol). M-A: Marnoso-arenacea Fm; SD: S. Donato Formation tbt: siliciclastic thin-bedded turbidites; es: barren euxinic shales and limestones.

foreland areas) are characterized by a very low sediment input. These areas are reached only by the finer-grained and more dilute portion of the low-density turbiditic flows plus hemipelagic sediments. The best representative outcrops are located in the Giaggiolo-Cella (Fig. 5E), Teodorano and Peglio-Pietrarubbia synclines and in the Marchean basins (Figs 1 and 14).

Taking an overall view of the sediments that were deposited within the northern Apennines, evaporites belonging to central basin deposits (coarse and medium sandstone) seem to be less commonly distributed with respect to the inner basin and to the finer-grained ones. Partially, this can be regarded as a genetic remnant of the primary evaporites from which they originated. The Vena del Gesso type primary evaporites are themselves characterized by a bi-modal population mainly made up of cm- to dm-sized selenitic crystals and black euxinic shales. Similarly the resedimentation of such marginal deposits should have preferentially produced bi-modal clastic evaporites.

Alternatively, the scarcity of arenitic components may be related to the structural setting of the Messinian foredeep. Since the Late Tortonian the structural depression that became filled by the resedimented evaporites started to form and progressively the depocentres of primary evaporites (the thrust-top basins) became isolated from the foredeep. Resedimentation of these evaporites occurred in tectonically active basins that have been only partially exposed during the subsequent exhumation of portions of the Apennine chain. A significant portion of the clastic evaporites is still buried in the core of the synclines and these probably are made up of lobe deposits, i.e. the arenitic sediments that were re-deposited by high to low-density gravity flows (Fig. 7). This fact implies a further effort in the reconstruction of the mechanisms and processes that resulted in evaporite resedimentation. Within the northern Apennines, the resedimented evaporite unit is also characterized by an overall vertical arrangement of the deposits with an overall coarsening-upward stacking pattern, i.e. the chaotic deposits

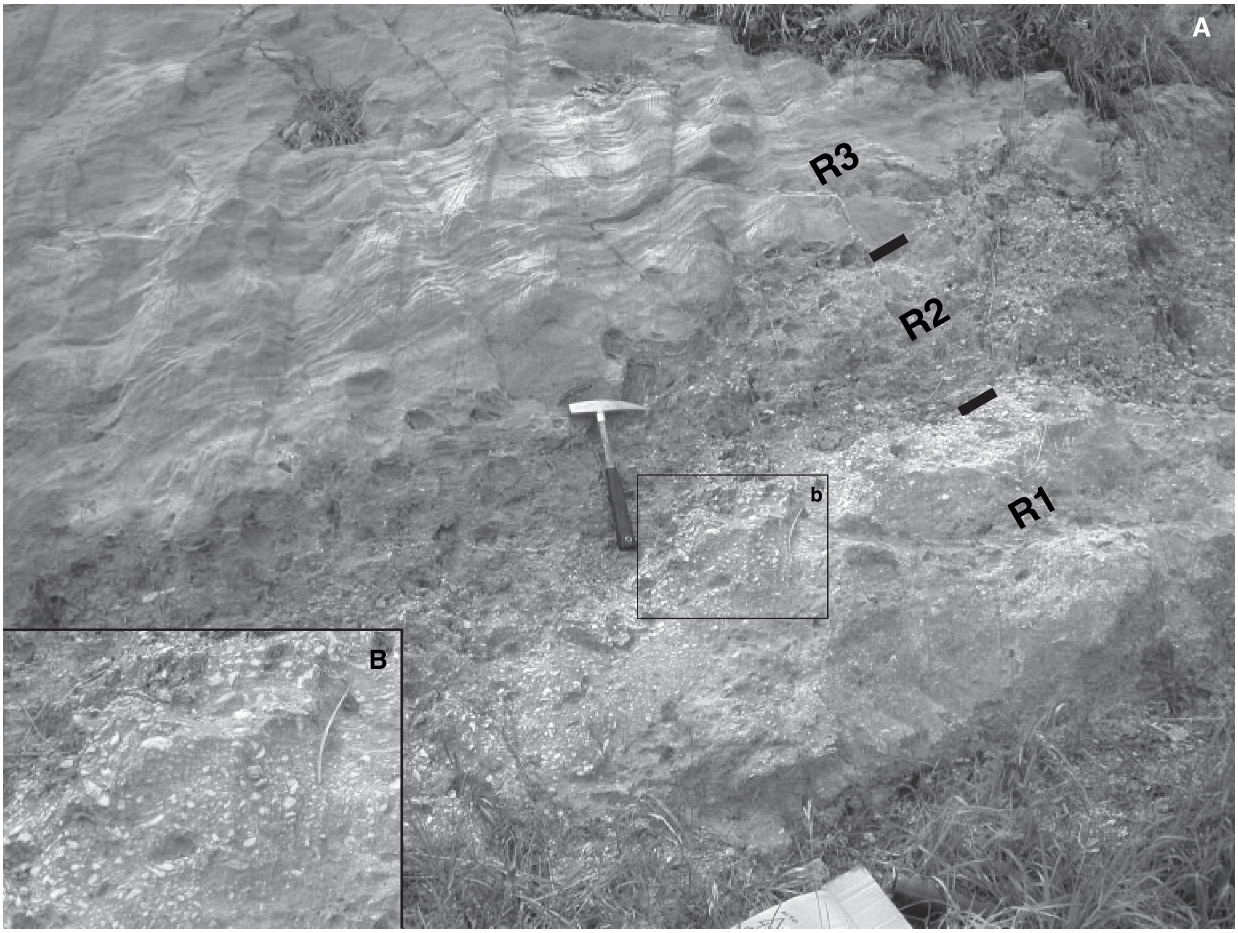

Fig. 10. Inner basin evaporites. (A) Composite graded bed showing a coarser-grained basal portion (*R1 facies*) consisting of an organic-rich shaly matrix-supported gypsrudite made up of either fragments or preserved twinned selenitic and prismatic gypsum crystals (see enlargement in B). A sharp surface separates this 'parent flow' deposit from an overlying clay-chip rich massive coarse gypsarenite (*R2 facies*). In turn this interval is abruptly capped by a thick plane-bedded to low angle cross-bedded gypsarenite interval (*R3 facies*). This composite bed represents the proximal stage of a single event of evaporite resedimentation; its distal evolution can be considered to be a low-density turbiditic gypsum-bearing flow. Slab enclosed in the upper chaotic member of the resedimented evaporites. Sapigno syncline, northern Marche.

of the inner basin overlie the finer-grained deposits of central basin; these in turn overlie the uplifted and starved intrabasinal areas deposits. This vertical superposition can be regarded as the result of the outward (towards the north-east) migration of the tectonic deformation.

TIME AND GENETIC RELATIONSHIPS BETWEEN PRIMARY AND RESEDIMENTED EVAPORITES

The distribution of clastic deposits within compressional basins strictly depends on two main factors: the sedimentary input and the tectonically enhanced accommodation space (i.e. the tectonic subsidence). When terrigenous input is scarce or deviated towards the more external part of the basin, the distribution of the clastic filling facies is strictly controlled by the tectonics and the intrabasinal highs that represent the main source areas.

Although the shallow water ideal depositional cycle of primary evaporites (Vai & Ricci Lucchi, 1976, 1977) assumed that resedimentation within the evaporitic basin was mainly due to the action of stream-currents, some other factors suggest that resedimentation of the evaporites was mainly triggered by major tectonic-induced gravitational submarine collapse. This is based on: (i) the lack of leaves, wood fragments or plant particles; (ii) the paucity of any terrigenous component; (iii) the wide diffusion of slides and slumps within the resedimented evaporite; and (iv) the areal facies distribution that is characterized by

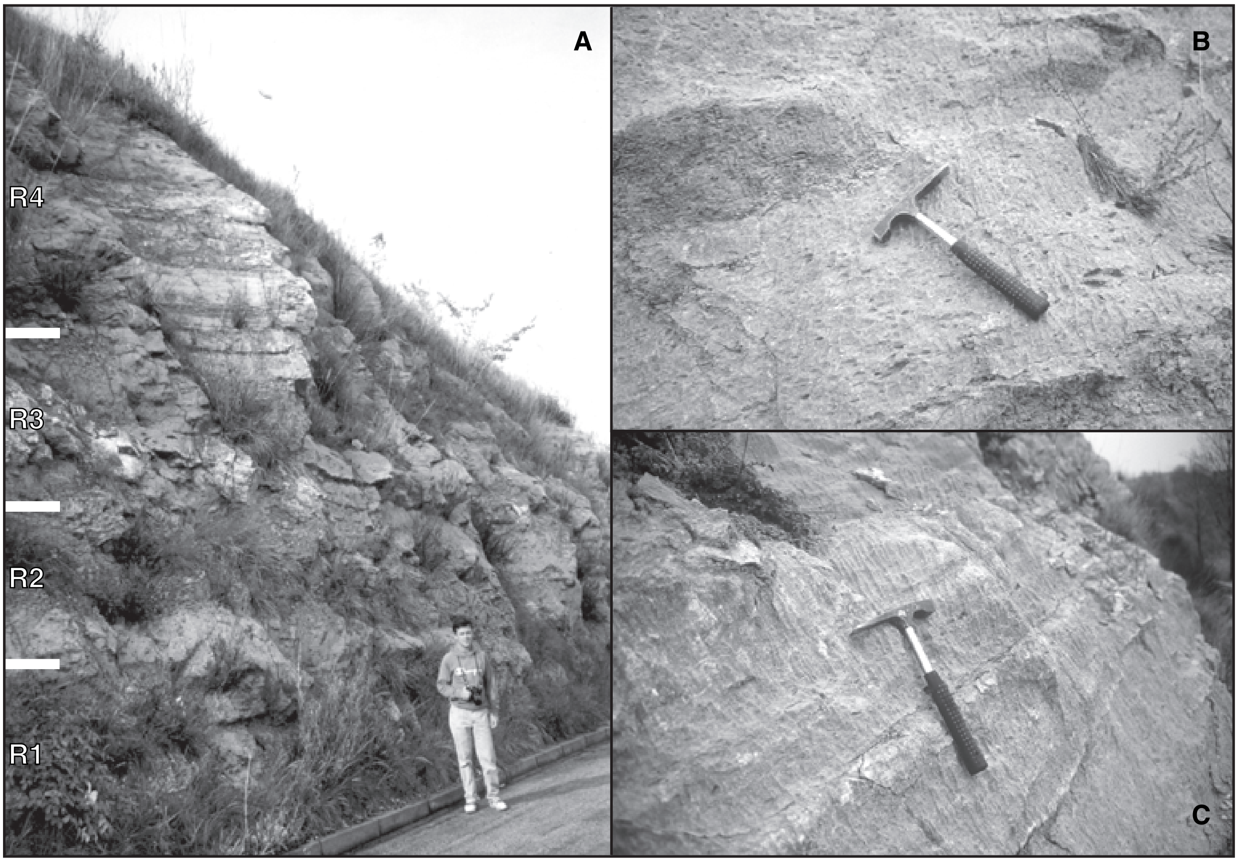

Fig. 11. Inner basin evaporites. (A) Up to 20 m thick composite graded megabed consisting of a basal chaotic division enclosing metric-size clay chip (*R1 facies*) abruptly overlain by a package of up to five beds of crudely laminated gypsrudite (photo B; *R2 facies*) and coarse gypsarenites (photo C; *R3 facies*) with clay chips alignment and traction carpets and capped in turn by plane and cross-laminated hybrid medium to fine gypsarenites (*R4 facies*). These facies are separated by sharp surfaces indicating sediment bypass. Pieve di Rivoschio (Figs 1 and 14 for location), Giaggiolo-Cella syncline southern flank, eastern Romagna.

complete facies transition from chaotic deposits, to lobe and to drape deposits and progressive thinning of these deposits moving from the main source areas, e.g. from the Vena del Gesso type marginal basin, to the deeper part of the basin.

According to this new interpretation, the high mechanical contrast between the primary evaporites and the underlying euxinic shales played a fundamental role in the development of large gypsum glides, whereas the presence of emerged areas close to the northern Apennine foredeep and the action of terrestrial input mechanisms, i.e. fluvial floods, are less evident.

Two-step model of evaporite resedimentation

Although resedimentation of the evaporites in the northern Apennines clearly occurred within a deformed foredeep fragmented into minor subsident basins (Figs 7 and 8), the presence of two main depositional units of clastic evaporites seems to be a common characteristic of the Apenninic, Messinian, post-evaporitic deposits. Within the successions of the main depocentres (the Sapigno, the Giaggiolo-Cella and the Peglio-Pietrarubbia synclines; Figs 1, 7 and 8), in the more internal basins, two sequences can be recognized (Fig. 15): a lower stratified unit made up of high to low-density turbiditic gypsarenites (central basin deposits) and an overlying upper chaotic unit made up of debrisflows, slumps and olistostromes (inner basin deposits). The reason for this double partition is probably the product of two distinct phases of tectonic activity, but an alternative explanation can be suggested from the character of the primary evaporites that underwent erosion and resedimentation (Fig. 16).

The Vena del Gesso primary evaporite succession and its equivalents can be divided into two

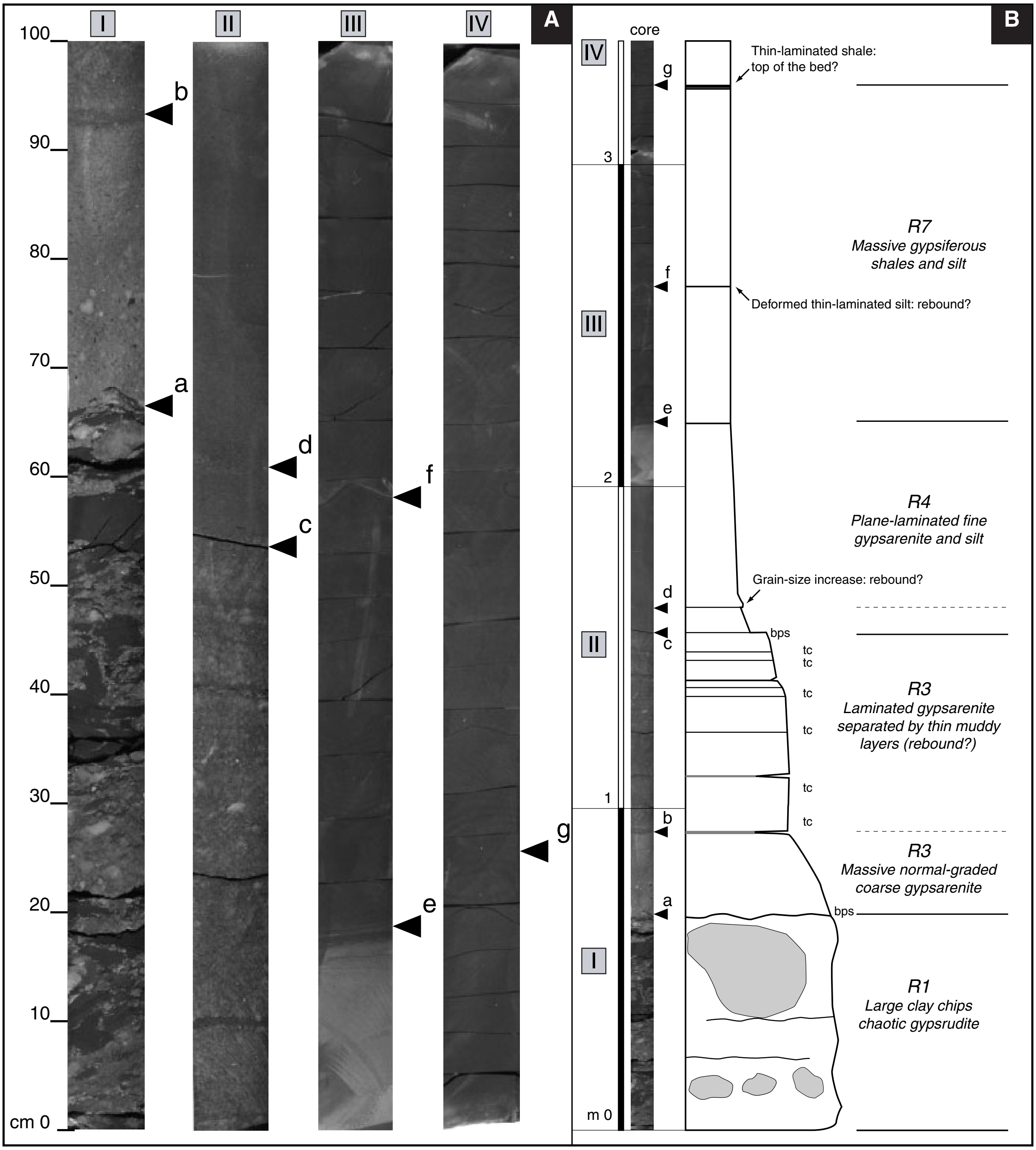

Fig. 12. Inner basin evaporites. Composite graded bed at the top of the resedimented evaporites: core photographs (A) and sedimentological interpretation (B). Up to five sedimentological divisions separated by sharp surfaces or bypass surfaces (bps) marked by a, b, c, and e can be recognized. tc: traction carpet. Campea well (Figs 1 and 14 for location), Giaggiolo-Cella syncline northern flank, eastern Romagna.

units with different bed thickness, internal texture and degrees of cementation (Vai & Ricci Lucchi, 1976, 1977; Vai, 1988). The lower unit consists (Fig. 4B) of tens of metres thick beds composed almost entirely of massive large primary selenite crystals, characterized by rigid behaviour, and interbedded with thin euxinic shale horizons. The upper unit consists of an alternation of thinner beds (a few meters thick) made up mainly of partially reworked, small, selenite crystals and of a white micritic carbonate or a dark euxinic shaly matrix. Within these beds

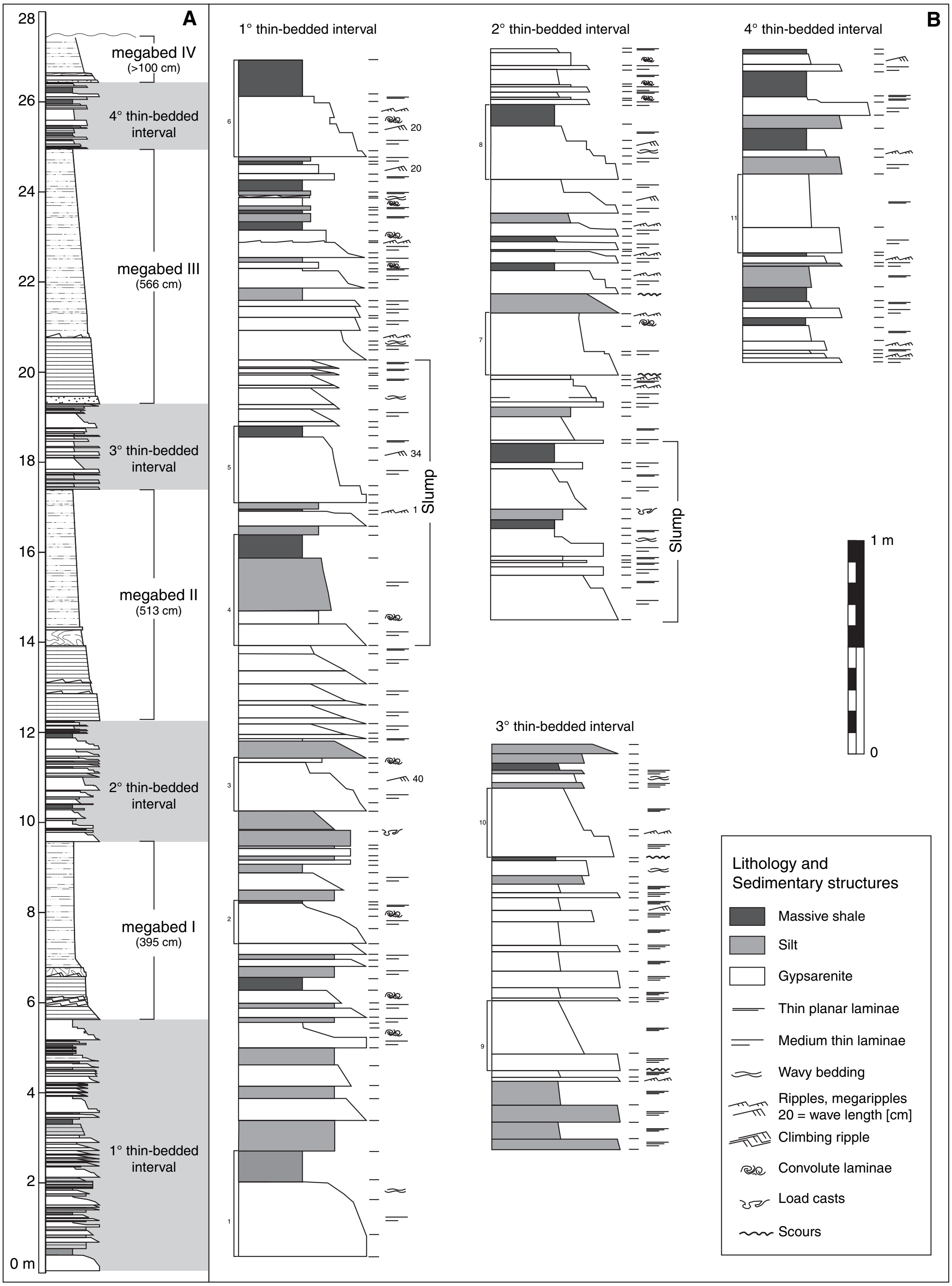

Fig. 13. Central basin evaporites. (A) The lowermost part of the Sapigno section ('Strato Maestro' *sensu* Ruggieri, 1958; unit l1 in Fig. 14), consists of thin-bedded alternation of gypsiferous and shaly layers, forming a 30 m thick tabular body. Up to four resedimented evaporitic thin-bedded metric intervals made up by plane laminated and cross-bedded gypsarenites with metric-spaced megaripple (*facies R4* and *R5*) abruptly capped by massive shales, can be seen (see detailed description in B). These deposits are interbedded by four composite megabeds up to 6 m thick and made up of plane laminated, cross-laminated and convolute fine gypsarenites and gypsum siltites. Changes in the ripple climbing direction (in the same layer) and thickness indicate ponding effect (Fig. 5d).

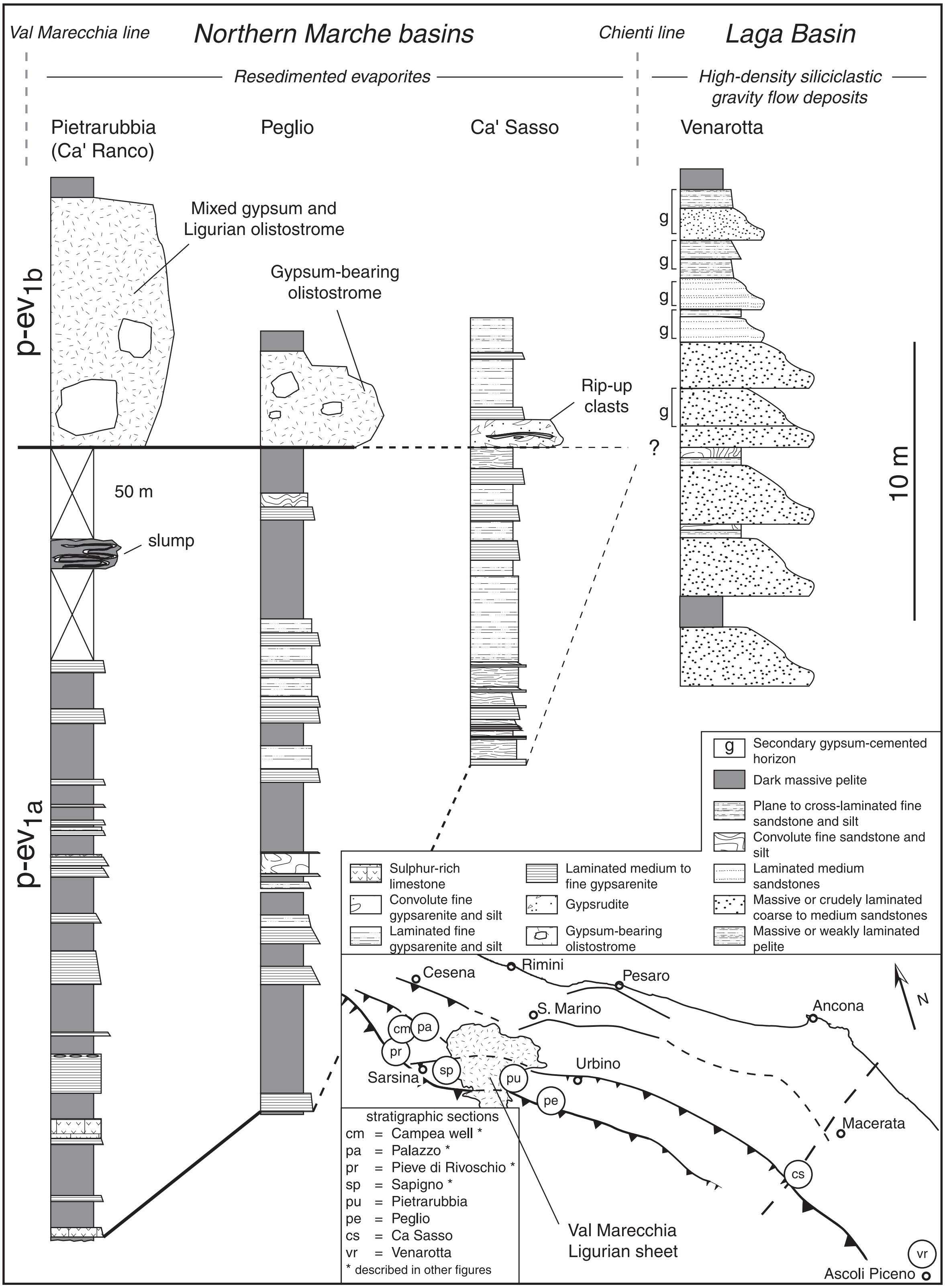

Fig. 14. Central basin and uplifted and starved intrabasinal area evaporites. Stratigraphic sections of the Marche basins, from the Val Marecchia to the Laga Basin. Note the bipartition as described in Fig. 9 for the Fanantello syncline.

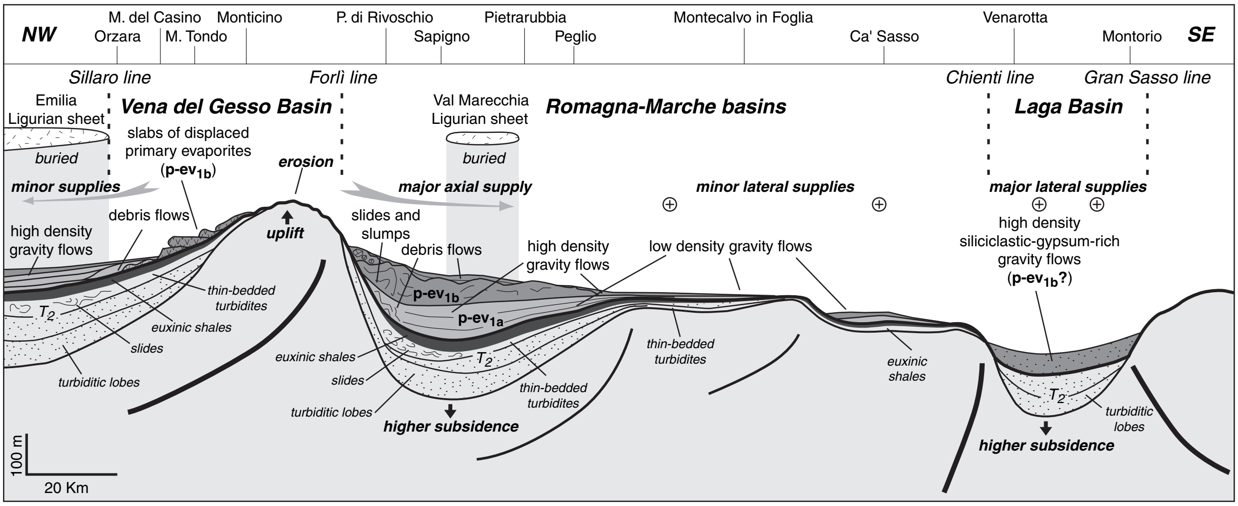

Fig. 15. Stratigraphic setting of the Messinian foredeep during evaporite resedimentation. Note the thick sedimentary wedge developed close to the Forlì Line bordering the Vena del Gesso Basin. Note the bipartition as described in Fig. 9 for the Fanantello syncline. After Roveri *et al.* (2003).

the *in situ* selenite forms only thin intervals at the base of the beds. These beds were only weakly cemented unlike those belonging to the lower unit. The different degree of cementation of these deposits and the different internal texture could have played a major role in the process of resedimentation.

The bipartite stratigraphy of the resedimented evaporites should have been related to two phases of primary evaporite dismantlement. During the first phase (Fig. 16, stage 3a), the erosion of still unlithified or poorly lithified sediments (upper cycles) promoted the formation of high to low-density turbiditic currents. During the second phase, the erosion of the early cemented thick beds of coarse-grained evaporites (lower cycles) must have been linked to a generalized phase of gravitational collapse that produced olistostromes and debrisflows (Fig. 16, stage 3b).

In areas closest to the Forlì line, clastic carbonates locally replace the clastic gypsum. These deposits can be regarded as the final products of the cannibalization of the marginal, primary evaporitic succession, i.e. the dismantling of the lowermost carbonate-evaporitic units also known as 'calcare di base' (stromatolitic carbonates *sensu* Vai & Ricci Lucchi, 1977). Possibly, this cannibalization process (Fig. 16, stage 3c) also affected the pre-evaporitic euxinic shale, contributing to the formation of a fine-grained terrigenous unit (S. Donato Formation). As a result of this process, the basinal areas show an overall inverted stratigraphy with respect to the marginal ones.

DID THE MEDITERRANEAN EVER UNDERGO A COMPLETE DESICCATION?

In the early 1970s the availability of good-quality seismic data in geological exploration, revealed the presence of widespread evaporites in the deeper part of the Mediterranean Sea. During the Deep Sea Drilling Project's Leg 13, the uppermost portion of the 'Messinian reflector' (M) was drilled for the first time. The recognition, in cores of the drill hole 124 of nodular and 'chicken wire' anhydrite, was considered by some authors as a strong indication of sub-aerial formation. This led Hsü *et al.* (1973) to postulate a desiccated deep basin model, contrasting with other models: the deep water–deep basin, the shallow water–deep basin and the shallow water–shallow basin models. Later, the Adriatic foredeep was excluded from the model and considered as an 'anomaly' characterized by a distinct hydrological setting with respect to the Mediterranean basin (Cita & Corselli, 1990, 1993). Nevertheless, the widespread and relatively homogeneous nature of the lithology and cyclic arrangement of pre-, syn and post-evaporitic Messinian deposits throughout the Apennines and many other peri-Mediterranean basins point to a common geological evolution (Roveri *et al.*, 2001).

As described earlier in this paper, the evaporites belonging to the Gessoso-solfifera Formation in the Apennines actually developed diachronously across the basin, with deep basinal deposits postdating the primary evaporites accumulated in shallow-water marginal settings. This

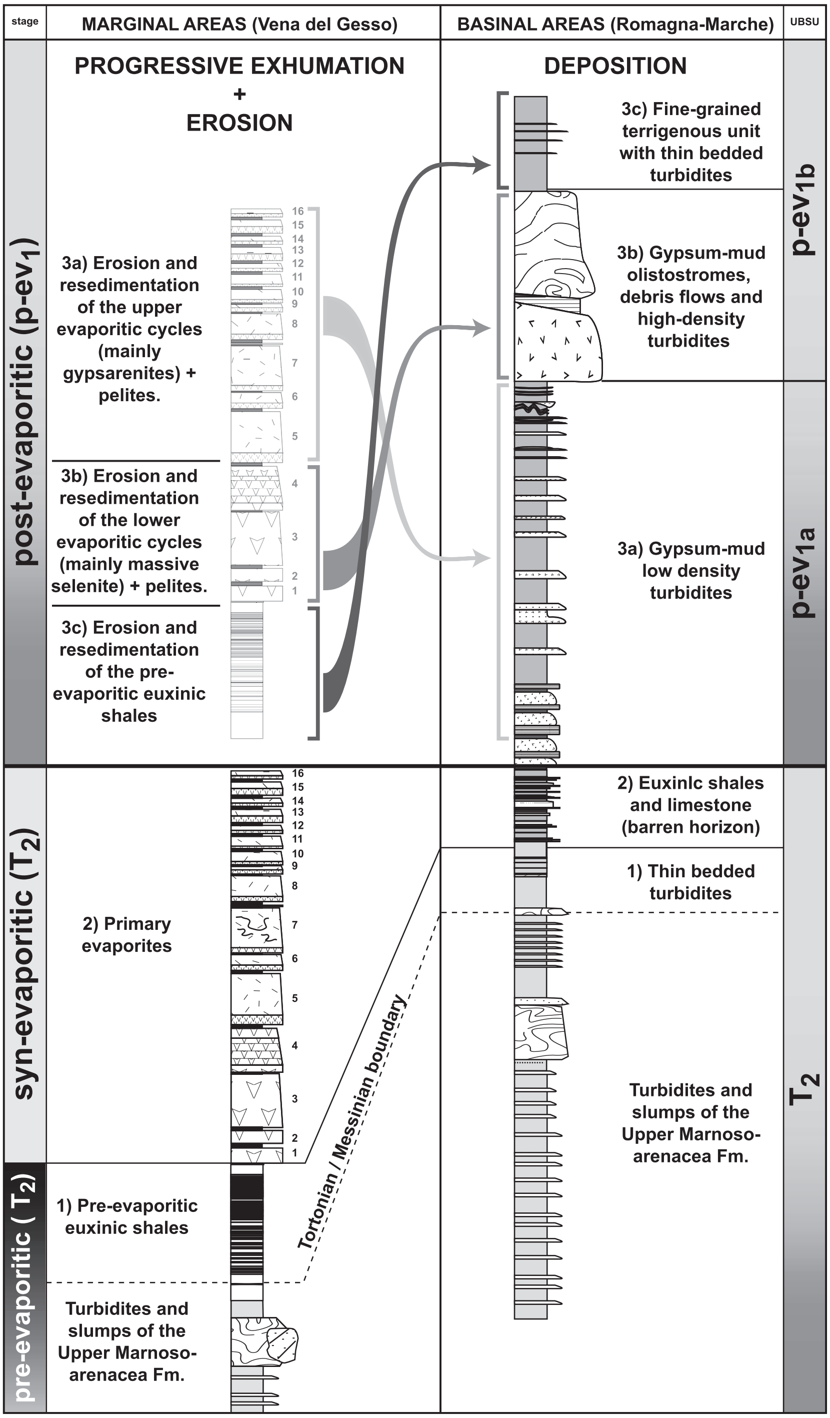

Fig. 16. The two phases of resedimentation of the primary evaporites related to the progressive exhumation and erosion of the Vena del Gesso Basin (marginal areas) and resedimentation in the Romagna-Marche basins. Note that basinal areas show an overall inverted stratigraphy with respect to the marginal ones.

is exactly what many evolutionary models for the Messinian Salinity Crisis envisage for other Mediterranean basins; the only difference is that in the Apennine foredeep, evaporites of deepest basins are clearly clastic and resedimented through fully subaqueous processes. These Apennine deposits suggest that the Adriatic foredeep never underwent complete desiccation, although small-scale sea-level fluctuations may have affected the marginal thrust-top basins during the evaporitic stage. Here nodular sulphates, commonly associated with resedimented evaporites, originated by burial diagenesis rather than in sabkha environments, as recently pointed out in a review of the DSDP Legs 13 and 42A cores by Hardie & Lowenstein (2004). If these features are not evidence of shallow-water or supratidal deposition, then the presence of deep-water sediments sandwiched or intercalated with the evaporites (Hsü *et al.*, 1973, 1977; Hsü, 1973) may not be considered evidence of desiccation. On the contrary, as suggested by this Adriatic foredeep example, where clastic evaporites are sandwiched between deep-water sediments as well, resedimentation of evaporites may also have played a major role in other deep Mediterranean settings. If this interpretation is correct, then a large part of the evaporites lying on the Mediterranean floor could have a clastic origin.

CONCLUSIONS

Due to the strong diagenetic overprint that affects these rocks, the study of resedimented evaporites of the Romagna-Marche Apennines is not an easy task. The integration of a siliciclastic approach to field recognition, microscope analysis and geochemical determinations permits a more accurate interpretation of the large variety of resedimented evaporites and led to some important implications for the events that characterize the Messinian Salinity Crisis.

1. Facies analysis of gypsum clastic deposits suggests a new genetic model for resedimented gypsum evaporites. As for siliciclastic models, a relationship between grain size and sedimentary structures has been proposed as a useful tool to indirectly determine the nature of diagenetically transformed resedimented evaporites. These facies descriptions can be used when deposits are mainly composed of gypsum whereas other deposits containing less gypsum (e.g. the Laga gypsarenites) can be properly described with the classic siliciclastic models.

2. In spite of what is commonly thought, much of the evaporite succession cropping out between the eastern edge of the Vena del Gesso and the Laga Basin has a clastic origin. Almost all the laminar (balatino) gypsum exposed in the northern Apennines, previously considered as a deep-water primary gypsum deposit, should be completely re-interpreted as the fine-grained product of high to low-density gravitational flows.

3. Moving south-east from the shallow water Vena del Gesso type marginal areas, towards the Romagna and Marche basinal ones, a complete transition from high to low-density gravity-driven deposits permits the reconstruction of the history of primary evaporite dismantling from shallower thrust-top basins and subsequent resedimentation to deeper and more subsident areas. The accumulation of such a wide spectrum of gravity-driven deposits, supported by the presence of slides, slumps and gravity-flow deposits, was probably related to the formation of large submarine collapse and glide structures triggered by tectonically induced gravitational instability.

4. The presence of gravity-driven deposits indicates short depositional events, and the evaporite resedimentation ought to have occurred within a sulphate-saturated water column in order to prevent the dissolution of clasts during the transport.

5. The relative scarcity of coarse and medium-grained sandstone in comparison with the plentiful conglomeratic and finer-grained deposits within the resedimented evaporites of the Apennines could be related either to the original grain population of the primary evaporites, as described above, or to their original depositional settings. The presence of various minor basins within the main foredeep could have forced the accumulation of resedimented evaporites in the central parts of the basins, i.e. in the cores of synclines, that commonly still remain buried.

6. Two tectonically induced phases of evaporite resedimentation, clearly recognizable within the more internal basins, can be related to the subsequent erosion and resedimentation of different kinds of primary evaporites. During a first phase, the upper part of the primary evaporites, with thinner, mainly reworked and unlithified evaporites could have been eroded and resedimented by high to low-density gravity flows throughout the Adriatic foredeep. Subsequently, the erosion of the early cemented thick beds of coarse-grained *in situ* evaporites could undergo a generalized phase of gravitational collapse that produced the resedimentation of olistostromes and debrisflows in the inner basins.

7. Although resedimentation of the evaporites occurred within a fragmented minor-basin foredeep, their wide, transitional distribution and depositional character suggests the absence of a basinal desiccation event during their emplacement. This important observation should be taken into consideration in the study of other Mediterranean areas, especially in the interpretation of deep-basin evaporitic deposits. For the reasons illustrated in this study, part of the evaporites in the deeper settings of the Mediterranean Sea may also represent resedimented evaporites rather than deposits formed in shallow-water to supratidal settings.

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