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Understanding the geological record of carbonate platform drowning across rifted Tethyan margins: Examples from the Lower Jurassic of the Apennines and Sicily (Italy)

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ABSTRACT

In the geological record a drowning process is documented by various types of shallow water-to-pelagic or shallow water to mixed benthic/pelagic carbonate transitions. Drowning unconformities are paraconformities, to disconformities, to angular unconformities, and their drowning surfaces range from planar to highly irregular morphologies. Drowning successions display a mix of products of both the benthic and pelagic carbonate factories. These successions can be also bounded by unconformities. Drowning unconformities and drowning successions are contrasted through a description and discussion of examples of escarpment-bounded platforms from the Jurassic of the Northern Apennines and, subordinately, from Sicily and other Tethyan sectors. The areal distribution of drowning unconformities and successions is discussed with reference to a complex depositional system whose architecture was the product of the rift-induced fragmentation of a regional Hettangian carbonate megabank. The examples in this study show drowning unconformities to be exclusive to intrabasinal highs, while drowning successions are found both on highs and in hangingwall basins. Drowning unconformities, with their long associated hiatuses, and drowning successions are often seen to merge laterally into one another over very short distances on the same intrabasinal high. The deposits of the drowning succession are sometimes missing on the top of the platform, while they are found forming clinoforms along its flanks, evidence that sediment could be permanently swept from the highs in these depositional systems at this stage.

1. Introduction

Research in the past three decades (Grigg, 1982, 1997; Hallock and Schlager, 1986; Hallock et al., 1988; Erlich et al., 1990; Jenkyns, 1991; Schlager, 1981, 1991; Wood, 1993; Föllmi et al., 1994; Chazottes et al., 2002; Mutti and Hallock, 2003) has demonstrated the drowning of carbonate platforms to be induced by several concomitant environmental, biological, geological, oceanographic and eustatic factors. While "platform drowning" is generally defined as an event (Schlager, 1981), geologists studying ancient platforms must at first tackle platform drowning as a final physical product (e.g. a facies change), irrespective of the underlying cause(s). In addition, the very time slice when the drowning event took place may be undocumented by any rock, and rather be corresponding to surface associated with a stratigraphic gap.

This paper reviews and analyzes the various attributes associated with different types of change from peritidal to pelagic carbonate rocks. In the first part, definitions related to these subjects are given, and those existing in the literature are reviewed. In the second part, case examples from the Lower Jurassic rifted Tethyan margins of Central Italy (Apennines) and, to a lesser extent, Western Sicily are discussed. Finally, attempts are made to interpret the Early Jurassic drowning, making use of the various parameters and concepts discussed earlier.

2. Geological setting

The carbonate platforms discussed in this paper are exposed in the Umbria–Marche and Sabina Domains of the Apennines (Central Italy), and in the Trapanese and Saccense (i.e. Sciacca) "Maghrebian" Domains of Western Sicily (Fig. 1). The stratigraphic record in these two regions documents dominantly shallow-water sedimentation in the Late Triassic (carbonates and evaporites) and early Early Jurassic, followed by deeper-water conditions through the remainder of the Mesozoic and part of the Tertiary, with deposition of pelagic carbonates, shales, and cherts. These successions were sedimented along the passive continental margins of the Adria and African Plates, respectively. Then orogenic processes, active in the Miocene and

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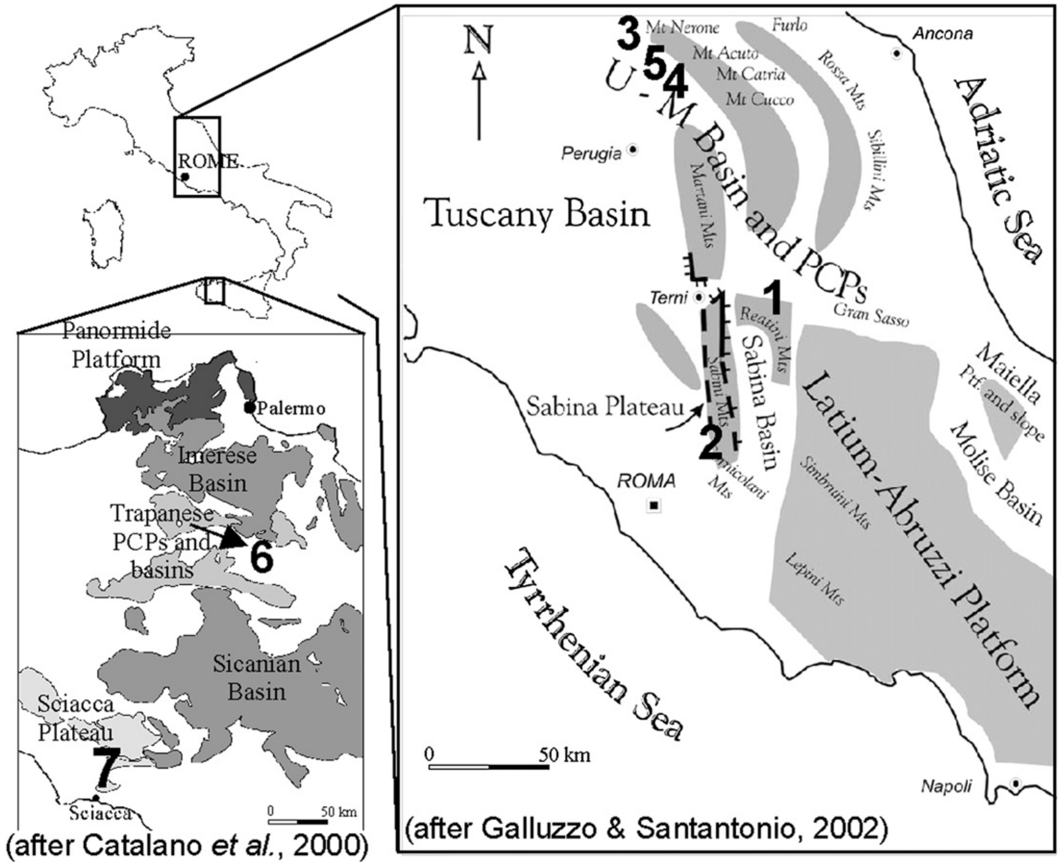


Fig. 1. Location of the investigated areas and paleostructures: 1: Mt Rosato PCP; 2: Sabina Plateau; 3: Mt Nerone PCP; 4: Mt Acuto High (see text); 5: Burano–Bosso Basin; 6: Kumeta High; 7: Sciacca Plateau.

Pliocene, produced the Apennines as a result of subduction of the Adria Plate towards south-west, and the Maghrebian Chains of Central and Western Sicily as a result of subduction of the African Plate towards the north, accompanied by the development of foredeep and thrust-top siliciclastic basins (Bernoulli, 1969; Bernoulli and Jenkyns, 1974; Biju-Duval et al., 1977; Bernoulli et al., 1979; Channell et al., 1979; Abbate et al., 1986; Zappaterra, 1990; Santantonio, 1994, and references therein; Catalano et al., 2000; Turco et al., 2007).

3. Platform drowning: definition, characteristics, and general remarks

"Geological drowning" is used here with reference to the superposition of open marine deposits on shallow water, peritidal (*sensu* Folk, 1973) carbonate platform beds. This change is marked by a faunal/floral turnover, indicating a halt or decrease of benthic-factory carbonate production (Schlager, 1994). The post-drowning deposits are most commonly pelagic carbonates (e.g. Tethyan Jurassic), but can be also deeper-water siliciclastics, resedimented deposits, or volcanoclastics. This paper solely addresses the switch from shallow-water carbonates of the so-called tropical type to pelagic or mixed benthic/pelagic deposits.

An abrupt lithological switch to pelagites can occur at a single surface, which represents a *drowning unconformity* (Schlager and Camber, 1986; Schlager, 1989). By contrast, an intermediate sediment package having a particular mix of benthic-and planktonic-factory elements is described as a *drowning succession*. Its base and top ideally mark the inception and completion, respectively, of the drowning process. Geological drowning is therefore seen here through a volume of rock rather than across a surface. Within a seismic section, a drowning succession might go unresolved, thus mimicking a drowning unconformity (Erlich et al., 1990). Deposits of the drowning succession can form small aprons on platform-flanks, having clinoform geometries, which rest unconformably on marginal escarpments, and are in turn unconformably overlain by the basin-fill strata. These can be referred to as unconformity-bounded drowning successions (see examples in Erlich et al., 1990, 1998; Zempolich, 1993).

4. Case studies

4.1. The change from peritidal to pelagic sedimentation in the Jurassic of the Apennines

In the Apennines, vast regional carbonate platforms (several thousands square kilometres) were dissected by rifting during the earliest Jurassic, generating a submarine morphology with structural highs and intervening deeper basins. Tectonic subsidence along normal faults initially caused a switch from peritidal to permanently subtidal ramp environments on hangingwall blocks in the latest Hettangian/early Sinemurian (Passeri and Venturi, 2005; Calcare Massiccio C drowning succession in Figs. 2 and 3). While sedimentation rates could initially keep pace with subsidence, accelerated faulting through the Sinemurian eventually produced submarine escarpments, and forced carbonate ramps to turn into deeper basins where pelagic carbonates and cherty carbonates could accumulate. Stratigraphic relationships at paleoescarpment onlap contacts with respect to platform tops indicates that vertical displacements in the order of about 1 km were produced in no more than 3 to 4 Myr, probably much less (Carminati and Santantonio, 2005; Santantonio and Carminati, 2010). These basins were the depocentres for

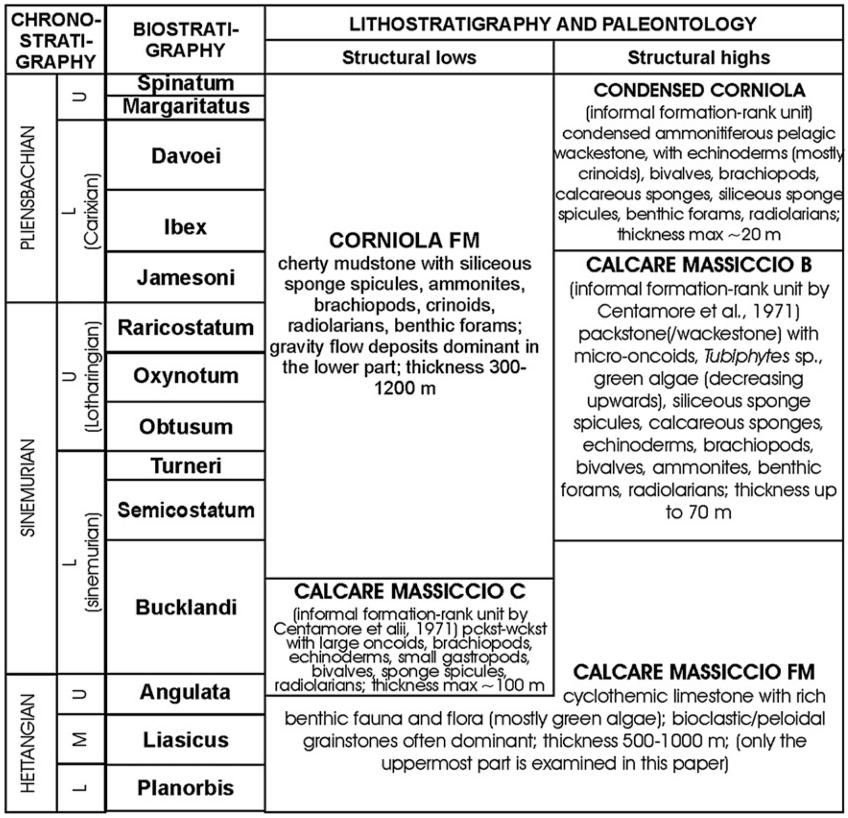


Fig. 2. Lithostratigraphic units in structural highs and lows, recording the pre-, syn-, and early post-drowning phases in the Apennines.

lithoclastic material derived from the flanks of structural highs, forming megaclastic wedges at their toe of escarpment, and for sediment which was still produced on the bank tops prior to their eventual drowning. Jurassic basinal successions are up to several hundred metres thick (Bernoulli, 1969), and in excess of 1 km in the Sabina Domain (Galluzzo and Santantonio, 2002). The syn-rift part of these successions (essentially the Sinemurian) was deposited at rates of about 30 to 120 mm/1000 yr (non-decompacted values).

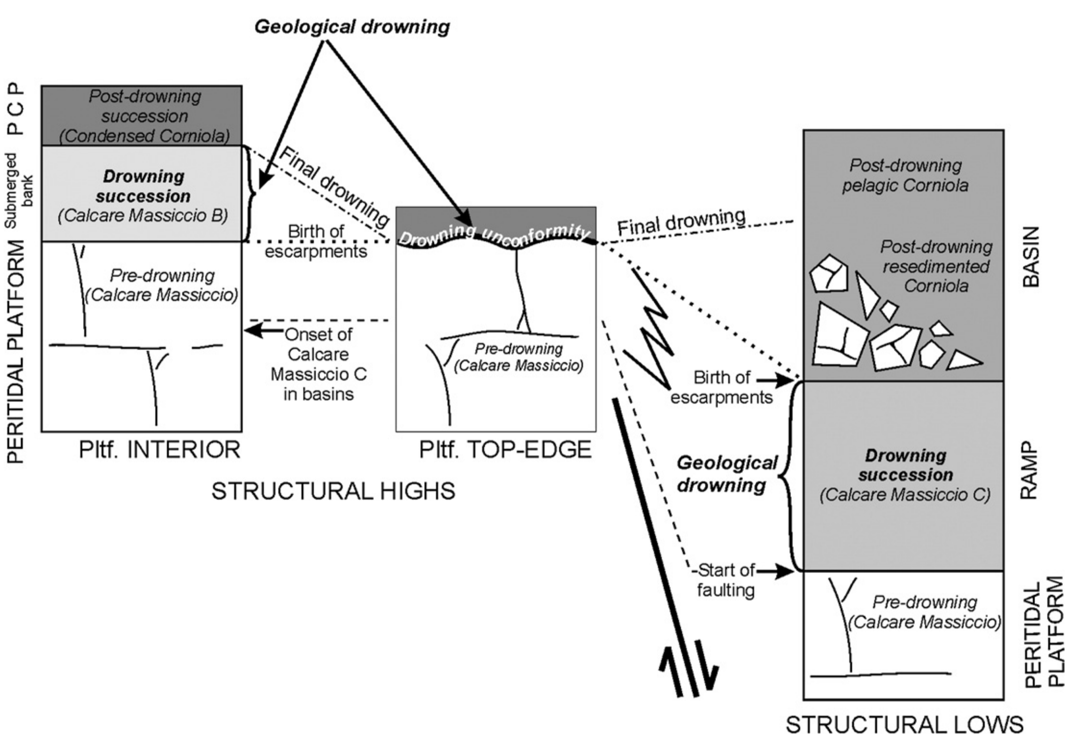


Fig. 3. Modes of lithologic change on Jurassic structures: drowning successions always occur in hangingwall basins, while on footwall platforms they can pass laterally to drowning unconformities as the platform edge is approached.

Coincident with the creation of submarine escarpments, the tops of footwall blocks saw the inception of a drowning succession (Calcare Massiccio B in Figs. 2 and 3) above peritidal carbonates (Morettini et al., 2002). Since the extensional pattern across the Umbria–Marche and Sabina region was characterized by a dense network of closely spaced faults, the highs were generally as small as few square kilometres (Santantonio and Carminati, 2010).

Definitive drowning of the platforms is recorded by condensed, ammonite-rich carbonates, starting in the early Pliensbachian (Carixian of Cecca et al., 1990; Morettini et al., 2002). This event turned structural highs into pelagic carbonate platforms (PCP). This term defines footwall blocks bounded by submarine escarpments, produced through tectonic extension of a once productive carbonate platform, and having their flat tops hosting a condensed pelagic succession. “Pelagic carbonate platform” is used as a substitute for the more ambiguous (in these continental-crust settings) “seamount”, a term often found in the Tethyan regional literature, while “Plateau” traditionally refers to larger-scale (hundreds to thousands of square kilometres) pelagic platforms (see discussion in Santantonio, 1993, 1994). The PCP-top post-drowning Jurassic successions, spanning the early Pliensbachian to the Tithonian or earliest Cretaceous, are no more than a few tens of metres thick. Average sedimentation rates are therefore in the order of few millimetres/1000 yr, or even less (e.g. Kimmeridgian and Tithonian) (Cecca et al., 1990). However, since such sedimentation-rate figures are the result of extrapolating stratigraphic thickness against geological time, the numerical results not only embed compaction, but also the episodic removal of sediment, and production of hiatuses below the limits of stratigraphic resolution. In other words, “biozones” in such settings are probably not complete units, but only short-duration parts of them, separated from each other by diastems (Santantonio, 1993).

4.2. Architecture and pelagic facies associations of PCP/basin systems in the Apennines, and the geometries of PCP-top successions

The areal distribution of pelagic facies in the Umbria–Marche and Sabina Apennines, as well as in other similar Tethyan settings, is closely linked to submarine paleotopography which is a product of the local extensional architecture. Santantonio (1993) proposed to group pelagic facies into three broad associations (Fig. 4): A) the condensed pelagic facies association, typical of thin PCP-top successions; B) the “normal” and resedimented pelagic facies association, typical of thick basinal successions; C) the composite pelagic facies association, with condensed, sometimes lithoclastic deposits, having an angular unconformity at their base, typically forming very thin discontinuous drapes on escarpments. The mixed benthic–pelagic deposition of the drowning succession does not obviously fit within any of these strictly pelagic facies associations. The PCP-top successions in general have convex-up geometries, similar to that observed in drowned atolls in the Pacific (e.g. Allison Guyot; Winterer, 1991) and on the Blake

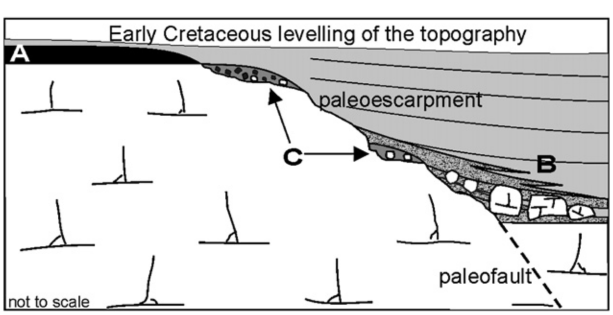


Fig. 4. Distribution of the pelagic facies associations proposed by Santantonio (1993) in a PCP–basin system. A): “condensed” on the PCP-top. B) “normal and resedimented” in the basin. C): “composite” (condensed and lithoclastic) in an epi-escarpment setting. The submarine rift topography was levelled by Early Cretaceous time in the Apennines.

Plateau (Pinet and Popenoe, 1985). This has been dubbed the “panettone” geometry by Galluzzo and Santantonio (2002), due to the obvious resemblance in cross-section with the famous Milanese cake. This can have a number of causes, which include the angle of repose of mud at the edge of a structure bordered by a steep escarpment made of lithified peritidal limestone, and, shaping by currents. Thinning of the condensed pelagic units across the Apenninic PCPs occurs in concert with changes in several bio-sedimentological attributes, ranging from pinch-out and/or downlap of individual beds, to lateral passage from mud/wackestones to wacke/packstone or rudstone textures, due to removal of mud and macrofossil enrichment, to taphonomy and condensation type (Galluzzo and Santantonio, 2002). Ammonite stratigraphy reveals that platform-edge sections are the most incomplete, with biozones disappearing laterally within metres, or with fossils having different ages being mixed within one bed (Cecca et al., 1986; Santantonio et al., 1996).

The escarpments separating the PCP-tops from basins were erosionally modified Early Jurassic normal fault-planes, corresponding to submarine outcrops of peritidal limestone (Fig. 4). These mainly acted as by-pass margins during the syn-rift, and then became erosional margins (*sensu* Read, 1982) when *in situ* platform production and fault activity came to a halt (Carminati and Santantonio, 2005). Thin discontinuous veneers of ponded condensed pelagites, occasionally bearing allochthonous lithoclasts, are found scattered on the paleoescarpment surface (epi-escarpment deposits). These patchwork deposits of the composite pelagic facies association have an unconformable base, and they document occasional sediment preservation in areally restricted *loci*, like scars left by fallen blocks, in a dominantly non-depositional or erosional (occurrence of lithoclasts) setting. Subsequently paleoescarpments were onlapped by the basinal deposits that slowly filled the basins, levelling the submarine rift topography by the Early Cretaceous (Fig. 4). While indeed the condensed pelagic veneers and the onlaps form sharp peritidal-to-pelagic limestone contacts, these two types of unconformities, which are found outside the perimeter of the platform top, must obviously not be treated as drowning unconformities. They record instead processes, like the filling of basins and the occasional sediment ponding along erosional margins, that may have occurred several tens of million years after the platform was drowned.

4.3. Examples of drowned platforms from the Umbria–Marche–Sabina Apennines

The character and type of geological drowning varies across different paleostructures (i.e. structural highs vs. lows) as well as across the same paleostructure; i.e. a drowning unconformity can pass laterally to a drowning succession as a result of varying sediment preservation.

4.3.1. Footwall-block platforms — Top of structural highs

Geological drowning can be represented by either a drowning unconformity or a drowning succession (Fig. 3). A drowning succession is geometrically concordant with the pre-drowning and post-drowning beds in the platform interior, and has variable thickness. Field observations were made on various sections (Table 1) on the top of the Mt Rosato PCP, on the Sabina Plateau (Mt Macchialunga, Fosso di Stroncone, Castiglione), and on the Mt Nerone PCP (Campo al Bello, Fosso dell'Eremo).

The Calcare Massiccio B, representing the drowning succession, is made of 0.2 to 1 m thick tabular beds of packstone to subordinately rudstone. This unit contains some green algae, which are common in the underlying peritidal unit, solenoporaceans (Fig. 5A), along with spicules of siliceous sponges (Fig. 5B), various calcareous sponges (including sphinctozoans; Pallini and Schiavinotto, 1981; Fig. 5C), echinoderms (crinoids and echinoids), brachiopods, molluscs

Table 1
Main characteristics of the geological drowning, as observed in the case-studies described in text.

Stratigraphic section	Physical (field) evidence	Geometry	Paleotopography/ paleoenvironment	Processes	Age of the oldest pelagites	$\delta^{13}C$
Mt Rosato PCP						
Mt. Rosato 33T 42°30′57″N 12°52′55″E	Drowning succession (~12 m)	Geometrically concordant at top and bottom	Top of structural high	Sedimentation by mixed benthic–pelagic factories	Early Pliensbachian (Ibex zone)	~1‰ positive shift at the top of drowning succession
Plateau Sabino						
Mt. Macchialunga 42°28′13″N 12°40′45″E	Drowning succession (~25 m)	Geometrically concordant	Northern part of the plateau. Tilted top of a structural high	Sedimentation by mixed benthic–pelagic factories	Early Pliensbachian (Ibex zone)	~1‰ positive shift at the top of drowning succession
Fosso di Stroncone 42°29′03″N 12°38′01″E	Drowning succession (~70 m)	Paraconformity at the top	Northernmost part of the plateau. Deeper part of the tilted top of a structural high	Sedimentation by mixed benthic–pelagic factories	Early Pliensbachian (Davoei zone)	
Castiglione 42°25′48″N 12°40′34″E	Drowning unconformity	Paraconformity and disconfomity	Eastern edge — southern part of the plateau	Probable emersion + submarine erosion/non sedimentation	Late Pliensbachian	
Mt Nerone PCP						
Campo al Bello 43°33′39″N 12°31′33″E	Drowning succession (10–15 m)	Geometrically concordant at top and bottom	Top of structural high	Sedimentation by mixed benthic–pelagic factories	Early Pliensbachian (Ibex zone)	~1‰ positive shift at the top of drowning succession
Fosso dell'Eremo 43°35′06″N 12°32′12″E	Drowning succession	(Para)conformity at the top	Edge of the top of structural high	Sedimentation by mixed benthic–pelagic factories/submarine erosion	? Pliensbachian	
Gorgo a Cerbara 43°35′29″N 12°32′21″E	Drowning succession	Unconformity-bounded at top and bottom	Lower paleoescarpment	Alternating resedimentation sourced by high/*in situ* organic binding/pelagic sedimentation/non-deposition–erosion	Late Sinemurian	
Mt Acuto High						
North-west slopes 43°28′51″N 12°40′34″E	Drowning succession	Unconformity-bounded at top and bottom	Flanks of non-depositional structural high	Alternating resedimentation sourced by high/pelagic sedimentation	Early Sinemurian	
Burano–Bosso Basin						
Ponte Grosso Quarry 43°30′06″N 12°38′01″E	Drowning succession	Geometrically concordant or locally low-angle unconformable at the top	Structural low — ramp to incipient basin	Sedimentation by mixed benthic–pelagic factories	Early Sinemurian	

(bivalves, gastropods, and cephalopods), benthic foraminifera, and radiolarians (Fig. 5D and E), and intraclasts. Virtually all bioclasts have micritic envelopes (micro-oncoids, *sensu* Flügel, 2004, Fig. 5D and E; see discussion below, in “Paleontological data”), and are set in a micrite matrix with packstone textures dominating. “*Tubiphytes*”-like forms can be common (Fig. 5F).

Above this unit, at the base of the condensed Corniola, there is a change to wackestone and mudstone. While coated grains completely disappear, benthic groups like crinoids, brachiopods, sponges, and foraminifera are still common, though their abundance decreases upsection. The lowest beds of this unit bear frequent ammonites, including a *Tropidoceras* sp.-dominated assemblage, indicating the Ibex Zone (lower Pliensbachian).

The composition of the micrite in the Calcare Massiccio B and condensed Corniola was examined through thin-section study (optical microscopy, ×1000 magnification) and observation of bulk rock samples through SEM (Fig. 6), by estimating qualitatively the relative abundance of coccospheres, coccoliths and unidentified remains (micarbs *sensu* Bellanca et al., 1996; Table 2). The basinal Corniola Formation was also investigated for a comparison. While thin-section microfacies examination in the Calcare Massiccio B documents the mixing of benthic and pelagic (e.g. radiolarians) organisms, nannofacies observation indicates that mud-grade sediment was being actively contributed by the pelagic carbonate factory in this environment.

The Sabina Plateau, being the largest pelagic platform of the three mentioned above, provides some instructive insight on the lateral variability of these drowning-related deposits and surfaces. In its northern part, the Calcare Massiccio B varies from 25 (Fig. 7A) to 70 m (thickening toward the north; see the thick Fosso di Stroncone section; Table 1). Above it, the lowest post-drowning pelagites have an early Pliensbachian age, so this is a relatively continuous succession. In the southern part of the Plateau (Castiglione, about 20 km south of Fosso di Stroncone), and in scattered localities in between, by contrast, Toarcian condensed pelagites rest directly on the Calcare Massiccio producing a drowning unconformity. Late Pliensbachian post-drowning condensed deposits (Fig. 7B) are here only preserved in laterally discontinuous erosional pockets, carved into the Calcare Massiccio, and in neptunian dykes. These stratigraphic relationships suggest that a long period of non-deposition and/or erosion followed the halt of peritidal sedimentation on this part of the Sabina Plateau (see also Farinacci, 1967). The top of the Calcare Massiccio is in fact known to be not younger than the early Sinemurian (Ciarapica and Passeri, 1998).

The variable aspects of geological drowning across the Sabina Plateau are collectively interpreted to be the product of an overall tilting of the fault-block to the north, thereby generating more accommodation space. The whole post-drowning (PCP-top) condensed succession (early Pliensbachian–Berriasian), is also thickest to the north (Galluzzo and Santantonio, 2002). In this case, tectonic

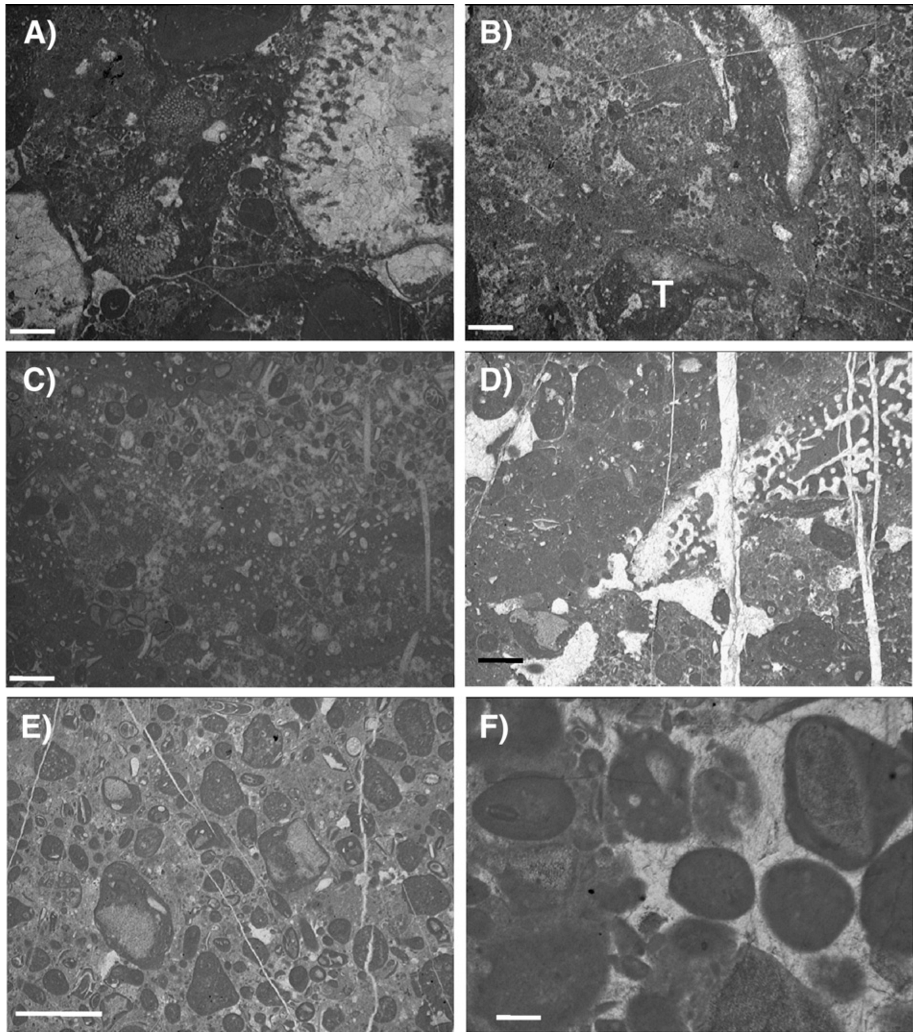


Fig. 5. Microfacies of Calcare Massiccio B on the top of the structural highs (scale bar = 1 mm). Mt Rosato area: A) Solenoporacean algae encrusting a calcareous sponge; B) wackestone with macro- and micro-oncoids, peloids, sponge spicules, and microbialite-associated *Tubiphytes* (T); C) micritic packstone with micro-oncoids and micritc envelopes around echinoderm fragments. Northern part of the Sabina Plateau: D): pack-wackestone with a calcareous sponge, micritized micro-oncoids, and echinoderms with micritic envelope; E) pack-wackestone with abundant sponge spicules and micritized micro-oncoids with benthic foraminifers (including *Throcolina* sp.) at nucleus. Mt Nerone area (Fosso dell'Eremo Section): F) to the left *Agerina martana* occurs within an algal nodule (see banding); see also echinoderms.

tilting caused the drowning succession to be wedge-shaped on a kilometre scale, closing to zero in sectors where subsidence was lesser, and erosion prevailed. The variable ages (Pliensbachian to Toarcian) recorded in the lowest pelagites which cap the Calcare Massiccio Formation and the Calcare Massiccio B across the Sabina Plateau only indicate when the conditions suitable for pelagic sediment to be preserved were set (see also Molina et al., 1999). Diachronous drowning across the paleostructure can be ruled out through careful survey of the sediment which directly overlies the drowning unconformity, which fails to show any logical age/sediment areal distribution. The age of drowning of the Sabina Plateau is best constrained by taking the oldest pelagites recovered, in this case those following the drowning succession, which have an early Pliensbachian (Ibex Zone) age. The Sabina Plateau represents an example of a drowning succession merging laterally into a drowning unconformity (see Zempolich, 1993, for an example from the Trento Plateau in Southern Alps).

Platform-edge conditions are exposed in the Mt Nerone area, at Fosso dell'Eremo (Fig. 8; Immerz, 1985). Here the drowning succession forms the uppermost tract of the paleoescarpment profile, and is as such topped by an erosional surface. This is locally sealed by a discontinuous condensed veneer of unconformable Lower Jurassic (condensed Corniola) epi-escarpment pelagites. This complex is then onlapped, through a further angular unconformity, by much younger basin-fill units: the Upper Jurassic cherty *Saccocoma* limestone (Kimmeridgian–Tithonian *p.p.*), and the calpionellid-limestone (Maiolica Formation).

4.3.2. Footwall-block platforms — Flanks of structural highs

Unconformity-bounded drowning successions are observed, in the Mt Nerone and Mt Acuto areas, a few hundreds of metres lower (paleotopographically) than the platform top. These drowning successions are mostly composed of thick beds (about 1 m) of Calcare Massiccio B-type sediment (see Fig. 9): packstone/wackestone to floatstone with peloids, micro-oncoids, fragments of porostromatae and codiacean algae (at the nucleus of micritic grains), rare dasycladaceans, echinoid and crinoid fragments, ammonites, gastropods, bivalves, corals, bryozoans, benthic foraminifera (valvulinids, lagenids, and spirillinids), sponge spicules and radiolarians. Some beds are lithoclastic, with intraclasts and scattered angular clasts of Calcare Massiccio Formation (Fig. 9F). These sediments alternate with thin beds (max 10 cm) and lenses of condensed pelagites made of radiolarian-mudstone to packstone with crinoids, ammonites, brachiopods, bivalves, gastropods, ostracods, benthic foraminifera, sphinctozoan sponges, sponge spicules and radiolarians (Fig. 9G).

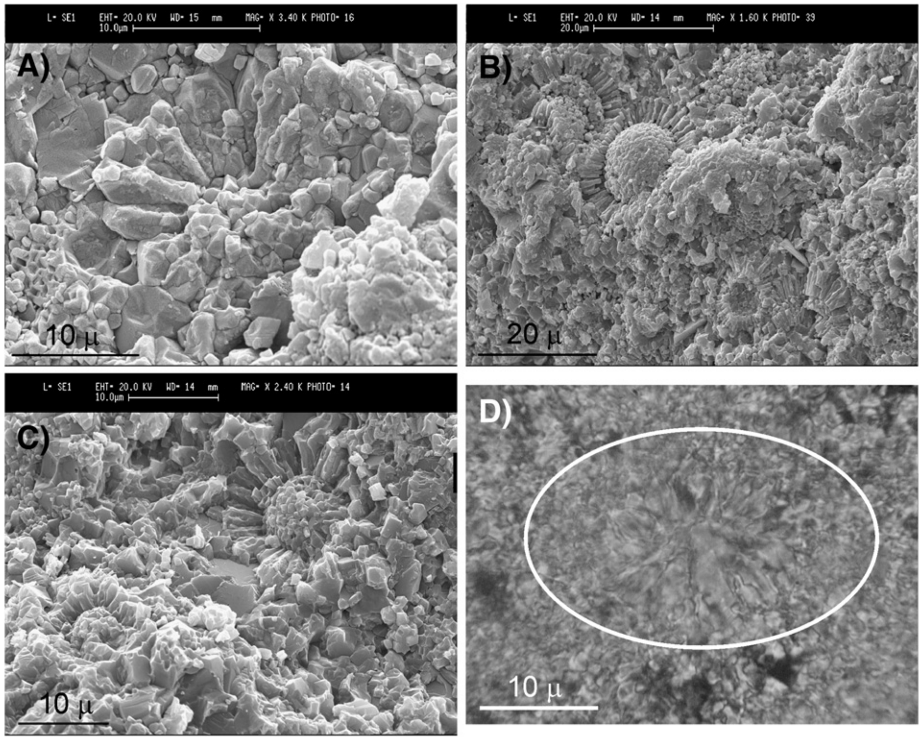


Fig. 6. Nannofacies of the lithostratigraphic units associated with the geological drowning; A) poorly preserved coccospheres with cement overgrowths, micarbs and unidentified coccoliths in the Corniola Fm. with whole coccospheres, and micarbs; B–C) whole specimens of *Schizosphaerella punculata* making most of the sediment, showing typical diagenetic alteration (Kälin, 1980) in the form of cement overgrowths, and micarbs in the condensed Corniola; D: remains of coccospheres observed in thin sections in the Calcare Massiccio B.

In the Mt Nerone area, the Gorgo a Cerbara section (Fig. 9A–E) displays the lower part of the north-facing marginal escarpment of the Mt Nerone PCP (see also Elmi, 1981; Immerz, 1985; Cecca et al., 1987a,b for bio-chronostratigraphic data). Here the drowning succession has an earliest Pliensbachian (early Carixian) age and is 10 to 15 m thick. *Tubiphytes*-like forms, nubecularid and microbial encrustations, are observed, suggesting an organic binding and stabilizing of sediment. Rudstone beds with remains of molluscs and echinoderms also occur. The drowning succession rests at a marked angular unconformity (onlap and downlap; Fig. 10) on an irregular paleoescarpment surface, made of pre-rift Calcare Massiccio Formation sealed by upper Sinemurian (Lotharingian) epi-escarpment pelagites. The top-surface of this drowning succession is also locally covered by unconformable condensed pelagites, of early Pliensbachian age (Ibex Zone). This complex is then enveloped by a major angular unconformity surface, being onlapped by middle–upper Pliensbachian (Corniola Formation) basin-fill pelagites, with slumps and turbidites.

Table 2
Results of the qualitative nannofacies analysis.

Lithostratigraphic unit	Figures	Provenance areas	Coccospheres	Coccoliths
Corniola Formation.	11a–c	Mt Acuto Burano Basin	Common poorly preserved *Schizosphaerella punctulata* Deflandre & Dangeard	Rare unidentified coccoliths
condensed Corniola	11d–i	Sabina Plateau Mt Rosato Mt Nerone (Gorgo a Cerbara)	Very abundant well preserved *Schizosphaerella punctulata*	
Calcare Massiccio B	11l–n	Sabina Plateau Mt Rosato Mt Nerone	Rare *Schizosphaerella punctulata*	Rare remains of schizospheres and *Mitrolithus*

The Mt Acuto High was a peculiar paleohigh, being cusp-shaped and devoid of any flat top (Marino, 2004a). This morphology has been interpreted by Santantonio and Carminati (2010) as having been produced by two closely-spaced, late Hettangian–early Sinemurian antithetic normal faults, intersecting within the Calcare Massiccio. Paleoescarpment-type contacts are ubiquitous, with unconformable contacts between the peritidal Calcare Massiccio, bearing scattered patches of epi-escarpment condensed pelagic deposits, and the younger basinal pelagites, up to the Lower Cretaceous Maiolica Formation (Fig. 11). The onlap of these basinal deposits encircles completely a core of Calcare Massiccio, whose dimensions are about 1.5×2 km when the post-Corniola units are stripped off. An unconformity-bounded drowning succession (Fig. 9L–M) drapes the lower part of the paleoescarpment (Calcare Massiccio B in Fig. 11). It is composed of clinoform beds, dipping 20 to 30° to the north and north-east when the Calcare Massiccio is restored to the horizontal, which rest unconformably on the Calcare Massiccio Formation and are onlapped by, or interfingered with, basinal cherty limestone [Corniola Formation; late Sinemurian (Lotharingian), Obtusum Zone; Dommergues et al., 1994]. The clinoforms are made of graded and laminated grainstone and packstone. Based on field geometries, the clinoform beds represent a wedge-shaped slope apron onlapping the paleoescarpment, similarly to the Lower Jurassic "Hierlatz facies" (Austrian Alps and Hungarian Bakony Mountains; Vörös, 1991). The bioclastic nature of these deposits, with algae being associated with echinoderms, sponges, molluscs and brachiopods in the carbonate factory, is evidence that the Mt Acuto paleohigh was still productive at photic depths soon after its birth (syn-rift and early post-rift stages). Carbonate production had to take place over a very small area in correspondence of the topographic culmination of the high. Three-dimensional growth of the carbonate factory was hampered by the ongoing tectonic deepening of surrounding areas, which provided the accommodation space for a clinoform apron. Intercalations of

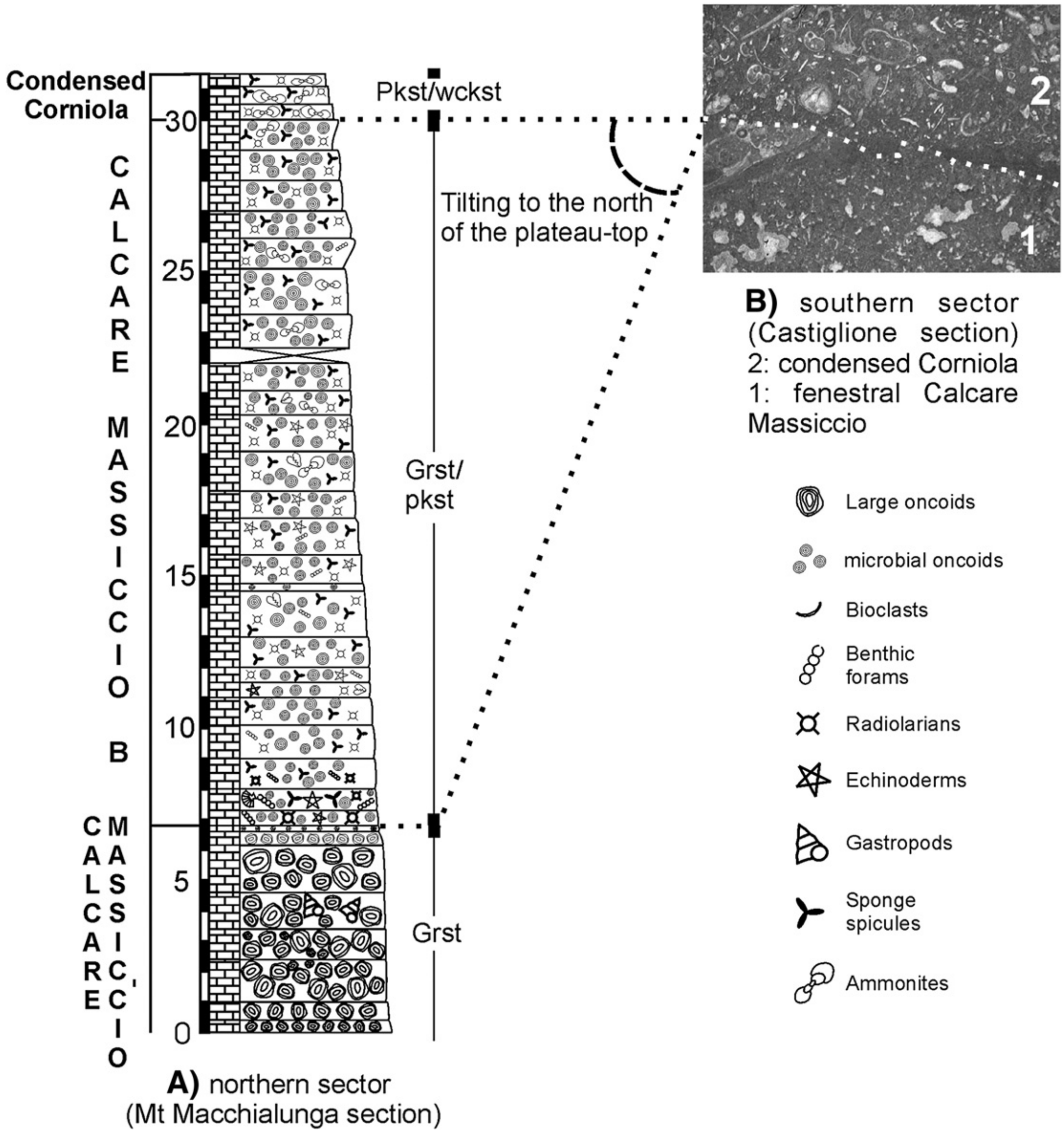


Fig. 7. Geological drowning on the Sabina Plateau. A) 25 m thick drowning succession in the northern sector. B) (thin section) drowning unconformity (white dots) capped by upper Pliensbachian condensed pelagites in the southern sector.

radiolarian-mudstone are interpreted as autochthonous pelagic drapes separating gravity flow deposits (see similar examples in Everts and Reijmer, 1995). Notably, at Gorgo a Cerbara, the younger epi-escarpment pelagites of the Ibex Zone are not covered by any Calcare Massiccio B deposits, confirming that benthic carbonate production had by then completely ceased.

4.4. Hangingwall-block rift basins: The Burano–Bosso Basin

The Burano–Bosso Basin, occupied by *ca* 400–600 m of Sinemurian to Tithonian sediments, marked the separation between the Mt Nerone and the Mt Acuto highs. Field outcrops of hanging-wall block Calcare Massiccio Formation are far less common in the region than their footwall counterparts because Neogene inversion has caused Jurassic structural highs to be preferentially overthrust and become exposed (Calamita, 1990; Bruni et al., 1997; Cannata, 2007). The geological drowning is here characterized by a drowning succession (Calcare Massiccio C, *sensu* Centamore et al., 1971), made of a minimum of 70 m (base not exposed; Figs. 12 and 13A) of very thick-bedded wackestone to packstone, with oncoids (up to 2 cm in size), peloids, abundant small-sized gastropods, bivalves, echinoderms, and brachiopods (Fig. 13B–F). Sponge spicules and radiolarians are the main components of the microbiofacies in the matrix. Foraminifera are mostly lagenids and spirillinids. Oncoids commonly have mollusc and echinoderm fragments at their nuclei. Any trace of peritidal cyclicity is missing, so these are entirely subtidal sediments, probably deposited at depths around fair-weather wave base within the photic zone, based on the presence of oncoids and the accompanying benthic fauna.

In the subsurface, in the Burano 1 Well (Martinis and Pieri, 1964), this drowning succession rests on shallow-water fenestral limestone rich in *Thaumatoporella parvovesiculifera* (Raineri), also bearing evidence for episodes of subaerial exposure (pisolitic crusts and microstalactitic cements) (Marino, 2004a). The boundary between the pre-drowning succession and the drowning succession cannot be placed precisely, but the total thickness must be less than 135 m.

Overlying the Calcare Massiccio C, the lowest post-drowning beds seen in outcrop (Corniola Formation;) (Figs. 12 and 13G and H) are composed of cherty wacke-mudstone with ammonites, brachiopods, echinoderm remains, bivalves, small-size gastropods, radiolarians and sponge spicules, alternating with detrital beds including graded and laminated levels, interpreted as turbidites, breccias and slumped beds.

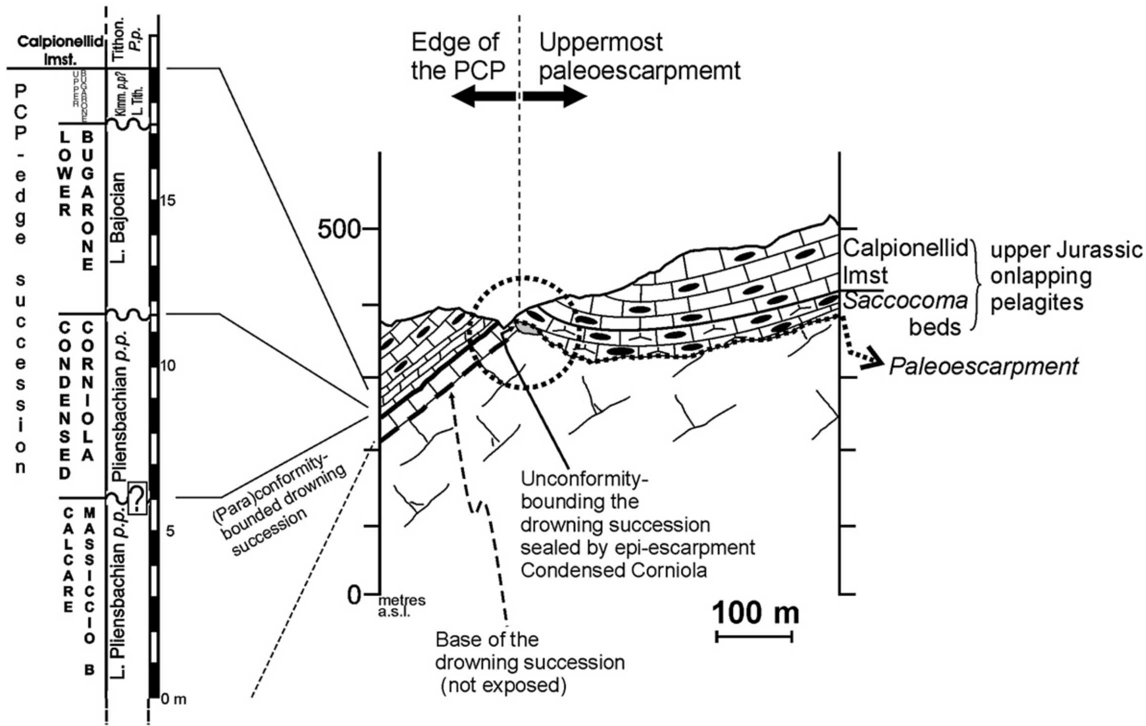


Fig. 8. The geological drowning at Fosso dell'Eremo (Mt Nerone PCP — upper paleoescarpment/PCP-edge): cross-section, and litho/chrono-stratigraphic correlation.

They are early Sinemurian in age (Bucklandi Zone; Passeri and Venturi, 2005).

Stratigraphy and sedimentology indicate the drowning of the Calcare Massiccio Formation platform and birth of the Burano Basin was a result of rift-related tectonics occurring around the Hettangian/Sinemurian boundary. Besides total thickness and lithologic composition of the local Jurassic succession, indicating a basin environment, the relatively sudden change to a style of sedimentation dominated by gravity flow is evidence for continued hangingwall subsidence in a syn-rift regime. In other localities closer to the margins of the multitude of basins that were born at the time, the Corniola Formation bears megabreccias and giant (up to >1 km across) olistoliths made of peritidal Calcare Massiccio Formation (Sabina Basin; Galluzzo and Santantonio, 2002). They document the birth of submarine escarpments corresponding to master faults at this early stage. Predating severe tectonic fragmentation and development of a high-relief submarine topography, the drowning succession (Calcare Massiccio C) described above suggests deposition in a short-lived carbonate ramp setting corresponding to an embryonic platform to basin transition.

4.5. Geochemical data — A review

Stable isotope curves ($\delta^{13}C$) have recently been published by Morettini et al. (2002) and by Marino (2004a), based on sampling through drowning successions on top of structural highs in Northern Apennines (Fig. 14), including some of the localities mentioned in this paper (Mt Rosato, Mt Nerone, and the Sabina Plateau). Morettini et al. (2002) and Marino (2004a) note a positive shift (*ca.* 1‰) in the $\delta^{13}C$ curve at the Calcare Massiccio B/condensed Corniola boundary, preceded by a marked negative shift, falling within the lower Pliensbachian Ibex Zone and corresponding with the onset of pure pelagic sedimentation. Marino (2004a) also notes a positive shift (*ca.* 0.5–1.5‰) at the Calcare Massiccio Formation/Calcare Massiccio B transition on the Sabina Plateau and at Mt Rosato. A possible analogue is described by Immenhauser et al. (2003) in the Carboniferous of Asturias, where a positive shift in $\delta^{13}C$ marks the transition from an inner lagoon/tidal flat environment to open marine conditions. Importantly, Morettini (1998) and Morettini et al. (2002) report correlative data from coeval basinal successions, like that of the Burano–Bosso Basin, lying south-east of the Mt Nerone PCP, where the positive shift can be up to 1.5‰, peaking in the middle of the Ibex Zone. This shift corresponds to a sedimentological turning point in the succession, marked by a halt in the sourcing of any gravity flow material of shallow-water origin that was due to shut-off of the local benthic carbonate factory of neighbouring Mt Nerone.

The available regional dataset is far from complete, and the curves from Mt Macchialunga (Sabina Plateau) and Cava Bugarone (Mt Nerone PCP) are potentially ambiguous as they contain peaks of the same amplitude as the Ibex Zone shift within the Calcare Massiccio B. Also, biostratigraphic control in the Calcare Massiccio and Calcare Massiccio B is sparse, and precise boundaries for ammonite biozones are often not easily placed. Having said that, however, it must be noted that a lower Ibex Zone *Tropidoceras*-dominated assemblage (Gemmellaroi Zone, *Tropidoceras mediterraneum* "biovent" in Faraoni et al., 1996) occurs everywhere corresponding with a peak in the $\delta^{13}C$ curve, and that in three out of four structural-high sections shown in Fig. 14 this corresponds in turn to the base of the Condensed Corniola. The same peak is well seen in the Burano–Bosso Basin log. Based also on data given by Morettini (1998) and by Rosales et al. (2001) for the Apennines and Spain (Subbetic domain and Cantabrian Basin), the trans-regional significance of the relative maximum in the Ibex zone was put in evidence by Jenkyns et al. (2002). This subject will be more amply discussed in a dedicated section below.

5. Examples from Western Sicily

At Mt Kumeta (Trapanese Domain, Fig. 1), a Jurassic escarpment is exposed, bordering an ancient PCP whose top is not preserved (Di Stefano and Mindszenty, 2000; Di Stefano and Mallarino, 2002; Di Stefano et al., 2002a; Marino et al., 2002), and whose morphology is unknown. During the Jurassic, this escarpment acted as a stepped margin, with only minor sediment preservation due to tectonic/gravitational instability. Di Stefano et al. (2002a) and Mallarino (2002) have addressed the possible causes for the drowning event.

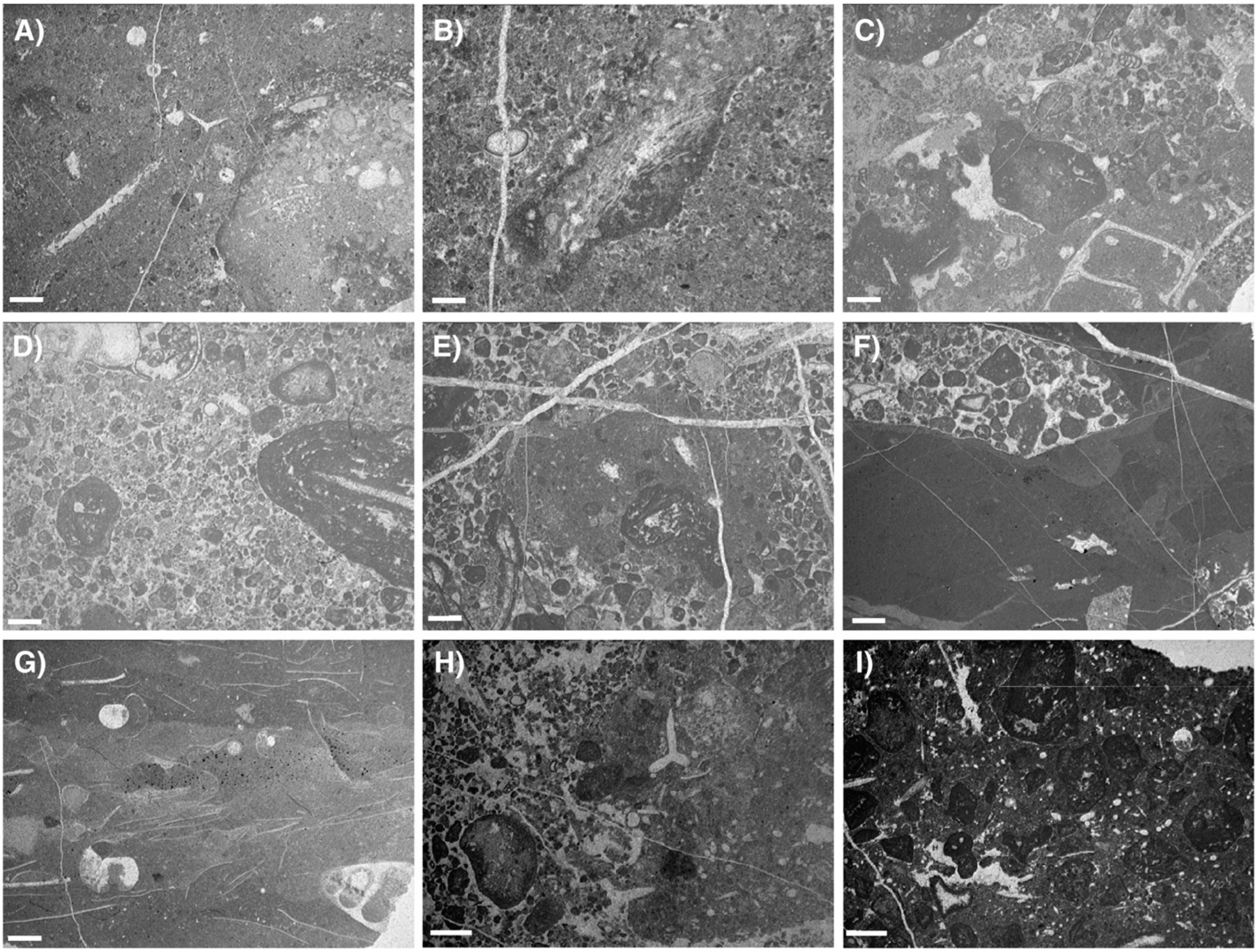


Fig. 9. Microfacies of Calcare Massiccio B along the flanks of the structural highs (scale bar = 1 mm). The Gorgo a Cerbara Section: A) floatstone with sponge spicules, bioclasts and micritic intraclasts (right); B) peloidal floatstone with a micrite clast(?) containing an algal stem; C) rudstone with ammonite bioclasts, probable reworked microbial oncoids, sponge spicules, peloids, and benthic foraminifers; D) packstone with micro-oncoids and larger Nubecularid microbialite encrusting possible bivalve fragment, and gastropod remains (upper part) ; E) micritic intraclast with radiolarians, set in a micro-oncoidal grainstone matrix; F) interbedded condensed Corniola: burrowed radiolarian-mudstone with angular clast of Calcare Massiccio grainstone ; G) ammonite-rich middle Carixian condensed Corniola, burrowed. Mt Acuto area: H) micro-oncoidal/peloidal grainstone (left), with "cloud" of peloidal micrite rich in sponge spicules; I) floastone with irregular micro-oncoids, often *Tubyphites*-associated microbialites, set in a sponge spicule-rich mud matrix, also with small-size ammonite.

The relevant geological drowning is represented by unconformity-bounded drowning successions, composed of earliest Pliensbachian deposits with a litho-biofacies similar to the Calcare Massiccio B [Di Stefano et al. (2002a) and Mallarino (2002)], and by lower-upper Pliensbachian encrinites (dominantly packstones). This facies occurs locally, filling erosional pockets on the escarpment surface. Otherwise the encrinites rest directly on the peritidal substrate. These encrinites compose a basinward thickening wedge, formed by export of sediment from the top of the structural high (Di Stefano et al., 2002a). The drowning succession is topped by a very irregular surface (Di Stefano and Mindszenty, 2000) onlapped by the condensed pelagic Ammonitico Rosso, marking an angular unconformity (see Fig. 16D). The characteristics and the growth mode of the drowning succession of the Mt Kumeta paleostructure are consistent with those of the drowning successions in some epi-escarpment settings of the Central Apennines.

The Sciacca Plateau (Fig. 1) was a Jurassic pelagic plateau of the Saccense Domain (south-western Sicily) (Baldanza et al., 2002; Di Stefano et al., 2002b; Muraro and Santantonio, 2002, 2003; Marino et al., 2004). The best geological evidence for drowning of the plateau is a regionally widespread paraconformity, with the upper Bajocian/Bathonian deposits of the Ammonitico Rosso lying directly on the Inici Formation (Marino et al., 2004; Muraro and Santantonio, 2002, 2003). Locally the unconformity is angular in nature (Fig. 15). Di Stefano et al. (2002b) have interpreted this geometry as being a product of synsedimentary extension and rollover of the underlying peritidal substrate. During a subsequent phase of subaerial exposure, predating the drowning, the tilted beds were eroded producing the unconformable surface. Post-drowning beds are geometrically concordant with the erosional surface, that is the drowning unconformity. While Bajocian deposits are generally found at the base of the plateau-top pelagic succession, discontinuous lenses of older pelagites can locally be observed, sealing the drowning unconformity. These are 0 to 30 cm-thick crinoid-rich mud-to wackestones, correlatable to equivalents of known Pliensbachian age, overlain by a laterally discontinuous Fe–Mn crust and an up to 40 cm-thick condensed level bearing late Toarcian/Aalenian ammonites (Di Stefano et al., 2002b; Pallini et al., 2004). These findings demonstrate that, despite the common occurrence of Bajocian pelagites directly capping the eroded platform limestone, the age of drowning of the Sciacca Plateau is actually at least 20 million years older (?Early Pliensbachian). This strongly suggests that much of

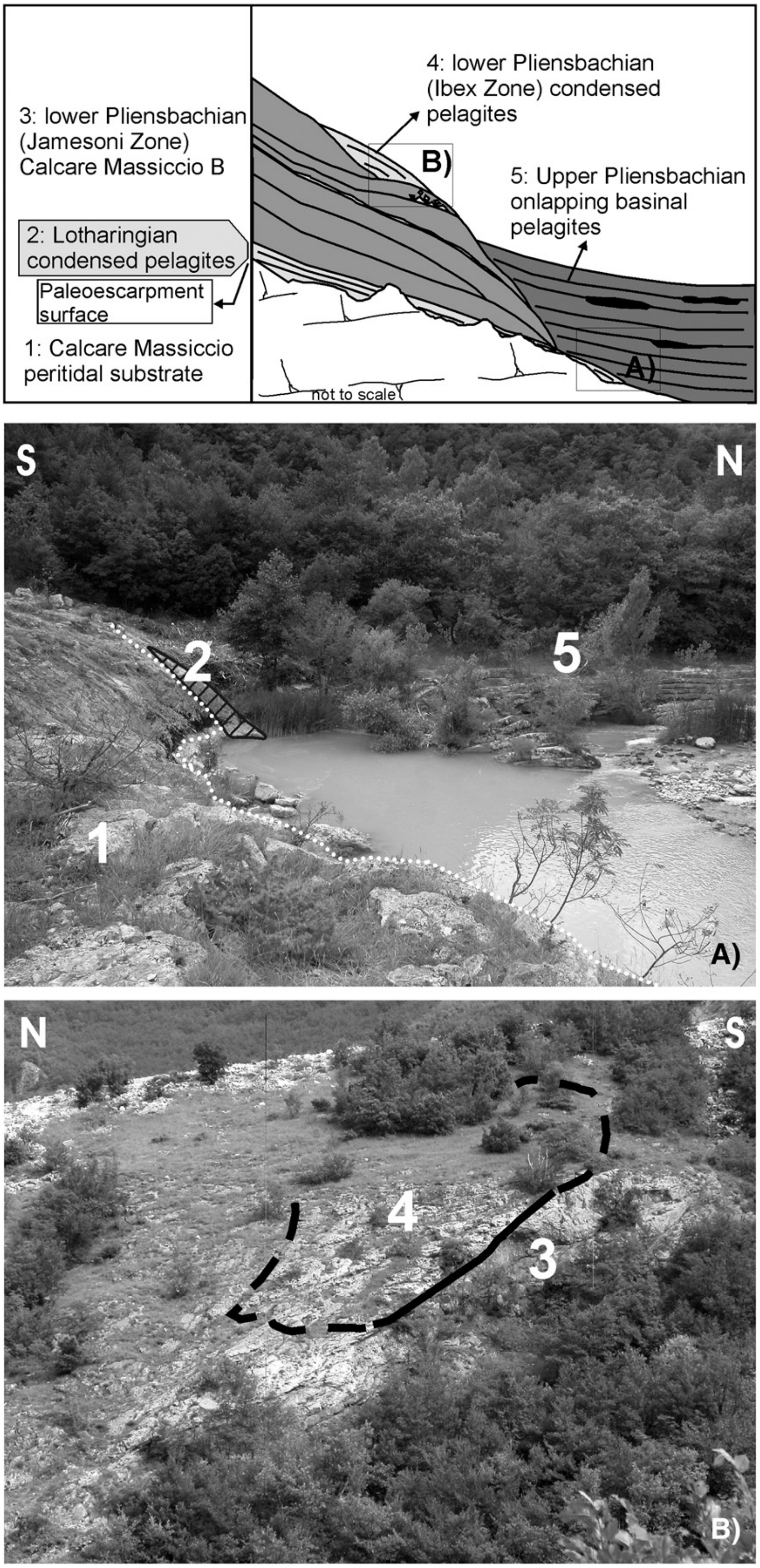


Fig. 10. Schematic reconstruction, and partial field views, of the stratigraphy and geometries at the lower palaeoescarpment of the Mt Nerone PCP. Numbers correspond to lithostratigraphic units shown in upper diagram; A) and B) in the line drawing represent the part of the succession pictured in the photos; white dotted line in photo A) is the trace of the escarpment unconformity.

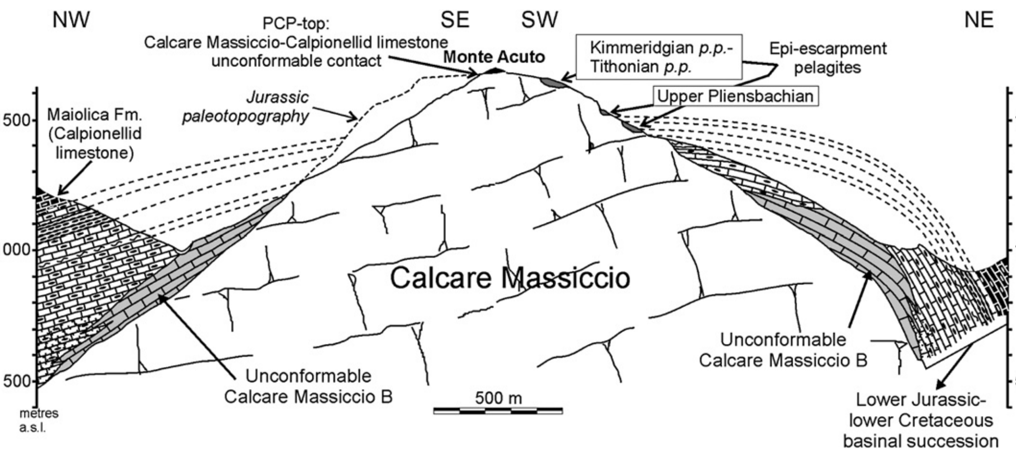


Fig. 11. Geological section of Mt Acuto. The Calcare Massiccio B is an unconformity-bounded drowning succession.

the Sciacca Plateau was dominantly non-depositional (where the above cited discontinuous deposits are missing), and/or being subjected to erosion, for several million years after demise of shallow-water carbonate production.

6. Discussion — Parameters associated with a geological drowning

The main characteristics associated with the geological drowning can be summarized, and are briefly discussed, as follows.

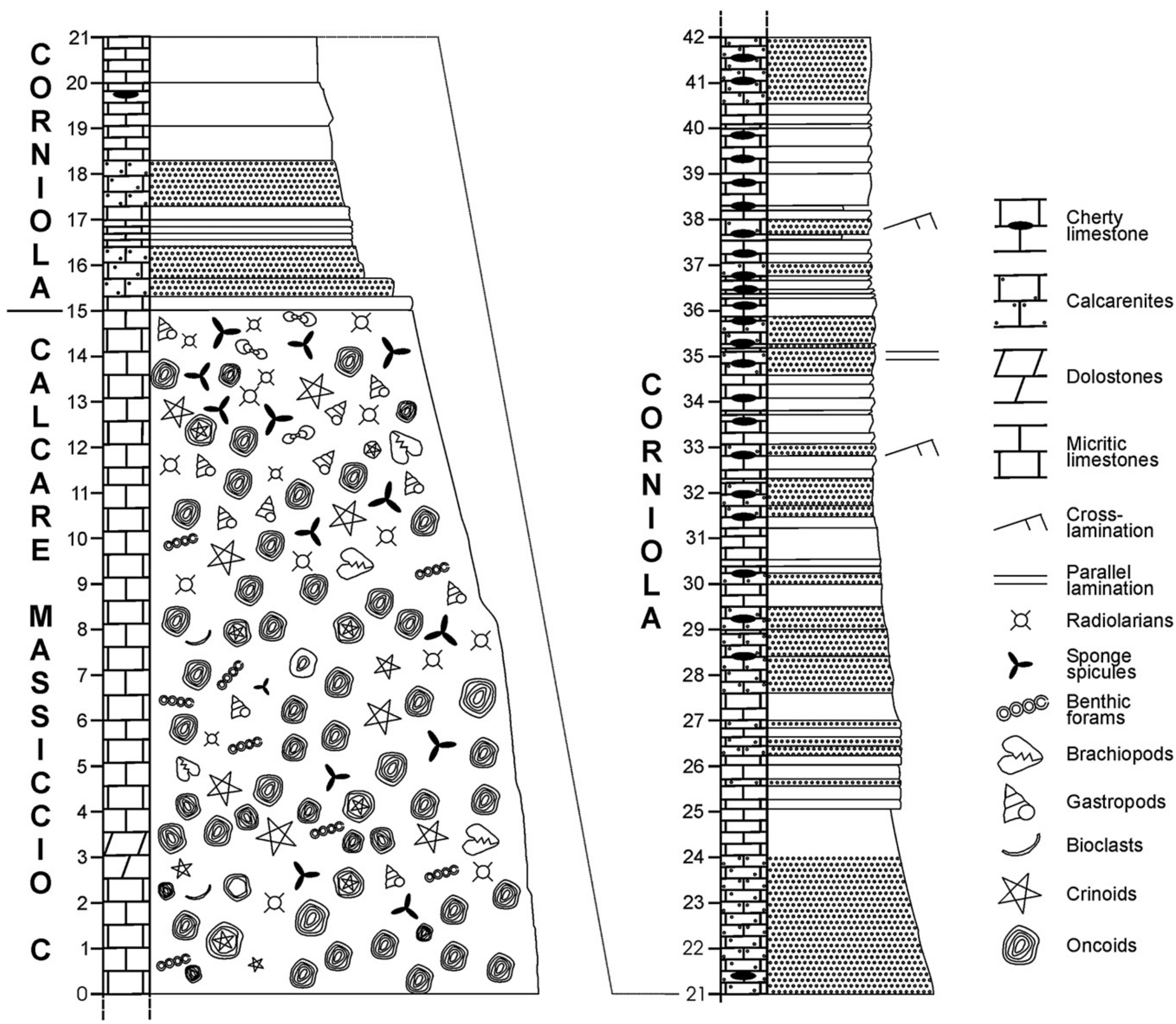


Fig. 12. Log of the Ponte Grosso section including the uppermost 15 m of Calcare Massiccio C and lower part of the Corniola Formation of the Burano–Bosso Basin.

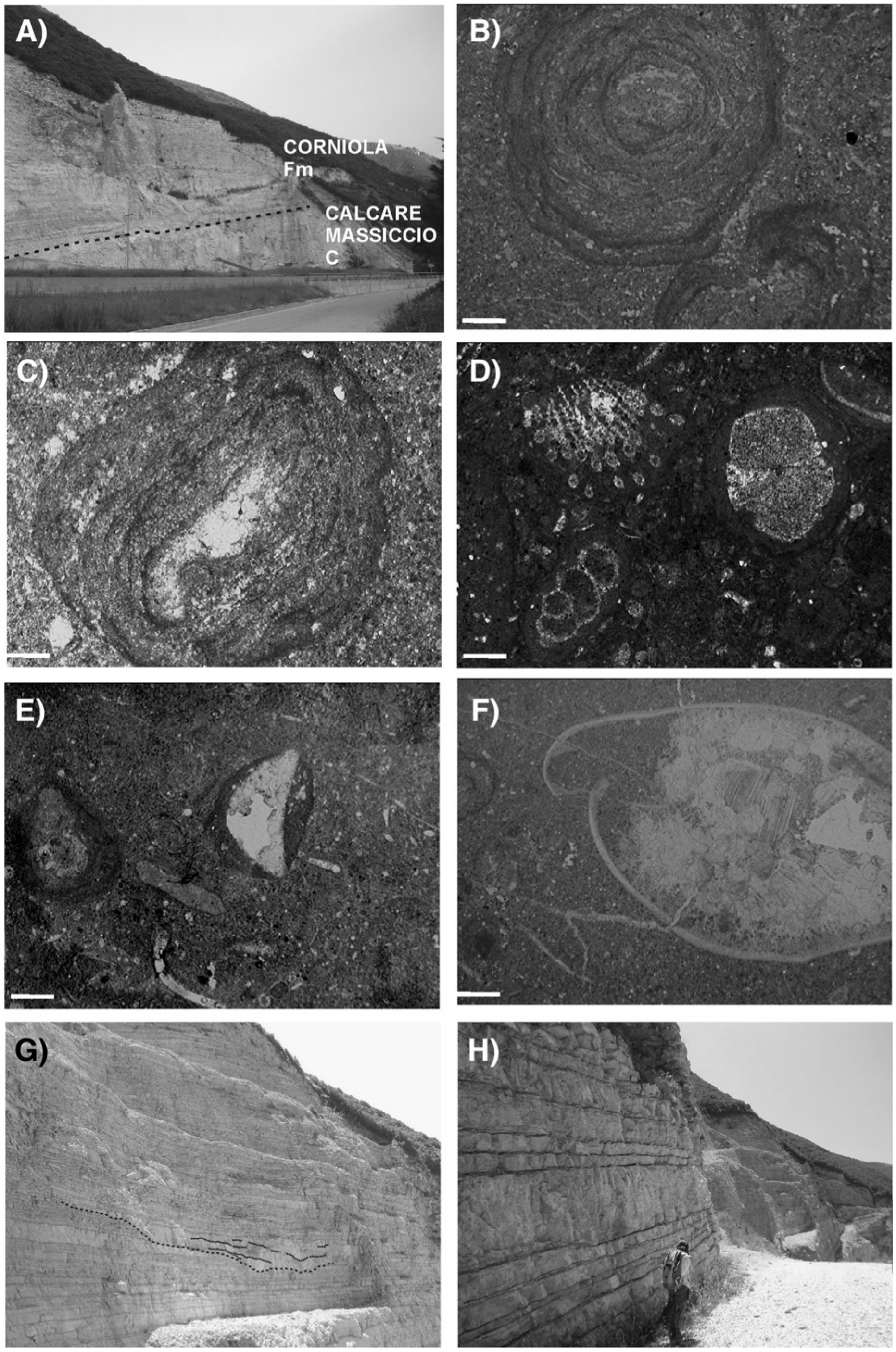


Fig. 13. Geological drowning of a hanging-wall basin, as exposed in the Burano Gorge: A) the Calcare Massiccio C/Corniola boundary exposed on a quarry wall. Microphotos of the drowning succession (Calcare Massiccio C; scale bar = 1 mm): B), C) typical large oncoids of the Calcare Massiccio C, with irregular dark laminae, locally embedding possible Nubecularid forams (arrowed); D) small gastropod and echinoderm (crinoid and echinoid spine) fragments, with micrite envelopes; E) wackestone with bioclasts having micrite envelopes, and sponge spicules; F) whole brachiopod, with geopetal infill. Burano Quarry, Corniola Fm.: G) thin-bedded pelagites, interbedded with thicker-bedded turbidites, with cut-and-fill structures and associated slumps; H) interbedded pelagites and thicker resedimented beds, also with scoured bases.

6.1. Lithology and texture — Intrabasinal highs

In the Italian Jurassic, as well as in other ancient continental margins of the Mesozoic Tethys, the lithologic change associated with a geological drowning is a shift from shallow-water platform carbonates to pelagic carbonates. With drowning unconformities on intrabasinal highs, this corresponds to a switch to mud-dominated textures, most commonly thinly bedded lime mudstones and condensed cephalopod-rich wackestones, sometimes nodular. These are considered typical of the PCP environment. In the Southern Alps (e.g. Trento Plateau) and in Western Sicily Rosso Ammonitico-type deposits occur locally with stromatolitic laminations (Massari, 1983).

Drowning successions are documented in different regions of the Italian Jurassic and elsewhere. Drowning successions are up to several tens of metres thick (Fig. 16A), made up of 0.2 to 1 m thick beds, with tabular geometries, typically having packstone, and subordinate wackestone, textures. These successions are often made of echinoderm (crinoids, echinoids)-rich calcarenites, sometimes cross-bedded (e.g. Western Sicily; Jenkyns, 1971), and they often have stacked mineralized hardgrounds (see also Kendall and

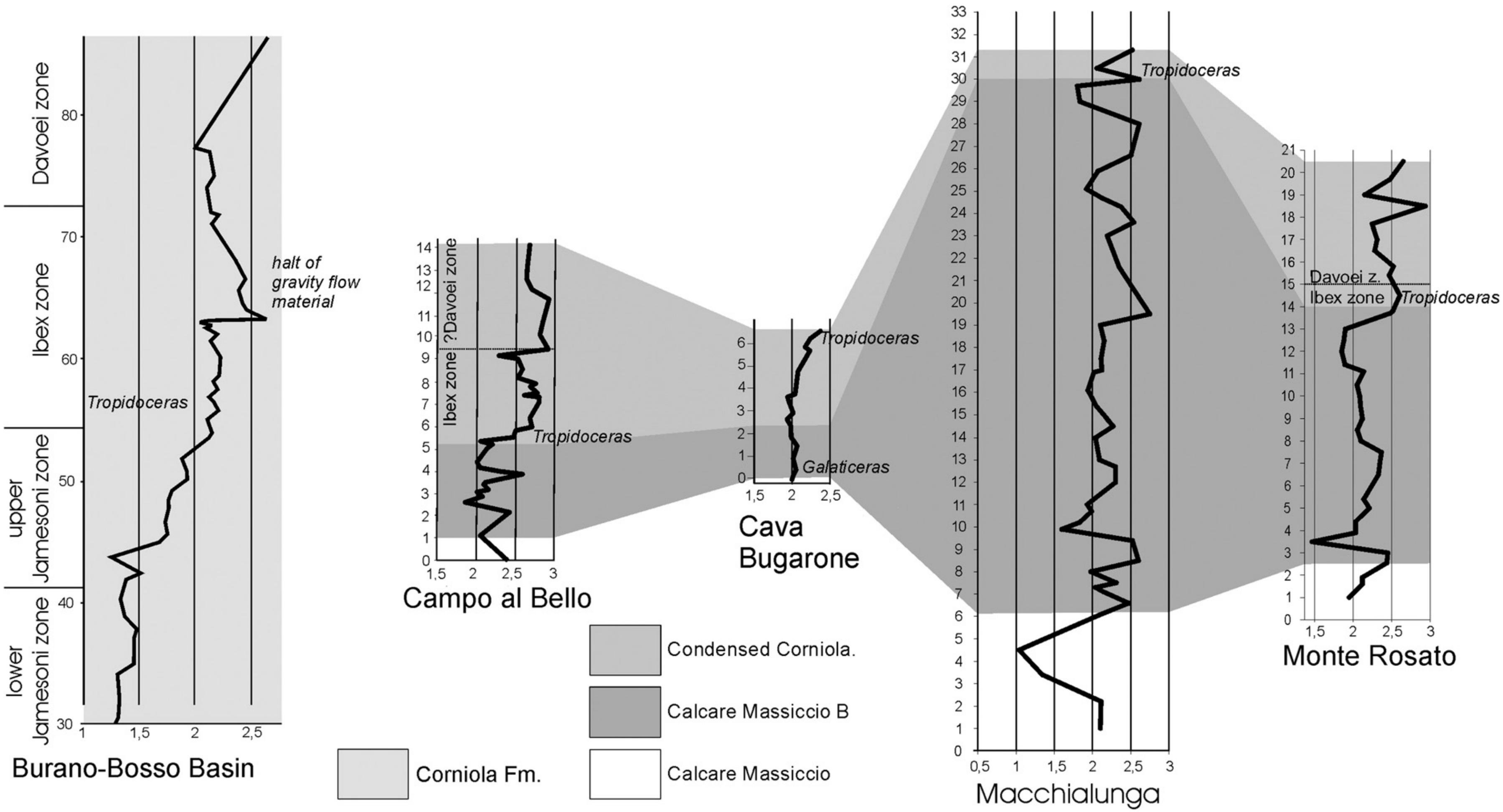


Fig. 14. Correlated $\delta^{13}C$ curves across the Central Apennines. The Campo al Bello and Cava Bugarone curves (both sections are in the Mt Nerone area), and the Burano–Bosso Basin curve after Morettini et al. (2002); Monte Rosato and Macchialunga (northern part of the sabina Plateau) after Marino (2004a,b). The occurrence of *Tropidoceras* sp. indicates the Ibex Zone (Carixian).

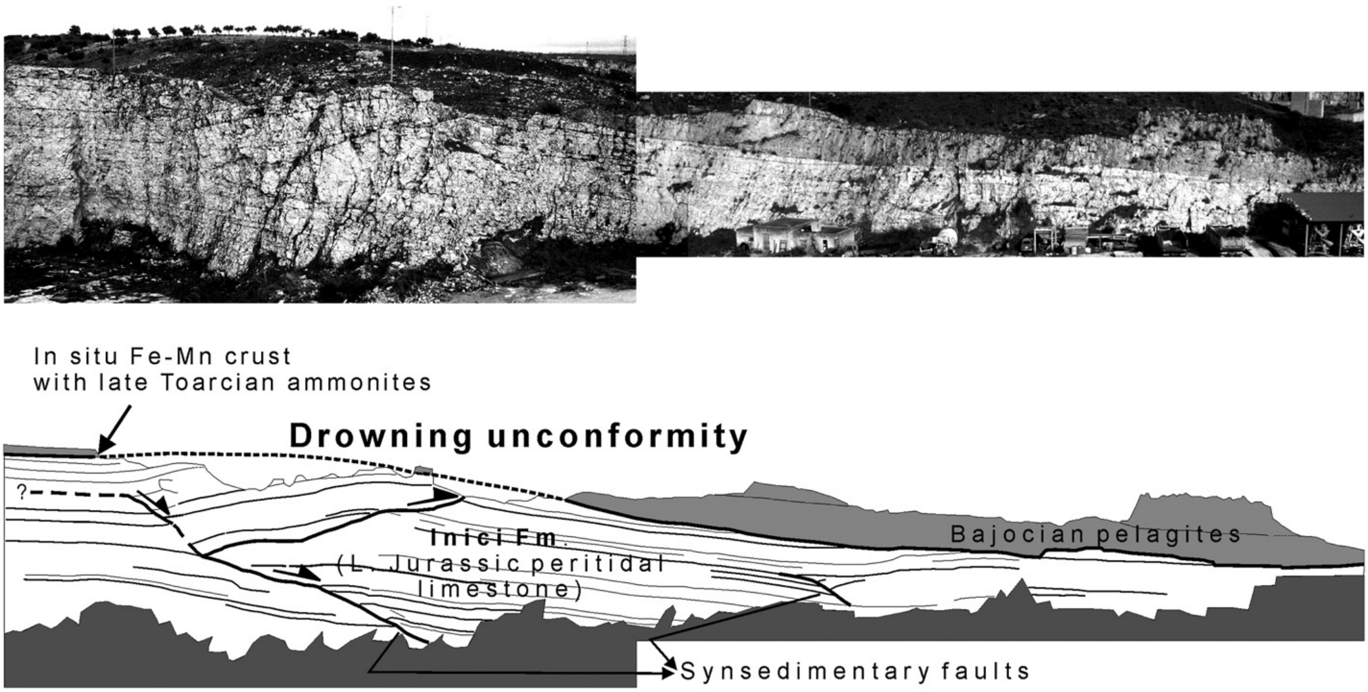


Fig. 15. Photo and line drawing of the geological drowning of the Sciacca Plateau, as exposed on a quarry wall in the Sciacca area. Extensional pre-drowning tectonic structures are evidenced (see Di Stefano et al., 2002b).

Schlager, 1981; Bova and Read, 1987; Erlich et al., 1990; Zempolich, 1993; Schlager, 1994). The Pliensbachian drowning succession in the Caloveto Group of north-east Calabria (Southern Italy; Santantonio, 1993, and bibliography therein) is a pink packstone exceptionally rich in rynchonellid brachiopods, passing to an encrinite. Based on descriptions given by Schirolli (1997), the drowning succession of the Botticino High in Lombardy (Southern Alps) is largely represented by a crinoidal grainstone, partly coeval with the Calcare Massiccio B. Elsewhere in Western Tethys, Blomeier and Reijmer (1999) describe a late Pliensbachian–early Toarcian drowning succession from the High Atlas of Morocco, where the switch to the "drowning phase" is marked by high-energy, above storm-wave base grainstone facies.

6.2. Lithology and texture — Hangingwall basins

The onset of the drowning succession in basinal sections of the Apennines is similarly marked on top of the pre-downfaulting, shallow-water cyclothemic limestone by a change to packstone and wackestone textures, displayed in metre-scale beds. The overlying early post-drowning deposits are dominantly consisting of material resedimented through gravity flows (turbidity currents and slumps), with talus deposits at the toe of newly formed submarine escarpments, since neighbouring structural highs were still productive (Bernoulli, 1969; Centamore et al., 1971; Bernoulli and Jenkyns, 1974; Cantelli et al., 1978; see also Eberli, 1987, for Alpine examples).

6.3. Types of contacts at drowning unconformities

Drowning unconformities occur in two main fashions:

1. As a surface separating parallel beds, and parallel to them (paraconformity). This is the most common geometry in the Apennines. (Fig. 16B)
2. As an angular unconformity. (A) An erosional surface truncates tilted peritidal beds, and is overlain by pelagic deposits generally parallel to it (Figs. 15 and 16C); (B) an erosional surface truncates either the pre-drowning beds or the drowning succession, and is unconformably overlain by untilted post-drowning condensed pelagites (onlap; see Di Stefano and Mindszenty, 2000; Fig. 16D).

Angular drowning unconformities are common wherever drowning occurs coincident with, or postdating, a phase of tectonic activity (see section with Sicilian examples). Schlager (1989) describes examples where the drowning unconformity is traced across a platform/slope system, with sandy slope flanks of drowned platforms being onlapped by pelagic/hemipelagic mud. These examples of angular unconformities best apply to platforms that are not bounded by escarpments, being a result of the contrasting grain-size and angle of repose of pre-drowning and post-drowning sediments. As such, they do not have to be related to synsedimentary tectonics (see also Blomeier and Reijmer, 1999).

6.4. Morphology of the drowning surface

In outcrop, on a centimetre to 100s of metres scale, the morphology of a drowning unconformities can range from perfectly flat, sharp surfaces, to pitted bioeroded and/or mineralized surfaces, to highly irregular disconformities. Sharp, regular surfaces are often found to correspond to long stratigraphic hiatuses (Fig. 16E — Bajocian/Pliensbachian contact), being also the product of a long-lasting phase of erosion. In those cases where platform drowning was preceded by emersion (*scenario 3* in Schlager, 1998), the possibility for the drowning surface to be either an irregular palaeokarst-related disconformity, or a perfectly flat surface, depends not only on duration of the subaerial exposure and on climate, but also is due to erosion and abrasion on the transgressive surface, such as that produced by coarse bioclastic sediment (Molina et al., 1999). These sediments may end up being locally preserved only in small erosional pockets at the unconformity, or form wedges across the drowned platform or on its slopes (see the Trento Plateau to Lombardy Basin transition in the Southern Alps; Barbujani et al., 1986).

6.5. Age of drowning

Age data through the drowning succession provide information on the duration of the process which ultimately led to dominance of the pelagic carbonate factory. By contrast, the age of the lowest bed capping a drowning unconformity only defines, at best, the timing of process completion. A common puzzle is that this age, which is generally derived from ammonite biostratigraphy, is often strongly variable over very short distances across a platform top, producing stratigraphic gaps of various duration (up to several millions of years). This is not an evidence for any diachronous drowning, but rather an indication that the sediment preservation potential was variable on the platform. The onset of conditions suitable for a sediment preservation could be delayed in situations such as the proximity of platform edges, and/or where winnowing by currents was strongest. In addition, the top beds of the platform succession might not represent the last episode of neritic sedimentation if a phase of subaerial (Molina et al., 1999), or submarine, erosion predated the drowning. The paper by Bosence et al. (2009) represents a recent attempt to perform foraminiferal biostratigraphy, in conjunction with Sr isotope stratigraphy, across several examples of peritidal-to-pelagic (or hemipelagic) transitions, aimed at dating the topmost pre-drowning strata.

6.6. Paleoecology

Fossil associations are the main indicators of changed environmental conditions. Following drowning, typical platform associations are replaced by nektonic and planktonic organisms (cephalopods, planktonic foraminifera, radiolarians, etc.), with mud-size sediment being almost entirely supplied by the “planktonic factory” (Schlager, 2003). Before that, certain heterotrophic benthic organisms (e.g. sponges, brachiopods, crinoids, gastropods, etc.) can still be abundant in the drowning succession and in the early post-drowning deposits, and this is generally interpreted as a product of change from oligotrophic to mesotrophic conditions (Morettini et al., 2002; Mutti and Hallock, 2003, and bibliography therein). Progressive changes within the benthic fossil associations are often observed through drowning successions (Carannante et al., 1988; Zempolich, 1993; Morettini et al., 2002; Racki et al., 2002; Whalen et al., 2002). *Tubiphytes*-like microbialite-associated foraminifera, which start in the pre-drowning succession in association with green algae, are typical components of drowning successions, and their relative abundance gradually decreases upsection. Oncoid-dominated subtidal facies, besides representing the deeper-water intervals of peritidal cycles, are sometimes observed to herald platform drowning (Bosence et al., 2009).

Curves of stable oxygen and carbon isotope variations within stratigraphic successions are used to highlight changes in the sea water environment (temperature, circulation, productivity, etc.) that are generally recorded at super-regional or global scale, often linked with climate change (Jenkyns and Clayton, 1986; Jenkyns, 1988; Hudson and Anderson, 1989; Marshall, 1992; Weissert and Mohr, 1996; Weissert et al., 1998; Morettini et al., 2002). This is for example the case with greenhouse periods, during which rivers discharge a heavier load of organic matter into marine basins, raising their trophic levels and altering carbonate ecosystems as a result (Wortmann and Weissert, 2000). The δ^{13}C curves often show positive shifts at drowning turning points, as expressed by facies change.

7. Sedimentary environment(s) of footwall-block drowning successions

According to Centamore et al. (1971), the Calcare Massiccio B (= drowning succession in this paper) was deposited on structural highs, in shallow water (intertidal to subtidal zone) environments connected with the open sea. This drowning event was considered to be a consequence of the gradual deepening of structural highs. Farinacci (1970) speculated that the drowning could be linked with environmental changes due to the arrival of cold water masses following Early Jurassic tectonics and the opening of new seaways. Bice and Stewart (1990) attempted a re-evaluation of the “Apenninic drowning”. In their interpretation, the whole PCP succession (lower Pliensbachian to lower Tithonian p.p.) is seen as an “incipient drowning”, while “complete drowning” is thought to have occurred only in the Tithonian, the calpionellid-limestone of the Maiolica Formation being the lowest post-drowning deposits. This interpretation is based on the fact that relatively shallow-water biota (deep photic encrusting microsolenid corals; Nicosia and Pallini, 1977; Gill et al., 2004, and bibliography therein) were able to thrive on PCPs as late as during Tithonian times. This is therefore a bathymetry-dependent, rather than carbonate-factory dependent, definition of drowning, and as such it does not take into account the change to dominantly pelagic sedimentation seen in the Pliensbachian, focussing instead on how PCPs failed to sink into very deep water during the Jurassic, a feature that is paleontologically documented by the above mentioned coral occurrences all across Northern Apennines (Gill et al., 2004).

7.1. Paleontological data

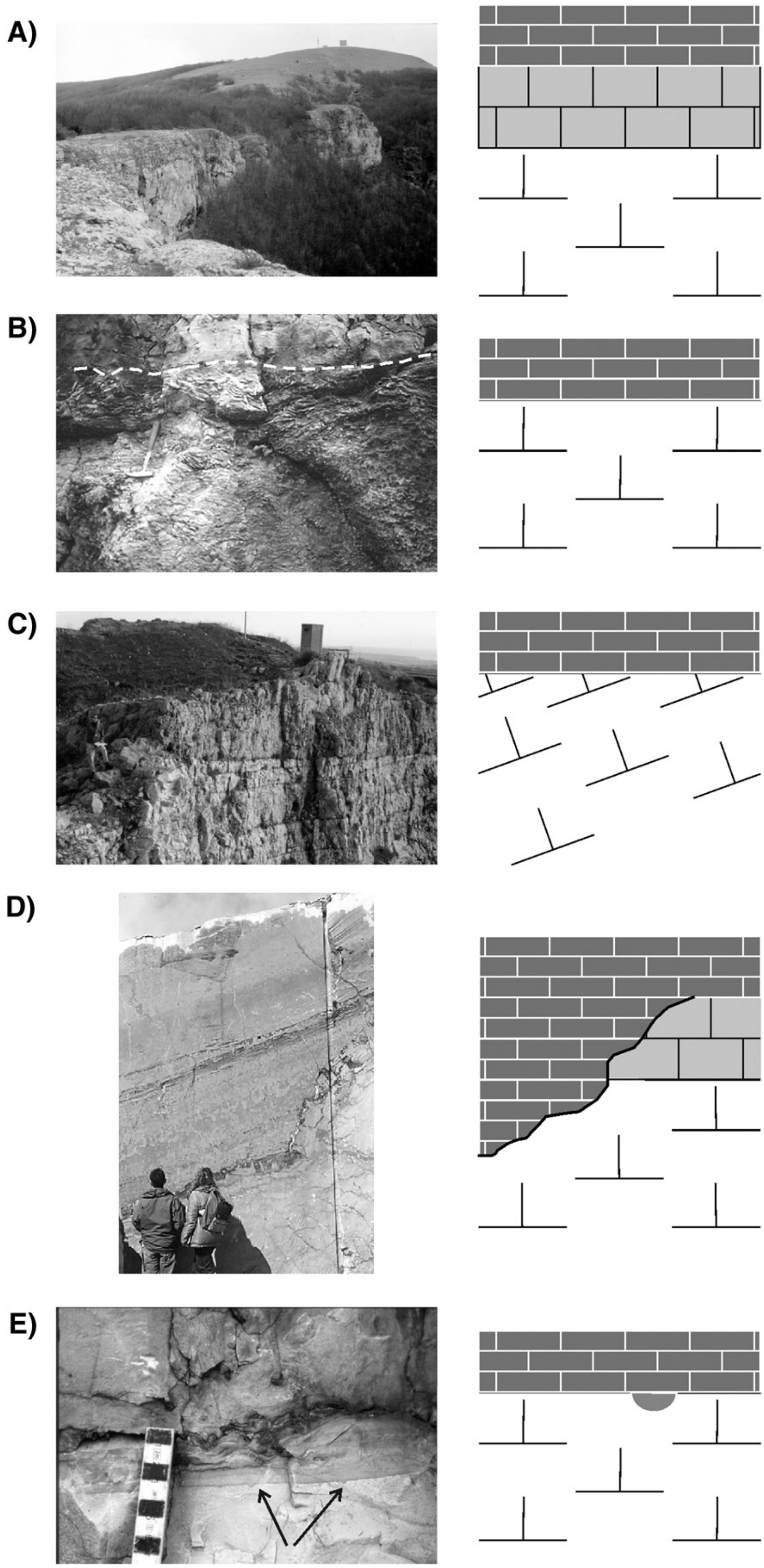
Contrasting the paleontological content of the pre-drowning and drowning succession carbonates provides some useful information in a paleoenvironmental key.

The pre-drowning is characterized by the dominance of calcareous algae, mostly dasycladaceans, codiaceans and solenoporaceans. The typical forms *Palaeodasycladus mediterraneus* (PIA), *Thaumatoporella parvovesiculifera* and *Cayeuxia* sp. are abundant. Healthy algal activity is also suggested by the presence of common large oncoids. Micritization of oncoids documents boring by endolithic algae.

Calcareous algae occur also in the drowning succession, being locally abundant at its base where they commonly encrust and bind other organisms. Besides algae, the prominent change in macrofossil assemblages at the base of drowning successions is marked by the more common occurrence (or first appearance) of organisms — such as echinoderms (echinoids and crinoids), brachiopods, sponges (including sphinctozoans, and other calcareous sponges, along with spicules belonging to siliceous sponges), bivalves, gastropods and ammonites — that are less common or missing (e.g. sponges and ammonites) in the pre-drowning stage. According to Nocchi et al. (1999), the composition of the foraminiferal assemblage in the Calcare Massiccio B (lower part of their “Assemblage A”) is comparable to that observed in coeval epicontinental European seas at lower-middle shelf depths (<100 m). However, the most distinctive feature of this unit are abundant micritic envelopes around individual bioclasts or forming aggregates. Forms belonging to the enigmatic genus “*Tubiphytes*” (a nubeculariid foraminifera, according to Dupraz and Strasser, 2002; a miliolid foraminifera, according to Schmid, 1996) can be abundant and are often associated with millimetre sized micro-oncoids (*sensu* Flügel, 2004; see also microbial oncoids, Reolid et al., 2004). *Tubiphytes* is commonly interpreted as light-dependent [Schmid (1996) suggested that *T. morronensis* (CRESCENTI), a Late Jurassic species, contained endosymbiontic algae] and is a widespread genus in shallow water, often in reef facies, through geologic time (Massari and Dieni, 1983; Senowbari-Daryan and Flügel, 1993). An alternative view is that of Dupraz and Strasser (2002), who question the light dependence of *Tubiphytes* and allied microbialites, these latter being seen as of probable bacterial origin.

7.2. Sedimentological data and paleoecology

The inception of drowning successions on intrabasinal highs in the Apennines is interpreted as being due to the small-scale fragmentation and dramatically changed water circulation around, and on, the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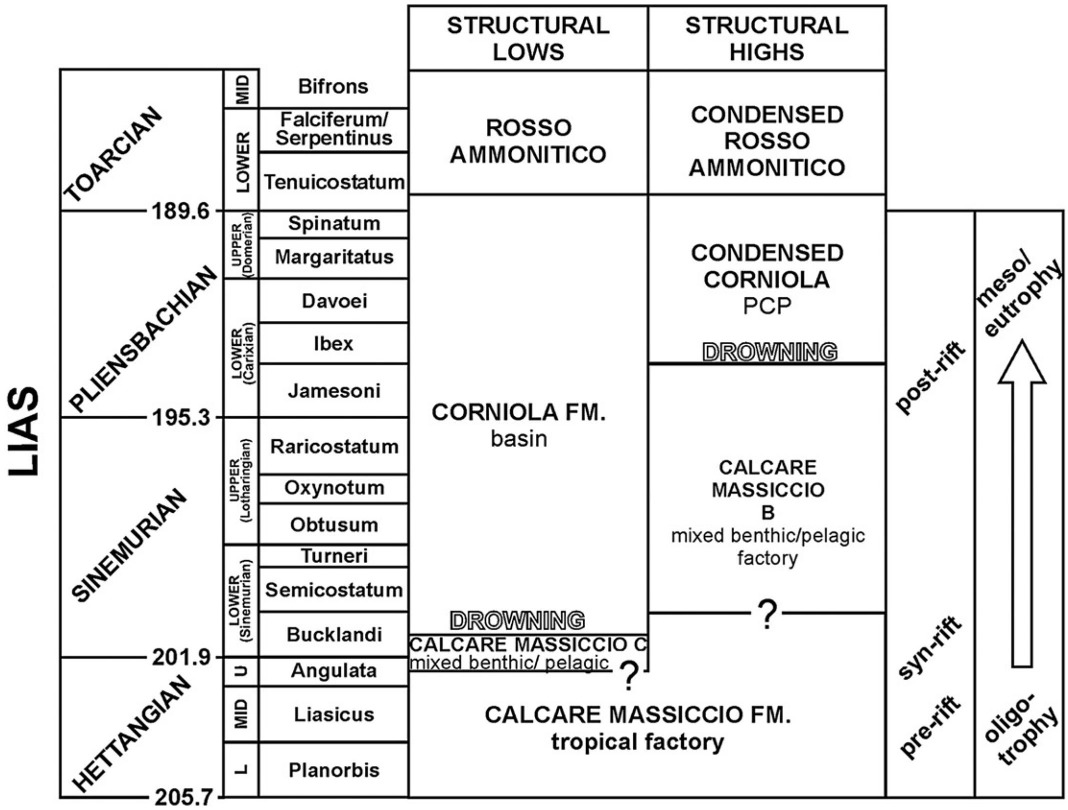

Fig. 17. The tectonic and stratigraphic/paleoenvironmental evolution of the Umbria–Marche–Sabina region in the Early Jurassic, and its correlation with chronostratigraphy and NW Europe ammonite biostratigraphy.

small remnant (often a few square kilometres) platforms (Morettini et al., 2002). These isolated platforms were unprotected by any organic or inorganic rim, so sites that once were sheltered in the middle of a vast regional platform were converted into small carbonate factories, which were encroached by oceanic waters having quite different physical/chemical properties and inhabitants. It is important to note that the Sinemurian was a period with only extremely rare coral reefs at a global scale (reportedly only British Columbia and Peru), which also corresponds to a prominent minimum in the numbers of coral genera and originations (see review in Lathuilière and Marchal, 2009). In drowning successions, the result was subtidal, non-cyclic photic zone (at least in the initial, algae-bearing part) carbonate sedimentation, benefiting from the coupled contributions of both the benthic and pelagic (occurrence of radiolarians and of a calcareous nannofossil-bearing mud matrix) factories (Schlager, 2003). This mixed-factory sedimentation persisted for 3 to 4 million years, working at relatively low rates (not more than 1 cm/1000 yr). The absence of grainstones would indicate dominantly low-energy conditions. However, the ubiquitous packstones with micro-oncoids could also be the result of episodic high-energy conditions, followed by settling and sieving of mud. The lack or scarcity of rippled calcarenites (Galluzzo and Santantonio, 1994), and lack of lateral accretion surfaces, suggest deposition in an environment not influenced by tidal waves (labelled as “submerged bank” environment in Fig. 3), below fair weather wave base, probably around the storm-wave base. Due to the reduced size and escarpment-bounded nature of these platforms, storms (or tsunamis?) or currents preferentially swept sediment off the platform, rather than redistributing it and redepositing it with distinctive sedimentary structures (graded tempestites etc.) on their tops. Clinoform beds resting unconformably on marginal escarpments (the unconformity-bounded drowning successions mentioned above), locally forming small aprons, were therefore probably more the result of sediment shedding from the platform top, and/or partly in situ growth, than of a genuine progradation. Limited size of the benthic factories, coupled with the absence at the time of fast-growing reefs keeping pace with subsidence, however slow, must have had a role in the inability of platform tops to aggrade to sea level, along with the absence in these isolated platforms of coastal-zone refugia, which commonly serve as starting points for full recovery of neritic sedimentation. The Calcare Massiccio B is technically a drowning succession in that it is sandwiched between peritidal and pelagic successions and it shares compositional features with both of them. However, it represents the product of sedimentation in an environment which remained stable for some millions of years. Therefore it cannot be viewed simply as a transitional stage, which would be abnormally long for a drowning process, but rather as the default type of sedimentation in such settings (Marino, 2004a,b).

7.3. End of the drowning succession

The end of the drowning succession, and onset of the condensed ammonite-rich Corniola (post-drowning succession), is marked by the total disappearance of algae and of coated grains. *Tubiphytes* and

Fig. 16. Field evidence and geometries of the geological drowning. A) Drowning succession: well bedded sediments (light grey), with mixed pre- and post-drowning elements, are interposed between the thick peritidal beds (white) and the thinly bedded pelagic condensed carbonates (dark grey), evidenced by gentle morphology (Mt Nerone area, Northern Apennines). B) Drowning unconformity in the Lessini Mts (Southern Alps). Pre-drowning Pliensbachian *Lithiotis* beds, and post-drowning Bajocian Ammonitico Rosso beds lie parallel to the drowning surface (white dashed line). C) Angular drowning unconformity in the Sciacca area (SW Sicily). Pre-drowning beds are tilted and cut by an erosional surface; post-drowning beds lie parallel to the erosional surface. D) Angular unconformity at the top of a drowning succession at Mt Kumeta (W Sicily). Rosso Ammonitico beds onlap crinoidal calcarenites. E) Bioeroded paraconformity at the top of the carbonate platform succession (Pliensbachian), overlain by post-drowning Bajocian Ammonitico Rosso (Lessini Mts, Southern Alps).

associated microbialites also disappear. Dupraz and Strasser (2002) interpret *Tubiphytes* as a form adapted to relatively high trophic levels in a very shallow-water environment. Eutrophication, occurring at the base of the post-drowning condensed Corniola (Morettini et al., 2002), cannot therefore be taken alone as a cause for its disappearance. While the photic zone dependence of *Tubiphytes* and of the microbial oncoids is still under debate, it is safe to state that raising of the lower photic zone boundary due to nutrient increase in the middle Carixian could have been a critical factor. As we mentioned, PCP's host regionally widespread corals, interpreted as deep photic zooxanthellate forms, at the end of the Jurassic, which has been interpreted as a probable result of prominent relative sea-level drops in the Tithonian (Nicosia and Pallini, 1977; Gill et al., 2004). This is an evidence that the region underwent very little subsidence following the late Hettangian–Sinemurian platform breakup (Bice and Stewart, 1990; Santantonio, 1993, 1994). Also in the light of this, the PCP environment is interpreted as lying generally at shallow subphotic depths through most of the Jurassic. Santantonio and Carminati (2010) note that the syn-rift stage ended in the Sinemurian in Northern Apennines as well as in Southern Alps, so vertical oscillations of the photic zone boundary could have been more effective carbonate-factory switches in the Pliensbachian than it was tectonic subsidence, even more so considering that we are dealing with footwall blocks. Fig. 17 summarizes the chronostratigraphy, biostratigraphy and lithostratigraphy of the main study area, also with an indication of the key paleoenvironmental and geodynamic turning points.

8. Correlation potential of the Early Pliensbachian platform drowning across the Western Tethys

As it was mentioned above, the Ibex Zone positive shift, and associated platform drowning are held by Jenkyns et al. (2002) as having a wide correlation potential across much of the Western Tethys. The data from Spain, Italy, Tunisia, Greece, and Morocco, given by Bosence et al. (2009; their fig. 2), may at first sight suggest that such a precise time correlation is not everywhere legit. However, the following can be noted: a) no distinction is made, regarding whether the logs in Bosence et al. (2009) were measured in correspondence of structural highs or lows (tectonic foundering of structural lows generally predates drowning of the highs in the Apennines and elsewhere); b) it is unclear if a drowning succession exists capping the peritidal limestones; c) reference to ammonite biostratigraphy is only made for two, out of seven sections discussed. Foraminiferal and Sr isotope data in Bosence et al. (2009) show that benthic factory-dominated carbonate sedimentation could locally persist into the early Early Pliensbachian (early Carixian, Jamesoni Zone), which is consistent with our data from the Apennines (Calcare Massiccio B): data provided in the Appendix section of Bosence et al. (2009) from the topmost platform levels of the Apennines, Greece (Evvoia), Betics (Southern Spain) and the High Atlas of Morocco, all consistently indicate a Jamesoni Zone age. The deeper-shelf subtidal facies of the Rio Palomar Fm. in the Iberian Chain of Spain, spanning most of the lower Carixian Jamesoni Zone, is interpreted by Gómez et al. (2003) to represent a photic environment with strong benthic carbonate productivity. The vertical change to the Almonacid de la Cuba Fm., the one indicating a more marked deepening, occurs shortly before the Jamesoni/Ibex boundary, but this is considered by Gómez et al. (2003) as an evidence for tectonic control over sedimentation across a shelf, which reached a maximum deepening in the Toarcian and subsequently saw platform progradation and eventually subaerial exposure in the Aalenian. This stratigraphic/tectonic evolution depicts a setting that is quite unlike the Apennines, where the Ibex Zone drowning occurred in the post-rift stage, and affected generally small isolated platforms. In the Betic Cordillera of Southern Spain, Ruiz-Ortiz et al. (2004) date a prominent drowning event and sequence boundary as middle Carixian, Ibex Zone. Regarding Gibraltar, platform carbonates have a Sinemurian top (Bosence et al., 2000, 2009). In the overlying deeper-water (Catalan Bay Shale) sediments, Bailey (1952) cites an ammonite assemblage that was identified by L. F. Spath as being not older than the Domerian (Late Pliensbachian), so drowning of the carbonate platform must have occurred in the Early Pliensbachian. In Tunisia, the ammonite age (early Carixian) assigned by Bosence et al. (2009) to the change from platform to deeper-water deposits in their Fig. 2 is questionable: the *Tropidocers demonense* Zone is in fact middle Carixian, being equivalent to most of the Ibex Zone (e.g. Faraoni et al., 1996). In the "Dorsale Tunisienne", Fauré et al. (2007), based on ammonite-and brachiopod-rich assemblages, confirm a Demonense Zone age for a regional drowning event. In Central Tunisia, in the "N–S Axis" (south of the "Dorsale Tunisienne"), Soussi and Ben Ismail (2000) describe as "Carixian" the drowning of the Hettangian–Sinemurian carbonate platform of the Lower Nara Fm. In a paper on the sequence stratigraphy of the Saharian Platform (central Atlas) of Tunisia, Tanfous Amri et al. (2008) cite the occurrence of "Pliensbachian" condensed deposits, marking a prominent seismic horizon which represents the drowning of a vast Sinemurian platform. In conclusion, although much research is still needed, there is strong evidence to date for a widespread platform drowning event in the middle Carixian Ibex Zone in the Western Tethys. Most of the data available either expressly make mention of the Ibex Zone (or its time-equivalent Demonense or Gemmellaroi Zones; see correlation chart in Faraoni et al., 1996), or they give a broader, somewhat less accurate, stratigraphic interval ("Carixian", "Pliensbachian") which does indeed include the Ibex Zone.

It is well known that certain vast platforms and shelves in the Western Tethys (e.g. the Latium Abruzzi Platform in Central Apennines, the Friuli Platform, the Apulia Platform; D'Argenio, 1976) apparently escaped the early Pliensbachian drowning, and continued their existence until the Tertiary. In order to understand why, and how did they manage to survive, much research remains to be done regarding: a) did, and if so in which fashion, the Hettangian/Sinemurian extensional phase affect them? b) Is any facies change observed in the Pliensbachian within their shallow-water successions? c) Does their size have to do with this? Santantonio and Carminati (2010) analyze the rift architecture, and the displacements and slip rates measured along rift faults in Northern Apennines, inferring diffuse splaying, from the thick (1.5–2 km) Late Triassic evaporites which underlie the Hettangian carbonates (acting as a detachment layer), of a lesser number of master faults rooted in the pre-Norian basement. This was the underlying cause producing the dense pattern of small-size isolated platforms treated in this paper, and one that could have had a number of linked consequences in terms of volumes of benthic carbonate produced in the post-rift, and capabilities to face environmental stress.

9. Conclusions

This paper describes case examples of Early Jurassic platform drowning across the Apennines and Sicily, highlighting their geological, physical (geometry, facies), palaeontological and geochemical characteristics. The way platform drowning is recorded geologically mostly depends on varying sediment preservation potential across the local paleotopography, which in the study region was largely a product of rift tectonics. The drowning of hangingwall basins occurred around the Hettangian/Sinemurian boundary as a result of tectonic extension, and started with the onset of permanently subtidal carbonate ramp conditions (Calcare Massiccio C — drowning succession). Inception of a drowning succession on intrabasinal highs (Calcare Massiccio B) occurred coincident with the birth of submarine fault escarpments and the branching of deep water seaways, as dramatically changed water circulation patterns and changed trophic levels put the unrimmed, small-sized platforms under stress while their tops were still in the photic zone. The final drowning of these platforms is a synchronous event taking place in the Early Pliensbachian (Ibex Zone, middle Carixian) in a post-rift setting, causing the planktonic carbonate factory to become dominant. Based on a multidisciplinary approach, this occurred due to alteration of a set of physical/chemical parameters governing carbonate productivity in the water column.

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References

Abbate, E., Bortolotti, V., Conti, M., Marcucci, M., Principi, G., Passerini, P., Treves, B., 1986. Apennines and Alps ophiolites and the evolution of the Western Tethys. Soc. Geol. Ital. Mem. 31, 23–44.

Baldanza, A., Cope, J.C.W., D'Arpa, C., Di Stefano, P., Marino, M.C., Mariotti, N., Nicosia, U., Pallini, G., Parisi, G., Petti, F.M., 2002. Stop 2 — Contrada Diesi (Sciacca) — paraconformable late Early Jurassic drowning surface; hiatuses, taphonomy and sedimentology of Upper Jurassic deposits; the Jurassic/Cretaceous boundary in the Sacense Domain. In: Santantonio, M. (Ed.), General Field Trip Guidebook. VI International Symposium on the Jurassic System, 12–22 September 2002. Palermo, Italy, pp. 173–182.

Barbujani, C., Bosellini, A., Sarti, M., 1986. L'oolite di San Vigilio nel Monte Baldo (Giurassico, Prealpi Venete). Ann. Univ. Ferrara 9, 19–47.

Bailey, E., 1952. Notes on Gibraltar and the Northern Rif. J. Geol. Soc. London 108, 157–175.

Bellanca, A., Claps, M., Erba, E., Masetti, D., Neri, R., Premoli Silva, I., Venezia, F., 1996. Orbitally induced limestone/marlstone rhythms in the Albian–Cenomanian Cismon section (Venetian region, northern Italy): sedimentology, calcareous and siliceous plankton distribution, elemental and isotope geochemistry. Palaeogeogr. Palaeoclimatol. Palaeoecol. 126, 227–260.

Bernoulli, D., Jenkyns, H., 1974. Alpine, Mediterranean, and Central Atlantic Mesozoic facies in relation to the early evolution of the Tethys. In: Dott, R. H., Shaves, R. H. (Eds.), Modern and Ancient Geosynclinal Sedimentation, SEPM Spec. Publ. 19, pp. 129–157.

Bernoulli, D., 1969. Redeposited pelagic sediments in the Jurassic of the Central Mediterranean area. Ann. Inst. Geol. Public. Hung. 54, 71–90.

Bernoulli, D., Kälin, O., Patacca, E., 1979. A sunken continental margin of the Mesozoic Tethys: the Northern and Central Apennines. Symposium "Sédimentation jurassique W européen". Assoc. Sédimentol. Fr. Publ. Spéc. 1, 197–210.

Bice, D.M., Stewart, K.G., 1990. The formation and drowning of isolated carbonate seamounts: tectonic and ecological controls in the northern Apennines. Int. Assoc. Sedimentol. Spec. Publ. 9, 145–168.

Biju-Duval, B., Dercourt, J., Le Pichon, X., 1977. From the Tethys Ocean to the Mediterranean Seas: a plate tectonic model of the evolution of the Western Alpine System, In: Biju-Duval, B., Montadert, L. (Eds.), International Symposium on the Stuctural History of the Mediterranean Basins, Editions Technip, Paris. Split (Yugoslavia) 25–29 October 1976, pp. 143–164.

Blomeier, D.P.G., Reijmer, J.J.G., 1999. Drowning of a Lower Jurassic carbonate platform: Jbel Bou Dahar, High Atlas, Morocco. Facies 41, 81–110.

Bosence, D., Procter, E., Aurell, M., Bel Kahla, A., Boudagher-Fadel, M., Casaglia, F., Cirilli, S., Mehdie, M., Nieto, L., Rey, J., Scherreiks, R., Soussi, M., Waltham, D., 2009. A dominant tectonic signal in high-frequency, peritidal carbonate cycles? A regional analysis of Liassic platforms from Western Tethys. Jour. Sed. Res. 79, 389–415.

Bova, J.A., Read, J.F., 1987. Incipiently drowned facies within a cyclic peritidal ramp sequence, Early Ordovician Chepultepec interval, Virginia Appalachians. Geol. Soc. Am. Bull. 68, 714–727.

Bruni, F., Calamita, F., Maranci, M., Pierantoni, P.P., 1997. Il controllo della tettonica giurassica sull'evoluzione neogenica dei Monti Martani meridionali (Pre-Appennino Umbro). Studi Geol. Camerti, Vol. Spec. 1995/1, pp. 121–135.

Calamita, F., 1990. Thrust and fold related structures in the Umbria–Marche Apennines (Central Italy). Annales Tectonicae 4, 83–177.

Cannata, D., 2007. Rilevamento Geologico e analisi di facies in due aree — campione dell'Appennino umbro–marchigiano–sabino: paleogeografia di dettaglio e tettonica giurassica, e loro impatto sulle fasi deformative successive. University of Rome "La Sapienza", PhD Thesis.

Cantelli, C., Castellarin, A., Praturlon, A., 1978. Tettonismo giurassico lungo l' "Ancona–Anzio" nel settore Monte Terminillo–Antrodoco. Geol. Romana 17, 85–97.

Carannante, G., Esteban, M., Milliman, J.D., Simone, L., 1988. Carbonate lithofacies as paleolatitude indicators: problems and limitations. Sed. Geol. 60, 333–346.

Carminati, E., Santantonio, M., 2005. Control of differential compaction on the geometry of sediments onlapping paleoescarpments: insights from field geology (Central Apennines, Italy) and numerical modeling. Geology 33, 353–356.

Catalano, R., Franchino, A., Merlini, S., Sulli, A., 2000. A crustal section from the Eastern Algerian basin to the Ionian ocean (Central Mediterranean). Soc. Geol. Ital. Mem. 55, 71–85.

Cecca, F., Cresta, S., Pallini, G., Santantonio, M., 1986. Biostratigrafia ed ammoniti del Dogger-Malm di Colle Tordina (Monti della Rossa, Appennino Marchigiano). Boll. Serv.Geol.d'It. 104, 177–204.

Cecca, F., Cresta, S., Pallini, G., Santantonio, M., 1987a. Le Lotharingien–Carixien de Gorgo a Cerbara (M. Nerone, Apenin des Marches), un exemple de passage d'un milieu de plate-forme carbonatée à un mileu pélagique. Cahiers Inst. Catho. Lyon, sér. Sci. 1, 57–66.

Cecca, F., Dommergues, J.L., Mouterde, R., Pallini, G., 1987b. Ammonites mediterranéennes du Lotharingien de Gorgo a Cerbara (M. Nerone, Apenin des Marches, Italie). Cahiers Inst. Catho. Lyon, sér. Sci. 1, 67–82.

Cecca, F., Cresta, S., Pallini, G., Santantonio, M., 1990. Il Giurassico di Monte Nerone (Appennino Marchigiano, Italia Centrale): biostratigrafia, litostratigrafia ed evoluzione paleogeografica. In: Pallini, G., Cecca, F., Cresta, S., Santantonio, M. (Eds.), Atti del II Convegno Internazionale "Fossili, Evoluzione, Ambiente" Pergola, 1987, pp. 63–139.

Centamore, E., Chiocchini, M., Deiana, G., Micarelli, A., Pieruccini, U., 1971. Contributo alla conoscenza del Giurassico dell'Appennino Umbro-Marchigiano. Stud. Geol. Camerti 1, 7–89.

Channell, J.E.T., D'Argenio, B., Horvath, F., 1979. Adria, the African promontory, in the Mesozoic Mediterranean paleogeography. Earth-Sci. Rev. 15, 213–292.

Chazottes, V., Le Campion-Alsumard, T., Peyrot-Clausade, M., Cuet, P., 2002. The effects of eutrophication-related alterations to coral reef communities on agents and rates of bioerosion (Reunion Island, Indian Ocean). Coral Reefs 21, 375–390.

Ciarapica, G., Passeri, L., 1998. Evoluzione paleogeografia degli Appennini. Atti Ticinensi di Scienze della Terra 40, 233–290.

D'Argenio, B., 1976. Le piattaforme carbonatiche periadriatiche. Una rassegna di problemi nel quadro geodinamico Mesozoico dell'area Mediterranea. Mem. Soc. Geol. It. 13, 1–28.

Di Stefano, P., Mindszenty, A., 2000. Fe–Mn-encrusted "Kamenitza" and associated features in the Jurassic of Monte Kumeta (Sicily): subaerial and/or submarine dissolution. Sed. Geol. 132, 37–68.

Di Stefano, P., Galácz, A., Mallarino, G., Mindszenty, A., Vörös, A., 2002a. Birth and early evolution of a Jurassic Escarpment: Monte Kumeta, Western Sicily. Facies 46, 273–298.

Di Stefano, P., Mallarino, G., Marino, M., Mariotti, N., Muraro, C., Nicosia, U., Pallini, G., Santantonio, M., 2002b. New stratigraphic data from the Jurassic of Contrada Monzealese (Saccense Domain, SW Sicily). Boll. Soc. Geol. Ital. 121, 121–137.

Di Stefano, P., Mallarino, G., 2002. Stop 5 — Portella delle Ginestre parking lot: tectonostratigraphic setting and Jurassic lithostratigaphy of Monte Kumeta. In: Santantonio, M. (Ed.), General Field Trip Guidebook", VI International Symposium on the Jurassic System, 12–22 September 2002. Palermo, Italy, pp. 196–198.

Dommergues, J.L., Ferretti, A., Meister, C., 1994. Les faunes d'ammonites du Sinémurien de l'Apennin Central (Marches et Toscane, Italie). Boll. Soc. Paleont. Ital. 33, 13–42.

Dupraz, C., Strasser, A., 2002. Nutritional modes in coral-microbialite reefs (Jurassic, Oxfordian, Switzerland): evolution of trophic structure as a response to environmental change. Palaios 17, 449–471.

Eberli, G.P., 1987. Carbonate turbidite sequences deposited in rift-basins of the Jurassic Tethys Ocean (eastern Alps, Switzerland). Sedimentology 34, 363–388.

Elmi, S., 1981. Sedimentation rythmique et organisation sequentielle dans les Ammonitico Rosso et les facies associés du Jurassique de la Mediterranée Occidentale. Interpretation des grumeaux et des nodules. In: Farinacci, A., Elmi, S. (Eds.), Rosso Ammonitico Symposium Proceedings. Roma, Edizioni Tecnoscienza, pp. 251–299.

Erlich, R.N., Barrett, S.F., Guo Bai, Ju., 1990. Seismic and geologic characteristics of drowning events on carbonate platforms. AAPG Bull. 74, 1523–1537.

Everts, A.J.W., Reijmer, J.J.G., 1995. Clinoform composition and margin geometries of a Lower Cretaceous carbonate platform (Vercors, SE France). Paleogeogr., Paleoclimatol. Palaeoecol. 119, 19–33.

Faraoni, P., Marini, A., Pallini, G., Venturi, F., 1996. New Carixian ammonite assemblages of Central Apennines (Italy), and their impact on Mediterranean Jurassic biostratigraphy. Palaeopelagos 6, 75–122.

Farinacci, A., 1967. La serie giurassica-neocomiana di Monte Lacerone (Sabina). Nuove vedute sull'interpretazione paleogeografica delle aree di facies umbro-marchigiana. Geol. Romana 6, 421–480.

Farinacci, A., 1970. Età, batimetria, temperatura, sedimentazione e subsidenza nella serie carbonatiche dell'intrageoanticlinale mesozoica umbro-marchigiana. Boll. Soc. Geol. Ital. 89, 317–332.

Fauré, P., Alméras, Y., Sekatni, N., Zargouni, F., 2007. Le Pliensbachien de Jebel Zaghouan (Tunisie). Nouvelles données fauniques. Implications biostratigraphiques et paléobiogeographiques. Geodiversitas 24, 473–506.

Folk, R.L., 1973. Evidence for peritidal deposition of Devonian Caballos Novaculite, Marathon Basin, Texas. AAPG Bulletin 57, 702–725.

Föllmi, K.B., Weissert, H., Bisping, M., Funk, M., 1994. Phosphogenesis, carbon-isotope stratigraphy, and carbonate platform evolution along the Lower Cretaceous northern Thethyan margin. Geol. Soc. Am. Bull. 106, 729–746.

Flügel, E., 2004. Microfacies of Carbonate Rocks. Analysis, Interpretation and Application. SpringerBerlin Heidelberg, New York.

Galluzzo, F., Santantonio, M., 1994. Geologia e paleogeografia giurassica dell'area compresa tra la Valle del Vernino e Monte Murano. Boll. Soc. Geol. It. 113, 587–612.

Galluzzo, F., Santantonio, M., 2002. The Sabina Plateau: a new element in the Mesozoic palaeogeography of Central Apennines. In: Barchi, M., Cirilli, S. (Eds.), Boll. Soc. Geol. Ital: Atti del Convegno Evoluzione Geologica e Geodinamica dell'Appennino (in memoria di G. Pialli), pp. 561–588. Vol. Spec. 1.

Gill, G.A., Santantonio, M., Lathulière, B., 2004. The depth of pelagic deposits in the Tethyan Jurassic and the use of corals: an example from the Apennines. Sed. Geol. 166, 311–334.

Gómez, J.J., Comas-Rengifo, M.J., Goy, A., 2003. Las unidades litostratigráficas del Jurásico Inferior de las cordilleras Ibérica y Costero Catalana. Rev. Soc. Geol. España 16, 227–237.

Grigg, R.W., 1982. Darwin Point: a threshold for atoll formation. Coral Reefs 1, 29–34.
Grigg, R.W., 1997. Paleoceanography of coral reefs in the Hawaiin–Emperor Chain — revisited. Coral Reefs 16, S33–S38.
Hallock, P., Schlager, W., 1986. Nutrient excess and the demise of coral reefs and carbonate platforms. Palaios 1, 389–398.
Hallock, P., Hine, A.C., Vargo, G.A., Elrod, J.A., Jaap, W.C., 1988. Platforms of the Nicaraguan Rise: examples of the sensitivity of carbonate sedimentation to excess trophic resources. Geology 16, 1104–1107.
Hudson, J.D., Anderson, T.F., 1989. Ocean temperatures and isotopic compositions through time. Trans. Edinb. Geol. Soc. 80, 183–192.
Immenhauser, A., Della Porta, A., Kenter, J.A.M., Bahamonde, J.R., 2003. An alternative model for positive shifts in shallow-marine carbonate $\delta^{13}C$ and $\delta^{18}O$. Sedimentology 50, 953–959.
Immerz, P., 1985. Facies relationships in the Jurassic and Lower Cretaceous pelagic limestone of the Monte Nerone Area, Province of Marche, Italy — sedimentation on a submarine high. Mitt. Bayer. Staatssamml. Paläontol. Hist. Geol. 25, 195–208.
Jenkyns, H.C., Clayton, C.J., 1986. Black shales and carbon isotopes in pelagic sediments from Tethyan Lower Jurassic. Sedimentology 33, 87–106.
Jenkyns, H.C., 1971. The genesis of condensed sequences in the Tethyan Jurassic. Lethaia 4, 327–352.
Jenkyns, H.C., 1988. The Early Toarcian (Jurassic) anoxic event: statigraphic, sedimentary, and geochimical evidence. Am. J. Sci. 288, 101–151.
Jenkyns, H.C., 1991. Impact of Cretaceous sea level rise and anoxic events on the Mesozoic carbonate platform of Yugoslavia. AAPG Bull. 75, 1007–1017.
Jenkyns, H.C., Jones, C.E., Gröcke, D.R., Stephen, P.H., Parkinson, D.N., 2002. Chemostratigraphy of the Jurassic System: applications, limitations and implications for palaeoceanography. Journ. Geol. Soc. London 159, 351–378.
Kälin, O., 1980. *Schizosphaerella punctuculata* Deflandre and Dangeard: wall ultrastructure and preservation in deeper-water carbonate sediments of the Tethyan Jurassic. Eclogae Geol. Helv. 73, 983–1108.
Kendall, C., Schlager, W., 1981. Carbonate and relative changes in sea level. Mar. Geol. 44, 181–212.
Lathuilière, B., Marchal, D., 2009. Extinction, survival and recovery of corals from the Triassic to Middle Jurassic time. Terra Nova 21, 57–66.
Mallarino, G., 2002. Crisi delle piattaforme carbonatiche liassiche e dinamica deposizionale delle piattaforme pelagiche giurassiche della Sicilia occidentale. University of Palermo, PhD Thesis.
Marino, M., Nicosia, U., Santantonio, M., 2002. Stop 15 — Late Jurassic evolution of the submarine escarpment at Monte Kumeta. In: Santantonio, M. (Ed.), General Field Trip Guidebook, VI International Symposium on the Jurassic System, 12–22 September 2002. Palermo, Italy, pp. 110–115.
Marino, M., 2004a. Multidisciplinar analysis of the geological record of a carbonate platform drowning: the Calcare–Massiccio–Corniola boundary in the Lower Jurassic of the Umbria–Marche–Sabina Apennines (Central Italy). University of Rome "La Sapienza", PhD Thesis.
Marino, M., 2004b. Sediment type and growth of incipiently drowned carbonate platforms in the Lower Jurassic of Central Apennines (Central Italy). 32nd IGC Florence — Scientific Sessions: abstracts (part 2), p. 1205.
Marino, M.C., Andreini, G., Baldanza, A., D'Arpa, C., Mariotti, N., Pallini, G., Parisi, G., Petti, F.M., 2004. Middle Jurassic–Early Cretaceous integrated biostratigraphy (ammonites, calcareous nannofossils and calpionellids) of the Contrada Diesi Section (South-Western Sicily). In: Parisi, G. (Ed.), Riv. Ital. Paleontol. Stratigr: The 6th International Symposium on the Jurassic System, 16–19 September 2002, 110, pp. 357–372.
Marshall, J.D., 1992. Climatic and oceanographic isotopic signals from the carbonate rock record and their preservation. Geol. Mag. 129, 143–160.
Martinis, B., Pieri, M., 1964. Alcune notizie sulla formazione evaporitica del Trias superiore nell'Italia centrale e meridionale. Soc. Geol. Ital. Mem. 4, 648–672.
Massari, F., 1983. Oncoids and Stromatolites in the Rosso Ammonitico Sequences (Middle–Upper Jurassic) of the Venetian Alps, Italy. In: Peyrit, T.M. (Ed.), Coated Grains. Springer-Verlag, Berlin, pp. 367–376.
Massari, F. and Dieni, I., 1983. Pelagic oncoids and ooids in the Middle–Upper Jurassic of Eastern Sardinia. In: Peyrit, T.M. (Ed.), Coated Grains, Springer-Verlag, Berlin, pp.
Molina, J.M., Ruiz-Ortiz, P.A., Vera, J.A., 1999. A review of poliphase karstification in the extensional tectonic regimes: Jurassic and Cretaceous examples, Bethic Cordillera, southern Spain. Sed. Geol. 129, 71–84.
Morettini, E., 1998. Lower Jurassic Stable Isotope stratigraphy (Carbon, Oxygen, Nitrogen) of the Mediterranean Tethys (Central Italy and Southern Spain). University of Lausanne, PhD Thesis.
Morettini, E., Santantonio, M., Bartolini, A., Cecca, F., Baumgartner, P.O., Hunziker, J.C., 2002. Carbon isotope stratigraphy and carbonate productivity during the Early–Middle Jurassic: examples from the Umbria–Marche–Sabina Apennines (Central Italy). Palaeogeogr., Palaeoclimatol. Palaeoecol. 184, 251–273.
Muraro, C., Santantonio, M., 2002. Stop 4 — Mound geometries and high-energy deposits in a Jurassic succession at Vallone San Vincenzo. In: Santantonio, M. (Ed.), General Field Trip Guidebook, VI International Symposium on the Jurassic System, 12–22 September 2002. Palermo, Italy, pp. 172–173.
Muraro, C., Santantonio, M., 2003. Uncommon facies and geometries on a Jurassic pelagic carbonate platform in Western Sicily, Italy. AAPG International Conference and Exhibition, September 21–24 2003 Barcelona, Crossroads of Geology, Energy and Cultures. Official Program: A66.
Mutti, M., Hallock, P., 2003. Carbonate systems along nutrient and temperature gradients: some sedimentological and geochemical constraints. Int. J. Earth Sci. 92, 465–475.
Nicosia, U., Pallini, G., 1977. Hermatypic corals in the Tithonian pelagic facies of Central Apennines. Evidences of Upper Jurassic sea-level changes. Geol. Romana 16, 243–261.
Nocchi, M., Parisi, G., Nini, C., 1999. Foraminifers and microfacies. Palaepelagos, Special Publication 3, 97–100.
Pallini, G., Schiavinotto, F., 1981. Upper Carixian-lower Domerian sphinctozoa and ammonites from some sequences in Central Apennine. In: Farinacci, A., Elmi, S. (Eds.), Rosso Ammonitico Symposium Proceedings. Edizioni Tecnoscienza, Roma, pp. 521–539.
Pallini, G., Elmi, S., Gasparri, F., 2004. Late Toarcian–Late Aalenian ammonites assemblage from Mt. Magaggiaro (Western Sicily, Italy). Geol. Romana 37, 1–66.
Passeri, L., Venturi, F., 2005. Timing and causes of drowning of the Calcare Massiccio platform in Northern Apennines. Bol. Soc. Geol. Ital. 124, 247–258.
Pinet, P.R., Popenoe, P., 1985. Shallow sesmic stratigraphy and post-Albian geologic history of the northern and central Blake Plateau. Geol. Soc. Am. Bull. 96, 627–638.
Racki, G., Racka, M., Matja, H., Devleeschouwer, X., 2002. The Frasnian/Famennian boundary interval in the South-Moravian shelf basins: integrated event-stratigraphical approach. Palaeogeogr., Palaeoclimatol. Palaeoecol. 181, 251–297.
Read, J.F., 1982. Carbonate platforms of passive (extensional) continental margins: types, characteristics and evolution. Tectonophysics 81, 195–212.
Reolid, M., Gaillard, C., Oloriz, F., Tovar, F.R., 2004. Microbial encrustations from the Middle Oxfordian–earliest Kimmeridgian lithofacies in the Prebetic zone (Betic Cordillera, Southern Spain): characterization, distribution and controlling factors. Facies 50 (2005), 529–543.
Rosales, I., Quesada, S., Robles, S., 2001. Primary and diagenetic isotopic signals in fossils and hemipelagic carbonates: the Lower Jurassic of northern Spain. Sedimentology 48, 1149–1169.
Ruiz-Ortiz, P.A., Bosence, D.W.J., Rey, J., Nieto, L.M., Castro, J.M., Molina, J.M., 2004. Tectonic control of facies architecture, sequence stratigraphy and drowning of a Liassic carbonate platform (Betic Cordillera, Southern Spain). Basin Res. 16, 235–257.
Santantonio, M., 1993. Facies associations and evolution of pelagic carbonate platform / basin systems: examples from the Italian Jurassic. Sedimentology 40, 1039–1067.
Santantonio, M., 1994. Pelagic carbonate platforms in the geologic record: their classification, and sedimentary and paleotectonic evolution. AAPG Bull. 78, 122–141.
Santantonio, M., Carminati, E., 2010. The Jurassic Rifting Evolution of the Apennines and Southern Alps (Italy): Parallels and Differences. GSA Bulletin, in press.
Santantonio, M., Galluzzo, F., Gill, G., 1996. Anatomy and palaeobathymetry of a Jurassic pelagic carbonate platform/basin system. Rossa Mts, Central Apennines (Italy). Geological implications. Palaeopelagos 6, 123–169.
Schirolli, P., 1997. La successione liassica nelle Prealpi Bresciane centro-occidentali (Alpi Meridionali, Italia): stratigrafia, evoluzione paleogeografico-strutturale ed eventi connessi al rifting. Atti Ticin. Sc. Terra (Serie Speciale) 6, 5–137.
Schlager, W., Camber, O., 1986. Submarine slope angles, drowning unconformities, and self-erosion of limestone escarpments. Geology 14, 762–765.
Schlager, W., 1981. The paradox of drowned reefs and carbonate platforms. Geol. Soc. Am. Bull. 92, 197–211.
Schlager, W., 1989. Drowning unconformities on carbonate platforms. In: Crevello, P.D., Wilson, J.L., Sarg, J.F., Read, J.F. (Eds.), SEPM Spec. Publ: Controls on Carbonate Platforms and Basin Development, 44, pp. 15–25.
Schlager, W., 1991. Depositional bias and environmental change — important factors in sequence stratigraphy. Sed. Geol. 70, 109–130.
Schlager, W., 1994. Sedimentology and Sequence Stratigraphy of Reef and Carbonate Platforms. A Short Course. Continuing Education Course Note Series # 34. A.A.P.G., Tulsa, Oklahoma U.S.A.
Schlager, W., 1998. Exposure, drowning and sequence boundaries on carbonate platforms. In: Camoin, G.F., Davies, P.J. (Eds.), Reefs and Carbonate Platforms in the Pacific and Indian Oceans: Int. Assoc. Sedimentol. Spec. Publ., 25, pp. 3–22.
Schlager, W., 2003. Benthic carbonate factories of the Phanerozoic. Int. J. Earth Sci. 92, 445–464.
Schmid, D.U., 1996. Marine Mikrobolithe und Mikroinkrustierer aus dem Oberjura. Profil 9, 101–251.
Senowbari-Daryan, B., Flügel, E., 1993. *Tubiphytes* Maslov, an enigmatic fossil: classification, fossil record and significance through time. Part I: discussion of Late Paleozoic material. In: Barattolo, F., De Castro, P., Parente, M. (Eds.), Studies on Fossil Benthic Algae: Boll. Soc. Paleont. Ital. Spec., 1, pp. 353–382.
Soussi, M., Ben Ismail, M.H., 2000. Platform collapse and pelagic seamount facies: Jurassic development of central Tunisia. Sed. Geol. 133, 93–113.
Tanfous Amri, D., Soussi, M., Bédir, M., Azaiez, H., 2008. Seismic sequence stratigraphy of the Jurassic of Central Atlas, Tunisia. J. Afr. Earth Sci. 51, 55–68.
Turco, E., Schettino, A., Conti, M. A., Di Stefano, P., Iannace, A., Liotta, D., Nicosia, U., Santantonio, M., Zamparelli, V., Zarcone, G., 2007. Mesozoic paleogeography of the central mediterranean region. Epitome, 2, Geoitalia 2007 VI Forum Italiano di Scienze della Terra, 12–14 Settembre 2007, 108.
Vörös, A., 1991. Hierlatzkalk — a peculiar Austro-Hungarian Jurassic facies. In: Lobitzer, H., Császár, G. (Eds.), Jubiläumsschrift 20 jahre Geologische Zusammenarbeit Österreich-Ungarn. Wien, September, pp. 145–154.
Weissert, H., Mohr, H., 1996. Late Jurassic climate and its impact on carbon cycling. Paleogeogr., Paleoclimatol. Paleoecol. 122, 27–43.
Weissert, H., Lini, A., Föllmi, K.B., Kuhn, O., 1998. Correlation of Early Cretaceous carbon isotope stratigraphy and platform drowning events: a possible link? Paleogeogr., Paleoclimatol. Paleoecol. 137, 189–203.
Winterer, E.L., 1991. The Tethyan Pacific during Late Jurassic and Cretaceous times. Palaeogeogr., Palaeoclimatol. Palaeoecol. 87, 253–265.
Whalen, M.T., Day, J., Eberli, G.P., Homewood, P.W., 2002. Microbial carbonates as indicators of environmental change and biotic crises in carbonate systems: examples from the Late Devonian, Alberta basin, Canada. Paleogeogr., Paleoclimatol. Paleoecol. 181, 127–151.
Wood, R., 1993. Nutrients, predation and history of reef-building. Palaios 8, 526–543.

Wortmann, U.G., Weissert, H., 2000. Tying platform drowning to perturbations of the global carbon with a delta (super 13) C (sub Org) — curve from the Valanginian of DSDP Site 416. Terra Nova 12, 289–294.
Zappaterra, E., 1990. Regional distribution models of source rocks in the Periadriatic region. Soc. Geol. Ital. Mem. 45, 817–822.
Zempolich, W.G., 1993. The drowning succession in Jurassic carbonates of Venetian Alps, Italy: a record of supercontinent breakup, gradual eustatic rise, and eutrophication of shallow-water environments. In: Loucks, R.G., Sarg, J.F. (Eds.), Carbonate Sequence Stratigraphy. Recent Developments and Applications: AAPG Mem., 57, pp. 63–105.