



An exceptionally well-preserved Jurassic plateau-top to marginal escarpment in the Northern Apennines (Central Italy): sedimentological, palaeontological and palaeostructural features

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Abstract

Submarine palaeo-escarpment tracts at the basin margins commonly border isolated drowned carbonate platforms in the Jurassic rifted margins of the Western Tethys and bear fundamental structural and palaeogeographic significance. These tectonically generated escarpments, rooted in late Hettangian-early Sinemurian master faults, provide key information on the regional architecture of the rift, and on the nature and timespan of activity of the faults which define them. An isolated drowned carbonate platform (the Sabina Plateau) in the Northern Apennines of Central Italy exhibits a wealth of peculiar details on the Jurassic submarine topography. The deposits covering this escarpment host multiple unconformities related to a margin-failure episode, documented by breccias resting on a submarine-scar surface, perched with respect to the basin bottom and draped discontinuously by condensed ammonite-rich pelagites. Thin lenses of graded and laminated oolitic limestones in the condensed pelagic succession of the Sabina Plateau are interpreted as likely produced by the overbanking of turbidity currents, which were shed into the basin by a neighbouring productive carbonate platform. The final leveling of the submarine rift bathymetry occurred in the earliest Cretaceous, as documented by the onlap of the aggrading basinal succession against the palaeo-escarpment, and the burial of the plateau-top condensed succession. This complex onlap surface exhibits a distinctive overprint, such as diffuse silicification driven by the transit of silica-rich diagenetic fluids sourced by the radiolarian-rich basinal units.

Keywords Pelagic carbonate platforms · Jurassic · Apennines · Gravity flow deposits · Submarine escarpments

Resumen

Los paleoescarpes submarinos localizados en las márgenes de cuencas de tipo rift del Jurásico del Tetis occidental con frecuencia bordean a plataformas aisladas y ahogadas (“drowned”), lo que les confiere gran importancia estructural y paleogeográfica. Los escarpes, inducidos tectónicamente por fallas maestras del Hettangiense superior -Sinemuriense inferior, proporcionan información clave sobre la arquitectura regional del rift y sobre la naturaleza y duración de la actividad de las fallas que los definen. La plataforma carbonatada aislada y ahogada del Plateau Sabino, en los Apeninos Septentrionales en la zona central de Italia, exhibe detalles peculiares sobre la paleotopografía submarina del Jurásico. Los depósitos que cubren este escarpe contienen múltiples discordancias relacionadas con colapsos marginales, documentados por brechas que descansan en una posición elevada respecto al fondo de la cuenca, y que a su vez están recubiertas por una sucesión de calizas pelágicas condensadas, ricas en ammonites. En esa sucesión pelágica se intercalan pequeños lentejones de calizas oolíticas gradadas y laminadas, que se interpretan como el depósito de desbordamiento de corrientes de turbidez, alimentadas por una plataforma carbonatada productiva, situada en las proximidades. El nivelado final de la batimetría del rift submarino ocurrió en el inicio del Cretácico inferior, como lo documenta el “onlap” de la sucesión

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pelágica aggradante contra el paleo-escarpe, y el enterramiento de los depósitos condensados de la parte superior del plateau. La superficie de onlap es compleja y exhibe características distintivas, como la silicificación difusa inducida por fluidos diagénicos ricos en sílice, ésta derivada de las unidades pelágicas ricas en radiolarios.

Palabras clave Plataformas pelágicas carbonatadas · Jurásico · Apeninos · Depósitos de flujo gravitacional · Escarpes submarinos

1 Introduction

The pelagic domains of Central and Northern Apennines of Central Italy offer a wealth of information on ancient submarine rifts. Intrabasinal highs in such pelagic depositional systems, like those also observed in the Jurassic of the Southern Alps, were the products of a rifting phase linked with the breakup of Pangaea, constituting the footwall blocks in this extensional system, facing deeper basins corresponding to hangingwall blocks (Bernoulli, 1964; Colacicchi et al., 1970; Centamore et al., 1971; Farinacci et al., 1981; Castellarin, 1982; Alvarez, 1989; Bice and Stewart, 1986; Bertotti et al., 1993; Santantonio, 1993, 1994). With carbonate depositional systems centered in prolific benthic factories, the platform-to-basin transition zone can migrate over space and time due to the complex interactions taking place among variable parameters, such as relative sea-level, accommodation space, or growth potential of the local carbonate factory (in turn the product of a number of biological/environmental factors). Differently, submarine rifted margins are essentially “frozen” structural snapshots, which is particularly true in pelagic domains as drowned platforms (pelagic carbonate platforms; Santantonio, 1993) have no progradation potential whatsoever. Their boundaries are rooted in extensional faults, although the platform-margin morphology can be subsequently re-shaped through collapse episodes during the post-rift stage. For these reasons, the palaeomargins, and their physical relationships with the hangingwall-basin units, provide direct information on the palaeogeographic pattern and modes of synsedimentary faulting, such as orientation and spacing of faults, slip rates and timing of footwall unroofing, displacement, and subsidence history (e.g. Carminati & Santantonio, 2005; Santantonio & Carminati, 2011; Cipriani et al., 2020; Santantonio et al., 2022). In orogenic belts, such as the Apennines, exhibiting a polyphase deformation history, restoring the pre-orogenic structural/palaeogeographic architecture can be a challenging task. For this reason, a set of specific criteria has been established for the identification in the field of preserved palaeomargin tracts, where an often complex pattern of unconformities characterise the peripheries of the highs. In this paper we test this approach in the Sabina Plateau (Galluzzo & Santantonio, 2002), an instructive case where an exhumed basin-dipping submarine escarpment

can be documented through the description of the geometries, biostratigraphy, sedimentology and diagenesis of the pelagic and clastic bodies found at the plateau edge.

2 Geological setting

The sedimentary cover of the Hercynian basement in the Northern Apennines is represented by locally thick Triassic continental red-bed deposits (Verrucano and Pseudoverrucano, see Perrone et al., 2006; Cassinis et al., 2018), followed by shallow-water deposits represented by the thick (up to >1–1.5 km) Dolomia Principale or by evaporites (Burano Anhydrite), so that the Rhaetian palaeogeography was dominated by widespread shallow-water carbonate platforms, although Rhaetian intraplatform basins, often with restricted circulation, developed locally (Cirilli, 1993). By the dawn of the Jurassic the conditions were set for the development of a vast tropical-type carbonate platform over most of today’s peninsular Italy.

In the Apennines, the Hettangian carbonate platform is represented by the Calcare Massiccio formation, an up to 1 km thick layer mostly made of stacked shallowing upwards cycles (Colacicchi & Pialli, 1967; Centamore et al., 1971; Farinacci et al., 1981; Santantonio & Carminati, 2011). A major rifting phase is recorded in latest Hettangian–Sinemurian in the Northern Apennines (*i.e.* the “stretching phase” of Chenin et al., 2022), which had several consequences in a sedimentary key. The accommodation space, generated by tectonic subsidence of the hanging wall, was used by the active benthic carbonate factory at a very early stage of faulting as room for footwall progradation, locally documented by low-angle clinofolds (Fabbi & Santantonio, 2012). Continued extension however caused this progradation to cease as benthic production by the carbonate factory in hanging wall blocks was outpaced by the fault slip rates. This means that the faults broke through the sea bottom, forming a steep escarpment, and hanging wall blocks sank to aphotic depths. Hangingwall basins thence started hosting pelagic sedimentation at rates as slow as few mm to few cm/kyr (Cecca et al., 1990). The main consequence of this switch to a slow pace of sedimentation was that it took tens of millions of years to infill the grabens and half-grabens and eventually level out the submarine rift topography.

2.1 Jurassic rifting in the Northern/Central Apennines

The Jurassic architecture of the submarine rift in Northern Apennines has puzzled geologists for decades, because rather than being represented by any regular pattern of normal faults and transfer faults or relay ramps it is instead an odd pattern of small highs, polygonal in map view, bounded by faults with seemingly random trends (Alvarez, 1989; Santantonio, 1994; Galdenzi & Menichetti, 1999). This has been interpreted as a result of the dehydration history of the >1–1.5 km thick Upper Triassic anhydrites (De Paola et al., 2007), which also acted as a detachment layer for Jurassic faults (Santantonio & Carminati, 2011). Field mapping provides figures for the vertical displacement which took place along the late Hettangian-early Sinemurian faults. This has been estimated to be in the order of 1–1.2 km, with rare exceptions exceeding 2 km (Galluzzo & Santantonio, 2002; Santantonio & Carminati, 2011). While an estimate of the submarine palaeotopographic relief produced by the faults can be classically derived for example by taking the tops of the pre-rift Calcare Massiccio in hanging wall and footwall blocks, respectively, as a reference, or by decompacting the thickness of the basin fill succession, estimating the slip rates of those faults requires *ad hoc* tools. These are described in two papers by Santantonio and Carminati (2011) and Santantonio et al. (2022) and are based on stratigraphic relationships at basin margins between the syn/early post-rift deposits and the pre-rift substrate, as well as on the drowning history of the footwall-block carbonate factories. Estimates of these slip rates fall conservatively within a range of ca. 1–3 km/Myr, a datum which, paired with the known total vertical displacement (see above), suggest that extension occurred through one or more clusters of bursts over a very limited interval of geologic time so that the region entered a post-rift stage as early as in the late Sinemurian. Following this, as the faults became essentially inactive, their tracts that were exposed at the sea bottom became the sites of onlap of the slowly aggrading basin-fill units against the unroofed pre-rift substrate, and as such are simply referred to as submarine escarpments (Carminati & Santantonio, 2005). Throughout the present paper, the concepts of pre-, syn- and post-rift are referred to the documented activity of rift-related faults in the Umbria-Marche Domain, and correspond to the “pre-rift”, “stretching phase” and “necking” to “post-rift” phases described by Chenin et al. (2022) in the “proximal domain” of a rifted margin.

2.1.1 The birth of pelagic carbonate platforms

Benthic carbonate production survived in variable forms on structural highs for a few million years (Marino &

Santantonio, 2010), so the escarpments were sites of bypass of neritic sediment which formed bypass wedges at their toes and further travelled across the basins producing an array of gravity flow deposits. The structural highs underwent drowning in the early Pliensbachian (Cecca et al., 1990), apparently for reasons unrelated to tectonics and linked instead with a synchronous super-regional palaeoceanographic perturbation which left a geochemical signature in the form of a positive shift in the $\delta^{13}\text{C}$ curve (Morettini et al., 2002; Marino & Santantonio, 2010; Franceschi et al., 2014, and references therein). This drowning marked the onset of very slow pelagic carbonate sedimentation on flat-topped structural highs, forming very thin condensed successions: at this stage, based on their morphology and type of sedimentation they are referred to as pelagic carbonate platforms (PCP hereafter) (Santantonio, 1993, 1994). This pattern of PCPs and basins lasted until the rift topography was infilled by Early Cretaceous (Berriasian-Valanginian) times.

2.2 Escarpment-type basin margins

For the reasons addressed above, deciphering the architecture of Western Tethyan Jurassic PCP/basin systems must rely on the identification and mapping of preserved submarine palaeo-escarpment tracts, which is not a trivial task in orogenic belts. Palaeo-escarpment analysis (see also Carminati & Santantonio, 2005) requires the use of a set of observational criteria, which include: (a) identification of the contact between the units of the basin-fill succession and those of the footwall blocks as stratigraphic (onlap) in nature; (b) cutoff angle of the palaeo-escarpment surface (with respect to the footwall strata); (c) dip of hangingwall-block strata with respect to the palaeo-escarpment surface, following re-orientation of footwall beds to the horizontal; (d) morphology of the palaeo-escarpment surface (e.g. spurs, grooves); (e) detection and age assessment of condensed epi-escarpment deposits and (f) diagenesis of the contact belt (e.g., silicification) as discussed below.

Indirect evidence for the presence of a submarine palaeo-escarpment includes: (i) the occurrence of exotic blocks, due to collapse of footwall margins, in the basin-margin succession; (ii) the bending of basin-margin strata in response to their differential compaction above a lithified inclined surface (the buried escarpment); (iii) the presence of biogenic sand drifts forming wedges at their toe, such as the rippled and/or hummocky cross-bedded *Saccocoma* sands described by Cecca et al. (1990), Santantonio (1993) and Santantonio et al. (1996), which could be the products of internal waves/solitons (see Pomar et al., 2019); (iv) in orogenic belts, the laterally-disharmonic/distorted folding of basin-margin beds during contraction, due to buttressing

against an inherited rheological discontinuity (the palaeo-escarpment) (Santantonio et al., 2016).

The marginal escarpments of Jurassic PCPs in the Apennines were essentially sites of erosion, as the top of the drowned platforms was no longer productive and was instead subjected to pelagic sedimentation as slow as few mm/kyr. Erosional morphologies, like grooves or scars left by olistoliths or submarine landslides, could however host thin perched patches of condensed pelagic sediment, often richly ammonitiferous, named epi-escarpment deposits and typically (but not only, see below) resting unconformably on the pre-rift peritidal limestone (Calcare Massiccio). The occurrence of these deposits, with their palaeotopography-sealing significance, indicates a preserved Jurassic seascape, as opposed to a modern morphology. Importantly, in addition, their preservation in a dominantly erosional setting, potentially prone to collapse, can be taken as an indirect indication of inactivity of the underlying parent fault.

Another remarkable aspect of palaeo-escarpments is a diagenetic overprint, which was first described by Santantonio et al. (1996). The pelagic basin-fill units are chert-rich, an extreme example of this being the well-known Tethyan upper Bajocian-Bathonian to lowermost Kimmeridgian radiolarian cherts. The onlap contacts with the basin-margin escarpments are commonly silicified, in forms ranging from chert crusts to sparse subspherical nodules, to rows of nodules or irregular bands running parallel to the bedding of the pre-rift limestone substrate and often enhancing primary structures like cryptalgal or fenestral lamination, to banded chalcedony and anhedral quartz crystals hosted in larger primary pores. This is interpreted as an effect of SiO₂ supersaturation, CaCO₃ replacement, and crystallization of diagenetic fluids sourced by the basinal units bearing organisms with an unstable opaline skeleton, like radiolarians or siliceous sponges, following a well-known diagenetic path from opal-A to opal-CT, to quartz (chalcedony to macro-quartz) (Hesse, 1988; Tréguer et al., 2021, and references therein). This silicification took place during the burial history of the rift basin, in correspondence of a texture/porosity jump (typically shallow-water grainstone vs. tight pelagic mudstone).

Finally, a recently discovered basin margin marker is the occurrence of microbial communities (endo-stromatolites) colonizing the laminoid spaces corresponding to cleavage planes in the Jurassic Longobucco rift basin of Northern Calabria (Southern Italy), where submarine escarpments are carved in low-grade metamorphites of the Hercynian basement (Santantonio & Fabbi, 2020). Palaeozoic metamorphites exhibiting parallel bands of calcite, whose microbially-induced growth resulted in cleavage-plane dilation and cracking of the host rock, mark the exhumed margins of the basin, forming linear belts that can be mapped for

tens of kilometers (Santantonio et al., 2016; Innamorati & Santantonio, 2018), and it is remarkable that those Jurassic microbes contribute to our understanding of the rift architecture of the region.

2.3 The Sabina plateau

The Sabina Plateau in Northern Apennines was a large-scale PCP, trending north-south for a few tens of kilometers, and rising prominently within the Sabina Basin (Figs. 1 and 2) (Galluzzo & Santantonio, 2002). The exposed marginal escarpment of the Sabina Plateau, trending north-south and facing the Sabina Basin lying to the east, has its roots in a rift master fault, which, according to Galluzzo and Santantonio (2002), produced a vertical displacement exceeding 2 km. As such, this is the major rift fault known in the region. To the east of the Sabina Basin, which was > 30 km across, lies the Latium-Abruzzi carbonate platform (Fig. 2). This latter platform escaped the Early Jurassic drowning and was able to shed neritic sediment into the adjacent basin throughout Jurassic to Miocene times. Due to this palaeotopography, the Sabina Plateau formed a submarine obstacle to the dispersal of the gravity flows from the shallow-water platform, which swept into the Sabina Basin from the east (Cipriani et al., 2020), as evidenced by their onlap against its east-dipping marginal escarpment. Those basins lying west of the Plateau are in contrast virtually devoid of such gravity flow deposits, due to the “shelter” effect of this intrabasinal high. A subsurface analogue of this situation has been observed off the buried margin of the Apulia Platform in the Adriatic Sea, where the resedimented neritic material was sequestered within a narrow basin locked between the platform and a submerged ridge made of offshore highs (“Elsa” PCP) (Santantonio et al., 2013). The Castiglione locality (Fig. 1), originally described by Farinacci (1967), documents the edge and upper escarpment margin of the Sabina Plateau. It offers a wealth of information and detail in a number of fields: submarine palaeotopography, rift basin analysis, sedimentology, stratigraphy (with an emphasis on ammonite biostratigraphy), palaeotectonics, diagenesis. This is an unprecedented concentrate of exceptional features, wonderfully exposed within an area only few hundred meters across.

3 Methods

The Sabina Plateau margin was investigated using traditional field and laboratory techniques of facies analysis specific to PCP/Basin depositional systems (Santantonio, 1993, 1994; Santantonio et al., 2017). These include geological mapping, sedimentology, in the field and in thin section,

Fig. 1 Location and simplified geological setting of the study area. (1) Lower Jurassic shallow-water carbonates (Calcare Massiccio); (2) Jurassic PCP-top condensed succession (Bugarone group); (3) Jurassic to Lower Cretaceous pelagic basinal succession; (4) Upper Cretaceous-Neogene deposits; (5) Pliocene-Middle Pleistocene marine-to-continental and volcanoclastic deposits; (6) Upper Pleistocene-Holocene continental deposits; (7) thrust fault; (8) fault. (Modified after Cipriani et al., 2020)

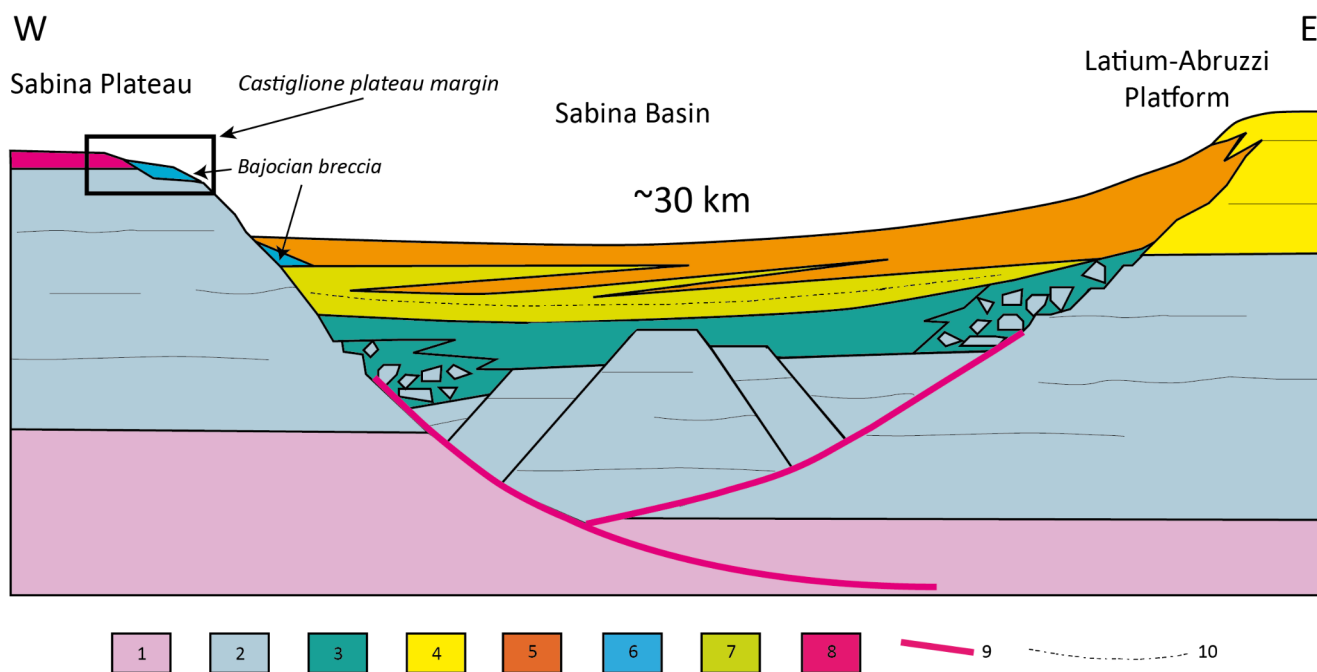
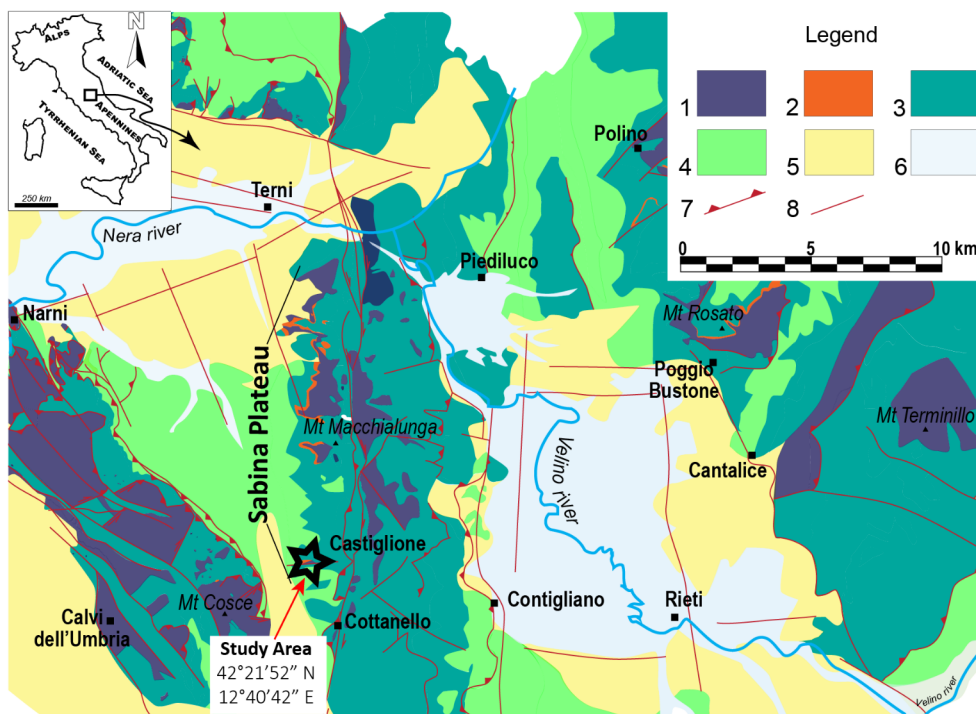


Fig. 2 Restored transect (Bajocian, Middle Jurassic) across the Sabina Plateau/Sabina Basin/Latium-Abruzzi Platform depositional system, cartoon not to scale; Legend: 1 - Upper Triassic evaporites and dolostones; 2- Hettangian-lowermost Sinemurian peritidal limestone (mostly pre-rift); 3- Sinemurian *p.p.*-Pliensbachian limestone, pelagic with various gravity flow and mass transport deposits (including megabreccias); 4- Shallow-water limestone (post lowermost Sinemurian); 5- Dominantly resedimented deposits and interbedded pelagites

(Toarcian-lower Bajocian); 6- Breccias, related to the early Bajocian margin-failure episode; 7 - Dominantly pelagites, with interbedded gravity flow deposits (Toarcian-lower Bajocian); 8- Condensed pelagic succession (Bugarone group, lower Pliensbachian-lower Bajocian); 9 - Rift master faults (late Hettangian-earliest Sinemurian); 10- black shales (early Toarcian oceanic anoxic event). Detachment in the evaporites had to be the result of stretching of the underlying basement. Modified after Galluzzo & Santantonio, 2002

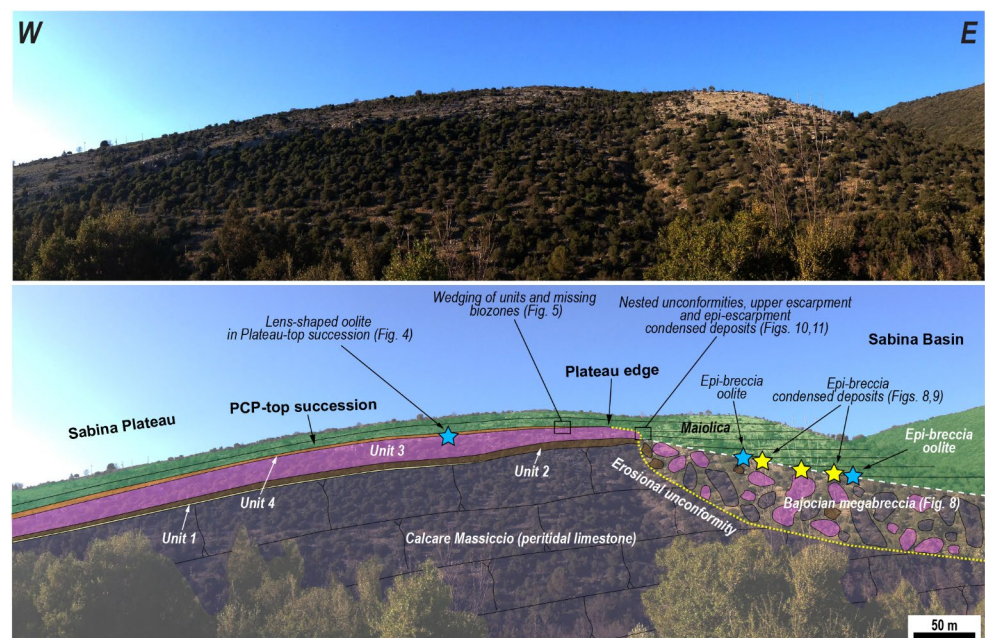
ammonite biostratigraphy, and use of the criteria for palaeo-escarpment analysis outlined above. In addition, a photogrammetric survey was performed by using the quadcopter drone DJI Mavic Air 2. It is an Unmanned Aerial System (UAS) equipped with a 1/2" CMOS Quad Bayer Sony IMX586 sensor camera, stabilized on a 3-axis gimbal. The camera is capable of shooting from 12 to 48 mpx, with a 24 mm focal length and $f/2.8$ aperture. Before the flight, the DJI drone was set on the Normal flight mode, with the aim of enabling the front and back collision avoidance sensors and exploiting the Advanced Pilot Assistance System 3.0 (APAS 3.0). The survey was constantly monitored from a smartphone connected to the remote controller through the DJI Fly app and the long-range transmission with the drone was guaranteed by the OcuSync 2.0 (using 2.4 and 5.8 GHz channels) technology. The shooting was performed setting the sensor to 100 ISO and the camera resolution to 12 mpx, due to the width of the outcrop, with the aim of reducing the processing time while still maintaining a high quality of the images. 603 zenital photos were taken alongside the wide surface, with a flight altitude ranging from 5 to 15 m. The images were exported as JPEG files, with 4000×2250 pixel resolution at 72 dpi. The aerial survey was manually completed in an hour. The processing was performed by using the software Agisoft Metashape Professional v. 1.5.3, aligning the images in order to produce a dense point cloud and, finally, a 3D textured mesh. Two 3D models were processed by using 603 and 383 photos, representing the whole outcrop and a detailed close-up of it, respectively.

4 Field data

4.1 The PCP-top succession

A condensed pelagic carbonate succession (Bugarone group), up to ca. 35 m thick (lower Pliensbachian *p.p.*-Tithonian; Galluzzo & Santantonio, 2002), overlies the peritidal limestone of the Calcare Massiccio (Hettangian-lower Sinemurian) at Castiglione (Fig. 2) either directly (*via* a drowning unconformity) or through an interposed transitional package where elements of the benthic, microbial and planktonic carbonate factories co-exist (drowning succession, upper Sinemurian-lowermost Pliensbachian; Marino & Santantonio, 2010, and references therein). This condensed succession comprises four stratigraphic units (Fig. 3), made of chert-free limestone and marly limestone. These units are not all “condensed” in the same sense: the lower three are condensed in that they are much thinner than their hanging wall basin counterparts (see original definition of “condensed sequence” by Jenkyns, 1971), while the fourth (lower Kimmeridgian *p.p.*-Tithonian) also exhibits an impressive concentration of ammonites, allowing for high-resolution biostratigraphy (Cecca et al., 1985). The lowest unit (Pliensbachian *p.p.*), a lime mudstone bearing radiolarians, sponge spicules, small terebratulid and rhynchonellid brachiopods and ammonites, which is up to 7 m thick elsewhere on the Sabina Plateau, is poorly exposed or missing at Castiglione. The second unit (Toarcian *p.p.*), 7.5 to 16 m thick at Castiglione, is poorly fossiliferous despite exhibiting a marly Rosso Ammonitico facies, represented by a nodular mudstone with sparse small thin-shelled bivalves *Bositra* (=“*Posidonia*”) and ostracods. The third

Fig. 3 Panoramic view of the Plateau edge and upper escarpment at Castiglione looking northwards (coordinates of the site in Fig. 1). Informal stratigraphy of condensed succession (Bugarone group) (after Galluzzo & Santantonio, 2002). Unit 1: Pliensbachian *p.p.*; Unit 2: Toarcian *p.p.*; Unit 3: latest Toarcian-early Bajocian; Unit 4: Kimmeridgian-Tithonian. (Modified after Cipriani et al., 2020)



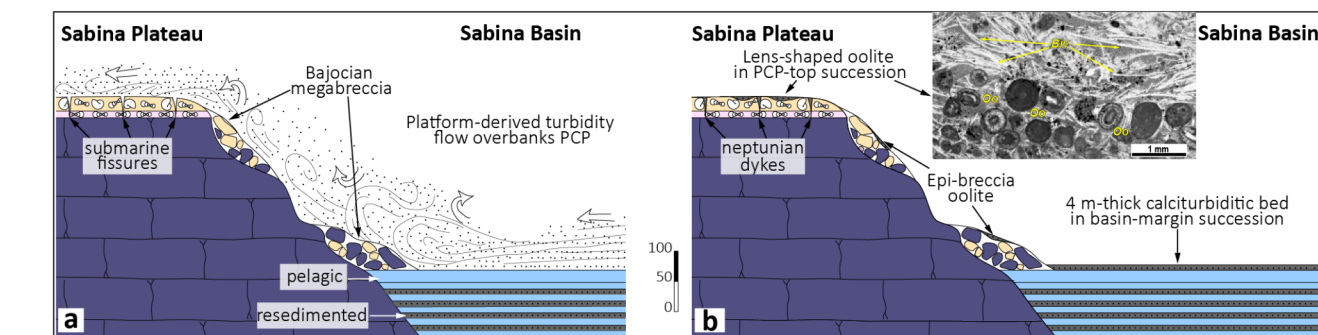


Fig. 4 a, b) Cartoon depicting the mechanism of overbanking for deposition of ooid-rich sands on the Plateau and along its margin. Inset in b, thin section from the Plateautop with ooids (Oo) and laminated thin-shelled bivalve packstone (Biv). (Modified after Cipriani et al., 2020)

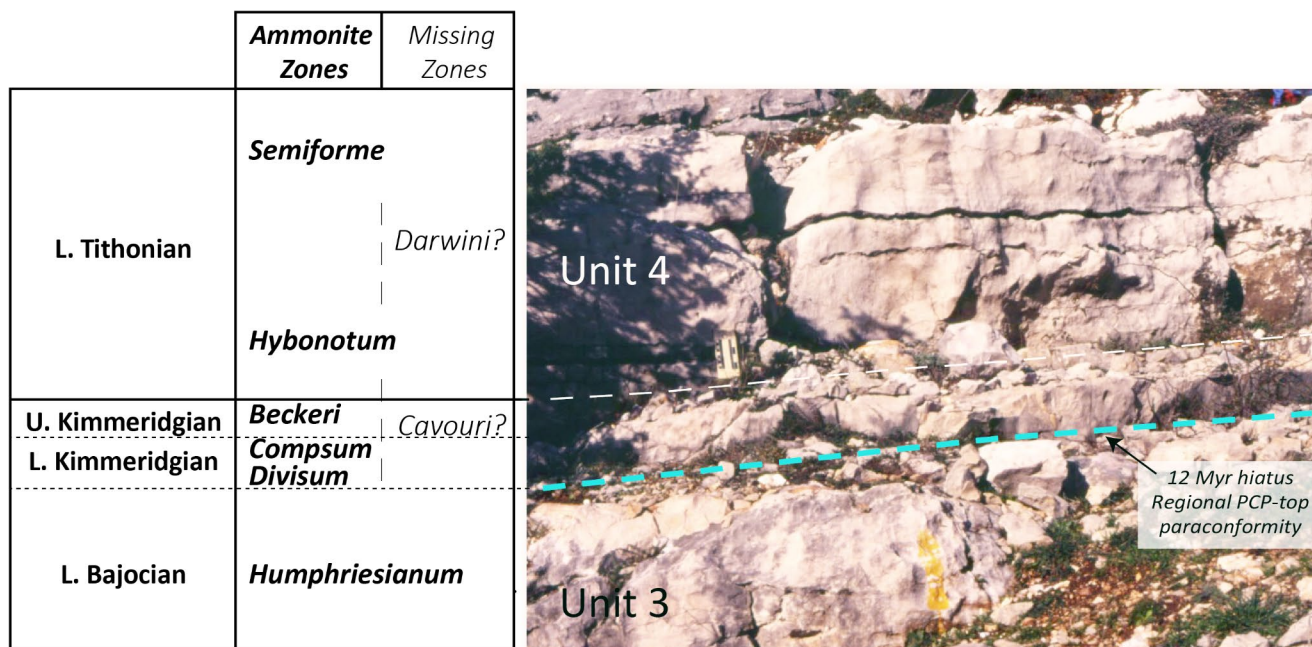


Fig. 5 Chronostratigraphy and ammonite biostratigraphy of the boundary of Units 3 to 4; Plateau-top succession

unit (upper Toarcian *p.p.*-lower Bajocian) is an up to ca. 19 m thick lime mud- to wackestone, with abundant thin-shelled bivalves and locally ammonites. The upper part of the third unit (lower Bajocian, Humphriesianum Zone) contains thin (cm- to dm-thick) lenses of graded and parallel-laminated oolitic and *Bositra* packstones, interbedded with the pelagic limestone (Figs. 3 and 4). The ooids are «well rounded micritic ooids with thinly laminated cortices» and «ooids with thinly laminated fine-radial cortices», according to the typologies of Strasser (1986) and are thus very shallow water in origin. The fourth unit is an up to ca. 6 m thick cephalopod (ammonites, aptychi, belemnites) floatstone (lower Kimmeridgian *p.p.*-Tithonian *p.p.*), also bearing corals including massive cerioid colonies (genus *Castiglionastrea*) and thamnasterioid pennular forms (Microsolenidae) (Gill et al., 2004); pennular corals are characterized by penulae, skeletal structures that hold particular gastrovascular

tubes, allowing for adaptation to oligophotic environments (Lathuilière & Gill, 1995). The third and fourth units are separated by a hiatus which is detected on each and every PCP of the region (Cecca et al., 1990), encompassing the late Bajocian, Bathonian, Callovian, Oxfordian and earliest Kimmeridgian (ca. 13 Ma; Cohen et al., 2013, updated version 2023/09) (Fig. 5). Going from the inner part of the Plateau towards its edge, this fourth unit thins from 6 to <2 m as individual beds thin-out and biozones disappear (Fig. 5). This PCP-top succession is locally crossed by at least two generations of neptunian dykes (Bajocian and?Barremian), the Bajocian ones locally bearing ooids (Fig. 6).

Fig. 6 Neptunian dykes (lower Bajocian) in the Rosso Ammonitico (Toarcian) of the Plateau-top succession, less than 50 m away from the Plateau edge/slide scar zone; note dense network with wandering trajectories (see text for explanation)

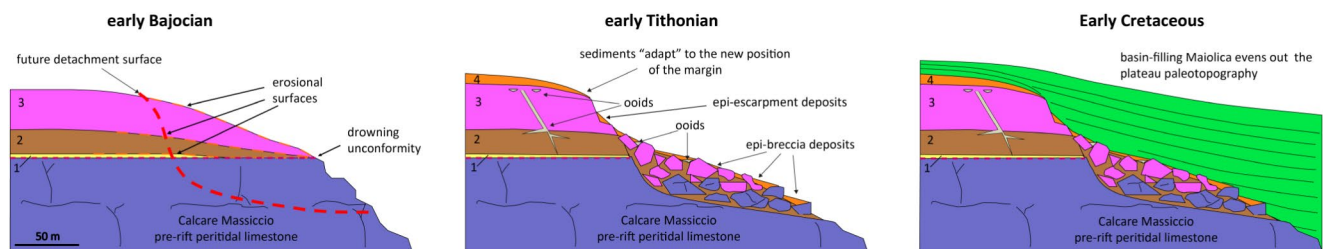


Fig. 7 Cartoon depicting the Early Jurassic to Early Cretaceous evolution of the Sabina Plateau margin at Castiglione. Stratigraphy as in Fig. 3, with the addition of PCP-top Unit 1: Corniola-equivalent formation (Pliensbachian *p.p.*)

4.2 Plateau edge and upper escarpment, and the breccia

The Castiglione outcrop offers an extremely detailed picture of the Sabina Plateau edge and upper escarpment (Figs. 3 and 7). Within a distance of few tens of meters, the fourth condensed unit thins from 3 m to 1.9 m as one approaches the platform edge, as mentioned above. Individual beds and biozones are seen to wedge out into a hiatal surface, a nice example being the Kimmeridgian part of the unit, which passes from 80 cm to 38 cm as the Cavouri Zone disappears (Fig. 5). Moving downslope, a megabreccia characterized by a very odd matrix (see below) and clasts up to several meters across abuts the lower part of the condensed succession and the underlying peritidal limestone, through a spoon-shaped basal contact corresponding to an erosional (scar) surface (Figs. 3 and 7). Clast sourcing is strictly local, as clasts (locally consisting of 2–4 stacked beds) belong to

the third condensed unit in the topographically higher part, while elements of the Calcare Massiccio occur downsection, *i.e.* where the incision carved deeper levels of the local stratigraphy. Field mapping reveals that this breccia is perched along the uppermost tract of the palaeo-escarpment profile: much of the clastic material however fell into the basin, whose bottom was about 300 m deeper at the time, forming a wedge interbedded with the pelagic/turbiditic hangingwall basin succession (not exposed at Castiglione). In other words, the tail of the breccia lies within its originating concave erosional surface. The stratigraphic thickness exposed at this scar surface is approximately 60 m.

Unexpectedly, the matrix of the breccia is made of the second condensed unit, the marly Rosso Ammonitico facies (Toarcian), which is older than the Bajocian youngest clasts (third condensed unit). This is possible because the marls injected into the breccia pervasively from below. Plastically deformed beds separate the larger clasts and locally form injection structures (Fig. 8c). This observation suggests that

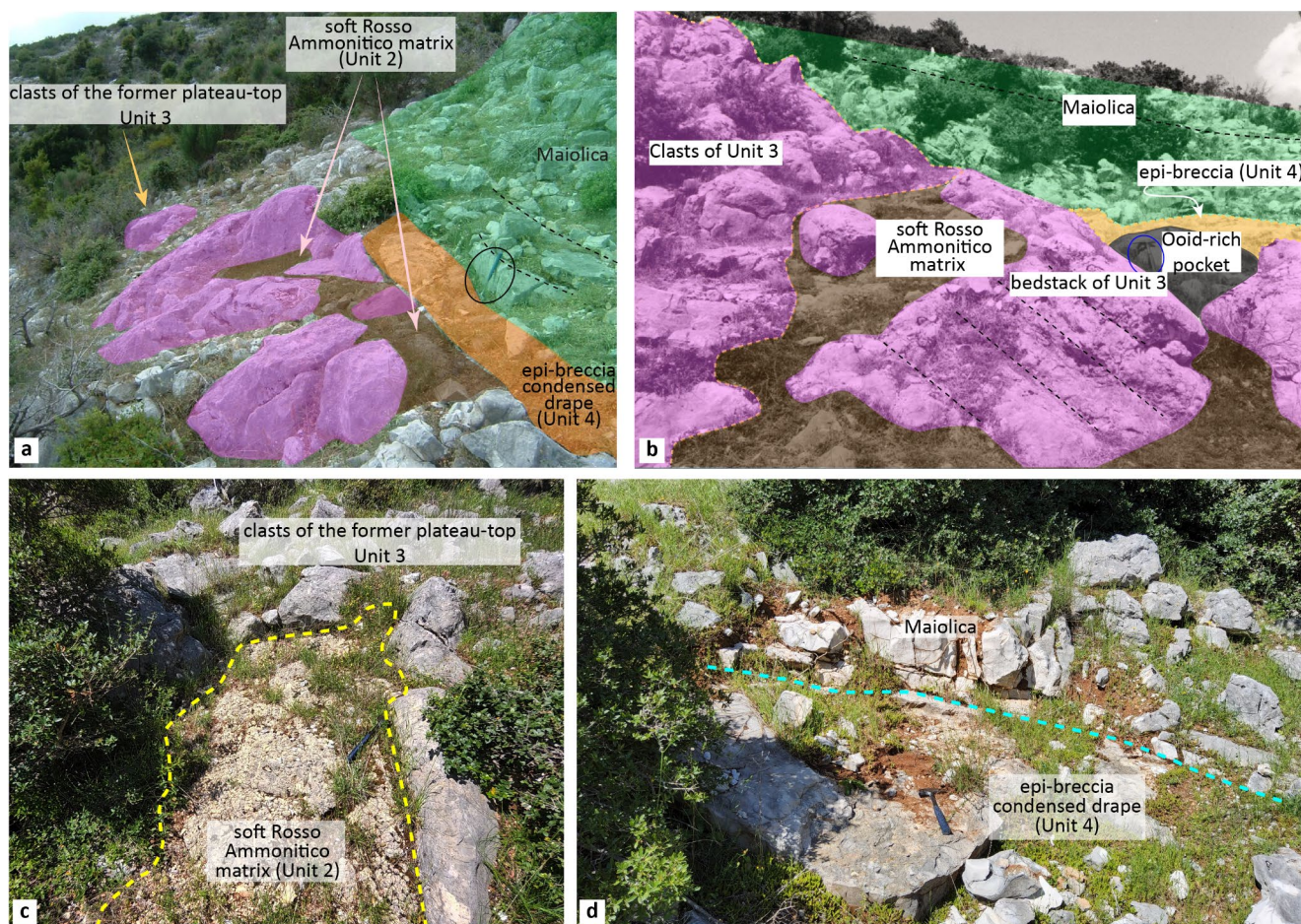


Fig. 8 Breccia, with megaclasts of Unit 3 floating in a matrix of poorly lithified Unit 2 (see text). (a) Onlap of the basinal Maiolica formation on the breccia, *via* an interposed lens of epi-breccia condensed deposits (Unit 4); (b) Breccia/matrix complex and onlap of the Maiolica formation *via* an interposed lens of epi-breccia condensed deposits

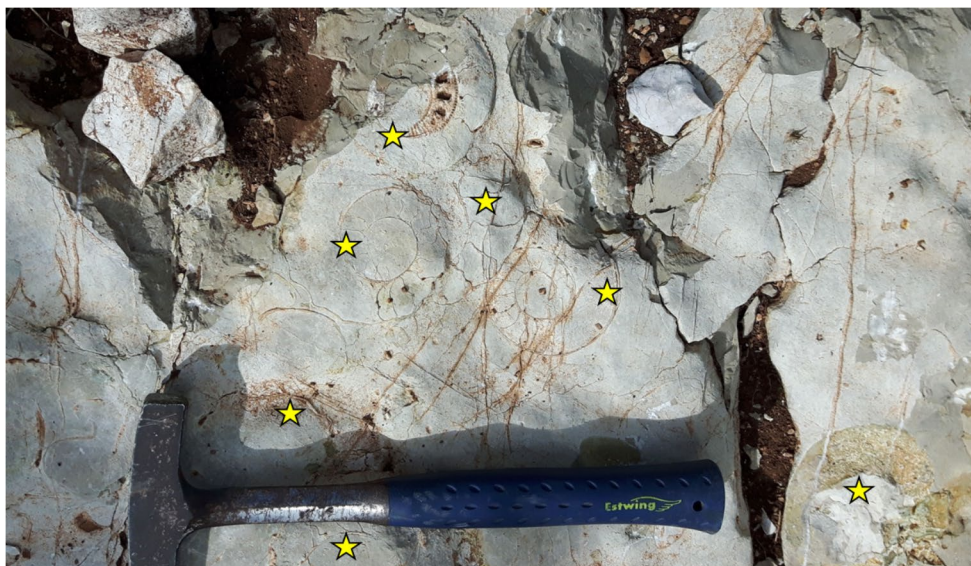
(Unit 4); note preserved pocket of ooid-rich overbank deposits filling an inter-block space at breccia top; (c) Breccia/matrix complex, with plastically deformed Rosso Ammonitico squeezed between boulders of younger Unit 3; (d) Onlap of the basinal Maiolica formation on the epi-breccia condensed deposits (Unit 4)

the Rosso Ammonitico had not undergone significant lithification at the time of the platform-margin collapse, unlike the other calcareous units in the stratigraphic succession. Particularly noteworthy is the contrast with the younger condensed unit 3, which produced angular clasts during the same event. As a consequence, the Rosso Ammonitico behaved plastically and was capable of flowing among the sliding boulders as a result of being “squeezed” under their load. Additional evidence for a comparatively slower diagenesis of the Rosso Ammonitico comes from neptunian dykes. Those crossing the marly Rosso Ammonitico have ill-defined walls and are pervasive, indicating that the host material was poorly lithified (Fig. 6). The top of the breccia hosts rare pockets of ooid-rich wacke- to grainstone in spaces among boulders (Figs. 7 and 8).

4.3 Epi-breccia deposits

The breccia is sealed by a discontinuous veneer of condensed pelagites, forming perched lenses several decimeters across among fallen clasts (Figs. 7 and 8), or locally a more continuous deposit, generally ranging 1 to 30 cm in thickness (epi-breccia deposits) (see Cipriani et al., 2016, and Fabbi et al., 2023, for other Jurassic examples). These deposits are rich in macrofossils (ammonites, aptychi, belemnites, solitary corals), and bear assemblages of variable age, mainly late Kimmeridgian (assemblages with *Hybonotoceras presulum*, *H. beckeri* and *Pseudowaagenia acanthomphala*) and early Tithonian (*Hybonotoceras hybonotum*, *Physodoceras sp.*, plus Lytoceratids and Phylloceratids) age, and as such are ascribed to the condensed unit 4 (Figs. 8d and 9). The tests of macrofossils are locally silicified. Had the breccia not been dated more precisely by means of the above palaeontological evidence, this unconformable drape would

Fig. 9 Pavement of epi-breccia condensed deposits (Unit 4), with ammonites (yellow star markers) truncated along equatorial planes at onlap surface of the Maiolica formation



have given a broader timeframe for its deposition (pre-Kimmeridgian), only based on stratigraphic relationships.

4.4 Nested unconformities, and the final onlap of the Maiolica formation

In analogy with the rest of the Umbria-Marche Domain of Northern Apennines, the Lower Cretaceous white calcionellid limestone (Maiolica formation) onlapped the uppermost escarpment tract and the condensed succession of the Sabina Plateau, thus leveling the submarine rift topography which had been created some 60Myr earlier (Fig. 7c). At Castiglione, the lower (Valanginian) part of the Maiolica is seen to progressively bury the breccia and its epi-breccia drape (Figs. 7 and 8d), for tens of meters of palaeotopographic relief, then the condensed Jurassic succession (Fig. 10), then eventually its older, Berriasian, Sabina Plateau-top counterpart (*i.e.* Maiolica on Maiolica unconformity), before achieving a tabular basin-wide geometry which is characteristic of the upper part (Hauterivian-Barremian) of this formation. Being a cherty limestone, this onlap unconformity is marked by silicification of the substrate (Fig. 10b), which is especially evident with quartz-replaced ammonite tests and aptychi in the condensed epi-breccia deposits (Fig. 9).

As expected, the breccia leaves room uphill to the slide crown zone, which is made of coalescing hemispherical scars, open towards the basin and up to about 7 m across (Fig. 11), with steep flanks carved into the third condensed unit (a major source of the breccia clasts). One prominent slide-scar is spoon-shaped and shallow (< 3 m). The floor of this concave scar is draped by thin condensed pelagites (unit 4), overlain by Valanginian beds of the chert-rich basinal Maiolica, which ultimately seal this complex erosional/depositional palaeomorphology (Fig. 11). The crown is itself

indented by a smaller-scale scar occupied by ponded epi-escarpment deposits of Unit 4 (unconformable condensed pelagic-on-condensed pelagic contact), 10–30 cm thick, of earliest Tithonian age (Hybonotum Zone), producing a nested-unconformities pattern (Figs. 10c and 11). Also here, the onlap surface of the Maiolica exhibits irregular chert crusts and silicified ammonite tests and aptychi (Fig. 10b, d).

5 Discussion

In the light of the collected data, Castiglione represents a remarkable example of all the typical features of a Jurassic PCP–basin transition (Fig. 12), displaying in addition a set of rare characteristics.

The natural transect dissecting the PCP displays lateral thickness variations in the condensed succession, from the inner sector of the PCP to the platform edge. The thinning of stratigraphic units towards the edge follows a pattern which is commonly observed on submarine highs receiving pelagic sedimentation (see Winterer, 1991, for the description of a submerged atoll in the Pacific; Santantonio et al., 1996), where it produces a general convex-up geometry that was dubbed “the panettone model” by Galluzzo and Santantonio (2002). These geometries are essentially related to (1) the removal of sediment (winnowing) by submarine currents, a process which is most effective, in terms of sediment waste and section reduction, close to the PCP edges, and (2) the much lower angle of repose of loose pelagic mud with respect to the underlying lithified shallow-water (pre-drowning) limestone (e.g., Schlager & Reijmer, 2009).

The thinning of Unit 4, in particular, can be interpreted as a consequence of the backstepping of the margin as this unit

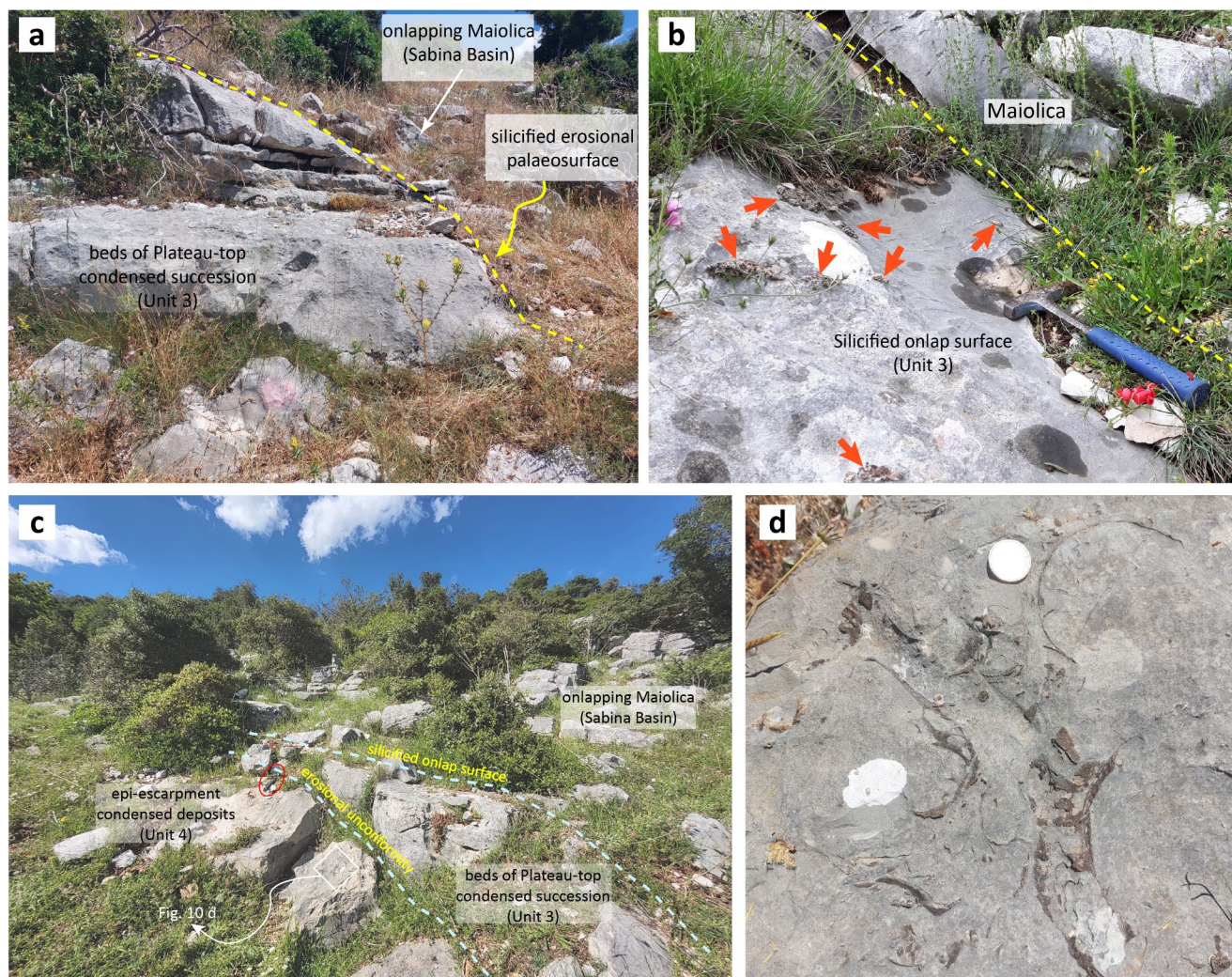


Fig. 10 (a) Erosional surface, truncating the Plateau-top condensed succession (Unit 3), with onlap of the basinal Maiolica formation; (b) Detail of erosional surface shown in a, with silicified zones (circled and arrowed); (c) Nested unconformities in the detachment scar carved

within the Plateau-top Unit 3, hosting unconformable pockets of epi-escarpment condensed deposits of Unit 4, and all in turn overlapped by the Maiolica formation; (d) detail of silicified ammonites and aptychi in Unit 4

“adjusted” its geometry to the new position of the edge: the underlying units are in contrast simply truncated by the scar surface (Fig. 7). As it is observed elsewhere on the Sabina Plateau, wherever the margin remained intact through the Jurassic, *i.e.* with no slide/rockfall-related indentations, the whole condensed succession maintains the “panettone” geometry (Galluzzo & Santantonio, 2002).

While condensed deposits were previously interpreted by default as the synonym of the PCP-top succession, their occurrence outside the perimeter of the high was noted by Santantonio (1993). This is consistent with the general concept that starved sedimentation is typical of any site that was elevated with respect to the basin bottom and as such subjected to net sediment loss in environments with low preservation potential. This includes not only the flanks of a high, but also instances of deposition as caps on the top of

large olistoliths or piles of clastic material (epi-escarpment, epi-breccia and epi-olistolith deposits, Fig. 12) (Galluzzo & Santantonio, 2002; Di Francesco et al., 2010; Cipriani et al., 2016; Santantonio et al., 2017; Fabbi et al., 2023).

The edge and marginal belt of a PCP are the sites of a complex array of unconformities (Fig. 12), which add to the paraconformities found in the Apenninic platform-top successions (drowning unconformity at the base of the condensed pelagic succession, and regional Bajocian-Kimmeridgian hiatus). The angular unconformities observed on the Sabina Plateau are:

- 1) Contacts along the escarpment surface carved in the footwall: (a) base of the breccia, (b) base of epi-escarpment deposits, and (c) onlap surface of the Maiolica.

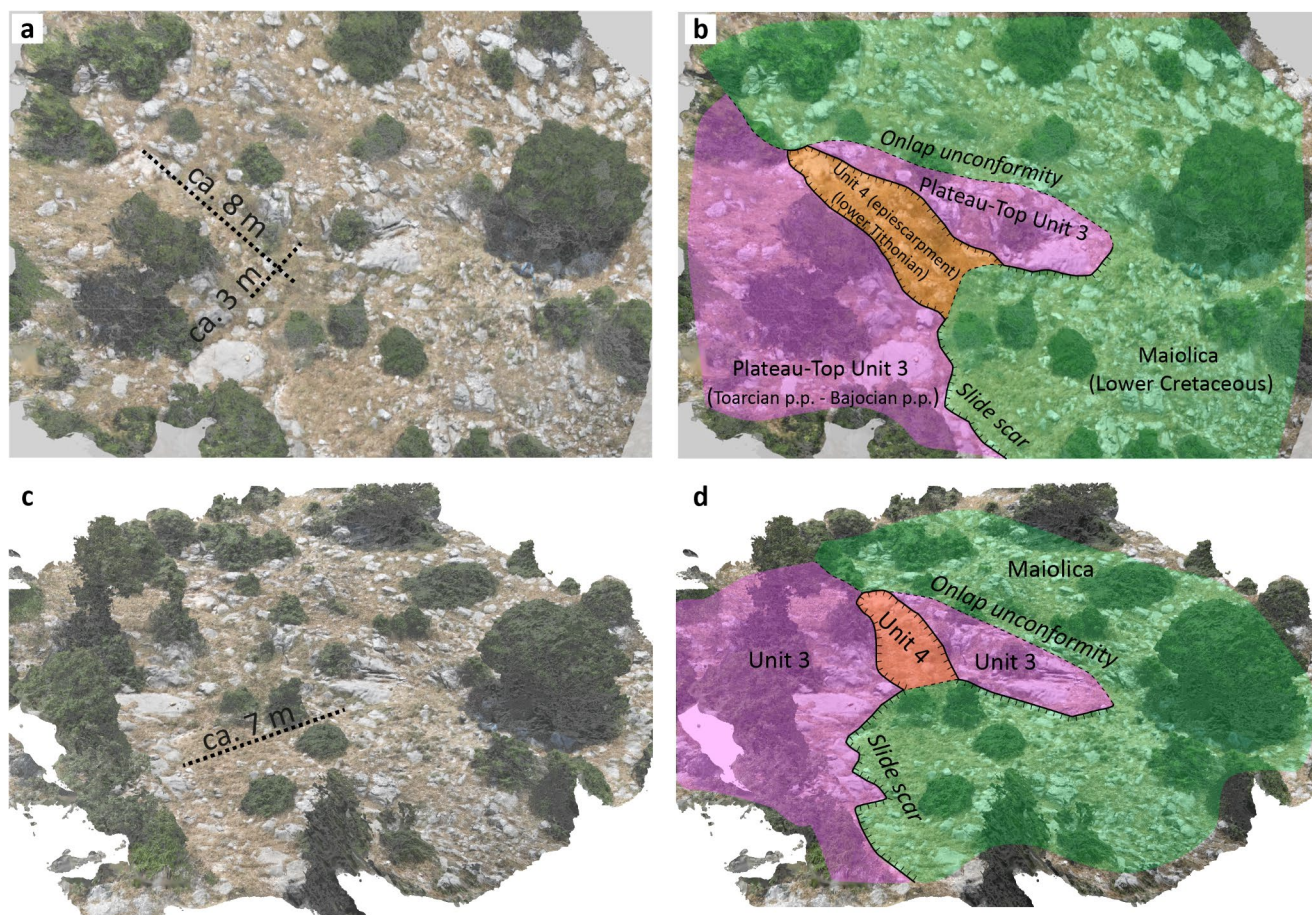


Fig. 11 Clean (a, c) and interpreted (b, d) drone views of the slide scar zone at the Plateau edge. Purple: eroded Plateau-top condensed succession; orange: epi-escarpment deposits (condensed pelagic drape of the scar zone); green: onlapping deposits of the final basin-fill stage

- 2) Contacts among PCP-margin units: (a) top of the breccia/base of epi-breccia deposits, and (b) top of epi-breccia deposits/onlap surface of the Maiolica.

Based on the above, epi-escarpment and epi-breccia deposits, as well as the breccia, qualify as unconformity-bounded units. Due to the chert-rich nature of the basinal Maiolica, contacts 1c and 2b are silicified surfaces.

The occurrence of ooids in a PCP-top succession (third unit) is unexpected, as in situ ooid production must be ruled out for five main reasons: (i) the platform had drowned a few tens of million years earlier; (ii) the ooids are only found at the base of thin laterally discontinuous lenses made of up to 10–20 cm-thick graded deposits, with scoured bases and parallel-laminated middle and upper portions made of *Bositra* pack- to wackestone; (iii) as such (see point ii) they in no way form cross-bedded shoals, the distinctive sign of any in situ ooid factory; (iv) no evidence exists throughout the top of the Plateau for the existence of a Bajocian shallow-water benthic carbonate factory, as it would be documented by palaeoenvironments (lagoons, tidal flats, etc.) lateral to the zone of ooid production; (v) the ubiquitous

pelagic mud characterizing the condensed Unit 3 indicates a low-energy environment, much unlike that required for the formation of ooid shoals. This punctuated occurrence has a key role in the interpretation of the Castiglione outcrop: the ooid-rich levels can be interpreted as representing overbank deposits, produced by turbulent flows sourced by the Latium-Abruzzi carbonate platform, and enriched along their journey with very thin *Posidonia* shells scoured and resuspended from the basin bottom, hitting the marginal escarpment of the Plateau (Galluzzo & Santantonio, 2002; see discussion in Cipriani et al., 2020). This is documented by mappable ooid-rich turbidites, in beds up to 2–4 m thick, abutting the pre-rift peritidal limestone exposed at the basin margin. These flows were then capable of “climbing” the escarpment (the Plateau top/basin bottom relief at the time was in the order of 250–350 m), leaving turbidite-sourced deposits on its top (Kneller & Buckee, 2000) (Fig. 4).

The Bajocian-Kimmeridgian hiatus, which is observed on all PCPs in the region, can be interpreted as a result of winnowing during a time span when Tethyan pelagic sedimentation at equatorial latitudes was dominated by radiolarians (see also Muttoni et al., 2005). The paucity of

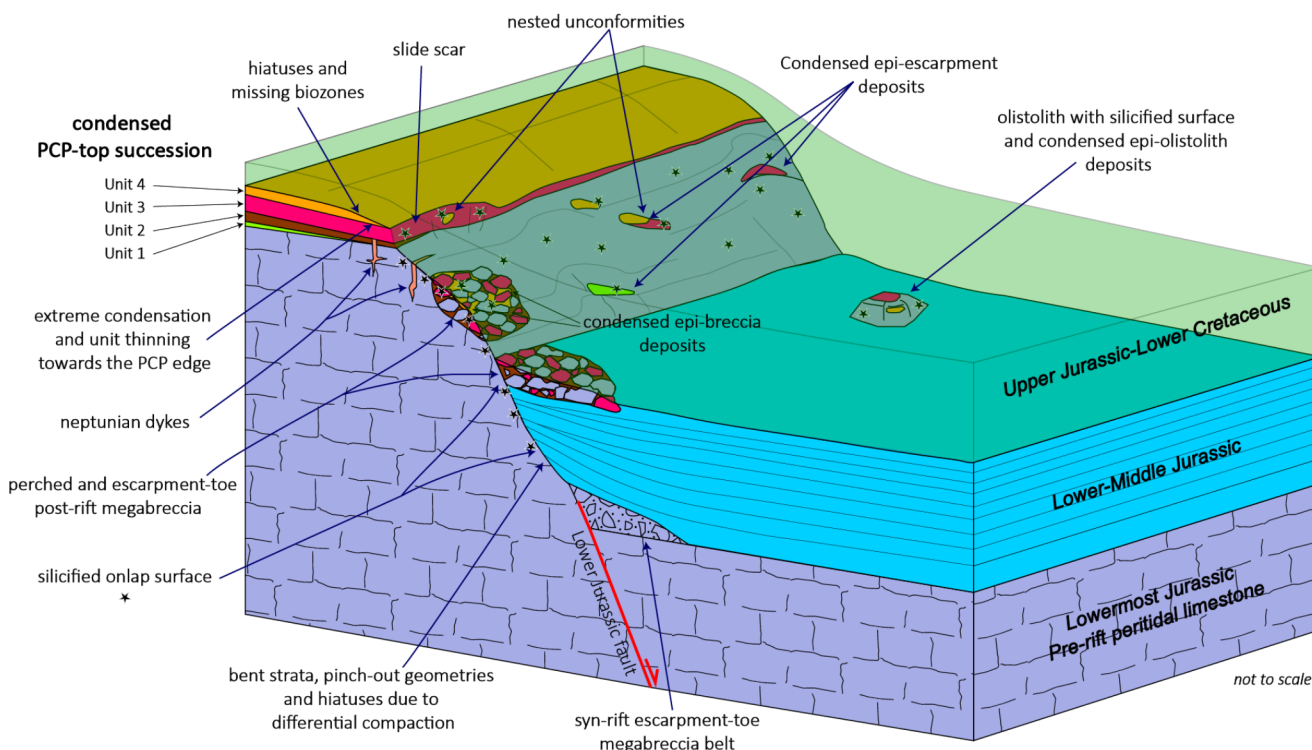


Fig. 12 Cartoon depicting the general facies and geometrical relationships of Hettangian to lowermost Cretaceous deposits at the eastern margin of the Sabina Plateau. See text for explanation

micron-sized particles due to a concomitant crisis in carbonate productivity (Bartolini & Cecca, 1999) made the very light-weight radiolarian tests, resting on the sea bottom, prone to episodic resuspension by currents in the absence of an adhesive carbonate mud matrix (Baumgartner, 1987; Santantonio et al., 1996; Bartolini & Cecca, 1999; Moretini et al., 2002). Carbonate sedimentation above the hiatal surface was resumed when the planktonic carbonate factory restarted, prior to the bloom recorded in the late Tithonian with the deposition of nannoconid-calpionellid limestone in the world oceans (“Kuenen event”, Roth, 1989).

The water depth of these condensed successions has been debated at length in the literature. A fundamental interpretative key to address this question is the presence of thamnasterioid corals, discovered in the lower Tithonian part of the succession. The thamnasterioid corals found in the fourth unit are interpreted as indicators of the lower part (100–250 m water depth) of the photic zone (Insalaco, 1996; Santantonio et al., 1996; Gill et al., 2004; Dieni & Massari, 2021). Their region-wide occurrence as synchronous short-lived appearances on PCPs in the early Tithonian has been used as a key for inferring a history of very slow subsidence of the footwall blocks (Nicosia & Pallini, 1977; Gill et al., 2004; Santantonio & Carminati, 2011). The recent discovery (Cipriani et al., 2019) of peculiar forms of zooxanthellate corals (*Ogilvinella*) in upper Tithonian deposits of the

Monte Nerone PCP in Northern Apennines supports such an interpretation, and it represents an even more extreme case suggesting a local depth at the time in the order of 40 m.

As already stressed, PCP margins are home to gravitational instabilities, such as rock falls, which are documented by breccias deposited at the toe and/or perched along the escarpments. These processes generate erosional morphologies of the PCP margins (spurs and slide scars), that can be admirably observed at Castiglione. In the specific case of the Castiglione breccia, direct evidence for assessing the age of the breccia is not available, in the absence of a “conventional” matrix. Circumstantial evidence, however, is plentiful, such as ooid-rich overbank deposits which are not solely found in the upper part (lower Bajocian) of condensed unit 3, but also occur in rare pockets resting on the breccia and within neptunian dykes, suggesting a coeval origination of these different geological bodies. All the evidence points to an early Bajocian age, a time frame of ephemeral revived tectonic activity that is locally documented in the Apennines of Central Italy, where it produced fault offsets up to 300 m (Cannata & Santantonio, 2010; Capotorti & Muraro, 2021).

The following history can thus be reconstructed: earthquakes triggered the inception of huge gravity flows at the shelf/slope break of the Latium-Abruzzi platform, and at the same time, as a far-field effect, the collapse of the margin of the Sabina Plateau; fractures developed in the rear of the

slide scar (Fig. 7b); the west-directed turbulent flow swept the Sabina Basin and eventually impacted the east-dipping escarpment of the Sabina Plateau; the flow surmounted the escarpment and the perched collapse breccia, which had become a part of the rejuvenated upper-escarpment profile, leaving scattered pockets of ooid sand at its top (Figs. 4 and 6); the remaining, waning, part of the flow swept the plateau, invaded the fractures, and eventually left the thin over-bank deposits, mentioned above, on its top (Figs. 4 and 7).

6 Conclusions

Drowned isolated carbonate platforms represent a common structural/sedimentological theme in the Western Tethyan Jurassic. The remarkable example described in this paper offers an uncommonly detailed picture of the PCP-to-basin transition (Fig. 12). The eastern margin of the Sabina Plateau retreated due to a phase of tectonic instability of the region. Collapse of the margin, which occurred in the early Bajocian as a result of seismic shocks related to this short-lived tectonic episode, is documented by a megaclastic body, whose tail rests on a system of detachment scars, and by genetically related neptunian dykes. The puzzling occurrence of ooid-rich deposits forming: (1) thin beds and lenses in the lower Bajocian part of the PCP-top condensed pelagic succession, (2) ponded pockets in inter-block lows at the top of the breccia along the escarpment profile, and (3) fracture fillings, describe the ascending path of gravity flows which originated tens of kilometers away to the east from a large shallow carbonate platform that had a dominantly non-skeletal rim made of ooid shoals. Exceptional details of the PCP edge and block detachment zone include multiple unconformities associated with coalescing hemispherical slide scars, veneers of condensed deposits, and their final burial by beds of the basin-filling succession. The onlap of Lower Cretaceous beds of the Sabina Basin on the PCP-top succession documents and constrains the age of the final sealing of the submarine topography which had been produced by the earliest Jurassic phase of continental breakup and opening of the Western Tethys some 60 My earlier (late Hettangian-early Sinemurian). The case example described in this paper is framed in a more general, super-regional picture of how ancient platform margins should be tackled through use of a set of dedicated observational criteria and a multidisciplinary approach. This highlights the potential of drowned-platform margins as key sectors for unraveling the sedimentary and tectonic evolution of a marine rift: from stable pre-rift conditions to syn-rift, to early post-rift platform drowning and onset of pelagic carbonate platform conditions, to punctuated episodes of backstepping of a Plateau margin and reorganization of pelagic carbonate bodies.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Alvarez, W. (1989). Evolution of the Monte Nerone seamount in the Umbria-Marche Apennines: 2. Tectonic control of the seamount-basin transition. *Bollettino Della Società Geologica Italiana*, 108, 23–29.
- Bartolini, A., & Cecca, F. (1999). 20 My hiatus in the Jurassic of Umbria-Marche Apennines (Italy): Carbonate crisis due to eutrophication. *Comptes Rendu Académie De Sciences Paris Sciences De La Terre and Planétaires*, 329, 587–595.
- Baumgartner, P. O. (1987). Age and genesis of Jurassic radiolarites. *Eclogae Geologicae Helveticae*, 80, 831–879.
- Bernoulli, D. (1964). Zur Geologie Des Monte Generoso (Lombardische Alpen). *Beiträge Zur Geologischen Karte Der Schweiz. Neue Folge*, 118, 1–134.
- Bertotti, G., Picotti, V., Bernoulli, D., & Castellarin, A. (1993). From rifting to drifting: Tectonic evolution of the South-Alpine upper crust from the Triassic to the Early Cretaceous. *Sedimentary Geology*, 86(1–2), 53–76.
- Bice, D. M., & Stewart, K. G. (1986). The formation and drowning of isolated carbonate seamounts: tectonic and ecological controls in the northern Apennines. In M.E. Tucker, J.L. Wilson.,

- P.D. Crevello, J.F. Sarg & J.F. Read (Eds.), *Carbonate platforms: facies, sequences and evolution* (pp. 145–168).
- Cannata, D., & Santantonio, M. (2010). Jurassic paleogeography and Neogene faulting at Corno Di Catria (Marche, Northern Apennines). *Rendiconti Online Società Geologica Italiana*, *11*, 721–722.
- Capotorti, F., & Muraro, C. (2021). Post-rift extensional tectonics at the edge of a carbonate platform: Insights from the Middle Jurassic-Early Cretaceous Monte Giano stratigraphic record (central apennines, Italy). *Geologica Acta*, *19*, 1–22. <https://doi.org/10.1344/GeologicaActa2021.19.12>
- 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*(5), 353–356. <https://doi.org/10.1130/G21262.1>.
- Cassinis, G., Perotti, C., & Santi, G. (2018). Post-variscan Verrucano-like deposits in Italy, and the onset of the alpine tectono-sedimentary cycle. *Earth-Science Reviews*, *185*, 476–497.
- Castellarin, A. (1982). La scarpata tettonica mesozoica Ballino-Garda (fra Riva e il Gruppo di Brenta). In A. Castellarin & G.B. Vai (Eds.), *Guida alla geologia del Subalpino centro-orientale. Guide geologiche regionali della Società Geologica Italiana* (pp. 79–95).
- Cecca, F., Cresta, S., Pallini, G., & Santantonio, M. (1985). Remarks on the Kimmeridgian-Lower Tithonian Ammonite biostratigraphy of two sections in the Central Apennines. *Newsletters on Stratigraphy*, *15*, 28–36.
- Cecca, F., Cresta, S., Pallini, G., & Santantonio, M. (1990). Il Giurassico di Monte Nerone (Appennino marchigiano, Italia Centrale): Biostratigrafia, litostratigrafia ed evoluzione paleogeografica. In: G. Pallini, F. Cecca, S. Cresta, & M. Santantonio (Eds.), *Atti II Convegno Internazionale Fossili, Evoluzione, Ambiente 1987* (pp. 63–139). Pergola, Italy.
- Centamore, E., Chiocchini, M., Deiana, G., Micarelli, A., & Pieruccini, U. (1971). Contributo alla conoscenza del giurassico dell'Appennino umbro-marchigiano. *Studi Geologici Camerti*, *1*, 7–90.
- Chenin, P., Manatschal, G., Ghienne, J. F., & Chao, P. (2022). The syn-rift tectono-stratigraphic record of rifted margins (part II): A new model to break through the proximal/distal interpretation frontier. *Basin Research*, *34*(2), 489–532.
- Cipriani, A., Citton, P., Romano, M., & Fabbi, S. (2016). Testing two opensource photogrammetry software as a tool to digitally preserve and objectively communicate significant geological data: The Agolla case study (Umbria-Marche Apennines). *Italian Journal of Geosciences*, *135*(2), 199–209.
- Cipriani, A., Fabbi, S., Lathuilière, B., & Santantonio, M. (2019). A reef coral in the condensed Maiolica facies on the Mt Nerone pelagic carbonate platform (Marche Apennines): The enigma of ancient pelagic deposits. *Sedimentary Geology*, *385*, 45–60.
- Cipriani, A., Caratelli, M., & Santantonio, M. (2020). Geological mapping reveals the role of Early Jurassic rift architecture in the dispersal of calciturbidites: New insights from the Central and Northern Apennines. *Basin Research*, *32*, 1485–1509.
- Cirilli, S. (1993). Il Trias Di Filetino-Vallepietra (Monti Simbruini, Appennino Centrale). *Bollettino Della Società Geologica Italiana*, *112*, 371–394.
- Cohen, K. M., Finney, S. C., Gibbard, P. L., & Fan, J. X. (2013). updated v. 2023/09) The ICS International Chronostratigraphic Chart. *Episodes*, *36*, 199–204.
- Colacicchi, R., & Piali, G. (1967). Dati a conferma di una lacuna dovuta ad emersione nel Giurese Di Monte Cucco (Appennino Umbro). *Bollettino Della Società Geologica Italiana*, *86*, 179–192.
- Colacicchi, R., Passeri, L., & Piali, G. (1970). Nuovi Dati Sul Giurese umbro-marchigiano ed ipotesi per un suo inquadramento regionale. *Memorie Della Società Geologica Italiana*, *9*, 839–874.
- De Paola, N., Collettini, C., Trippetta, F., Barchi, M. R., & Minelli, G. (2007). A mechanical model for complex fault patterns induced by evaporites dehydration and cyclic fluid pressure increase. *Journal of Structural Geology*, *29*, 1573–1584.
- Di Francesco, L., Fabbi, S., Santantonio, M., Bigi, S., & Poblet, J. (2010). Contribution of different kinematic models and a complex Jurassic stratigraphy in the construction of a forward model for the Montagna Dei Fiori fault-related fold (Central Apennines, Italy). *Geological Journal*, *45*(5–6), 489–505.
- Dieni, I., & Massari, F. (2021). The coral *Synastrea bellula* (d'Orbigny) in the Berriasian of Venetian Prealps (NE Italy). A key for interpreting the palaeobathymetry of the Maiolica on the Trento Plateau. *Cretaceous Research*, *125*, 104871. <https://doi.org/10.1016/j.cretres.2021.104871>
- Fabbi, S., & Santantonio, M. (2012). Footwall progradation in syn-rift carbonate platform-slope systems (early jurassic, Northern Apennines, Italy). *Sedimentary Geology*, *281*, 21–34. <https://doi.org/10.1016/j.sedgeo.2012.07.008>.
- Fabbi, S., Innamorati, G., Mariotti, N., & Santantonio, M. (2023). The Il Torno collapsed basin-margin tract and rockfall deposits: The stunning snapshot of a preserved Jurassic submarine topography in the Longobucco Basin (Calabria, Italy). *International Journal of Earth Sciences*, 581–584. <https://doi.org/10.1007/s00531-022-02279-x>
- Farinacci, A. (1967). La Serie Giurassico-Neocomiana Di Monte Lacerone (Sabina). Nuove Vedute Sull'interpretazione paleogeografica delle aree di facies umbro-marchigiana. *Geologica Romana*, *6*, 421–480.
- Farinacci, A., Mariotti, N., Nicosia, U., Pallini, G., & Schiavinotto, F. (1981). Jurassic sediments in the Umbro-Marchean Apennines: an alternative model. In: A. Farinacci, & S. Elmi, (Eds.), *Rosso Ammonitico Symposium Proceedings* (pp. 335–398). Edizioni Tecnoscienza, Roma.
- Franceschi, M., Dal Corso, J., Posenato, R., Roghi, G., Masetti, D., & Jenkyns, H. C. (2014). Early Pliensbachian (Early Jurassic) C-isotope perturbation and the diffusion of the Lithotia Fauna: Insights from the western Tethys. *Palaeogeography Palaeoclimatology Palaeoecology*, *410*, 255–263. <https://doi.org/10.1016/j.palaeo.2014.05.025>
- Galdenzi, S., & Menichetti, M. (1999). Tectono-sedimentary evolution of the Jurassic in the Umbria-Marche Basin. *Palaeopelagos*, *3*, 143–148.
- Galluzzo, F., & Santantonio, M. (2002). The Sabina Plateau: A new element in the Mesozoic palaeogeography of Central Apennines. *Bollettino Della Società Geologica Italiana*, *1*, 561–588.
- Gill, G. A., Santantonio, M., & Lathuilière, B. (2004). The depth of pelagic deposits in the Tethyan Jurassic and the use of corals: An example from the apennines. *Sedimentary Geology*, *166*(3–4), 311–334. <https://doi.org/10.1016/j.sedgeo.2004.01.013>
- Hesse, R. (1988). Diagenesis #13. Origin of chert: Diagenesis of biogenic siliceous sediments. *Geoscience Canada*, *15*(3), 171–192.
- Innamorati, G., & M. Santantonio (2018). Evidence for extended Hercynian basement and a preserved Jurassic basin-margin tract in Northern Calabria (Southern Italy): The Longobucco Basin. *Sedimentary Geology*, *376*, 147–163.
- Insalaco, E. (1996). Upper Jurassic microsolenids biostromes of northern and central Europe: Facies and depositional environment. *Palaeogeography Palaeoclimatology Palaeoecology*, *121*, 169–194.
- Jenkyns, H. C. (1971). The genesis of condensed sequences in the Tethyan Jurassic. *Lethaia*, *4*, 327–352. <https://doi.org/10.1111/j.1502-3931.1971.tb01928.x>

- Kneller, B., & Buckee, C. (2000). The structure and fluid mechanics of turbidity currents: A review of some recent studies and their geological implications. *Sedimentology*, 47, 62–94.
- Lathuilière, B., & Gill, G. A. (1995). Some new suggestions on functional morphology in pennular corals. *Publications Du Service géologique Du Luxembourg*, 29, 259–263.
- Marino, M., & Santantonio, M. (2010). Understanding the geological record of carbonate platform drowning across rifted Tethyan margins: Examples from the Lower Jurassic of the Apennines and Sicily (Italy). *Sedimentary Geology*, 225, 116–137.
- Morettini, E., Santantonio, M., Bartolini, A., Cecca, F., Baumgartner, P. O., & Hunziker, J. C. (2002). Carbon isotope stratigraphy and carbonate production during the Early-Middle Jurassic: Examples from the Umbria-Marche-Sabina Apennines (central Italy). *Palaeogeography Palaeoclimatology Palaeoecology*, 184, 251–273. [https://doi.org/10.1016/S0031-0182\(02\)00258-4](https://doi.org/10.1016/S0031-0182(02)00258-4)
- Muttoni, G., Erba, E., Kent, D., & Bachtadse, V. (2005). Mesozoic Alpine facies deposition as a result of past latitudinal plate motion. *Nature*, 59–63. <https://doi.org/10.1038/nature03378>.
- Nicosia, U., & Pallini, G. (1977). Hermatypic corals in the Tithonian pelagic facies of Central Apennines. Evidences of Upper Jurassic sea-level changes. *Geologica Romana*, 16, 243–261.
- Perrone, V., Martín-Algarra, A., Critelli, S., Decandia, F. A., D'errico, M., Estevez, A., Iannace, A., Lazzarotto, A., Martin-Martin, M., Martín-Rojas, I., Mazzoli, S., Messina, A., Mongelli, G., Vitale, S., & Zaghoul, M. N. (2006). 'Verrucano' and 'Pseudoverrucano' in the Central-Western Mediterranean Alpine Chains: Palaeogeographical evolution and geodynamic significance. *Geological Society London Special Publications*, 262(1), 1–43.
- Pomar, L., Molina, J. M., Ruiz-Ortiz, P. A., & Vera, J. A. (2019). Storms in the deep: Tempestite-and beach-like deposits in pelagic sequences (Jurassic, Subbetic, South of Spain). *Marine and Petroleum Geology*, 107, 365–381. <https://doi.org/10.1016/j.marpe>
- Roth, P. H. (1989). Ocean circulation and calcareous nannoplankton evolution during the Jurassic and Cretaceous. *Palaeogeography Palaeoclimatology Palaeoecology*, 74(1–2), 111–126.
- 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 Bulletin*, 78, 122–141.
- Santantonio, M., & Carminati, E. (2011). Jurassic rifting evolution of the Apennines and Southern Alps (Italy): Parallels and differences. *Geological Society of America Bulletin*, 123, 468–484.
- Santantonio, M., & Fabbi, S. (2020). Anatomy and Jurassic evolution of a Hercynian basement high (Caloveto High– Calabria, Southern Italy). *Italian Journal of Geosciences*, 139, 30–53. <https://doi.org/10.3301/IJG.2019.16>
- 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.
- Santantonio, M., Scrocca, D., & Lipparini, L. (2013). The Ombrina-Rospo Plateau (Apulian platform): Evolution of a carbonate platform and its margins during the Jurassic and Cretaceous. *Marine and Petroleum Geology*, 42, 4–29.
- Santantonio, M., Fabbi, S., & Aldega, L. (2016). Mesozoic architecture of a tract of the European–Iberian continental margin: Insights from preserved submarine palaeotopography in the Longobucco Basin (Calabria, Southern Italy). *Sedimentary Geology*, 331, 94–113.
- Santantonio, M., Fabbi, S., Bigi, S. Discussion on «Geological map of the partially dolomitized Jurassic succession exposed in the central sector of the Montagna dei Fiori Anticline, Central Apennines, Italy» by by, Storti, G., Balsamo, F., & Koopman, A. (2017). (2017). *Italian Journal of Geosciences*, 136(2), 312–316.
- Santantonio, M., Cipriani, A., Fabbi, S., & Meister, C. (2022). Constraining the slip rate of Jurassic rift faults through the drowning history of a carbonate platform. *Terra Nova*, 34(2), 137–145.
- Schlager, W., & Reijmer, J. J. (2009). Carbonate platform slopes of the Alpine Triassic and the Neogene—a comparison. *Austrian Journal of Earth Sciences*, 102(1), 4–14.
- Strasser, A. (1986). - Ooids in Purbeck limestones (lowermost Cretaceous) of the Swiss and French Jura. *Sedimentology*, 33, 711–727.
- Tréguer, P. J., Sutton, J. N., Brzezinski, M., Charette, M. A., Devries, T., Dutkiewicz, S., Ehlert, C., Hawkings, J., Leynaert, A., Liu, S. M., Llopis Monferrer, N., López-Acosta, M., Maldonado, M., Rahman, S., Ran, L., & Rouxel, O. (2021). Reviews and syntheses: The biogeochemical cycle of silicon in the modern ocean. *Biogeosciences*, 18(4), 1269–1289. <https://doi.org/10.5194/bg-18-1269-2021>.
- Winterer, E. L. (1991). The Tethyan Pacific during late Jurassic and Cretaceous times. *Palaeogeography Palaeoclimatology Palaeoecology*, 87(91), 253–265. <https://doi.org/10.1016/0031-0182>