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A reef coral in the condensed Maiolica facies on the Mt Nerone pelagic carbonate platform (Marche Apennines): The enigma of ancient pelagic deposits

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ABSTRACT

A coral interpreted as a shallow-water zooxanthellate (z-) form has been recovered from the uppermost part of a condensed, pelagic carbonate platform-top succession, in levels with transitional characters between the Jurassic Bugarone Group and the Maiolica Formation, a calpionellid-bearing pelagic deposit. While the existence of z-corals in the Jurassic pelagic facies of northern Apenninic structural highs is well documented, with early Tithonian forms diagnostic of the lower layers of the photic zone, the species described in this paper is slightly younger (late Tithonian), possesses a different morphology and is known from typical reef facies. While this finding provides welcome evidence for the paleodepth interpretation of otherwise enigmatic facies, it also challenges our understanding of pelagic deposits, in paleoenvironments that have no modern counterparts.

1. Introduction

Deciphering the paleodepth of ancient pelagic deposits can be a tricky exercise due to the common lack of diagnostic organisms or sedimentary structures (Gill et al., 2004). On top of this, anachronistic environments could have existed over geologic time, leaving physical signatures that we simply have no tools to interpret unequivocally. Condensed ammonite-rich pelagic deposits are commonly detected on the top of pelagic carbonate platforms (PCPs) across the western Tethyan realm, representing sedimentation on the structural highs which were produced by incipient plate separation in the Early Jurassic (Santantonio, 1994). Being the product of biological, geographic and oceanographic conditions that are not duplicated today (see also Cecca et al., 1992), this class of deposits is hardly interpretable in an uniformitarian key. Condensed deposits form thin (few tens of meters maximum for the lower Pliensbachian to upper Tithonian/lowest Cretaceous interval) successions, having facies associations and bed geometries which can be taken as diagnostic for the different sub-environments of a PCP and its margins (Cecca et al., 1990; Santantonio, 1993; Santantonio et al., 1996, 2017; Galluzzo and Santantonio, 2002). Unequivocal paleontological elements for interpreting the water-depth component in a paleoenvironmental reconstruction, however, are rare, as depth-dependent benthic (or planktonic) foraminifer assemblages, for example, are generally missing (e.g., Katz et al., 2013). Corals are a fortunate exception in this respect, as they can be relatively common at specific stratigraphic levels in the Kimmeridgian-Tithonian (or locally Berriasian) part of the condensed succession (Bugarone Group) across the Umbria-Marche-Sabina Apennines (Nicosia and Pallini, 1977; Cecca et al., 1990; Galluzzo and Santantonio, 2002). Identifying the zooxanthellate (z) vs azooxanthellate (non-z) nature of these corals is obviously crucial, as z-corals are the sole ones with a potential for constraining water depth, down to the level of distinct layers within the photic zone. In regional geologic studies this can in turn produce stringent constraints when paleotectonic/geodynamic reconstructions (e.g., the subsidence history of continental margins) are required. In the specific case of Central and Northern Apennines, the occurrence of corals interpreted as z-corals in deposits postdating by some 50 million years the acme of tectonic extension (Gill et al., 2004), linked with propagation of the Tethys Ocean toward the western quadrants, not only serves to our understanding of rifting mechanisms in the region (Santantonio and Carminati, 2011), but also sheds light on the origin of pelagic deposits in the Jurassic and early Cretaceous. This paper describes a new coral recovered from the top of the Mt Nerone PCP in the Marche region. Unlike thin laminar thamnasterioid

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forms (*Kobya monteneronensis*; Gill et al., 2004) previously described in the area, interpreted as z-corals indicating the lower part of the mesophotic zone, the species reported here, *Ogilvinella elegans* (Eliášová, 1973), has the typical dome-shaped morphology and skeletal architecture of a reefal colony and is interpreted as a shallow-water zooxanthellate form. The coral is associated with a peculiar pelagic facies, which indicates the persistence of the paleogeographic conditions typical of the Jurassic Bugarone Group (hereafter Bugarone Grp) after the super-regional switch to Maiolica-type sedimentation (white calpionellid-rich mudstone) which followed the global bloom of calcareous nannoplankton ("Kuenen event"; Roth, 1989).

2. Material and methods

The study coral *Ogilvinella elegans* is stored at "*Museo dei Fossili e dei Minerali del M. Nerone*" of Apecchio (Pesaro-Urbino, Marche, Italy) (inventory number: 94504). A 3D photogrammetric model of the coral was obtained using a 24 Megapixel Canon EOS 750D (18 mm focal length) and built using the software Agisoft PhotoScan Pro (e.g., Citton et al., 2015, 2016, 2017, 2019; Cipriani et al., 2016; Fabbi et al., 2016a; Romano and Citton, 2017) (Fig. 1). A digital 3D model in .PLY format is provided as Supplementary material. Detailed geological mapping (1:5.000) of the coral-bearing area was performed to reconstruct the Jurassic-Cretaceous stratigraphic and paleotectonic setting. Three detailed (cm-scale) stratigraphic sections were measured in key outcrops, with a focus on the Bugarone superiore/Maiolica transition. The coral itself, the embedding pelagites, and the other lithostratigraphic units outcropping in the area were sampled and analyzed in thin-section for microfacies and biostratigraphic investigation. Four thin sections were obtained from the coral and the embedding pelagites, collected from the base, the flank and the top of the specimen (numbered 94504-A, 94504-B, 94504-C and 94504-D and stored at "*Museo dei Fossili e dei*

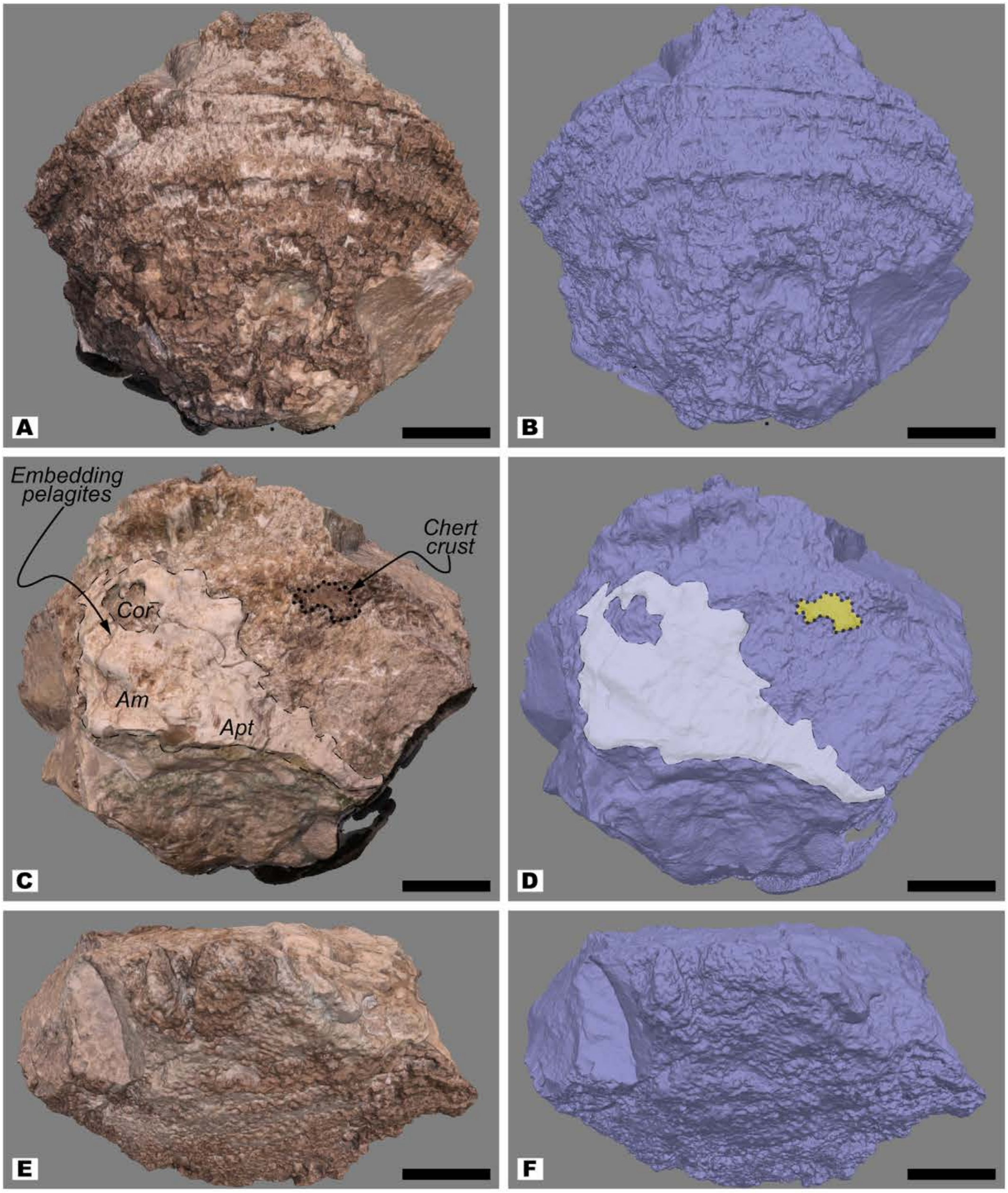


Fig. 1. Photogrammetric textured (A, C, E) and solid (B, D, F) model of the study coral from different angles, obtained using the software Agisoft PhotoScan Pro. In D); in blue is the coral, in white are the embedding pelagites and in yellow is the chert crust. *Am*) ammonite; *Apt*) aptychus; *Cor*) coral. Scale bar: 5 cm. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Minerali del M. Nerone" of Apecchio); a comprehensive view of the full thin section is provided as Supplementary material.

3. Geological setting

The Umbria-Marche Apennines of Central Italy exhibit an Upper Triassic-Miocene stratigraphic succession that documents sedimentation in conditions changing from shallow-marine to deep-water through the pre-rift, to syn-rift, to passive margin, to foredeep/collisional evolution of the region (Carminati and Doglioni, 2012; Pierantoni et al., 2013). The Jurassic-Lower Cretaceous portion of the succession is especially instructive to those investigating the various typologies of interplay between synsedimentary extension and carbonate sedimentation. The future Umbria-Marche region was experiencing plate separation, resulting in a degree of tectonic-topographic complexity, which would influence the nature and three-dimensional development of marine facies for tens of million years (Farinacci et al., 1981; Galdenzi, 1986, 1988; Alvarez, 1989a, 1989b; Santantonio, 1993; Galluzzo and Santantonio, 1994, 2002; Santantonio et al., 1996; Galdenzi and Menichetti, 1999; Marino and Santantonio, 2010; Donatelli and Tramontana, 2014; Fabbi, 2015; Cipriani, 2016), following the dismembering of the superregional Hettangian carbonate platform represented by the Calcare Massiccio Formation (hereafter Fm) (e.g., Santantonio and Carminati, 2011, and references therein). While tectonic subsidence caused the

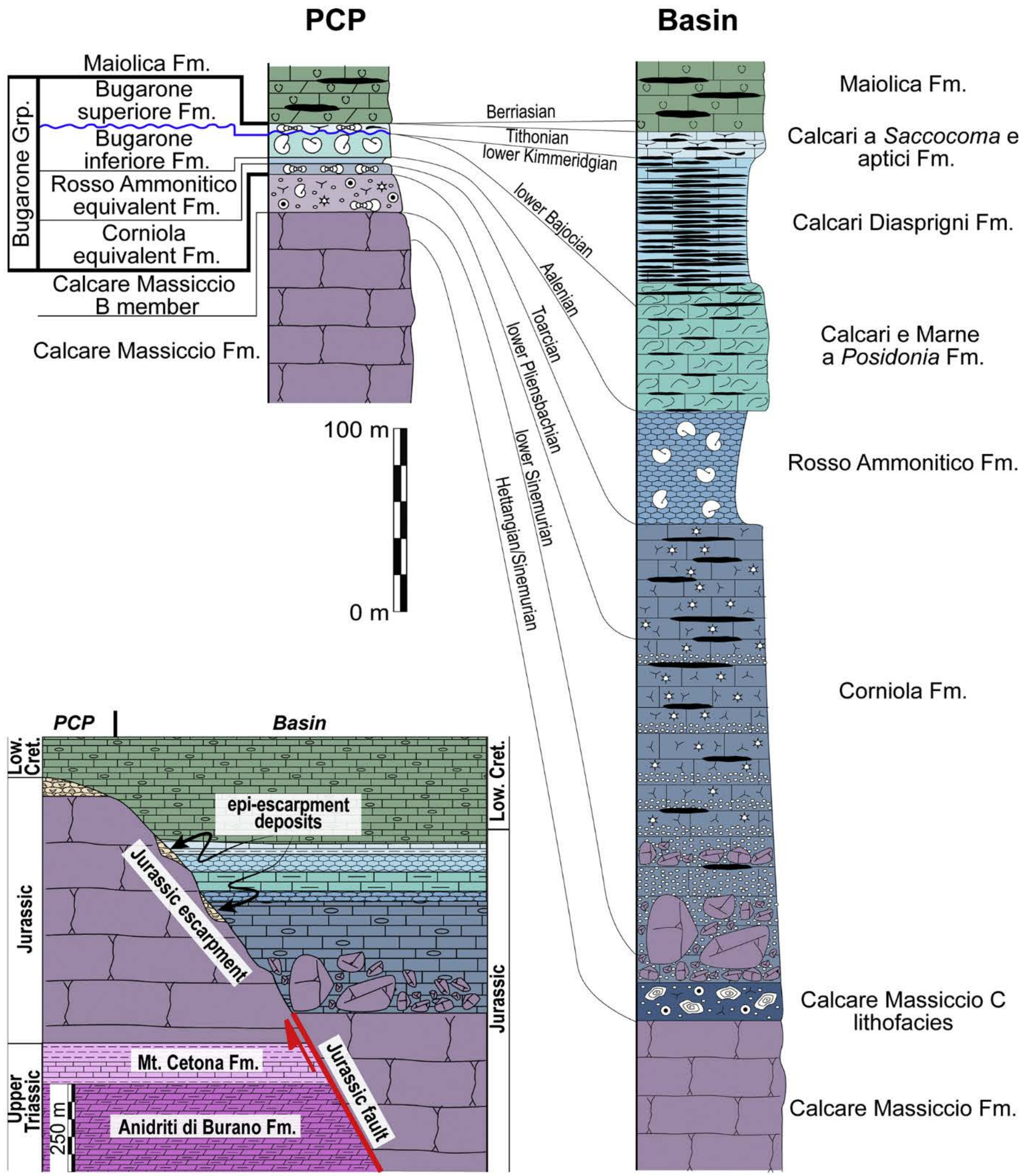


Fig. 2. Idealized stratigraphic scheme, and correlated Jurassic-Lower Cretaceous successions in PCP-Basin systems of the UMS Domain. Correlation lines are time lines.

demise of benthic carbonate production on hangingwall blocks by outpacing the aggradational potential of the platform, thus forcing the change to pelagic/turbiditic sedimentation at the Hettangian/Sinemurian boundary, carbonate factories survived – albeit with changing characters through time - on footwall blocks until the earliest early Pliensbachian (early Carixian) (Marino and Santantonio, 2010; Fabbi and Santantonio, 2012). In particular, a typical very shallow-water factory with elements (e.g., dasycladacean algae, mollusks, assorted coated grains) analogous to those of the pre-rift phase persisted on structural highs until the early Sinemurian, morphing in the late Sinemurian (Lotharingian) into a transitional facies, meaning here a facies resulting from the joint contributions of the benthic and planktonic carbonate factories. This facies ("Calcare Massiccio B"– Centamore et al., 1971; "drowning succession" in Marino and Santantonio, 2010) is typically made of a packstone dominated by benthic elements like microbial oncoids, crinoids, gastropods, small brachiopods and calcareous sponges among others, but also exhibits sparse cephalopods, radiolarians and siliceous sponges in a dominantly pelagic mud matrix (Marino and Santantonio, 2010). The demise of this peculiar carbonate factory in the early Pliensbachian (Ibex Zone - Morettini et al., 2002) switched the structural highs to pelagic carbonate platforms (PCPs) hosting a condensed pelagic ammonite-rich succession through the Tithonian-Berriasian (Bugarone Grp). Drowning of the numerous footwall-block factories was a regionally synchronous event (Cecca et al., 1990; Santantonio, 1993, 1994; Santantonio et al., 1996). This change is interpreted as unrelated with tectonics – it took place in an early post-rift regime (Santantonio and Carminati, 2011) - and driven instead by an oceanographic perturbation that also left a geochemical signature (e.g., Korte and Hesselbo, 2011; Franceschi et al., 2014; Masetti et al., 2016).

The lower Pliensbachian to Tithonian (locally Berriasian) condensed PCP-top succession constitutes the Bugarone Grp (Cecca et al., 1990 - originally a formation-rank unit; Jacobacci et al., 1974), which is made of four formations (Corniola-equivalent, Rosso Ammonitico-equivalent, Bugarone inferiore and Bugarone superiore Fms) representing the thin chert-free equivalents of the Corniola, Rosso Ammonitico/Marne di Monte Serrone, Calcari e marne a *Posidonia* and Calcari a *Saccocoma* e aptici Fms known in hangingwall-basin successions (Fig. 2). Notably, the stratigraphic interval covered by the Calcari Diasprigni Fm (radiolarian cherts) in basinal successions is encompassed by a circa 20 My hiatus on all PCPs of the Apennines (e.g., Cecca et al., 1985, 1990; Santantonio, 1993).

3.1. Condensed successions

The very existence of condensed successions is related to the existence of PCPs as intrabasinal highs, since the nature of this type of deposits is due to the lower preservation potential predicted for

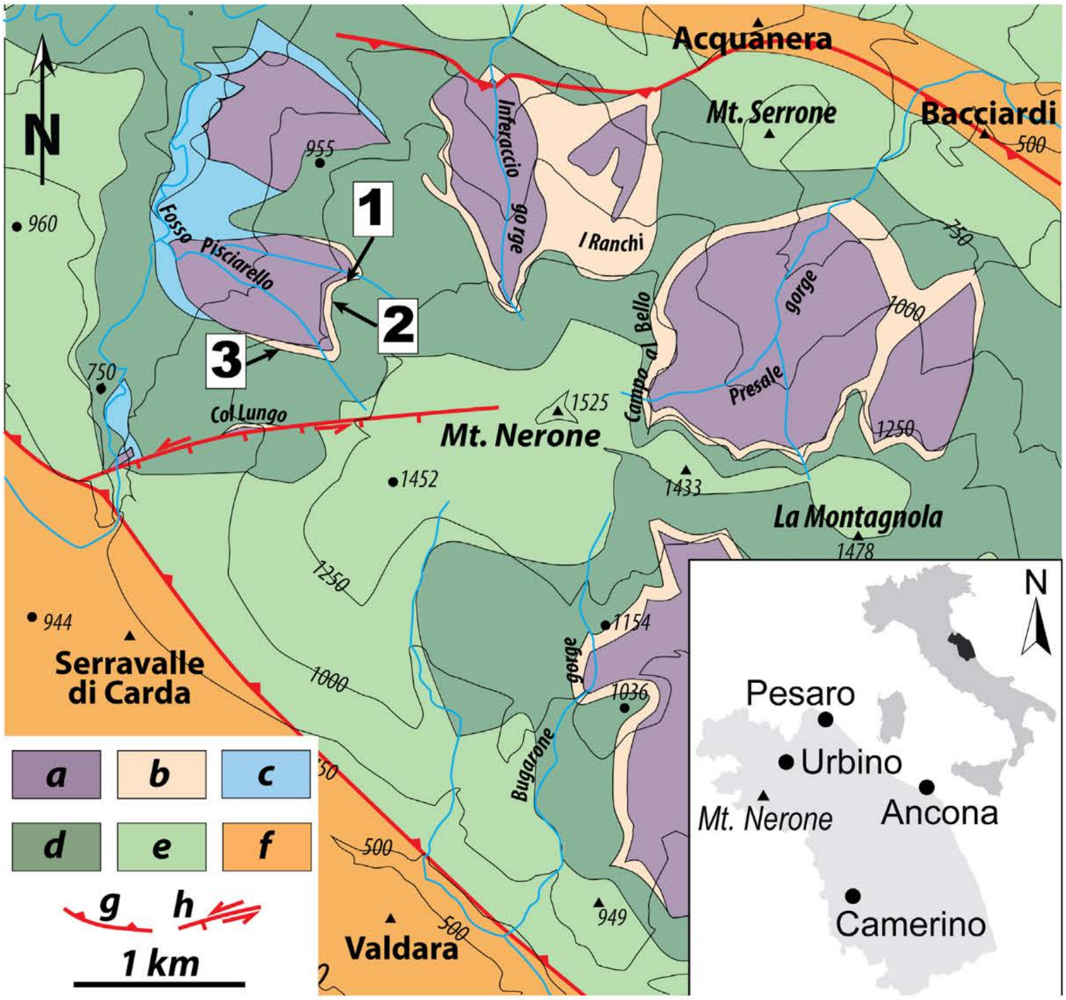


Fig. 3. Geographical localization and simplified geological map of the Mt Nerone area. 1) Fosso Pisciarello I section (43°33′40.15″N; 12°30′10.92″E); 2) Fosso Pisciarello II section (43°33′39.09″N; 12°30′8.78″E); 3) Fosso Pisciarello III section (43°33′41.48″N; 12°29′49.40″E). *Legend*: a) Calcare Massiccio Fm; b) Bugarone Group; c) Jurassic basinal succession; d) Maiolica Fm; e) upper Lower Cretaceous-Oligocene deposits; f) Miocene-Recent deposits; g) main thrust faults; h) left-lateral transtensive fault.
Modified from Romano et al. (2019).

any sediment which settles on elevated topography with respect to the basin bottom (Santantonio, 1993), where sediment is unstable and/or prone to periodic removal by currents. In addition, through most of the Jurassic the planktonic carbonate factory had an overall low efficiency (Cobianchi and Picotti, 2001), despite the substantial increase of differentiation of planktonic organisms (dinoflagellates, calpionellids, planktonic foraminifers - e.g., Knoll and Follows, 2016; Fraaije et al., 2018). The sum of these factors produced extreme instances of condensation, to the point that computing sedimentation rates for certain chronostratigraphic intervals gives unrealistic results (e.g., <1 mm/1000 y for the Kimmeridgian/Tithonian; Cecca et al., 1990; Santantonio, 1993). The relative importance of the erosional component in the composition of PCP-top successions emerges from high-resolution ammonite biostratigraphy and sedimentology, revealing that these successions are riddled with stratigraphic gaps as only short snippets of individual biozones are preserved. Furthermore, the upper sides of ammonites are often badly preserved and/or truncated, which also suggests punctuated episodes of exhumation (Cecca et al., 1985, 1990).

When the burst in planktonic carbonate productivity took place in the late Tithonian ("Kuenen event"; Roth, 1989), raising net sedimentation rates in the world oceans, the infilling of hangingwall rift-basins in the future Umbria-Marche region, initiated around the Hettangian/Sinemurian boundary, was nearly complete. The upper Tithonian-lowermost Aptian Maiolica Fm, the "global" formation which records that biological turnover (Wieczorek, 1988), is in fact traditionally described as the stratigraphic unit which eventually evens out the topographic relief generated by extensional faults (Centamore et al., 1971; Farinacci et al., 1981). Field mapping demonstrates that the Maiolica Fm typically onlaps the highest part of submarine footwall paleoescarpments, that is the pre-rift Calcare Massiccio Fm plus the thin PCP-top succession overlying it, including the lower beds of the Maiolica itself (condensed upper Tithonian-Berriasian levels), in the Valanginian (see for example the eastern margin of the Sabina Plateau - Galluzzo and Santantonio, 2002). Following this, pelagic beds can generally be traced continuously all across former buried PCP-basin systems, although the submarine paleotopography could be locally rejuvenated by revived extensional faulting in the Barremian/Aptian (Fabbi, 2015; Cipriani, 2016; Fabbi et al., 2016b; Cipriani and Bottini, 2018, 2019). To summarize, the levels that produced the coral discussed in this paper represent the uppermost part of the condensed succession, where the relative abundance of fossil remains, which is typical of the pre-upper Tithonian succession, co-exists with Maiolica-type sediment.

3.2. The Col Lungo-Fosso Pisciarello area – Paleotectonic setting

Col Lungo and Fosso Pisciarello are two classical stratigraphic sections for the Jurassic of the paradigmatic Mt Nerone PCP (e.g., Centamore et al., 1971; Cecca et al., 1990; Romano et al., 2019, and references therein) (Fig. 3). These localities are along the western slopes of Mt Nerone, at the northern termination of the NW-SE-trending/NE-vergent Mt Catria – Mt Nerone anticline. The backbone of the anticline locally is made of Calcare Massiccio Fm, which crops out in deeply-incised gullies (e.g., Col Lungo and Fosso Pisciarello). In the study area the drowning of the Calcare Massiccio carbonate platform is marked by up to 3 m of Calcare Massiccio B, followed by a thin condensed succession (Bugarone Grp). The Pliensbachian to Tithonian interval shows a west/northwestward wedging-out trend, as their thickness decreases from 16 m in the Col Lungo section to 0 m in the northwesternmost outcrops of Fosso Pisciarello, over a distance of 500 m.

As a general reference for the Mt Nerone PCP, the Bugarone Grp in its type-locality (about 2,5 km east of our coral site) representing a platform-interior setting, is 40 m-thick for the same stratigraphic

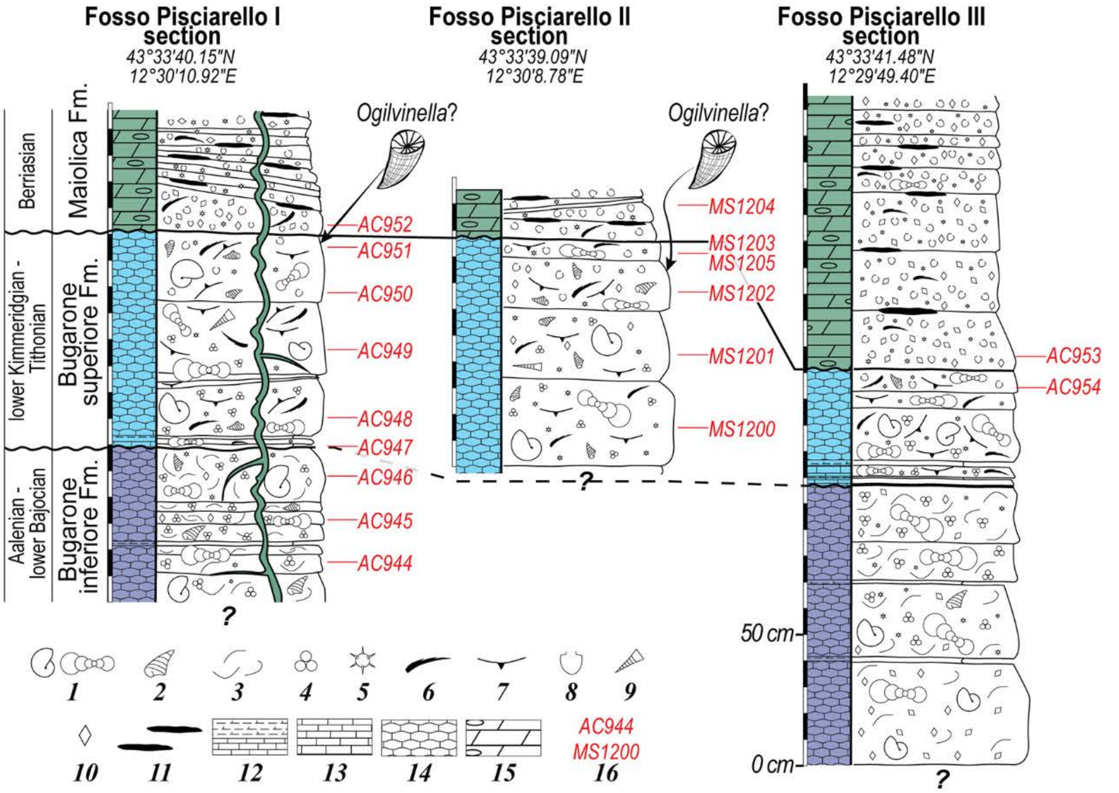


Fig. 4. Stratigraphic sections measured in the coral-bearing Fosso Pisciarello outcrops. 1) ammonites; 2) gastropods; 3) thin-shelled bivalves; 4) *Globuligerina oxfordiana*; 5) radiolarians; 6) aptychi; 7) *Saccocoma* spp.; 8) calpionellids; 9) belemnites; 10) dolomitization; 11) chert; 12) marls and marly limestones; 13) limestones; 14) nodular limestones;15) cherty limestones; 16) position and acronym of the samples used for microfacies and biostratigraphic analysis.

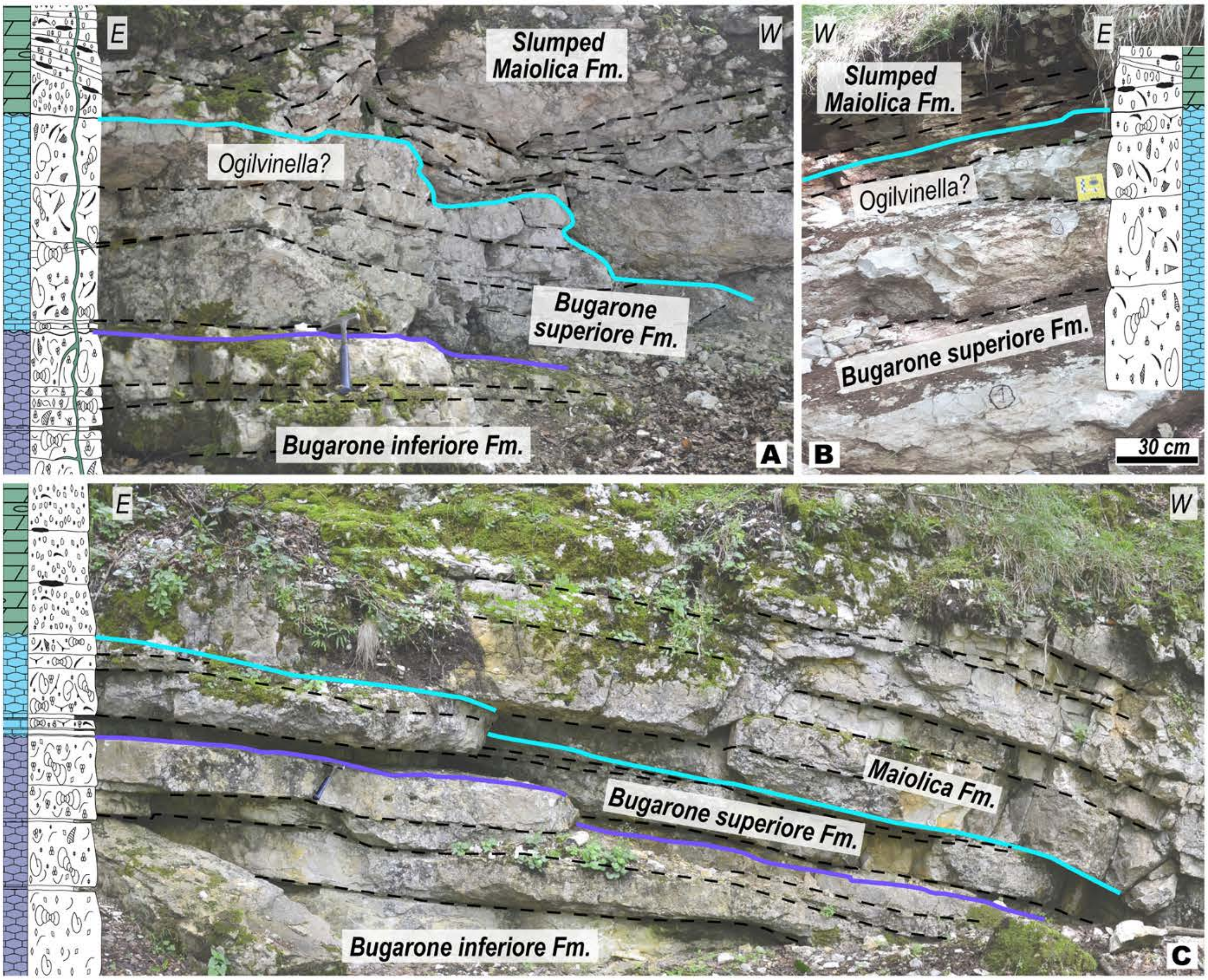


Fig. 5. Outcrop view of the Fosso Pisciarello sections. A) Fosso Pisciarello I outcrop; B) part of the Fosso Pisciarello II section; C) field view of the Fosso Pisciarello III section.

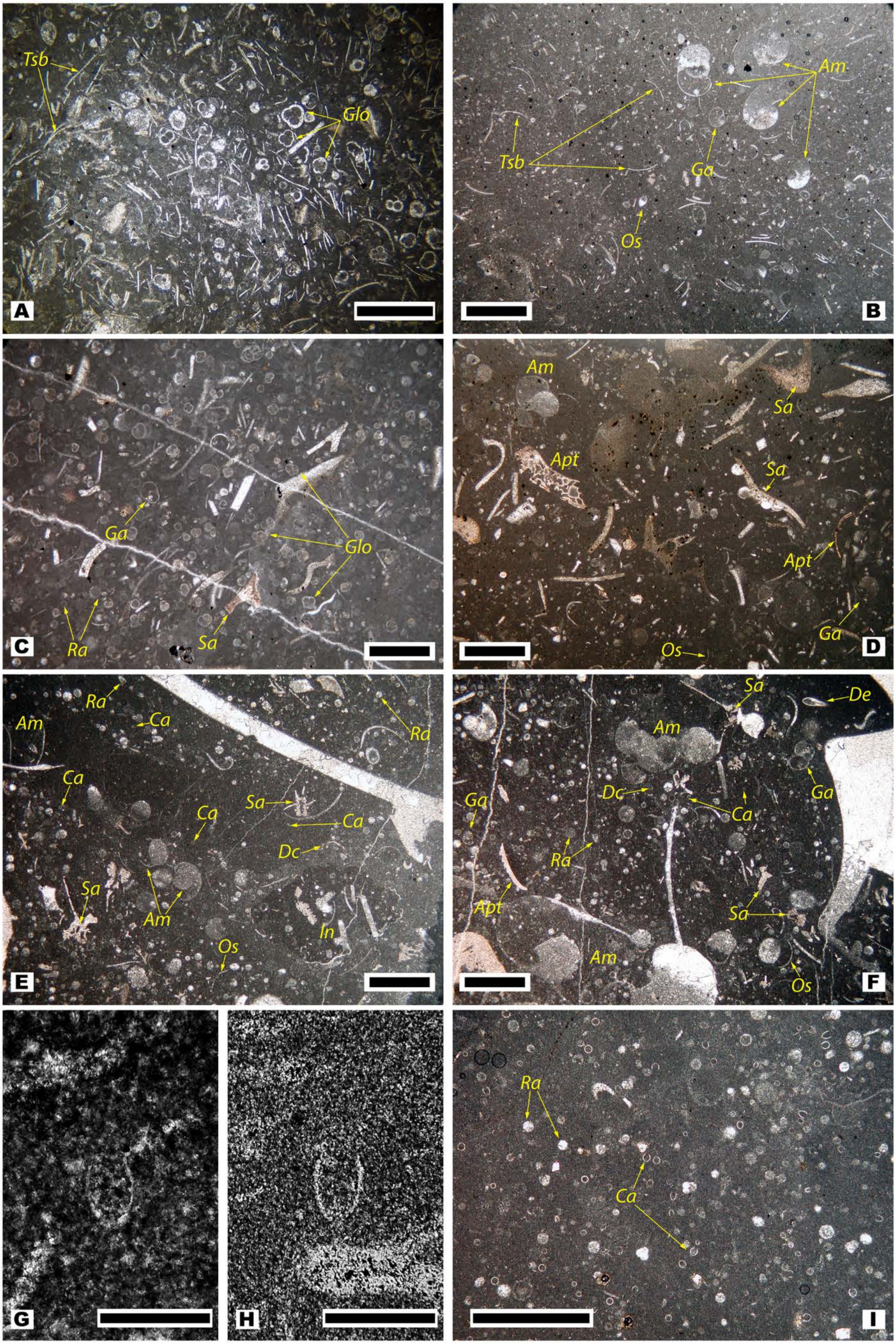
interval (Centamore et al., 1971; Cecca et al., 1990). The wedge-out geometry of the condensed succession is accompanied by i) the occurrence of erosional surfaces and truncated beds, ii) the existence of numerous hiatuses (paraconformities), only detectable through ammonite biostratigraphy (e.g., Cecca et al., 1990) and iii) the increase in fossil abundance. Thin, discontinuous, and often exceptionally fossiliferous sections are therefore indicative of PCP-edge settings (Santantonio et al., 1996). Where the Bugarone Grp thins-out to 0 m (i.e., the northwesternmost outcrop of the Mt Nerone PCP-edge), the Maiolica Fm rests directly on the Calcare Massiccio Fm. The Fosso Pisciarello edge changes abruptly to a steep, circa NW-dipping escarpment hosting the youngest onlap unconformity of the basin-filling Maiolica Fm.

3.3. The Fosso Pisciarello Sections

The *Ogilvinella* specimen was recovered as loose material in the Fosso Pisciarello valley, adjacent to the Pliensbachian-to-Tithonian outcrops of Bugarone Grp. Three stratigraphic sections were analyzed at a cm-scale to exactly define the source interval for this exceptional remain (Figs. 4 and 5). Two sections (Fosso Pisciarello I and III, respectively 187 and 255 cm thick) encompass the Bajocian-to-Berriasian interval of the Bugarone inferiore, Bugarone superiore and Maiolica Fms, while one section (Fosso Pisciarello II, 105 cm thick) records the Bugarone superiore/Maiolica boundary.

The orange-colored, faintly nodular and pervasively dolomitized bajocian facies of the Bugarone inferiore Fm, rich in “thick-shelled” *Globuligerina oxfordiana* (Giovagnoli and Schiavinotto, 1987), thin-shelled bivalves, and ammonites (Fig. 6A–B), passes to the lower Kimmeridgian-lower Tithonian Bugarone superiore Fm through a paraconformity. A 3 cm-thick mineralized (FeMn) hardground marks this unconformity surface. The pale brown, incipiently nodular and dolomitized facies of the Bugarone superiore Fm bears rich cephalopod assemblages (aptychi, belemnites and ammonites) along with *Saccocoma* sp., “thin-shelled” *Globuligerina oxfordiana* sensu Giovagnoli and Schiavinotto (1987), brachiopods, undeterminable mollusk fragments and corals (Fig. 6C–D). The uppermost part of the Bugarone superiore Fm is an ammonite-rich Maiolica-type facies (whitish mudstone/wackestone), bearing aptychi, calpionellids

Fig. 6. Microfacies and microfossil content of the Fosso Pisciarello sections. A) “Thick-shelled” *Globuligerina oxfordiana* and thin-shelled bivalves in a bioclastic wackestone. Sample: AC944. B) Ammonitiferous wackestone, with thin-shelled bivalves and small gastropods. Sample: AC946. C) Bioclastic wackestone/packstone bearing “thin-shelled” *Globuligerina oxfordiana*, gastropods, aptychi and *Saccocoma* sp. fragments. Sample: AC948. D) Aptychi, *Saccocoma* sp., gastropods and juvenile ammonites in a bioclastic wackestone. Sample: AC949. E–F) Intrabioclastic wackestone rich in ammonite embryos, calpionellids, *Saccocoma* spp., ornamented gastropods and ostracods. Sample: AC951. G) *Tintinnopsella* cf. *carpathica*. Scale bar: 0,1 mm. H) *Crassicollaria* cf. *massutininana*. Scale bar: 0,1 mm. I) *Calpionella alpina*-rich wackestone. Sample: AC952. *Legend*: *Tsb*) thin-shelled bivalves; *Glo*) *Globuligerina oxfordiana*; *Os*) ostracods; *Am*) ammonites *Ga*) gastropods; *Ra*) radiolarians; *Sa*) *Saccocoma* spp.; *Apt*) aptychus; *Ca*) calpionellid; *Dc*) dinoflagellate cyst; *In*) intraclast; *De*) *Dentalina* sp. In A–F) and I) the scale bar is equal to 1 mm.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(*Crassicollaria* cf. *massutininana*, *Tintinnopsella* cf. *carpathica*), rare saccocomids, calcisphaerulids, small gastropods, ostracods and intraclasts (Fig. 6E–H).

The thickness of the Bugarone superiore Fm in the measured sections ranges from 80 cm (Fosso Pisciarello I) to 40 cm (Fosso Pisciarello III), while it is at least 90 cm in the Fosso Pisciarello II section. The passage to the overlying Maiolica Fm is sharp and marked by the first appearance of chert-rich beds. Unconformity surfaces, interpreted as slump-scars, with associated onlap and draping by the post-failure deposits (rich in *Calpionella alpina* – Fig. 6I), are spectacularly exposed in the Fosso Pisciarello (see Fig. 5) and in the nearby locality of Col Lungo, being a typical feature of the PCP-edge setting.

4. Microfacies of the coral sample

The dominant texture is a cephalopod floatstone (ammonites, aptychi). The whitish mud matrix bears ostracods, radiolarians, *Saccocoma* cf. *vernioryi*, crinoids, calpionellids (*Crassicollaria* cf. *massutiniana*, *C.* cf. *parvula*, *Tintinnopsella* cf. *carpathica*), dinoflagellate cysts (*Colomisphaera* sp.), benthic foraminifers (*Dentalina* sp.), small ornamented gastropods, juvenile ammonites, plus unidentifiable bioclasts and small intraclasts (Fig. 7A–F). These characteristics are virtually identical to those described in the Fosso Pisciarello sections for the Bugarone superiore/Maiolica transition. As a consequence, these deposits are the prime candidates for being the source of our study specimen.

The matrix also fills the voids in the coral structure. In doing so, it grades into clotted micropeloidal fabrics, interpretable as of microbial origin (automicrite; Keim and Schlager, 1999), which is best developed in the cryptic microenvironments inside the coral structure. Ghosts of clotted fabrics are also locally seen in the calcite crystals of the coral septa, suggesting that the original test was dissolved, bacteria colonized the moulds left by septa, then recrystallization took place. The dissepimental vesicles also host microbialites, plus several microproblematica (?*Lithocodium*) (Fig. 7G). Bladed crystals of calcite showing pyramid-like terminations form thin isopachous crusts grown on the coral structure. Bladed calcite is usually followed by blocky calcite, the latter representing the final geopetal filling of primary voids (Fig. 7H).

Glauconite is observed, as well as silicified (chalcedony) patches (Fig. 7I). This latter feature is the distinctive diagenetic signature of the zones where chert-rich basinal units onlap the rift topography (Santantonio et al., 1996, 2017; Galluzzo and Santantonio, 2002), like the edges and margins of PCPs, producing an overprint (silicification) in rocks – e.g., the Calcare Massiccio Fm and overlying Bugarone Grp - that are otherwise chert-free away from the unconformities.

The occurrence of *Crassicollaria* cf. *massutiniana* and *Tintinnopsella* cf. *carpathica*, coupled with the scarcity of *Calpionella alpina* specimens (the bloom of *Calpionella alpina* is a paleoecological event that characterizes the Tithonian/Berriasian boundary– Calpionella Zone/Alpina Subzone in Lakova and Petrova, 2013), allows to assign this calpionellid assemblage to the Crassicollaria Zone/Massutiniana Subzone sensu Lakova and Petrova (2013). The age of the coral is therefore latest Tithonian.

5. Coral systematics

Genus *Ogilvinella* (Eliášová, 1976)
Type species *Ogilvinella elegans* (Eliášová, 1973)
Ogilvinella jurassica (Geyer, 1954)
Figs. 8–9
Synonymy
1954 - *Barysmilia*? *jurassica* Geyer, p. 192, pl. 16, fig. 9
1973 - *Ogilviella elegans* - Eliášová, p. 276, pl. 4 fig. 1a, b texte fig. 3.4
1976 - *Ogilvinella elegans* (Eliášová) - Eliášová, p. 186
1985 - *Ogilviella* cf *elegans* Eliášová - Rosendahl, p. 70
1991 - *Kologyra jurassica* (Geyer) - Lauxmann, p. 138, pl. 5 fig. 4-7
Type material: *Barysmilia*? *jurassica* Geyer, 19276 SNHM Stuttgart (http://www.dbsmns.naturkundemuseum-bw.de/dev5/anzeigen.php?is=7andinv=19276andobjekt=10119)

5.1. Description

The discovered coral is a large (about 25 cm diameter) tridimensional colony with a general dome-shaped external morphology but also with the corresponding internal structure characterized by the divergence of growth axes of corallites (Fig. 8A). The colonial structure is clearly plocoid with exsert corallites separated by a peritheca made of dissepiments (Figs. 8B–C and 9A). The mode of increase is extracalicular. The bilateral symmetry is made by the elongation of the corallites, the elongation of the columella and the curvature of septa. The radial symmetry is not easy to decipher. The corallites show a septal apparatus made of strong costosepta highly unequal in thickness and length, and small thin septa often lonsdaleoid. Costosepta are typically rhipidogyrid, compact, bicuneiform with a well-developed costal part, straight or curved, ornamented with many lateral granules (Fig. 9B–C) and with flabelliform auriculae on their inner margin (Fig. 9D). The septal part of small septa can display a zigzag pattern (see Fig. 9B at top). A lamellar columella is present (see especially Fig. 8C; more difficult to decipher but present in Fig. 9A). From Fig. 9A, the wall seems mostly parathecal. The endotheca is made of numerous vesicular dissepiments.

5.2. Dimensions

Number of septa: 24 (measured on two calices in thin section, involving lonsdaleoid septa). External diameter of corallites: 5–6 mm. Internal diameter of corallites: 3–4 mm. 18 dissepiments vertically crossed in 5 mm.

5.3. Material

A single specimen housed in "*Museo dei Fossili e dei Minerali del M. Nerone*" of Apecchio (Pesaro-Urbino, Marche, Italy), depository number 94504, from which we obtained 4 thin sections (numbered 94504-A, 94504-B, 94504-C and 94504-D and provided in the Supplementary material).

5.4. Remarks

We put here for the first time *O. jurassica* (Geyer, 1954) in synonymy with the type species of the genus *O. elegans*. In the first description of *O. jurassica* by Geyer (1954) the columella was not observed. While this columella is generally not easily observed, it is actually visible in the type specimen itself (see website of SMN Stuttgart). In the material from the same region, Lauxmann observed more abundant material (16 colonies) and illustrated also the lamellar columella (Lauxmann, 1991, pl. 5, fig. 7). Lauxmann (1991) noted the similarity with *Ogilvinella*, but enigmatically cited a paper of Beauvais (1973) in which we were unable to find any mention of *Ogilvinella elegans*. As she quoted "page 273", we interpret this reference as due to a confusion between the publications of Beauvais (1973) and Eliášová (1973), for which this page number is indeed meaningful.

We have also given in the comparison table (Table 1) the citations of *O. morycowae*, another morphospecies of the same genus characterized by higher dimensions. We mention this close species especially because it was recently described from the typical shallow-water platform environments of the Ellipsactinia limestones (Rusciadelli et al., 2011; Ricci et al., 2018) in Central Apennines. A third nominal species *Ogilvinella paraelegans* Sikharulidze, 1979 was created for Albian corals from Georgia and is also known from the Aptian of China (Löser and Liao, 2001; Löser et al., 2002).

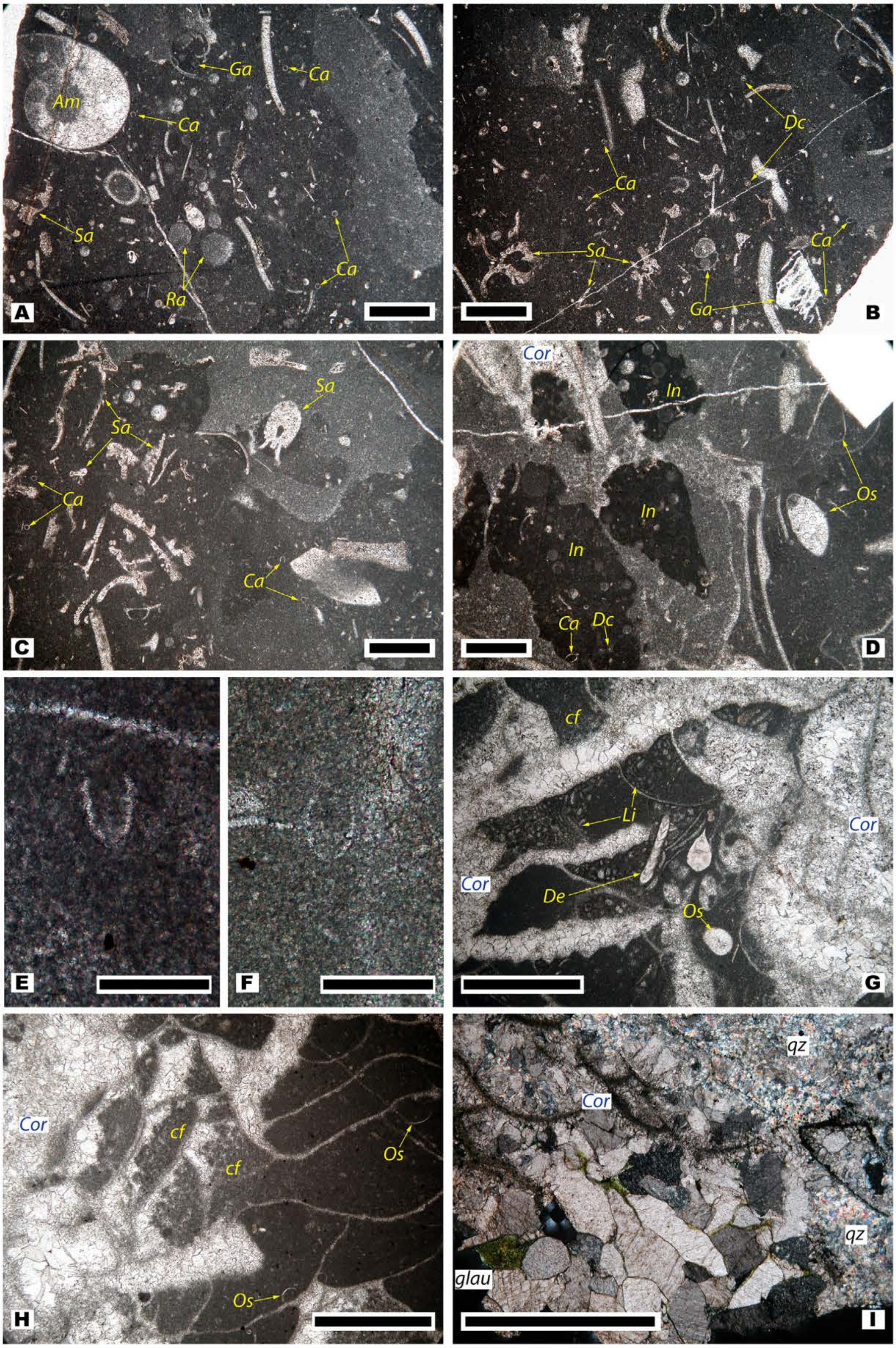

Fig. 7. Microfacies of the pelagites embedding the coral. A–D) Intrabioclastic wackestone. Sample: 94504-A. E) *Crassicollaria* cf. *massutininana*. Scale bar: 0,1 mm. Sample: 94504-A. F) *Tintinnopsella* cf. *carpathica*. Scale bar: 0,1 mm. Sample: 94504-A. G–H) Coral floatstone. Vesiculose dissepiments and the coral itself show local colonization by the microproblematicum ?*Lithocodium* sp.; micropeloidal clotted fabric change laterally to pelagic facies or to geopetal structures. Samples: 94504-A and 94504-B. I) Crossed polars view of the coral. Note the bladed calcite crystals overgrowing the vesiculate dissepiments, passing abruptly to blocky calcite. Intercrystalline voids are filled with microcrystalline quartz. Sample: 94504-B. *Legend*: *Am*) ammonites *Ga*) gastropods; *Ra*) radiolarians; *Sa*) *Saccocoma* spp.; *Ca*) calpionellid; *Dc*) dinoflagellate cyst; *Os*) ostracods; *In*) intraclast; *Cor*) coral; Li) ?*Lithocodium* sp.; *De*) *Dentalina* sp.; cf) clotted fabric; *geo*) geopetal structure; *qz*) microcrystalline quartz; *glau*) glauconite. In A-D) and G-I) the scale bar is equal to 1 mm.

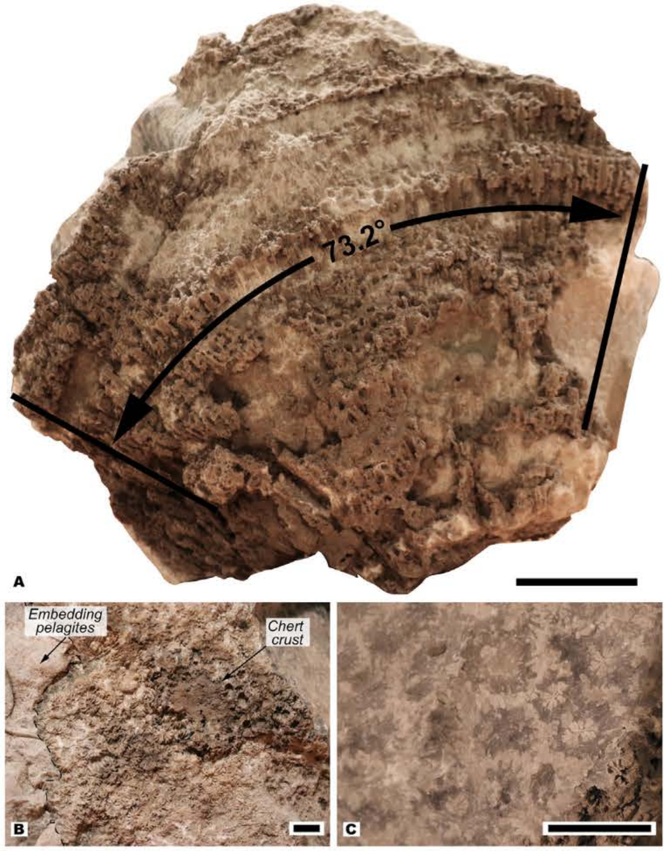

Fig. 8. *Ogilvinella jurassica* (Geyer, 1954) from Fosso Pisciarello (Mt Nerone), depository number 94504, belonging to the collection of the Museum "*Museo dei Fossili e dei Minerali del M. Nerone*" of Apecchio (Pesaro-Urbino, Marche, Italy). A) General external view showing the divergence of corallite growth axes. Scale bar = 5 cm. B) Distal view of calicular surface. Scale bar = 1 cm. C) Natural transverse section showing two corallites with their lamellar columella. Scale bar = 1 cm.

5.5. The coral: paleoautecological analysis

Ogilvinella jurassica belongs to an extinct genus that belongs for its part to an extinct family. Consequently, the classical approach of taxonomic uniformitarianism cannot be applied. However, the paleoautecological interpretation may take advantage of two other methods: the analysis of the distribution of the taxon and the functional morphologic analysis.

5.6. Distribution of the taxon

The genus *Ogilvinella* is known only in the shallow water window. The species *O. jurassica* was initially described in the Nattheimer Schichten in a set of outcrops reviewed by Geyer (1954) often as coral beds of reworked corals but more rarely under the form of reefs (e.g., in Arnegg). We do not know exactly the precise geographic origin of the 16 colonies examined by Lauxmann (1991) but they originate from this set of outcrops from Württemberg. The species has also been cited under the name *O. elegans* from the Tithonian of Stramberk (Czech Republic) by Eliášová (1973, 1976). The facies is typically originating from reefs reworked in olistoliths (Eliášová, 2015, and references therein). The species is also cited from the Kimmeridgian of Sao Bras de Alportel, southern Portugal (Rosendahl, 1985). The environment is also described as reefal with accompanying biota typical of very shallow environments (chaetetids, nerineids, diceratids, stromatoporoids, solenoporaceans and other shallow water corals). In conclusion, the distribution of the genus as well as the distribution of the species point to a shallow water euphotic environment.

5.7. Functional morphologic analysis

From the above description, several features of paleoecological interest can be highlighted. First, the colony has a massive tridimensional shape or, to follow the terminology of Coates and Jackson (1987), a multiserial erect, mound-like morphology. In their own terminology, Graus and Macintyre (1982) distinguished colony shapes according to the range of maximum angle measured between the vertical and the most divergent axis of the corallite growth (Table 2). If we apply these categories to our fossil colony, we observe from the photo a maximum angle of divergence between corallite axes of 73.2° (see Fig. 8A). This value is high compared to many platy corals that are usually found in reefs (platestones and sheetstones of Insalaco, 1998). Following the procedure of Graus and Macintyre (1982), we can estimate an angle with the vertical of 36.1°. So, despite its external appearance, our colony falls into the platy category sensu Graus and Macintyre (1982). A higher value in the younger stages of the colony is expected due to growth under mechanical constraints explained by Barnes (1973). This flattening related to the age of the colony was also observed in the fossil record (Lathuilière, 2000). If, by a pure postulate, we considered that *O. jurassica* had the same growth properties as *Montastrea annularis*, we could plot our morphology in the diagram of Graus and Macintyre (1982) and we would obtain a colony that has grown at light corresponding to a depth between 35 and 40 m. Of course, we have no idea of the specific physiological peculiarities of our fossil species and the possible relations with the various genetic variants we can imagine in the evolving world of ancient zooxanthellae (see for instance Frade et al., 2008). However, we observe in the Recent seas that tridimensional colonies are generally related to the shallower part of the reef window. The experience of divers and various publications (e.g., Barnes, 1973; Dustan, 1975; Weber et al., 1975; Fricke and Meischner, 1985; Díaz et al., 2000; among others) show that below a certain depth (~30 m) massive zooxanthellate corals tend to be flat. The main functional morphologic explanation can be simplified as follows and holds in two points: 1) the production of carbonate is related to light availability through a complex set of interactions between the coral and the algae both with their own genetic and functional variability; 2) the proportion between the surface of the soft tissue and the volume of the secreted skeleton is ruled by the point 1. As a result, when light is maximum, the carbonate production is maximum, then the produced skeletal shape tends toward the sphere. Conversely, in low light levels, the carbonate production is low and the produced skeletal shape tends toward the plate. A complementary explanation is that corals adopt shapes that optimize light trapping surfaces when the irradiance decreases (e.g., Fricke and Schumacher, 1983). The zonation of shapes within reefs has already been a basis for an interpretation in terms of light decrease in numerous paleoecological studies (Geister and Lathuilière, 1991; Insalaco, 1996; Nose and Leinfelder, 1997; Leinfelder et al., 1996, 2002; Lathuilière et al., 2005; Martin-Garin et al., 2007). At the scale of a single species, the co-occurrence of all gradients from hemisphere to plate is probably the best criterium we have to diagnose a symbiotic relationship in fossils (Lathuilière, 2000). Presently for *Ogilvinella* we do not have yet such a series, but it is a test that should be investigated.

Secondly, the size of the colony is rather large. We do not know in the Recent record a similar example of massive coral of this size. We know large colonies of dendroid *Lophelia*-like colonies that represent significant skeletal volumes but not massive colonies of this size.

Thirdly, the colonial structure is plocoid. This colonial structure is considered as a high level of integration according to Coates and Jackson (1987). In itself it is favorable to the symbiotic diagnosis but not sufficient to demonstrate the zooxanthellate character without a risk of error.

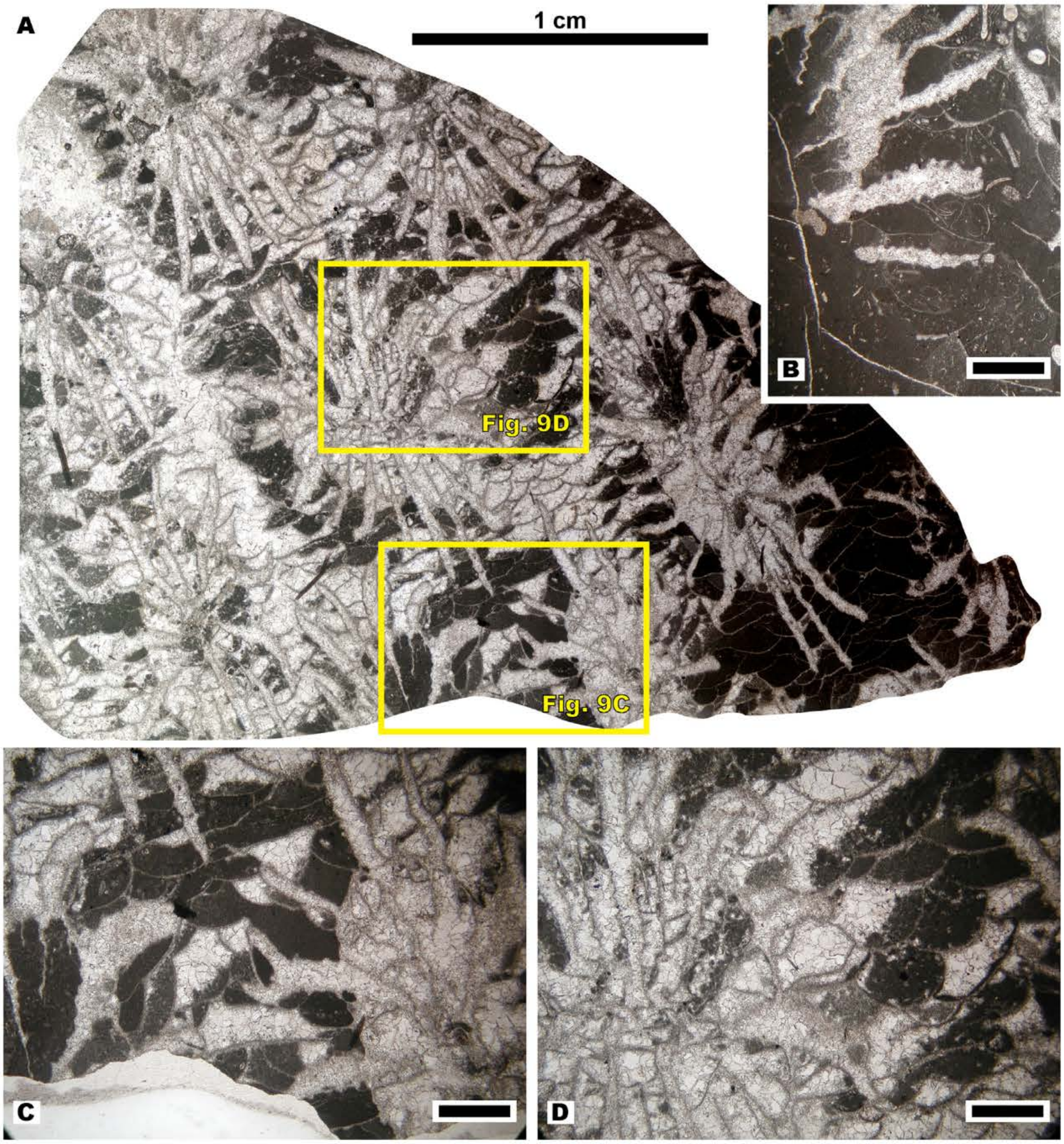

Fig. 9. *Ogilvinella jurassica* (Geyer, 1954) from Fosso Pisciarello (Mt Nerone), depository number 94504, belonging to the collection of the Museum "*Museo dei Fossili e dei Minerali del M. Nerone*" of Apecchio (Pesaro-Urbino, Marche, Italy). A) Oblique thin section. Samples: 94504-B. B) Transverse thin section showing the ornamentation of septa. Samples: 94504-A. Scale bar = 1 mm. C) detail of panel A showing the peritheca made of vesiculose dissepiments. Scale bar = 1 mm. D) detail of panel A showing the flabelliform auriculae at the inner edge of septa. Scale bar = 1 mm.

If we attempt to consider together these three lines of evidence: shape, size and level of integration, they point to a common fundamental trait of zooxanthellate corals, their ability to produce higher volumes of carbonate with respect to their non-symbiotic counterparts. The three lines of evidence and the distribution analysis point to the same "diagnosis", the simplest one: *Ogilvinella* was zooxanthellate. However, if we try to advocate for the opposite hypothesis of *Ogilvinella* as a non z-coral, the best candidate for an extant coral that could look similar in

Table 1
Comparisons between various occurrences of *Ogilvinella* specimens.

	Diameter	Number of septa
Ogilvinella elegans (Eliášová, 1973) holotype	3–4.5 mm (we interpret internal diameter from the figures and scale)	26–30 (from the drawing)
Ogilviella cf. *elegans* Eliášová, – (Rosendahl, 1985)	4–6 mm	20–30
Barysmilia? *jurassica* (Geyer, 1954)	14/12, 15/11, 12/11 and 9/6 mm	24
Kologyra jurassica (Geyer, 1954) in Lauxmann (1991)	d = 6–12 mm to D = 9–14 mm (probably internal diameter from the figures and their scale)	24–36 + S4 12–18 costae
Ogilvinella elegans (Eliášová, 1973)	External 5–6 mm	24
This study	Internal 3–4 mm	
Ogilvinella morycowae (Kolodziej, 2003)	3.5–8 mm	12–35
Ogilvinella cf. *morycowae* in Ricci et al. (2018)	Min d = 5 .3mm to max D = 13 mm (external diameters)	36? to 48?
Ogilvinella paraelegans Sikharulidze, 1979	4–5.5 mm	48 (36–38)

Table 2
Classification of massive shapes of *Montastrea annularis* according to Graus and Macintyre (1982).

Shape	Range of maximum angles (in degrees) with vertical
Hemisphere	120–180
Tapered hemisphere	105–120
Column	75–105
Flared column	45–75
Plate	0–45

terms of shape, size and level of integration we should look to the genus *Madracis*. *Madracis* is an ecologically very complex plocoid genus that includes several species among which some are massive and some other ramose, some are zooxanthellate some others are not, and also within a single species the presence and density of zooxanthellae is highly variable (Chevalier, 1987; Fenner, 1993). In other terms some species can switch from z- to non z-corals (apozooxanthellate character). *Madracis* is known between 0 and 700–800 m of depth. Within a potentially massive species like *M. decactis*, the potential good candidates for a comparison are situated in shallow water environment. For instance, Zlatarski and Martinez Estalella (1982) have described hundreds of specimens with their precise bathymetry all around Cuba between 0 and 70 m.

Chevalier (1987, p. 473) mentioned that the apozooxanthellate species *Madracis asperula* changes its morphology according to the presence or absence of zooxanthellae. Zooxanthellate forms are massive, while skeletons in the azooxanthellates are skinnier. In the same book, Chevalier (1987, p. 548) presents *Madracis* as the champion of skeletal growth for an "ahermatypic" coral, but specifies that the species does exhibit zooxanthellae in variable number. Should we consider *Madracis* as a homogenous unit in terms of physiology, we would clearly make a mistake. In conclusion, the use of the *Madracis* analogy as a real non zooxanthellate coral should be careful and is in need of additional actualistic documentation. In other terms a recent colony of *Madracis* genuinely devoid of zooxanthellae, showing the whole set of morphological characters of our fossil colony (size and shape), has not been recovered to date, and this would be required to support any hypothesis for a non z-coral interpretation.

6. Paleodepth interpretation and geological implications

The recovery of a shallow-water coral in the calpionellid limestone is certainly unexpected, which is perhaps a testament to how little we possibly know about the environmental significance of ancient pelagic deposits. The necessity of disassociating a fixed paleodepth range from the lithofacies of Tethyan pelagic deposits has been stressed in various papers in the past, mostly regarding Northern Apennines, as their worldwide distribution coupled with the nearly synchronous nature of lithostratigraphic boundaries strongly suggests a control other than water depth on their development (Farinacci et al., 1981; Cecca et al., 1990; Santantonio, 1993; Santantonio et al., 1996; Morettini et al., 2002; Gill et al., 2004). Besides inferences, however, field mapping proves invaluable for paleoenvironmental reconstructions. Being able to constrain the paleodepth of intrabasinal highs by means of corals becomes a tool to also constrain the paleodepth of otherwise enigmatic pelagic deposits (e.g., radiolarites, thin-shelled bivalve limestone), those forming the hangingwall-basin successions, once the onlap lines of individual formations against the high are mapped. Then, a simple geological cross-section can be used to derive the paleodepth range of basinal formations, by undoing any orogenic rotation and measuring the paleotopographic relief existing at different time slices with respect to a reference level (e.g., a bed bearing z-corals) on the high. This produces a range rather than accurate estimates, since the only safe "golden spike" exists in the Tithonian. However, this range is necessarily finite, as no tectonic yo-yoing whatsoever can be inferred for the stable Umbria-Marche and Sabina structural highs during the post-Sinemurian to pre-Tithonian interval, which is tectonically quiescent with the exception of a minor phase of local fault rejuvenation and/or formation of mappable "lowered steps" marginal to the highs in the Bajocian or a little earlier (Galluzzo and Santantonio, 2002; Cannata, 2007; Cipriani et al., 2016; Paparella et al., 2017; Citton et al., 2019). In other words, considering the early Sinemurian as zero water-depth level (healthy benthic carbonate factory), and the Tithonian as <200 m conservatively (but see below), it is conceivable that the thickness of the water column above PCPs can have ranged within that 0–200 m bracket during that interval of geological time, plus or minus the modulation due to changing sea level. Recent studies on Jurassic sea-level indicate rises and drops of third-order cycles not exceeding 80 m (Haq, 2014, 2018). As a consequence, we can assume that PCPs were never deeper than about 280 m. Moreover, according to Haq (2018) a major sea-level fall (about 75 m) characterizes the upper part of the Crassicollaria Zone (JTi7) and could have triggered the optimal paleoecological conditions for the growth of the studied coral (Fig. 10).

Gill et al. (2004) noted that the occurrence of z-corals on PCPs is actually punctuated in the Tithonian, being largely limited to the Semiforme and Volanense Zones (Cecca and Santantonio, 1989), and interpreted this as due to prominent sea-level drops "switching the

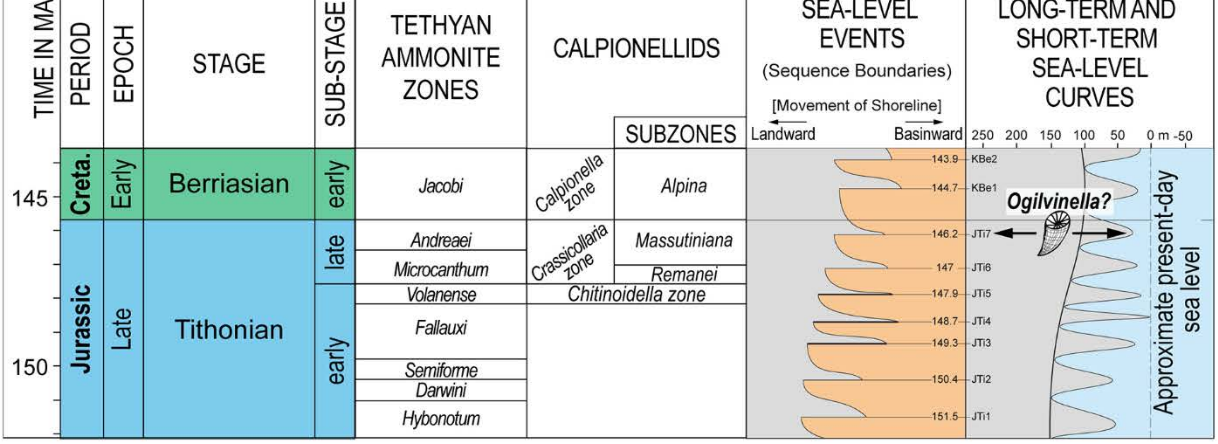

Fig. 10. Tithonian-Berriasian ammonite and calpionellid biostratigraphy, and correlation with sequence stratigraphy and eustacy. Modified from Haq (2018).

light on" on platform tops and upper escarpments. The paleodepth was based on the inferred deeper-photic significance of lamellar thamnasterioid microsolenid corals, which places them within a ~−30 to ~−250 m depth range, also based on comparison with modern forms displaying highly specialized modes of adaptation to weak photon fluxes (see extensive discussion in Gill et al., 2004). The recovery of *Ogilvinella* suggests much shallower depths, in the order of −20/−30 m, likely attained for a very short time in coincidence with an absolute sea-level drop, which perhaps shifts the "maximum −200 m" general figure in the paleodepth bracket (plus or minus sea-level change), discussed above, upward by several tens of meters, at least for the Mt Nerone PCP (Fig. 11).

In a sedimentological key, it must be re-stressed that the mud-rich condensed pelagic carbonate successions found on PCP tops generally provide little direct clue for a paleodepth interpretation. Broadly speaking, the concentration of cephalopod shells, which is much higher than that observed in correlative basinal beds, suggests permanent loss of fine-grained sediment due to episodic removal by currents as ammonites with their sediment-infilled living chambers were too heavy to be displaced. As it was mentioned above, the relative position within the perimeter of the PCP (e.g., platform edge vs interior) dictated the general geometries of the condensed succession as a general effect of current shaping, as well as the degree of fossil enrichment within individual beds, producing a laterally variable pattern of hiatuses across the PCP top that can be highlighted by means of ammonite biostratigraphy (Galluzzo and Santantonio, 2002). Widespread bioturbation and the diverse faunal assemblages (Santantonio, 1993) indicate well oxygenated waters. The taphonomy of ammonite shells locally reveals in addition peculiar patterns of burial, reworking and exhumation, apparently due to the joint effects of burrowing, size variability of ammonites and extremely low sedimentation rates. Santantonio et al. (1996) described in this respect examples of "fake" faunal mixing in the Upper

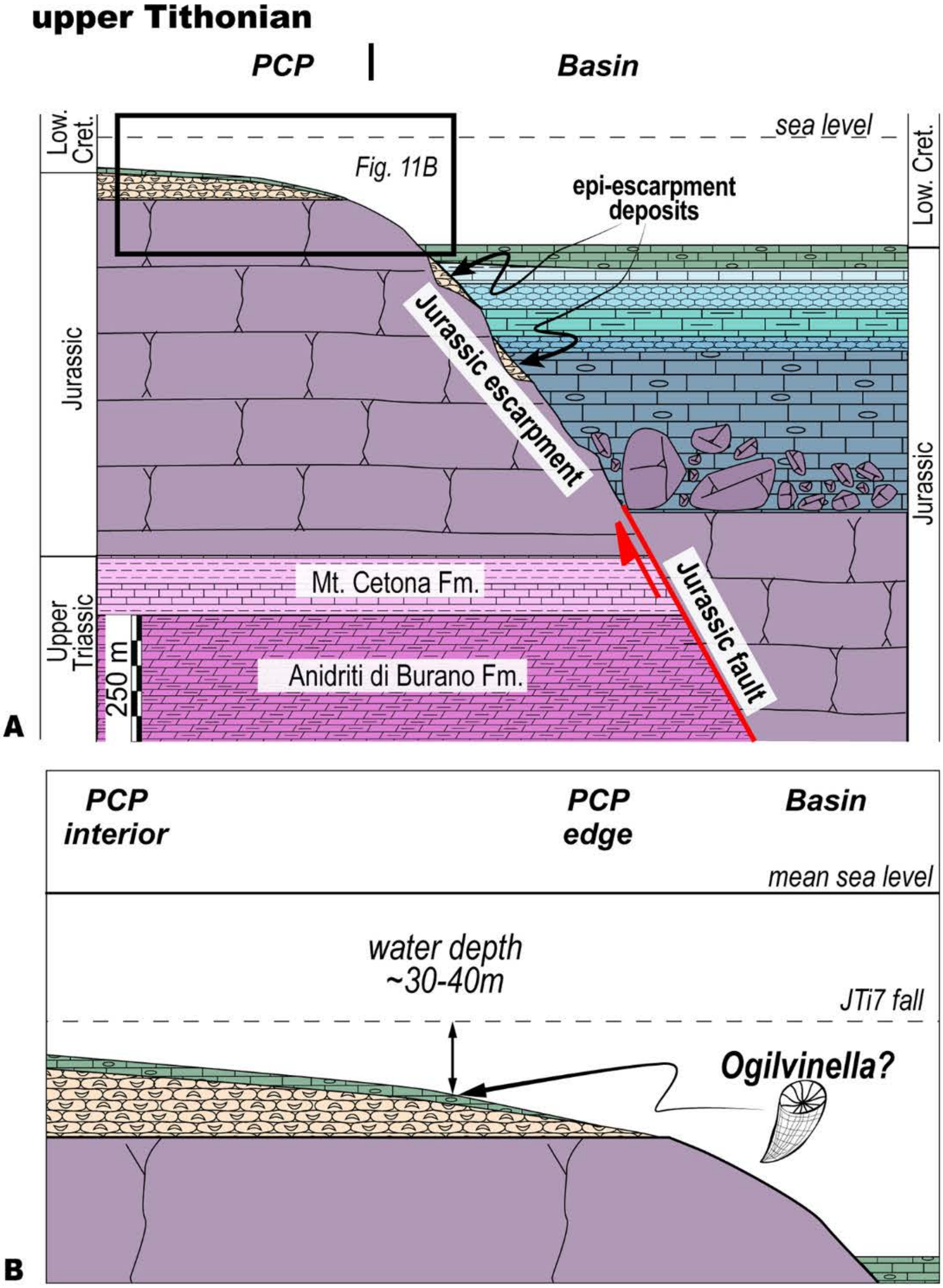

Fig. 11. A) block diagram showing the Mt Nerone PCP-basin system during the late Tithonian and B) cartoon showing the detail of its margin. Note the location of the coral *Ogilvinella* and the hypothetic position of the sea level during the JTi7 fall (not to scale).

Jurassic, where small ammonites could be preserved within the deep umbilicus of larger aspidoceratids, belonging to the immediately underlying biozone, because the maximum whorl width of those bulky ammonites lying parallel to bedding was greater than the thickness of the biozone to which they belonged, so they were only partially buried.

While the paleontological/sedimentological features briefly summarized above do provide a general paleoenvironmental setting for the Apenninic PCP successions, unequivocal sedimentary structures, commonly held as diagnostic in a paleobathymetric key in carbonate systems, are missing. We must therefore only conservatively note that the ubiquitous mud-rich textures, paired with the lack of ripple cross-lamination even in the presence of a bioclastic sand component, only indicates that pelagic deposition took place below fair-weather and storm-wave bases.

As a concluding remark, constraining the water depth on an Apenninic PCP to few tens of meters in the terminal Jurassic/earliest Cretaceous indicates very little subsidence (also allowing for the accommodation of a circa 40 m thick PCP-top condensed succession) through the circa 60 My time span (Cohen et al., 2013, updated) which followed the acme of rifting, which is not unexpected due to the essentially stable nature of Jurassic horst blocks in this region. The hangingwall-basin successions in contrast record deepening in the relatively short syn-rift phase (essentially latest Hettangian-Sinemurian), followed by shallowing linked with sediment aggradation and the progressive burial of footwall blocks (Santantonio and Carminati, 2011).

7. Conclusions

While the term “pelagic” only has a compositional significance, and not any depth connotation, common sense typically leads us to assume that certain formations must have been deposited at depths not shallower than a certain “psychological threshold”. This attitude has obviously solid foundations and is wisely conservative for good reason, as certain pelagic lithofacies are indeed unquestionably related to deep-water or even abyssal conditions. Moreover, the absence of bio-sedimentological markers unequivocally attributable to very shallow-water in a uniformitarian key, and typical of tropical carbonate platforms and shelves (e.g., shallowing-upward cycles, fenestral lamination, etc.), prevents us from inferring very shallow depths for pelagic deposits, and rightly so. With that said however, below the very narrow surficial depth window of unequivocal sedimentary structures like those mentioned above, we must come to the conclusion we know perhaps less than we would like to admit, about paleoenvironments and types of sedimentation that have no modern equivalents. This was already addressed by Gill et al. (2004), who noted for example that a modern equivalent of the north European Chalk, a pelagic sediment deposited on a continental shelf, at depths as shallow as about 50 m (Stow et al., 1996; Gale et al., 2013), does not exist today. We absolutely do not want to imply with this discussion that, contrary to common wisdom, the pelagic formations, which are typical of the Tethyan Jurassic (Winterer and Bosellini, 1981), should be considered as of “shallow water”. Only, also based on fortunate recoveries like the one subject of this article, and those reported since the seminal paper by Nicosia and Pallini (1977), we consider it safe to re-state that the depth range of these lithofacies is wider than commonly believed. An accurate depth is often virtually impossible to decipher, unless reliable pieces of evidence, like z-corals come to the rescue. As usual in these cases, this in turn opens new scenarios of uncertainty, which will require further research, and will possibly bring new unexpected elements in a sense or another.

Data availability

Research data provided as supplementary material are stored in the repository Mendeley Data (https://data.mendeley.com/) and can be downloaded here (Cipriani et al., 2018): https://data.mendeley.com/datasets/3rdnc2nzm3/draft?a=09c7b6fe-6fb9-41a9-bc81-9775c8e82bd5.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at https://doi.org/10.1016/j.sedgeo.2019.03.007. These data include the Google map of the most important areas described in this article.

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