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# The Toarcian stage in key outcrops of the Umbria-Marche (Northern Apennines, N Italy) and Longobucco (Sila Greca, S Italy) Basins: ammonite biostratigraphy, sedimentology and paleoenvironmental considerations

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## Article

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## ABSTRACT

This study investigates seven stratigraphic sections within the Umbria-Marche and Longobucco Basins, with a primary focus on the biostratigraphy and sedimentology of the Toarcian stage. Biostratigraphic correlation was conducted using the standard Tethyan and Mediterranean ammonite biozonations, revealing fully comparable faunal assemblages across the analyzed stratigraphic sections. In the Umbria Marche Domain, the Emaciatum Zone of the upper Pliensbachian occurs within pelagic limestone of the Corniola, and occasionally into the marly/clayey facies of the Marne di Monte Serrone. Conversely, the Emaciatum Zone at Caloveto is in a shallow-water carbonate facies. The passage from the Emaciatum to the Polymorphum Zone falls within a transitional formation boundary when it occurs between the Corniola and Marne di Monte Serrone, while it is abrupt and often marked by a hard-ground between the Corniola and Rosso Ammonitico. At Caloveto, the Pliensbachian-Toarcian boundary is marked by a hiatus extending to at least the Polymorphum Zone, while the Serpentinum Zone, is documented in the literature. Above the Polymorphum Zone, the T-OAE occurs as a black shale horizon or, in its absence, is distinguished by a marked faunal turnover passing in the Serpentinum Zone. The Bifrons Zone occurs within nodular marly limestones, exhibiting an upward increase in CaCO<sub>3</sub> content. Notably, the Marne di Monte Serrone are often heteropic with the Rosso Ammonitico in the lower Toarcian. Sedimentation becomes increasingly calcareous at the Toarcian/Aalenian boundary, coinciding with the first appearance of chert.

**KEYWORDS:** Ammonite biostratigraphy, Tethys, Oceanic anoxic events, Jurassic.

## INTRODUCTION

In this paper we present results from the analysis of seven stratigraphic sections (Fig. 1) of Toarcian pelagic successions from different geological settings of the Umbria-Marche Basin (Northern Apennines, N Italy) and Longobucco Basin (Sila Greca, S Italy) to provide biostratigraphic correlation, sedimentological analysis and paleoenvironmental considerations.

The Toarcian is the final stage of the Early Jurassic and lasts for 9.5 Myrs (Cohen et al., 2013; updated 2020), spanning from ~184.2 Ma to ~174.7 Ma (Fig. 2) (Hesselbo et al., 2020). The Toarcian GSSP is located in Portugal, and the base of the stage is determined through ammonite biostratigraphy, and marked by the first occurrence of *Dactyloceras (Eodactylites) simplex*, *D. (E.) polymorphum* and *D. (E.) pseudocommune* (da Rocha et al., 2016; Hesselbo et al., 2020; Remírez & Algeo, 2020). To date, the Toarcian stage is not further formally divided even if subdivisions into two or three sub-stages (early/late; early/middle/late) have been proposed in the literature (e.g., Gradstein et al., 2004; Swan et al., 2011; Boulila et al., 2014; Ogg et al., 2016).

The Toarcian is characterized by widespread input of terrigenous material in sedimentary basins, testifying for the Paleotethys realm an increase of weathering triggered by an intensification of the hydrological cycle (Remírez & Algeo, 2020)

as indicated by several proxies (Cohen et al., 2004; Dera et al., 2009; Hermoso & Pellenard, 2014; Fu et al., 2017; Fantasia et al., 2018a, 2018b, 2019a, 2019b; Thibault et al., 2018; Satolli et al., 2018; van Acken et al., 2019; Kemp et al., 2019). The high flow of nutrients through river systems caused by this significant increase in weathering also led to a substantial increase in oceanic primary productivity (Cohen et al., 2004; Hermoso & Pellenard, 2014; Montero-Serrano et al., 2015; Percival et al., 2015; Fantasia et al., 2018a; Xu et al. 2018). For this reason, the Tethyan Toarcian pelagic successions are dominated by marly facies, which commonly yield large amounts of macrofossils.

The lower Toarcian is characterized by an Oceanic Anoxic Event (OAE) (Jenkyns, 1988; 2010), known at global scale. The T-OAE can be considered as one of the most significant global events representing a severe and abrupt paleoenvironmental perturbation affecting the Early Jurassic Marine ecosystem (Jenkyns and Clayton, 1997; Hesselbo et al., 2007; Reolid et al., 2020; Van de Schootbrugge et al., 2020). This global event is characterized by: i) deposition of sediments rich in organic matter in pelagic and hemipelagic settings (Jenkyns, 1988; Baudin et al., 1990; Suan et al., 2018); ii) a consistent negative carbon-isotope excursion detected from marine carbonates, marine organic carbon and wood (Saalen et al., 1996; Hesselbo et al., 2000, 2007; Schouten et al., 2000; Röhl et al., 2001; Cohen et al., 2004; van de Schootbrugge et al., 2005; Sabatino et al., 2009, 2013; Al-Suwaidi et al., 2010; Hesselbo and Pieńkowski, 2011; Kafousia et al., 2011; 2014; Izumi et al., 2012; Reolid, 2014; Suan et al., 2015; Bodin et al., 2016; Martindale et al., 2017; Fantasia et al., 2019a; Baghli et al., 2020; Ruebsam et al., 2020); iii) increased seawater temperatures (Bailey et al., 2003; Rosales et al. 2004; van de Schootbrugge et al. 2005; Suan et al. 2008; Korte et al. 2015); iv) consistent sea level fluctuations (Jenkyns, 1985; Hallam, 1987; de Graciansky et al., 1998; Pittet et al., 2014; Haq, 2018; Thibault et al., 2018; Krencker et al., 2019); v) a crisis in carbonate production (Mattioli et al., 2008); vi) increase in marine primary productivity (Bodin et al., 2010; Montero-Serrano et al., 2015; Xu et al., 2018); vii) a severe biotic crisis in both marine and terrestrial ecosystems (Little & Benton, 1995; Aberhan and Fürsich, 2000; Wignall et al., 2005; Gómez and Goy, 2011; Caruthers et al., 2014; Danise et al., 2015; Rita et al., 2016; Baker et al., 2017; Caswell and Frid, 2017; Mander & McElwain, 2019; Slater et al., 2019; Jiang et al., 2020; Pol et al., 2020).

Various causes have been proposed in the literature for this major Mesozoic disturbance, although a general consensus has not yet been reached on this topic (see Reolid et al., 2020). Among the causes we find: i) massive emissions of CO<sub>2</sub> and thermogenic CH<sub>4</sub> by the coeval Karoo-Ferrar Large Igneous Province (Pálffy & Smith, 2000; Courtillot & Renne, 2003; McElwain et al., 2005; Hesselbo et al., 2007; Svensen et al., 2007; Fantasia et al., 2019a; Ruebsam and Al-Husseini, 2020); ii) an increase in the rate of wetland methanogenesis (Them et al., 2017); iii) deterioration of permafrost reservoir caused by intense global warming (Ruebsam et al., 2019, 2020); iv) a destabilization of methane hydrates in marine environments (Hesselbo et al., 2000; Kemp et al., 2005).

In the Umbria-Marche Basin the T-OAE is represented by a dark bituminous level, always occurring within clayey facies,

observed and analyzed in greater detail at the type locality of the Marne del Monte Serrone formation and in Valdorbia (Sabatino et al., 2009; Satolli et al., 2018).

Concerning ammonite faunas from the Mediterranean Tethys, Bilotta et al. (2010) propose that two very different assemblages are separated by the T-OAE in the Apennine. In particular, faunal composition before the oceanic anoxic event are characterized by taxa present already in the Pliensbachian, including Arieticeratinae, Phyllocerata, Protogammoceratinae and Reynesocoeloceratinae; differently, the period following the great disturbance in the marine environment is marked by the evolutionary radiation of ammonites within the Hapoceratinae, Hildoceratinae, Nodicoeloceratinae and subsequently also within Hammatoceratidae, Mercaticeratinae and Phymatoceratidae (Bilotta et al., 2010). The authors also stress the fact that the ammonite fauna found below the T-OAE can be interpreted as a marked endemic fauna represented by more than 15 genera, thus proposing to use a Mediterranean zonation in the Apennine (Bilotta et al., 2010).

The second order mass extinction for ammonites characterizing the Pliensbachian–Toarcian interval has been analyzed in detail by Dera et al. (2010), based on an extensive dataset of 772 ammonite species from NW Tethyan and Arctic domains. The result of the analysis indicates that the highest extinction rate between 70–90% has been detected for the Margaritatus to the Dispansum Chronozone, even if each subchronozone is characterized by an average of ammonite species extinction in the range of 40–65% (10–30% for genera). The authors overall identified five distinct extinction pulses in the Pliensbachian–Toarcian interval, referred as to the Gibbosus, PTB (Pliensbachian–Toarcian Boundary), Semicelatum, Bifrons–Variabilis, and Dispansum, differing even in a substantial way in the palaeogeographical, morphoselective and taxonomic dynamics (see Dera et al., 2010).

The areas studied in the present contribution (Fig. 1) belonged, in the Toarcian, to the Northern (Longobucco Basin) and Southern (Umbria-Marche Basin) margins of Western Tethys Ocean (e.g., Mariotti et al., 2010; Santantonio et al., 2016). The Toarcian occurs with different facies: a typical Toarcian facies of the Tethys is the Rosso Ammonitico (Pilla, 1847), made of red marly limestones and marls (Farinacci et al., 1981; Petti & Falorni, 2007; Cipriani et al., 2020), which characterizes most of the Toarcian successions of the Umbria-Marche-Sabina pelagic domain, and also (with differences, see below) the Toarcian successions of the Caloveto Group (Calabria, S Italy) (Teale, 1988; Santantonio, 2012; Santantonio & Fabbi, 2020).

Another typical facies of the Umbria-Marche Basin is the Marne di Monte Serrone (Pialli, 1969), made of grey/greenish marls and most likely sedimented at paleodepths deeper than the Rosso Ammonitico (Monaco et al., 1994; Parisi et al., 1998; Satolli et al., 2018).

Along with these facies, which are the main object of the present paper, other Toarcian units of the Umbria-Marche Basin are the top of the Corniola, the base of the Calcari e Marne a Posidonia and the condensed equivalents of Rosso Ammonitico and Calcari e Marne a Posidonia sedimented in PCP settings (see below).

In the Longobucco Basin the early Toarcian is also represented by the top of the Trionto fm. which records sedimentation in a



Fig. 1 - Location of the studied stratigraphic sections. Basemap retrieved from Google Earth.

deep turbiditic basin (Young et al., 1986; Santantonio et al., 2016), whereas the late Toarcian is represented by the base of the *Zoophycos* and *Posidonia* marls and of the “gray limestones with black chert” (Santantonio et al., 2016).

## MATERIAL AND METHODS

The present study aims at establishing correlations among coeval Lower Jurassic successions, deposited in different sedimentary contexts of Umbria-Marche Domain and Calabria.

An exhaustive biostratigraphic study was conducted through the detailed measurement and sampling of stratigraphic sections. Additionally, geological surveying at a 1:10,000 scale was carried out in the surrounding areas of the studied outcrops. Thin sections were prepared from samples collected during the geological survey, for micropaleontological analysis.

Detailed logs of seven selected stratigraphic sections were realized, resulting from a thorough analysis on both lithology/lithostratigraphy and biostratigraphy, with particular emphasis on ammonite assemblages. The stratigraphic analysis was conducted

on a bed-by-bed basis, through the detection of diverse ammonite faunas, and allowed the building of an ammonite-based bioevent chart for each stratigraphic section.

These charts have been cross-referenced with standard biostratigraphic scales (Fig. 2) for the Mediterranean and NW European domains (Elmi et al., 1991, 1997; Page, 2003; Bilotta et al., 2010).

## GEOLOGICAL SETTING AND STRATIGRAPHY

The studied sections are located in the Northern Apennines Umbria-Marche Domain (Southern margin of W-Tethys) and Calabria Longobucco Basin (northern margin of the W-Tethys) and their geological features are described separately.

### Umbria-Marche Domain (Southern margin of Tethys)

The studied sections were sampled in different localities belonging to the Mt. Nerone (Gorgo a Cerbara), Mt. Subasio (Eremo delle Carceri and Cava Gabbiano), Mt. Serano (Pettino) and Mt. Serrone ridges in the Umbria-Marche domain (Figs. 1, 3a).

The Jurassic stratigraphy of the Umbria-Marche Domain

was controlled by a Rhaetian-Hettangian extensional phase (Bernoulli, 1967; Colacicchi et al., 1970; Centamore et al., 1971; Farinacci et al., 1981; Santantonio and Carminati, 2011; Fabbi and Santantonio, 2012; Fabbi, 2015; Cipriani, 2016; Santantonio et al., 2017), which dismembered the regional-scale “Calcere Massiccio” carbonate platform producing a complex horst-graben submarine paleotopography (Fig. 3b). Such morphostructural settings had a different structural and stratigraphic evolution, hosting distinct sedimentary successions (Santantonio, 1993, 1994; Galluzzo & Santantonio, 2002; Santantonio et al., 2017): in the rapidly subsiding hanging walls of Jurassic faults the shallow-water carbonate factory drowned around the Hettangian/Sinemurian boundary (Bucklandi Zone - Passeri & Venturi, 2005) and a thick (some hundred meters in average) Jurassic pelagic succession was deposited. Differently, in footwall blocks the platform drowned in the early Pliensbachian (Ibex Zone - Morettini et al., 2002; Marino & Santantonio, 2010) and was followed by a thin (some meters), very condensed, cephalopod-rich pelagic succession (“condensed series” *sensu* Centamore et al., 1971; “facies association A” *sensu* Santantonio, 1993) in settings described as Pelagic Carbonate Platforms (Santantonio, 1993, 1994) or PCP (Fig. 3b). The submarine paleoescarpments, which linked the PCP tops and the

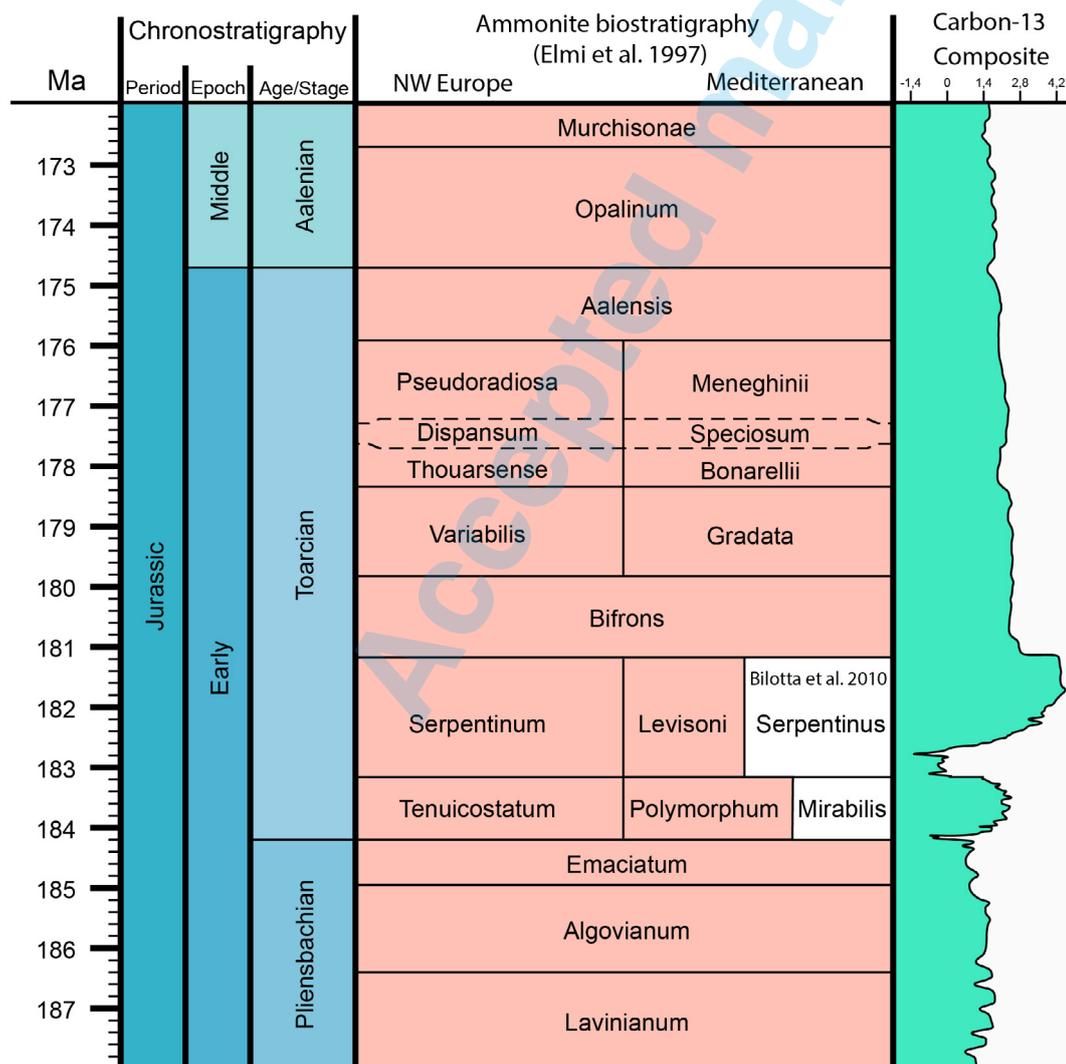


Fig. 2 - Latest Pliensbachian to early Aalenian chronostratigraphic chart and ammonite biostratigraphy.

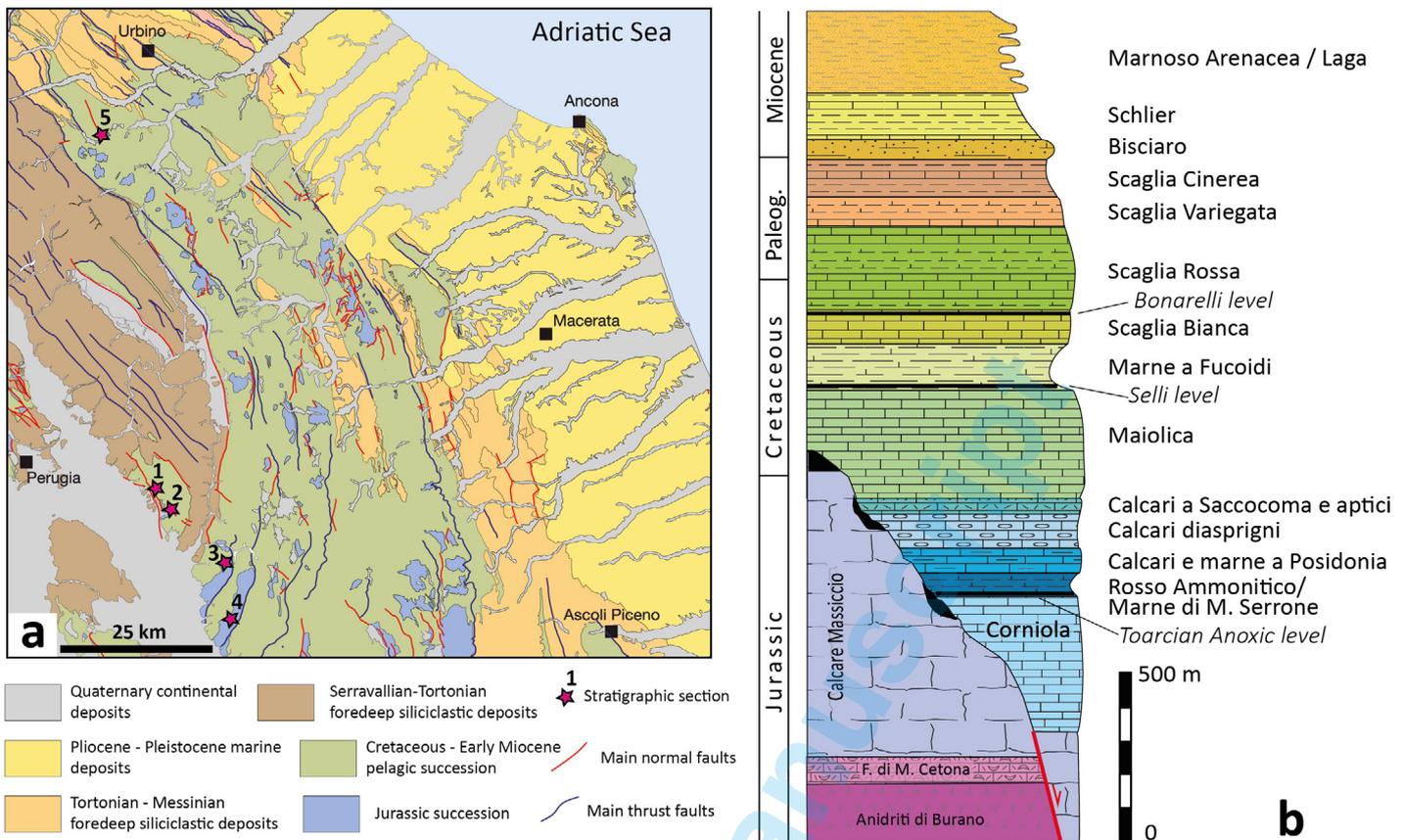


Fig. 3 - a) Geological sketch of the Umbria-Marche Apennines with location of the stratigraphic sections (modified after Conti et al., 2020): 1, Eremo delle Carceri; 2, Cava Gabbiano; 3, Monte Serrone; 4, Pettino; 5, Gorgo a Cerbara; b) Stratigraphy of the Umbria-Marche domain (modified after Fabbi, 2015).

basin floor, were essentially erosive/non-depositional margins, progressively unconformably covered by the basin-fill onlapping deposits. Such paleoescarpments could host patches of very condensed facies, directly resting above the Calcare Massiccio, in the form of epiescarpment deposits (Galluzzo & Santantonio, 2002; Santantonio et al., 2017). As widely described in literature (Centamore et al., 1971; Farinacci et al., 1981; Cecca et al., 1990; Santantonio, 1994; Galluzzo & Santantonio, 2002; Fabbi, 2015; Cipriani et al., 2019), the Jurassic submarine relief was finally blanketed in the Early Cretaceous by the Maiolica (late Tithonian p.p. - early Aptian p.p.).

The stratigraphic succession begins with the Calcare Massiccio, a regional shallow-water carbonate megabank which was dismembered by the mentioned Early Jurassic rifting stage and drowned diachronously in basinal or PCP settings (Passeri & Venturi, 2005; Marino & Santantonio, 2010; Fabbi & Santantonio, 2012).

In pelagic basins the oldest unit is the Corniola (Sinemurian p.p. - lowest Toarcian), a grey-hazel cherty mudstone and wackestone containing abundant radiolarians and sponge spicules, and less abundant brachiopods, ostracoda, benthic forams and ammonoids. The sedimentation of the lower portion of the unit was syn-tectonic, and marked by great volumes of benthic material and lithoclasts, sourced from the neighboring, still productive carbonate platform structural highs, and organized in thick turbiditic beds (Fabbi & Santantonio, 2012). Following the end of parosistic tectonics and

the drowning of carbonate platforms in the early Pliensbachian, the Corniola became generally free of any coeval resedimented material, becoming a well-bedded pelagic mudstone with white chert nodules. The thickness of this unit in the study area is variable but ranges between ~200 and >400 m (Cecca et al., 1990; Fabbi, 2015).

The typical Toarcian succession of the UM domain includes two partly heteropic units: the marne di Monte Serrone (Pialli, 1969) and the Rosso Ammonitico (Pilla, 1847).

The Marne di Monte Serrone (lower – middle Toarcian) was first studied by Pialli (1969) in the type locality of Monte Serrone (Fig. 3a). The unit consists of grey/greenish well-bedded marly lithotypes (marls, marly limestones and clayey marl) intercalated with grayish limestone with chert nodules, and rich ferruginous oxides (Pialli, 1969; Centamore et al., 1975; Sabatino et al., 2009). Calcareous intercalations are generally laminated, and contain ostracods, echinoids, sponge spicules, crinoids and rare radiolarians; remains of thin-shelled bivalves (*Posidonia auctt.*) can be found in the upper portion of the unit.

The calcareous intercalations are composed of calcarenites that are frequently graded with grain size varying from fine to medium (rarely coarse) with layers thickness ranging from 20 cm to 2 m, often showing a thin plane-parallel to cross lamination; hummocky-like structures have also been reported (Monaco et al., 1994). At the base of coarser layers flute casts, groove casts or ripple marks occur (Centamore et al., 1975).

A black shale horizon, rich in bituminous organic matter, occurs in the lowermost portion of the unit throughout the Region, and is related to the early Toarcian anoxic event (T-OAE) (Jenkyns, 1988, 2010; Parisi et al., 1996; 1998; Bilotta et al., 2010; Satolli et al., 2018).

The alternance of micritic limestones and marls of the lower Toarcian has been recently interpreted as a local response to the transient climatic perturbation caused by the emplacement of the Karoo-Ferrar large igneous province (Satolli et al., 2018).

The unit can be subdivided in three lithofacies (Baldanza et al., 1989; Pialli, 1969).

i) a “calcareous-marly lithofacies”, consisting of an alternation of reddish marly limestones organized in layers about 20 cm thick, interbedded with greenish clayey marls, in layers 5 to 10 cm thick; ii) a “clayey-marly lithofacies”, consisting of gray-green clayey marls, and marly gray finely laminated clays with few bioturbations; iii) a “marly lithofacies”, consisting of interbedded polychrome marls, clayey marls and calcarenites.

The distinction in lithofacies is not always easily applicable in the field, due to thickness and lithological variability coupled with outcrop conditions. Where the thickness of the unit is greater, a great amount of calcarenitic sediments, mostly in turbidite facies, can be observed (Monaco et al., 1994).

A gradual decrease of CaCO<sub>3</sub> content from the first to the second lithofacies is observed, followed by a new increase in the uppermost lithofacies. The thickness of the Marne del Monte Serrone is variable from 60m in the type section to 0 where the Rosso Ammonitico directly rests on the Corniola (e.g., Cecca et al., 1990). The boundary with the Corniola can be sharp or alternatively transitional and marked by an increase in clayey intercalations in the succession. The boundary with the overlying Rosso Ammonitico can be both transitional or abrupt or can be partially heteropic. The macrofossiliferous content of the Marne di Monte Serrone is mainly characterized by ammonites.

The Rosso Ammonitico (Toarcian *p.p.*) was first described by Pilla (1847), and subsequently studied by many other authors due to its particularly rich fossil content (Canavari, 1879; Fucini, 1911; Gallitelli Wendt, 1969; Centamore et al., 1971; Venturi, 1972, 1973; Farinacci et al., 1981; Baldanza et al., 1988; Cresta et al., 1989; Cecca et al., 1990; Nini et al., 1997; Cipriani et al., 2020).

The most representative stratigraphic sections of Rosso Ammonitico in Umbria-Marche are Valdorbìa, Bosso, Burano, Mt. Gemmo, Mt. La Pelosa (Centamore et al., 1971; Nicosia & Pallini 1977; Monaco et al., 1994; Nini et al., 1997). The formation consists of red to pink limestones, marly limestones and nodular marls; nodules are interpreted as being the result of early diagenesis of burrows and indicate slow sedimentation rates (Elmi, 1981). The bed maximum thickness is about few decimeters. The Rosso Ammonitico can be divided into three main lithofacies (Venturi, 1972, 1973; Farinacci et al., 1981; Nini et al., 1997; Petti & Falorni, 2007): i) clays and marls: this lithofacies represents the basal portion of Rosso Ammonitico, and consists of reddish to dark red marls often bioturbated. The marls are interbedded with nodular levels; the clay component decreases upwards; ii) nodular marly limestones: this lithofacies constitute the central part of the

formation, it consists of nodular well-bedded marly limestones, with a dark red color, with pervasive bioturbation; iii) alternations of marls and marly limestones: this lithofacies represents the top of the Rosso Ammonitico and is made of an alternation of reddish marls with white nodules and gray marly limestones. This lithofacies is bioturbated.

The boundary with the underlying Corniola is sharp and often marked by an unconformity surface (Centamore et al., 1971). Locally, the formation rests on top or is laterally heteropic with the Marne di Monte Serrone, consequently, the thickness of the unit ranges from few meters up to 40 m. The boundary with the overlying Calcari e Marne a *Posidonia* Fm is transitional and occur through an increase in the CaCO<sub>3</sub> content and is marked by the first occurrence of chert.

The faunal content is characterized by abundant ammonites (Cresta et al., 1989; Gallitelli Wendt, 1969; Venturi, 1972, 1973). Along with ammonites the Rosso Ammonitico contains abundant thin-shelled bivalves (*Bositra buchii* and *Lentilla humilis*) (Conti & Monari, 1992), gastropods, crinoids, brachiopods, ostracods, benthic foraminifers; also remains of vertebrate fauna (hybodontids) were described from of the Rosso Ammonitico (Romano et al., 2019).

The following unit is the Calcari e marne a *Posidonia* (lower Toarcian *p.p.* – lower Bajocian *p.p.*) which consists of reddish/grey marly limestones and marls with chert, the latter abruptly increasing up-section. Faunal assemblages are dominated by pelagic thin-shelled bivalves (*Bositra buchii* and *Lentilla humilis* - *Posidonia* auctt.), along with radiolarians and ammonoids. The transition to the overlying unit (Calcari Diasprigni) is marked by the disappearance of the thin-shelled bivalves (Galluzzo and Santantonio, 2002).

The basinal succession is replaced on PCP tops, after the drowning of the Calcare Massiccio B Mbr., by a condensed pelagic succession, made up of four informal units, which belong to the ‘Bugarone Gr.’ (e.g., Galluzzo & Santantonio, 2002; Fabbì, 2015). The Bugarone group ranges from the early Pliensbachian to the earliest Berriasian (Fabbì, 2015; Cipriani et al., 2019) and encompasses a wide depositional hiatus (Cecca et al., 1985). Toarcian deposits of the condensed successions are equivalent to the Rosso Ammonitico and Calcari e Marne a *Posidonia*, and are:

i) the “Calcari nodulari e marne Verdi de I Ranchi” (Toarcian *p.p.*), a nodular yellow micritic marly limestone, incipiently dolomitized, in dm-thick beds; ii) the lowermost part of the ‘Calcari nodulari a filaments di Fosso del Presale’ (late Toarcian *p.p.* – early Bajocian), a brown micritic limestone with thin-shelled bivalves, radiolarians, sponge spicules and small ammonoids.

The total thickness of Toarcian condensed units ranges from 0 to about 10 m (Centamore et al., 1971; Galluzzo & Santantonio, 2002; Cipriani et al., 2020).

### Longobucco Basin (Northern margin of Tethys)

The Longobucco Basin (Fig. 4a) records the evolution of a Rhaetian/Hettangian alluvial plain to a Toarcian deep turbiditic basin characterized by the occurrence of morphostructural intrabasinal high, in turn evolving in a Middle-Late Jurassic pelagic basin

(Young et al., 1986; Teale, 1988; Bouillin et al., 1988; Santantonio et al., 2016; Santantonio & Fabbi, 2020; Fabbi et al., 2023; Innamorati et al., 2024). Two distinct stratigraphic successions have been described in the area (Fig. 4), the Longobucco Group and the Caloveto Group (Young et al., 1986; Santantonio & Teale, 1987; Teale, 1988; Santantonio, 2012; Santantonio et al., 2016; Santantonio & Fabbi, 2020).

The Longobucco area was affected by the Early Jurassic rifting stage, which firstly produced marine flooding and the onset of a mixed carbonate shelf sedimentation (Bocchigliero Formation, <100m; Hettangian *p.p.*-Sinemurian *p.p.*) and subsequently a rapid deepening of the sedimentary environment, documented by hemipelagic marls of the Petrone Formation (<200 m; Sinemurian *p.p.*-lower Pliensbachian). Continued subsidence is recorded by the thick (>1 km) siliciclastic turbidites of the Trionto Formation (upper Pliensbachian-lower Toarcian). Recently, it has been demonstrated the physical continuity between the Longobucco and Caloveto Groups, which both evolve upwards with the same pelagic stratigraphy (Sant'Onofrio Subgroup: Aalenian-?Hauterivian), including gray *Posidonia* limestones, partly heteropic with red *Zoophycos* marls (see below), radiolarites and Maiolica-type limestones (Santantonio et al., 2016).

The main rifting-related extensional tectonic phase occurred around the Sinemurian/Pliensbachian boundary and, besides the deepening of the Longobucco Basin, produced accommodation space around emergent structural highs, favoring the growth of shallow water carbonate bodies along their flanks which mark the beginning of the Caloveto Group sedimentation (Lower Caloveto fm. – Pliensbachian). A new Toarcian extensional phase produced the fragmentation and drowning of the benthic carbonate factories, and

widespread onset of dominantly pelagic sedimentation throughout the Longobucco-Caloveto Basin (Santantonio et al., 2016).

The studied Toarcian sections belong to the Caloveto Group (Santantonio, 2012; Mariotti et al., 2007, 2010; Santantonio et al., 2016); for a thorough geological, historical and stratigraphic analysis of the Caloveto Group, accompanied by a geological map of the type locality, the reader is referred to the paper of Santantonio & Fabbi (2020).

The succession starts with the Lower Caloveto fm., a white siliciclast-rich lime- grainstone, typically organized in 2-50 cm thick beds. Coarse conglomerates with pebbles to boulders of the Paleozoic basement characterize the unit, close to the high-angle contact of the unit with the Paleozoic basement. Coated grains (cortoids) are common components of the limestone (Innamorati & Santantonio, 2018; Santantonio & Fabbi, 2020). Bioclasts include crinoids, echinoids, bivalves, gastropods, benthic forams (including *Agerina martana* in the upper part), rare calcareous sponges, *Tubiphytes* and various colonial and solitary corals (Santantonio & Fabbi, 2020).

The thickness of the Lower Caloveto fm. is variable, reaching a maximum of around 100 m. The passage to the overlying pelagites of the Upper Caloveto fm. can be abrupt or can occur through a drowning succession.

At Brulline (see below) the drowning succession is a 6 m-thick bed package which evolves from a pink brachiopod (rhynchonellids, terebratulids) coquina, to a pink/red packstone with small gastropods, ammonites, echinoderms, benthic forams, and sponge spicules. Upwards the succession evolves with the appearance of abundant thin shelled bivalves and aptychi, in turn covered by red encrinetes.

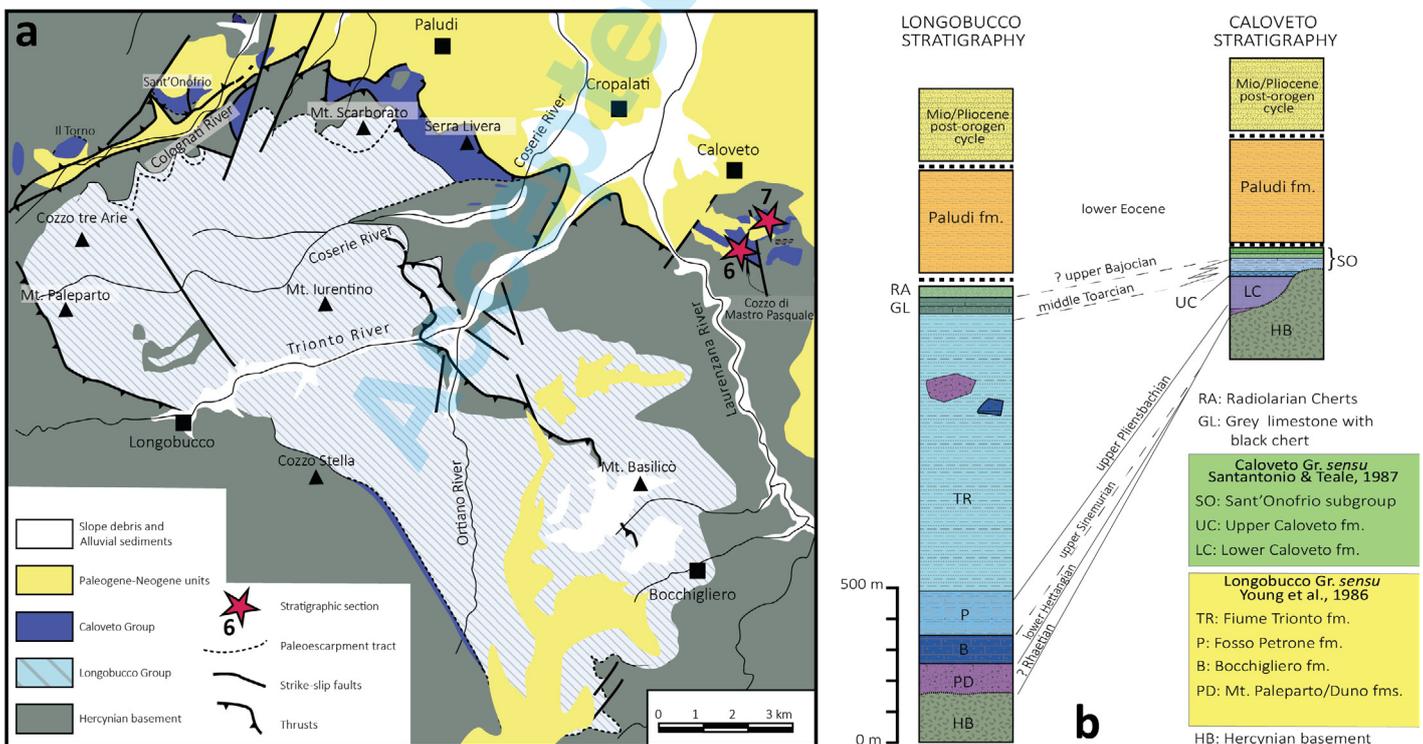


Fig. 4 - a) Geological sketch of the Longobucco Basin with location of the stratigraphic sections (modified after Santantonio & Fabbi, 2020): 6, Cozzo di Mastro Pasquale; 7, Brulline; b) General stratigraphy of the Longobucco Basin (modified after Santantonio & Fabbi, 2020).

The Lower Caloveto fm. is considered to be essentially Pliensbachian (see discussion in Santantonio & Fabbi, 2020), the uppermost beds yielded an upper Pliensbachian ammonite (*Arietoceras* sp.; Santantonio et al., 2016), but the drowning succession can range within the base of the Toarcian, due to the occurrence of *Posidonia* auctt. (Santantonio & Fabbi, 2020).

At Cozzo di Mastro Pasquale, where the passage between the Lower and the Upper Caloveto Fms. is represented by an abrupt surface (drowning unconformity), it appears as an irregular rockground (*sensu* Fuersich, 1979) documenting early lithification followed by erosion, although gastropods and uppermost Pliensbachian ammonites (*Protogrammoceras* sp.) are preserved.

The Upper Caloveto fm. is a typical Rosso Ammonitico facies, composed of thinly bedded (5-20 cm) nodular lime to marly mudstone with thin shale interbeds. The fossil content includes ostracods, benthic forams, thin-shelled bivalves (*Posidonia*), echinoderms and ammonites, which are not so abundant such as in the Umbria-Marche Rosso Ammonitico. The unit bears heterometric siliciclastic detritus in the form of sparse angular clasts of phyllite or quartz. The thickness is strongly variable from few decimeters to a maximum of about 9 m. Both the top and the base of the unit are diachronous, thus the age can range from the early Toarcian to the late Toarcian *p.p.* (Serpentinum to Dispansum Zones), but the succession is often incomplete, such as at Cozzo di Mastro Pasquale, where a *hiatus* exists between the top of the Lower Caloveto Fm (Emaciatum Zone) and the base of the Upper Caloveto fm. (Bifrons Zone) (Santantonio & Fabbi, 2020).

The Upper Caloveto fm. is unconformably covered by the Zoophycos and *Posidonia* marls of the Sant'Onofrio Subgroup, made of dark red marls and marly limestones, characterized by the pervasive bioturbation (*Zoophycos*, *Chondrites*) and the abundance of *Posidonia* coquinas. Remarkably the unit yielded abundant belemnite faunas (Combemorel et al., 1994; Mariotti et al. 2007, 2010), with assemblages comprising *Pachybelemnopsis* (*Holcobelus*, *Pachybelemnopsis*, *Hibolithes*) and less common Belemnitina (*Brevibelus*, *Megateuthis*). The ammonite assemblage is also significant: the base of the unit bears ammonites of the latest Toarcian Aalensis Zone, whereas the topmost levels bear *Docidoceras* sp. and "*D.*" cf. *perfectum* (Combemorel et al., 1994; Santantonio & Fabbi, 2020), indicating the early Bajocian Discites Zone (Mariotti et al., 2007). The marls range therefore from latest Toarcian to earliest Bajocian; laying on a rugged submarine topography they exhibit a strongly variable thickness (from few to about 30 m).

## STRATIGRAPHIC SECTIONS

In this chapter the seven stratigraphic sections are described in detail. Significant ammonites used for biostratigraphic correlations are represented in Figs. 5 and 6.

### Monte Subasio

Mt. Subasio is a mountain ridge reaching 1.290 m a.s.l., located in the Northern Umbria Region, near the town of Assisi (Fig. 3a). It is a wide anticline where a continuous marine succession crops out,

encompassing the Lower Jurassic to Miocene units of the Umbria-Marche succession (Fazzini & Mantovani, 1965).

Two stratigraphic logs have been made at Mt. Subasio (Fig. 7a, b): the first section ("Eremo delle Carceri") is located on the right side of Fosso delle Carceri, near the town of Assisi (PG), while the second section ("Cava Gabbiano") is located at the front of an abandoned Corniola quarry, on the right side of Fosso Renaro (see Fig. 1 for location and coordinates).

### Eremo delle Carceri Section

The section measures about 9 m (Fig. 9) and the Toarcian is about 6 m thick; the base of the section is about 1 m of pelagic mudstone referred to the Corniola. The top of the Corniola is a hardground; above, 13 cm of clay and marly limestone are referred to the "Lecceti" bioevent (Venturi et al., 2010), which predates the T-OAE (Fig. 8a). The T-OAE consists of dark polychrome marls and clayey marls with total thickness 30 cm (Fig. 8a). The following 62 cm are mainly dark green clayey sediments with grey calcareous intercalation.

This interval is followed by a 31 cm thick interval of gray marly limestone in dm-thick beds, which yielded fragments of *Hildaites* sp. (Levisoni Zone), the sediment then becomes a red clayey marl and marl, for a thickness of 1.05 m. The alternation of clay and marl layers becomes more regular in the subsequent 33 cm, which yielded several ammonites, including *Nodicoeloceras* sp., *Mesodactylites sapphyucus*, *Hildaites* sp. and *Alocolytoceras dorcadis*, marking the passage from the Levisoni to the Bifrons Zone. Upwards, a 1.25 m thinly bedded marly interval yielded *Alocolytoceras* sp. and *Hildoceras lusitanicum*, the latter indicates the Bifrons Zone.

Above this interval 44 cm of marls, partly nodular contain *Hildoceras sublevisoni*, *Polyplectus appenninicus* and *Audaxlytoceras spirorbis*. *H. sublevisoni* that marks the Sublevisoni subzone within the Bifrons Zone.

Upwards about 1.61 m of nodular marls occur, bearing a rich ammonite assemblage with *Pseudomercaticeras* sp., *Hildoceras* sp., *Polyplectus appenninicus*, *Polyplectus* sp. and *Hildoceras semipolatum*, marking the uppermost portion of the Bifrons Zone.

Upwards, 30 cm thick horizon of red marl with white flames is followed by 10 cm of clays and 20 cm of red nodular marly limestones with white spots, in turn, followed by 11 cm of clays with lensoid marly intercalations. Such beds are pervasively bioturbated.

The last portion, about 70 cm thick, is made up of pink marly limestones white- or red-spotted, intercalated with clay horizons, more frequent towards the top while the basal portion show a nodular texture.

Beyond this interval, the vegetation and debris hide the rest of the succession (Fig. 4b), although, about 10 m above the last sampled bed, a good outcrop of Calcari e Marne a *Posidonia* occurs, thus the Toarcian-Aalenian boundary should be below this outcrop.

### Cava Gabbiano Section

This is a composite stratigraphic section (Fig. 10), measured in three different outcrops which were physically separated by the quarrying activity (Fig. 7a). In this section the Pliensbachian-Toarcian boundary and the lower Toarcian have been analyzed.

The first 1.60 m of the section are well-bedded pelagic mudstones with thin grey clay interbeds; upwards the log evolves in 60 cm of thinly beds of marly limestones and clayey marls, also including a horizon made of densely packed bivalve shells.

The subsequent about 10 m are hidden by debris, followed by 2.7 m of hazel-colored marls and clays alternations, in a typical "Marne del Monte Serrone" facies. This interval contains *Neoliocera* sp. and *Protogrammoceras* sp., allowing to ascribe it to the topmost beds of the Pliensbachian.

Following, 20 cm of pseudo-nodular clayey marls and 60 cm of hazelnut marls are alternated to gray/purple clay levels. After about 1 m of vegetation cover, a 20 cm thick horizon of brown clays rich in organic matter is interpreted as representing the T-OAE (Fig. 8b).

Above this level, 1.3 m of hazel-colored clayey marls, 5 cm of black shale, and 75 cm of the previous hazel-colored

clayey marls occur. This represents the last level of the Marne del Monte Serrone, following about 1 m of vegetation cover, in fact, about 1,5 m of red clayey marl occurs, ascribable to the Rosso Ammonitico.

### Monte Serrone

Monte Serrone is a mountain reaching 1046 m asl, located in eastern Umbria Region, east of the city of Foligno (Fig. 3a). It is a portion of a wide anticline which also includes the Sasso di Pale and Mt. Aguzzo intrabasinal highs (Pialli, 1970). The pelagic succession of Mt. Serrone was sedimented in a basin limited by the Sasso di Pale Jurassic PCP to the N, and the Mt. Aguzzo Jurassic high to the S. Along the southern flank of Mt. Serrone the Jurassic stratigraphy is well exposed from the Corniola to the Maiolica Fms (Pialli, 1970). Monte Serrone is the type locality of the Marne di Monte Serrone. A

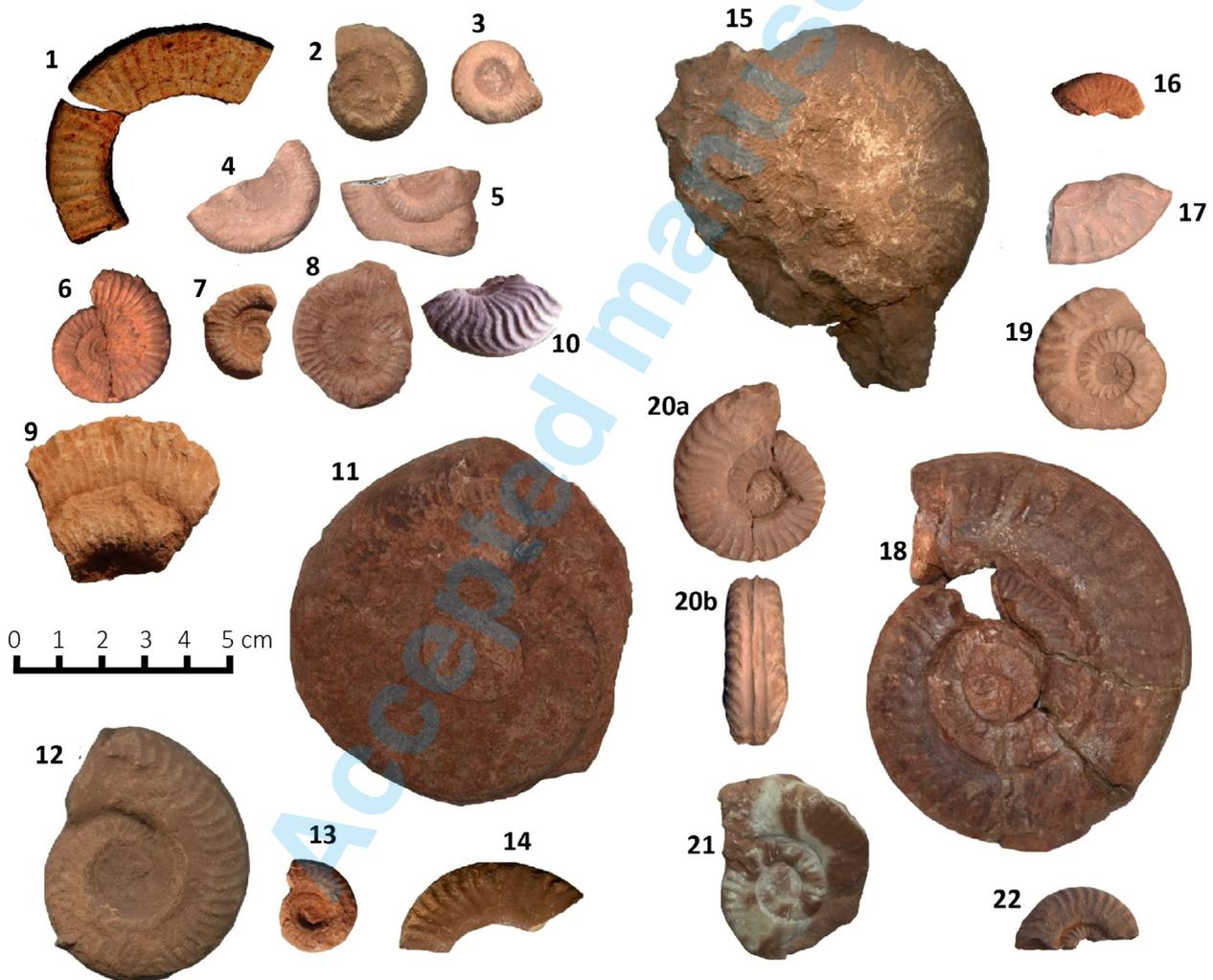


Fig. 5 - 1. *Dactylioceras (Eodactylites) pseudocommune*, Polymorhum Zone, Gorgo a Cerbara. 2. *Mesodactylites sapphicus*, Levisoni Zone, Eremo delle Carceri. 3. *Mesodactylites merlai*, Bifrons Zone, Gorgo a Cerbara. 4. *Nodicoeloceras choffati*, Levisoni Zone, Gorgo a Cerbara. 5. *Nodicoeloceras vorticellum*, Bifrons Zone, Gorgo a Cerbara. 6. *Telodactylites eucosmus*, Bifrons Zone, Gorgo a Cerbara. 7. *Telodactylites renzi*, Bifrons Zone, Pettino. 8. *Collina gemma*, Gradata Zone, Pettino. 9. *Collina kapemorpha*, Gradata Zone, Pettino. 10. *Harpoceras gr. mediterraneum*, Bifrons Zone, Gorgo a Cerbara. 11. *Harpoceras cf. mediterraneum*, Bifrons Zone, Cozzo di Mastro Pasquale. 12. *Hildoceras sublevisoni*, Bifrons Zone, Eremo delle Carceri. 13. *Hildoceras gr. lusitanicum*, Bifrons Zone, Pettino. 14. *Hildaites* sp., Levisoni Zone, Eremo delle Carceri. 15. *Polyplectus apenninicus*, Eremo delle Carceri. 16. *Hildoceras semipolitum*, Bifrons Zone, Pettino. 17. *Orthildaites douvillei*, Levisoni Zone, Gorgo a Cerbara. 18. *Hildoceras cf. sublevisoni*, Bifrons Zone, Brulline. 19. *Mercaticeras mercatii*, Bifrons Zone, Gorgo a Cerbara. 20. *Mercaticeras thyrrenicum*, Bifrons Zone, Gorgo a Cerbara - a: lateral view, b: dorsal view. 21. *Hildaites* sp., Levisoni Zone, Eremo delle Carceri. 22. *Pseudomercaticeras rotaries*, Gradata Zone, Pettino.

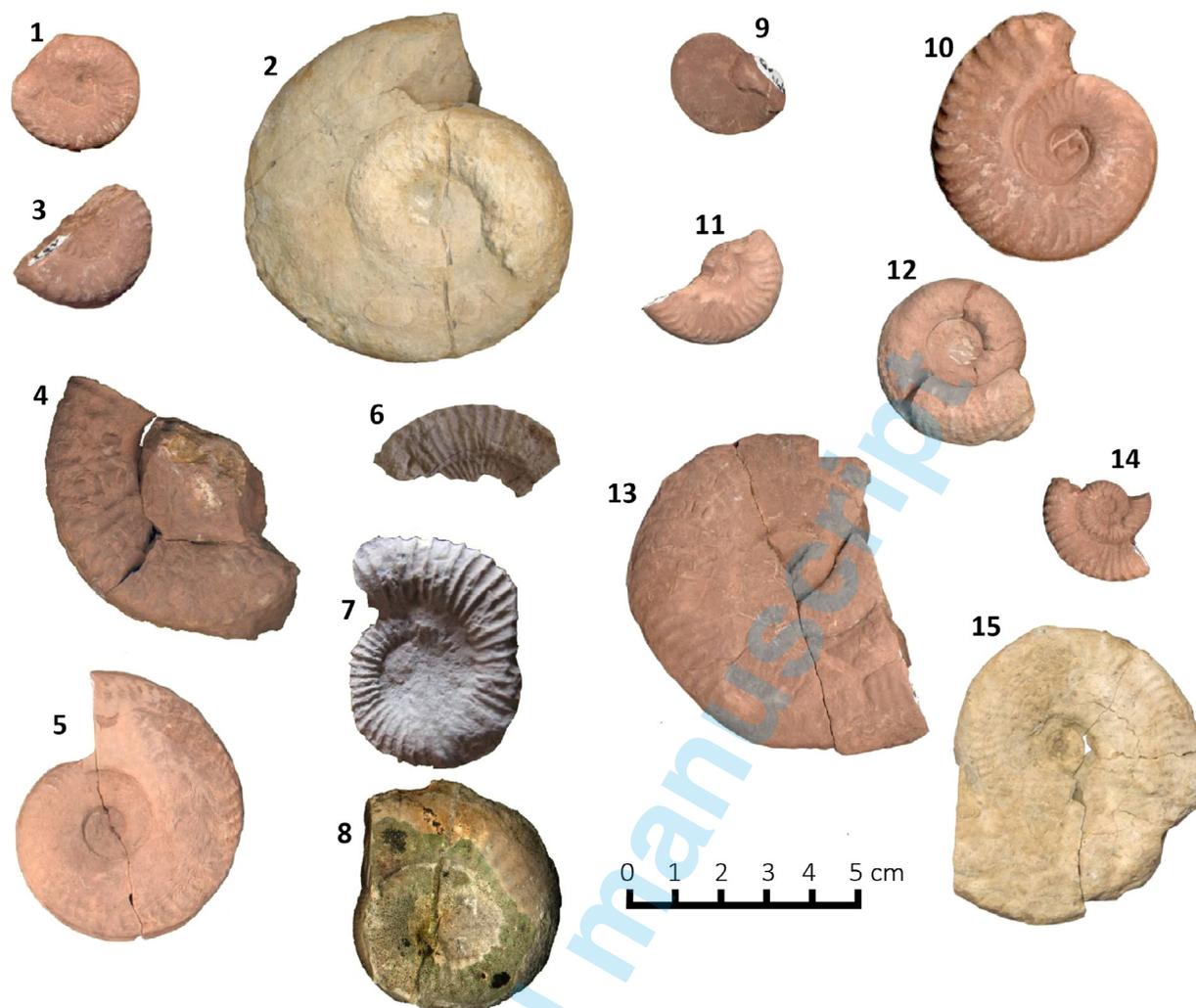


Fig. 6 - 1. *Pseudomercaticeras venzoi*, Gradata Zone, Gorgo a Cerbara. 2. *Merlaites alticarinatus*, Gradata Zone, Gorgo a Cerbara. 3. *Crassiceras latum*, Gradata Zone, Gorgo a Cerbara. 4. *Furloceras* gr. *cornucopia*, Gradata Zone, Gorgo a Cerbara. 5. *Pseudogrammoceras subregale*, Gradata Zone, Gorgo a Cerbara. 6. *Doumortiera* sp., Meneghinii Zone, Gorgo a Cerbara. 7. *Tmetoceras scissum*, Opalinum Zone, Gorgo a Cerbara. 8. *Erycites fallifax*, Opalinum or Murchisonae Zones, Gorgo a Cerbara. 9. *Polyplectus pluricostuatus*, Levisoni Zone, Gorgo a Cerbara. 10. *Pseudomercaticeras frantzi*, Gradata Zone, Gorgo a Cerbara. 11. *Osperlioceras rivierense*, Gradata Zone, Gorgo a Cerbara. 12. *Cagliceras elaphus*, Bonarellii Zone, Gorgo a Cerbara. 13. *Phymatoceras* gr. *elegans*, Bifrons Zone, Gorgo a Cerbara. 14. *Erycites intermedius*, Opalinum Zone, Gorgo a Cerbara. 15. *Erycites intermedius*, Opalinum Zone, Gorgo a Cerbara.

single stratigraphic section has been made at Mt. Serrone, the Mt. Serrone Section, located along the road for the Sassovivo Abbey, from the northern flank of Mt. Aguzzo to the southern flank of Mt. Serrone (Fig. 1).

### Mt. Serrone Section

The section is about 66 m thick (Figs. 7c, 11), and includes the Pliensbachian-Toarcian boundary and the lower/middle Toarcian (up to the Gradata Zone).

The section begins with 1 m of hazel-coloured lime-mudstone, ascribed to the Corniola. After about 4 m of vegetation cover, 4.6 m of the same lime-mudstone crop out, with gradual increase of the clay fraction up-section, showing slump structures. Such interval yielded *Reynesoceras* sp. and *Dactylioceras* (*Eodactylites*) *mirabilis*, the latter referred to the very base of the Toarcian (Polymorphum Zone). These beds represent the topmost levels of the Corniola.

Upwards, 1 m of limestone with black chert nodules is followed by 5 m of calcareous marls interbedded with gray/greenish clays and clayey marls, bearing *Lytoceras* sp., *Dactylioceras* (*Eodactylites*) *polymorphum* and *Protogrammoceras bassanii* referred to the Polymorphum Zone of the basal Toarcian. Upwards 3.2 m of marly limestones with chert nodules and slumps occur, followed by 3.5 m of clayey marls, evolving in a dark brown clay horizon (Fig. 8c) referred to the T-OAE (Bilotta et al., 2010).

Above the T-OAE, 4.6 m of clay and clayey marls occur, followed by 70 cm of gray/violet clayey marls and 19 m of grey/greenish clay with sparse calcareous levels.

At the base of this portion, about 5 m above the T-OAE, a *Orthildaites douvillei* was found, indicating the passage to the Levisoni Zone. Six meters above this horizon the beds yielded *Mesodactylites sapphicus* and *Hildoceras sublevisoni*, marking the base of the Bifrons Zone. At the top of this interval the ammonite assemblages are characterized by *Hildoceras sublevisoni* and *Mercaticeras mercati* still belonging to the Bifrons Zone.



Fig. 7 - a) View of Cava Gabbiano; yellow stars indicate the location of the measured sections; b) field view of the Eremo delle Carceri section; c) field view of the Monte Serrone section; d) hardground at the top of the Corniola in the Gorgo a Cerbara section; e) view of the Rosso Ammonitico outcropping in the Pettino section.

The following 8 m are made of clayey marls, in turn followed by the first yellow calcarenite intercalation. Calcarenite and marly calcarenite beds become common upsection, interbedded with grey marls for a 4.70 m thick interval. Then a 60 cm-thick bank of green/red nodular marly limestone occurs, again followed by 5.20 m of calcarenite/clayey marls alternation. The whole described interval is mostly ascribable to the Bifrons Zone, bearing, among others, *Hildoceras gr. bifrons*, *Hildoceras semipolitum* and finally *Transicoeloceras viallii*, which marks the passage to the Gradata Zone, to which was ascribed the last 1 m-thick sampled interval, made of graded and laminated calcarenites, which also yielded *Collina gemma*, a typical taxon indicating the Gradata Zone.

### Monte Serano

Monte Serano is a mountain ridge reaching 1429 m asl, located in eastern Umbria Region, near the towns of Trevi and Campello sul Clitunno (Fig. 3a). It is a wide anticline, cut to the west by a normal fault, which borders the ridge towards the Umbria Valley, and to the east by a NW-verging thrust (Accordi & Moretti, 1967). The typical Calcare Massiccio to Maiolica Jurassic succession is well-exposed along the flanks of the mountain.

A single stratigraphic section has been made at Mt. Serano, the Pettino Section, located near the village of Pettino (Fig. 1).

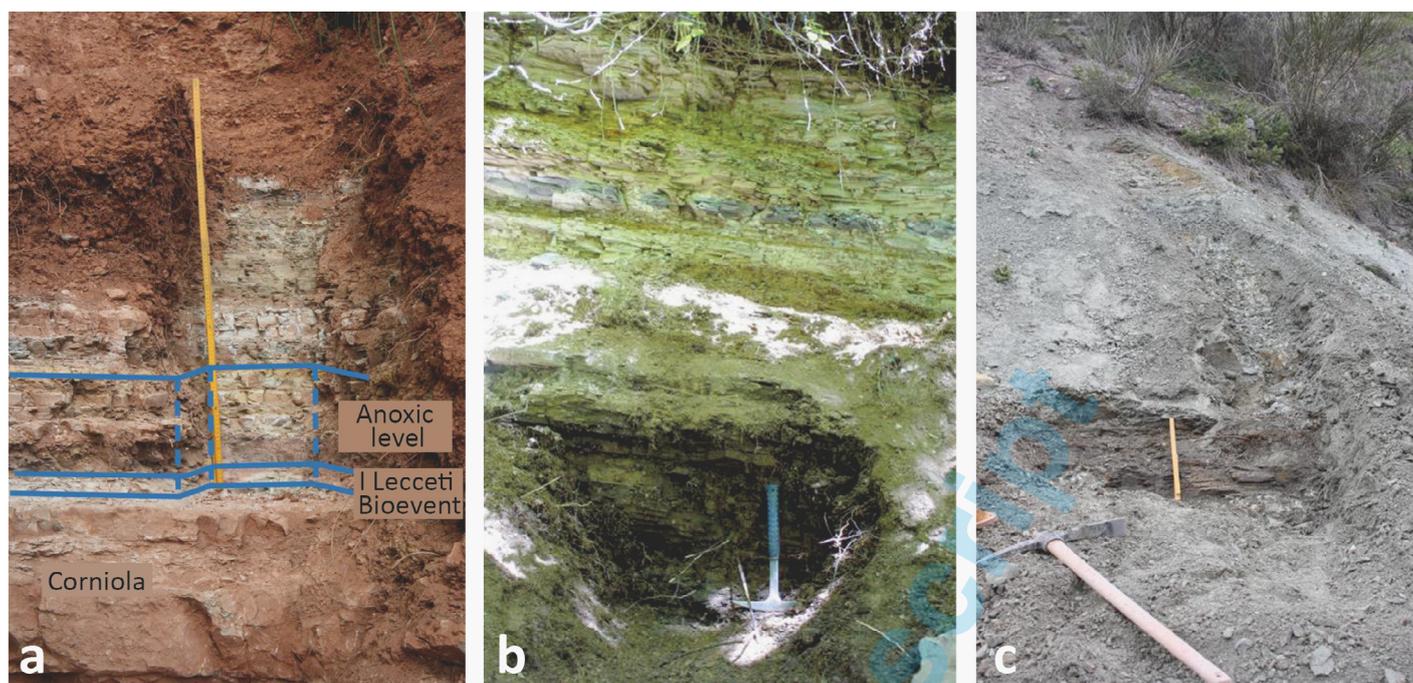


Fig. 8 - Evidence of the T-OAE in the studied sections: a) Eremo delle Carceri; b) Cava Gabbiano; c) Monte Serrone.

### Pettino Section

This is an almost complete section, composed of the Corniola, Rosso Ammonitico and Calcari e Marne a Posidonia formations, thus allowing to observe both the Pliensbachian-Toarcian boundary and the Toarcian-Aalenian boundary.

Unfortunately, it was not possible to directly observe in the section the T-OAE, which was however observed in the surrounding areas, where it occurs as a very thin (few cm) black horizon.

The section is approximately 18 m thick (Fig. 11); the base is represented by the topmost layers of Corniola, which show a marly facies with purple flames, bearing *Lytoceras* sp and *Protogrammoceras* sp., the latter allowing to ascribe these levels to the uppermost Pliensbachian.

Above, the section continues with about 5.30 m of red marly clays (Fig. 7e) with rare calcareous levels; although not particularly fossiliferous, this interval yielded a *Dactylioceras* (*Eodactylites*) sp., which allow to ascribe it to the *Polymorphum* Zone.

The following 6.30 m are nodular red marls, intercalated by clayey levels; towards the top of this bed package abundant crinoid fragments occur. This interval contains abundant ammonite assemblages.

In the basal portion *Mesodactylites* ?*sapphicus*, *Hildoceras* gr. *lusitanicum* (sensu Di Cencio, 2007), *Mercaticeras* sp., *Hildoceras* sp., *Mesodactylites* sp., *Hildoceras* gr. *bifrons*, *Pseudogrammoceras* ?*rotaries* and *Hildoceras* *semipolytum* occur, all taxa belonging to the Bifrons Zone.

In the middle portion *Telodactylites* ?*renzi*, *Collina gemma*, *Collina kampemorpha*, ?*Pseudogrammoceras* sp. and *Merlaites* sp. occur, testifying the Gradata Zone.

In the crinoid-rich horizons *Geczyeras* sp. and *Geczyeras* gr. ?*perplanum*, typical taxa of the Bonarellii Zone, are found.

The following 4 m are made of marls with clay interbeds, evolving in marly limestones towards the top. Bioturbation is common throughout the interval, which yielded large *Philloceratida* along with a *Hammatoceratida*, indicating the terminal portion of the Toarcian.

The last sampled interval is made of about 50 cm thick gray lime-mudstones, with purple flames, containing abundant thin-shelled bivalves and a *Holcophiloceras ultramontanum*, which is a typical Aalenian taxon.

Abundant ammonites were also found as displaced material close to the studied outcrop such as *Harpoceras* gr. *serpentinum*, *Mesodactylites* sp., *Furloceras* sp., *Hildoceras lusitanicum*, *Hildoceras* sp., *Hildoceras* cf. *semipolium*, *Hildoceras sublevisoni*, *Hildoceras acarnicum*, *Nodideloceras* sp., *Nodidactylites* sp., *Polyplectus discoides*, *Mercaticeras* sp., ?*Rarenodia*, and *Alocolytoceras* sp., which define a middle Toarcian assemblage.

### Monte Nerone

Monte Nerone is a mountain reaching 1525 m asl, located in the northern Marche Region between Pioraco and Apecchio towns (Fig. 3a). Monte Nerone is one of the largest PCPs of the Umbria Marche Domain and is a classic locality for the study of Jurassic palaeontology and sedimentology (Zittel, 1870; Centamore et al., 1971; Farinacci et al., 1981; Alvarez, 1989; Cecca et al., 1990; Santantonio, 1994; Romano et al., 2018, 2019a, 2019b, 2021; Cipriani et al., 2019; Citton et al., 2019, 2021).

The NW flank of Monte Nerone, deeply incised by the Candigliano river valley, exhibits a spectacular cut of the margin of this Jurassic PCP and of the overlapping pelagic succession, in particular at Gorgo a Cerbara, 3 km E of the town of Piobbico (Fig. 3a, e.g., Romano et al. 2019b), where a stratigraphic section has been measured (Fig. 1).

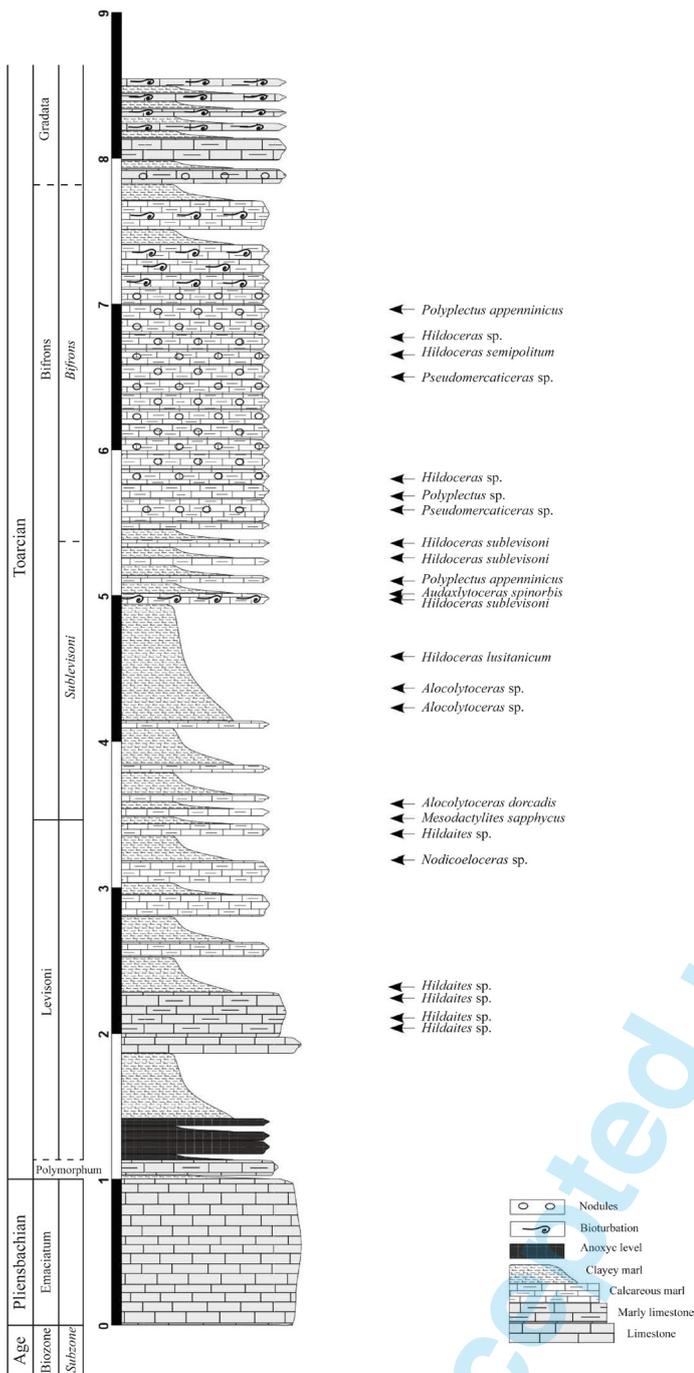


Fig. 9 - Stratigraphic log of the Eremo delle Carceri section.

**Gorgo a Cerbara Section**

The section is about 11.50 m thick (Fig. 13), from the uppermost portion of the Corniola to the lowermost portion of the Calcari e Marne a Posidonìa.

The first 60 cm are grey lime-mudstone ascribed to the Corniola; this interval yielded *Fucineras seli*, *Fucineras lavinianum*, *Fucineras portisi*, *Fucineras inclitum*, *Juraphyllites libertus* and *Protogrammoceras bonarelli*, which is a typical Pliensbachian assemblage.

Above, the passage to the Toarcian is abrupt, marked by a hardground (Fig. 7d), followed by 50 cm of marly limestones yielding near the base *Dactyloceras (Eodactylites) pseudocommune*.

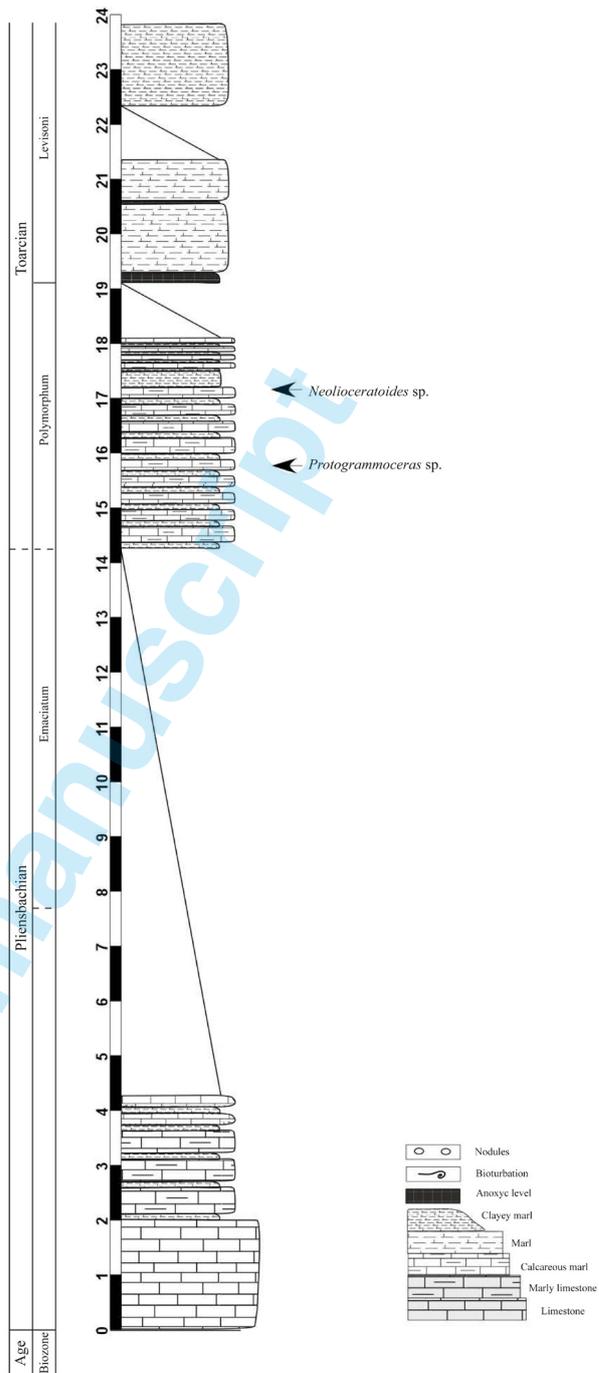


Fig. 10 - Stratigraphic log of the Cava Gabbiano section.

The following 1.30 m are made of red marly clays evolving in 1.20 m of nodular marls, in turn overlain by 75 cm of nodular calcareous marls. Such interval was ascribed to the Polymorphum and Levisoni Zones, due to the occurrence of *Hildaites* sp. e *Nodicoeloceras choffati*.

The following 1.75 m are characterized by calcareous marls, nodular clayey marls and nodular marls, bearing *Hildoceras lusitanicum*, *Hildoceras sublevisoni*, *Polyplectus pluricostatum*, *Hildoceras lombardicum* and *Harpoceras gr. mediterraneum*, indicating the Sublevisoni Subzone of the Bifrons Zone, followed by *Mesodactylites merlai*, *Mercaticeras tyrrhenicum*, *Mercaticeras mercati*, *Furloceras gr. cornucopia* and *Hildoceras*

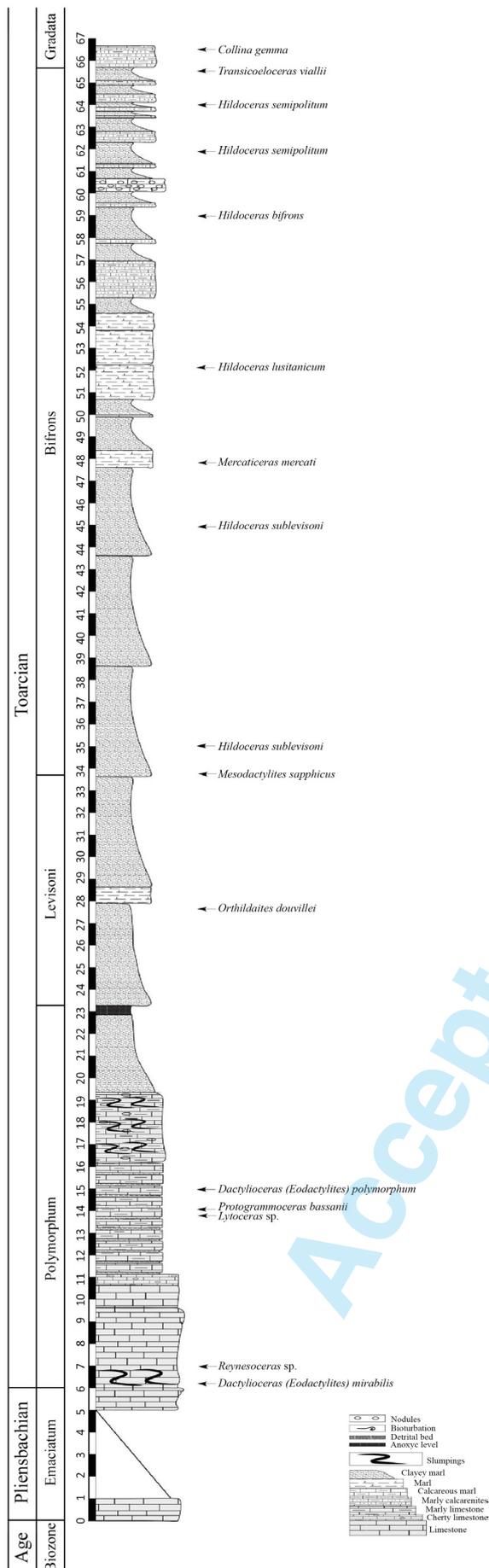


Fig. 11 - Stratigraphic log of the Monte Serrone section.

*semipolatum*, which characterize the Bifrons Subzone of the Bifrons Zone.

The following 2.30 m are red/whitish bioturbated calcareous marls/clayey marls intercalations. The lowermost portion yielded *Telodactylites eucosmus*, *Collina gemma* and *Furloceras armatum*, and is referable to the Gemma Subzone of the Gradata Zone while the middle portion yielded *Merlites gr. gradatum*, *Merlites alticarinata*, *Rarenodia* sp. and *Pseudogrammoceras subregale*, indicating the Alticarinata Subzone of the Gradata Zone, where also the Subregale biohorizon was detected. Finally, the uppermost portion of this interval yielded *Pseudogrammoceras mediterraneum*, *Mouterdiceras* sp., *Gecziceras* cf. *porcarellense* and *Cagliceras elaphus*, indicating the Bonarellii Zone.

The following 60 cm of marls yielded *Geczyceras* gr. *speciosum*, indicating the Speciosum Zone.

Upwards, a 10 cm thick calcareous bed pass to 40 cm of marly lime-mudstones and 60 cm of clayey marls/marly limestone intercalations, the base of this interval bears *Dumortieria meneghini*, marking the base of Meneghini Zone. Above, 60 cm of pale marly limestones contain *Catullocceras perroudi*, indicating the Aalensis Zone, the last of the Toarcian.

The last metre of the section is made of marly limestones/clayey marls/lime-mudstones, bearing *Temtoceras scissum*, *Erycites intermedius* and *Erycites fallifax*, indicating the Aalenian Opalinum Zone.

### Caloveto

The hills neighbor to the village of Caloveto (e.g., Mt. Brulline, Cozzo Cerasello, Cozzo di Mastro Pasquale), in the Sila Greca mountains (northern Calabria) represent the type locality of the Caloveto Group (Fig. 4a) (Santantonio, 2012; Santantonio & Fabbi, 2020). Here the Toarcian Upper Caloveto fm. occurs at the top of the Lower Caloveto fm., marking the drowning of the shallow water carbonate factory and the inception of pelagic sedimentation in the area (Fig. 14).

At Caloveto two stratigraphic sections have been made: the Cozzo di Mastro Pasquale section and the Brulline section (Figs. 1, 4a), which are very close each other, but record sedimentation in different geological settings (Fig. 14c).

### Cozzo di Mastro Pasquale section

The section is about 8 m thick (Fig. 15), and ranges from the Pliensbachian to the Aalenian; it begins with 1 m of shallow-water carbonates characterized by a packstone texture, with benthic forams, small ostreid bivalves, gastropods, crinoids and various coated grains, belonging to the Lower Caloveto fm. The top of this unit is a sharp erosional surface (Santantonio et al., 2016; Santantonio & Fabbi, 2020), characterized by a metallic crust (Fe-Mn) and the occurrence of abundant fossils, such as gastropods and ammonites (*Polyplectus* sp. – Fig. 14c) which indicate the top of the Pliensbachian.

Above this surface, the first bed of the Upper Caloveto fm. is a 10 cm-thick clayey/marly horizon, bearing whole echinoids and a specimen of *Harpoceras* cf. *mediterraneum*. This is followed by

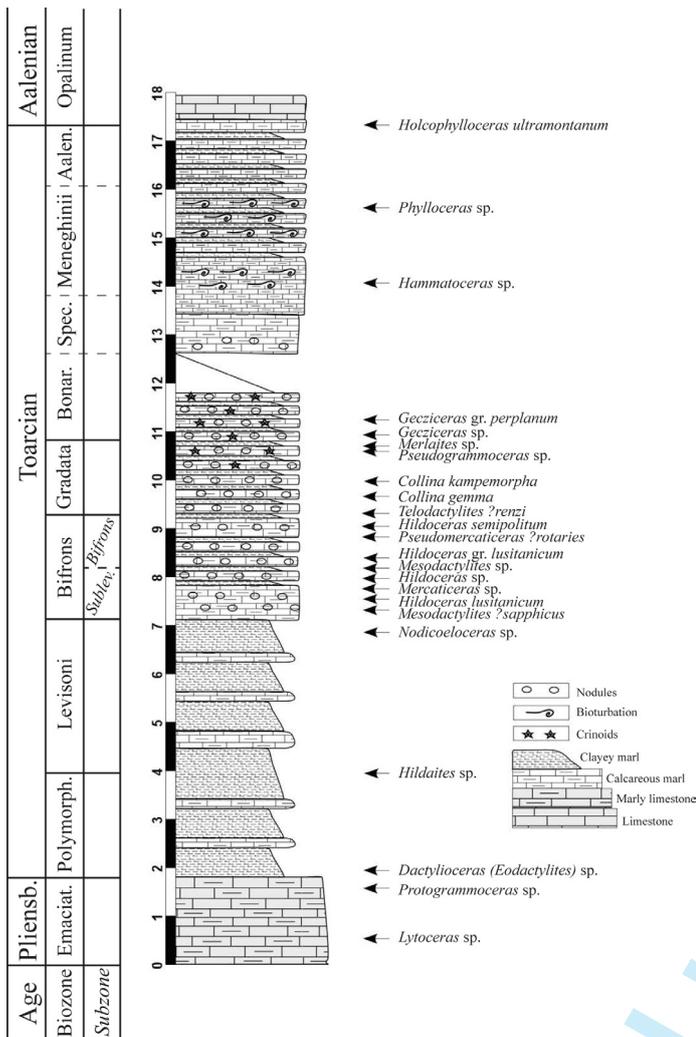


Fig. 12. Stratigraphic log of the Pettino section.

1 m of nodular red marly limestones with red clay intercalations, bearing *Hildoceras gr. bifrons* and *Lytoceras velifer*. This first interval is referred to the Bifrons Zone.

Above, 3 m of red marly limestones, partly nodular, occur, but they resulted almost barren, only yielding a specimen of *Calliphylloceras* sp.

On top of this interval, about 2.5 m of red marls have been sampled, belonging to the Zoophycos and Posidonia marls; these contain *Tmetoceras scissum* and *Erycites fallifax*, indicating the lower Aalenian Opalinum Zone, followed by 60 cm of marls containing *Planammatoceras planiforme*, indicating the Aalenian Murchisonae Zone.

**Brulline section**

The section has been measured at Carito saddle, just below the top of Mt. Brulline, and is about 9.60 m thick (Fig. 16).

It starts with 4 m of grey to pink bioclastic limestones, belonging to the Lower Caloveto fm. (Fig. 14c, d), containing abundant echinoid fragments, gastropods, bivalves, ammonoids and brachiopods. In the middle portion of this interval a distinctive brachiopod (terebratulids and rynchonellids) coquina occurs

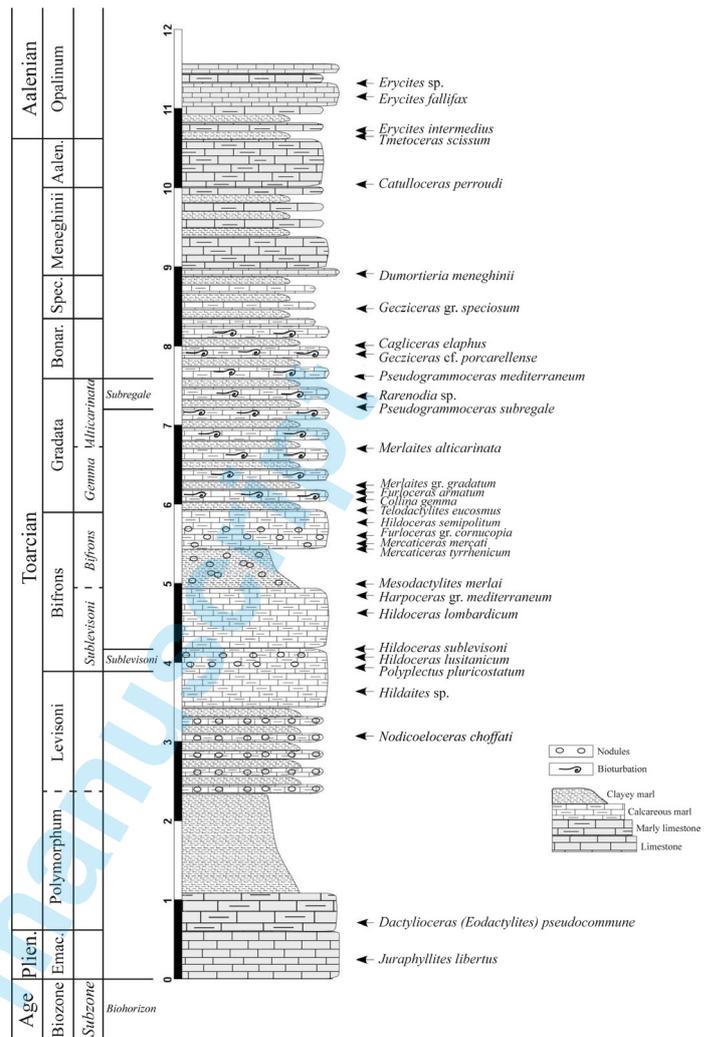


Fig. 13. Stratigraphic log of the Gorgo a Cerbara section.

(Fig. 14f), whereas the brachiopod content decrease up-section. The upper portion of this interval, characterized by a pink/red color, yielded *Protogrammoceras* sp. *Arietoceras* sp. indicating the uppermost Pliensbachian.

Following this interval, about 1.60 m of red marly limestones occur, with the lower portion which is essentially an encrinure, this yielded *Calliphylloceras* sp., *Lytoceras velifer* and a specimen of *Hildoceras gr. sublevisoni*, which marks the Bifrons Zone.

The following 4 m are composed of red marls belonging to the Zoophycos and Posidonia Marls, which resulted almost barren and yielded no ammonites (Fig. 14d).

**DISCUSSION**

The analysis of the studied outcrops has revealed a significant variation in lithofacies and thickness of coeval Toarcian successions (Fig. 17). In the Mediterranean region, Pliensbachian beds at the base of Toarcian successions are always represented by pelagites of the uppermost Corniola (Emaciatum Zone). In the Umbria-Marche Basin, they mainly consist of lime-mudstone with sponge spicules and radiolarians. However, the lithological characteristics of the

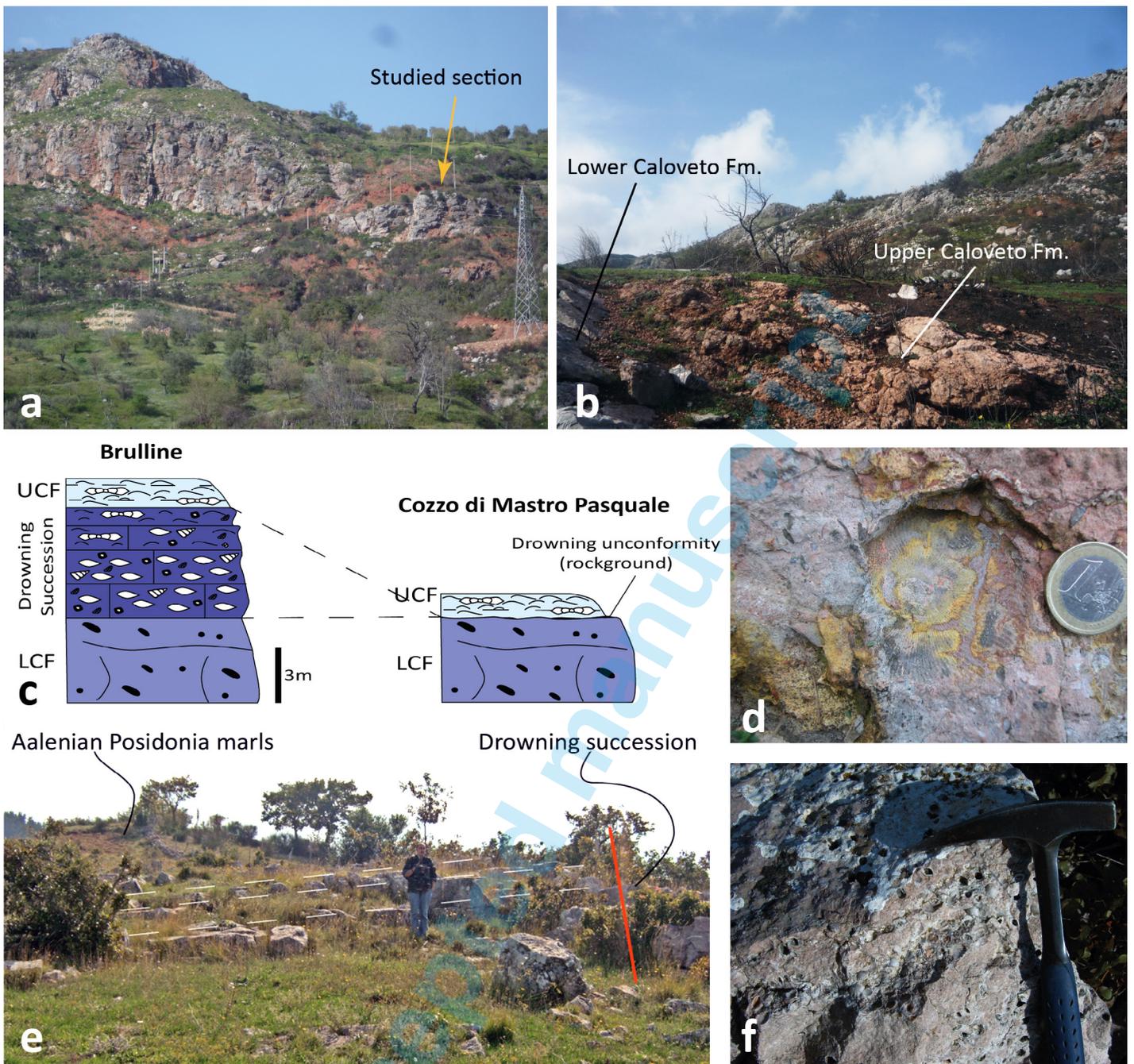


Fig. 14. a, b) Field views of the Cozzo di Mastro Pasquale locality; c) Difference between the Brulline and Cozzo di Mastro Pasquale geological settings (modified after Santantonio & Fabbi, 2020); d) *Polyplectus* sp. at the top of Upper Caloveto fm. at Cozzo di Mastro Pasquale; e) field view of the Brulline section (modified after Santantonio et al., 2016); f) brachiopod coquina marking the drowning unconformity in the Brulline section.

boundary with the overlying Toarcian units can vary significantly. In the “Eremo delle Carceri” section, the last beds of Corniola are in typical facies, and the topmost bed is a hard-ground, similar to the “Gorgo a Cerbara” section. In the Pettino section, the top of Pliensbachian is already in “Marne del Monte Serrone” facies, similar to the Cava Gabbiano and Monte Serrone sections. The marly lithology of the Emaciatum Zone (upper Pliensbachian) marks the beginning of terrigenous sedimentation, which will characterize the Toarcian, although it begins earlier in some areas. This opens a discussion on biostratigraphy versus lithostratigraphy. In fact, often disregarding the fundamental rules of lithostratigraphy (Germani & Angiolini, 2003), there is a tendency to classify formations based

on their fossil content, and therefore their age; However, by doing so, the Pliensbachian base of the Marne di Monte Serrone detected at Pettino (see above) should fall within the Corniola, which is commonly considered to reach the lowest Toarcian (e.g., Petti et al., 2007), as observed in the Mt. Serrone section (see below). In such contexts, adopting a purely lithostratigraphic approach proves more objective, highlighting the diachronous boundary between the Corniola and the overlying units.

With the beginning of the Toarcian (Polymorphum Zone), the clay component became predominant. Only in the Monte Serrone area, where the Polymorphum Zone reaches the maximum thickness (about 17 m), the sediments are still calcareous in the

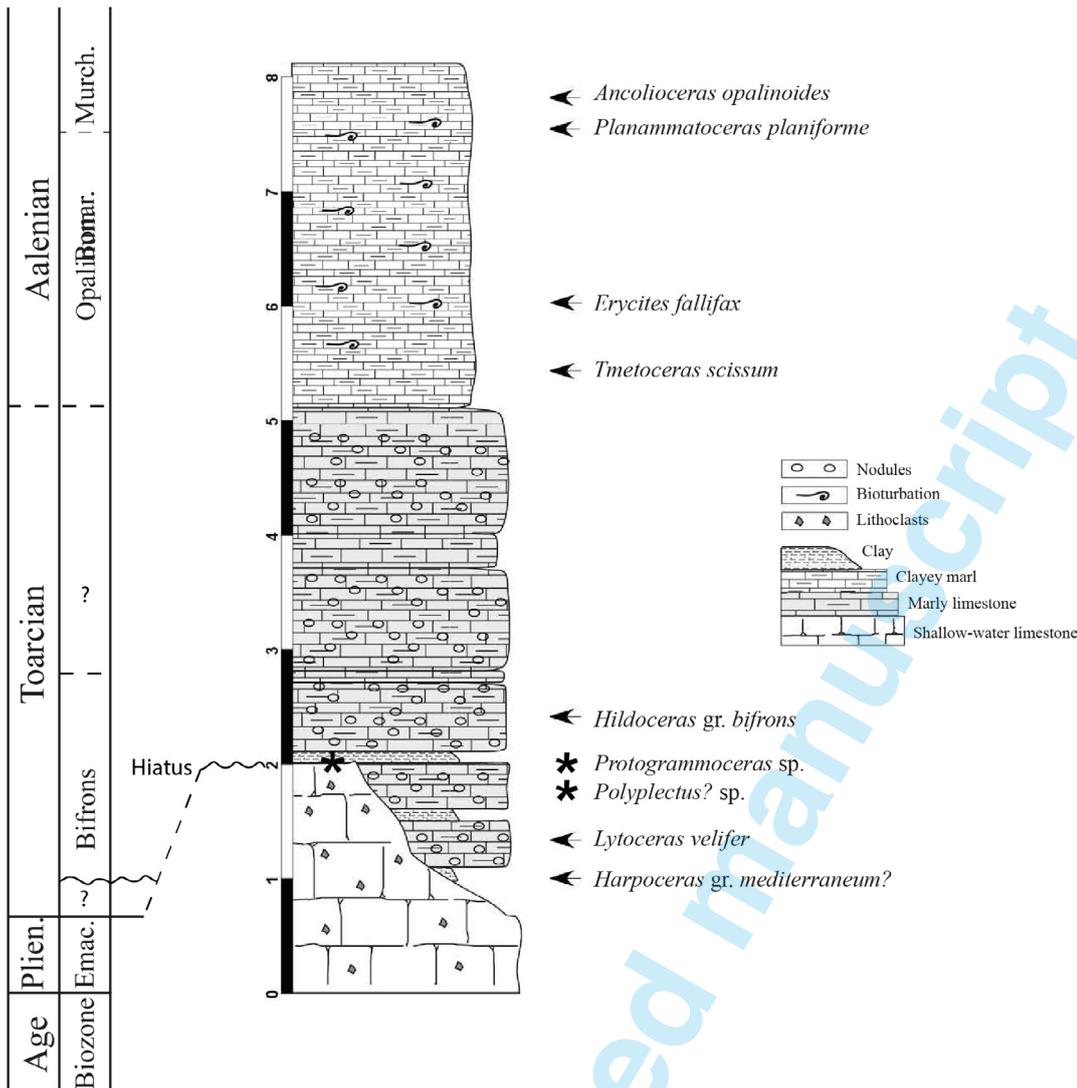


Fig. 15. Stratigraphic log of the Cozzo di Mastro Pasquale section.

basal portion. On the other hand, the smallest thickness is recorded in the Eremo delle Carceri section, where the Polymorphum Zone is only 13 cm thick and testifies the “I Lecceti” bio-event (Bilotta et al., 2010). Such a characteristic fauna was first described by Faraoni et al. (1994), who detected ammonite assemblages from the Mirabilis (= Polymorphum) and Serpentinus (=Levisoni) Zones in the “I Lecceti” locality, along the Bosso River Valley (SE of Mt. Nerone). The importance of this outcrop is given by the presence of very fossiliferous Marne di Monte Serrone facies at the base of the Rosso Ammonitico, while the coeval biozones are commonly not recorded or poorly fossiliferous elsewhere (Bilotta et al., 2010; Rodriguez-Tovar et al., 2016). In the other sections, the Polymorphum Zone shows homogeneous clayey/marly lithology with a thickness of 2 m.

In the Eremo delle Carceri, Cava Gabbiano, Pettino, and Monte Serrone sections, the T-OAE (Jenkyns, 1988; Bilotta et al., 2010; Rodriguez-Tovar et al., 2016) occurs as a black shale horizon located at the base of the Levisoni (Falciferum in Jenkyns, 1988) Zone. Regarding the stratigraphic position of the T-OAE, there was uncertainty in the literature, with some authors (Monaco et al.,

1994, Parisi et al., 1996, 1998; Parisi & Morettini, 1999) placing it in the Polymorphum Zone, while others (Jenkyns 1988; Hesselbo et al. 2000; Macchioni, 2002; Rodriguez-Tovar et al., 2016) locating the black shales in the Levisoni (Serpentinum) Zone. The T-OAE exhibits variable thickness, ranging from 40 cm (Mt. Serrone) to zero, but can always be recognized due to the significant faunal shift. Approximately 90% of the ammonite fauna become extinct during the T-OAE, a value higher than the 43% extinction rate recorded at the base of the Toarcian (Macchioni & Cecca 2002). Thus, the T-OAE represents an important turning point for ammonite differentiation, with the extinction of Protogrammoceratidae and Arietoceratidae, and the first appearance of Hammatoceratidae and Phymatoceratidae.

As previously mentioned, the T-OAE marks the base of the Levisoni Zone. In our sections, this biozone is observed within clayey lithologies, although an increase in the carbonate fraction can be observed towards the top in the Gorgo a Cerbara section. The thickness of the Levisoni Zone varies from 10 m (Mt. Serrone) to less than 2 m (Gorgo a Cerbara), while in the Cava Gabbiano section, only the base of the biozone has been observed.

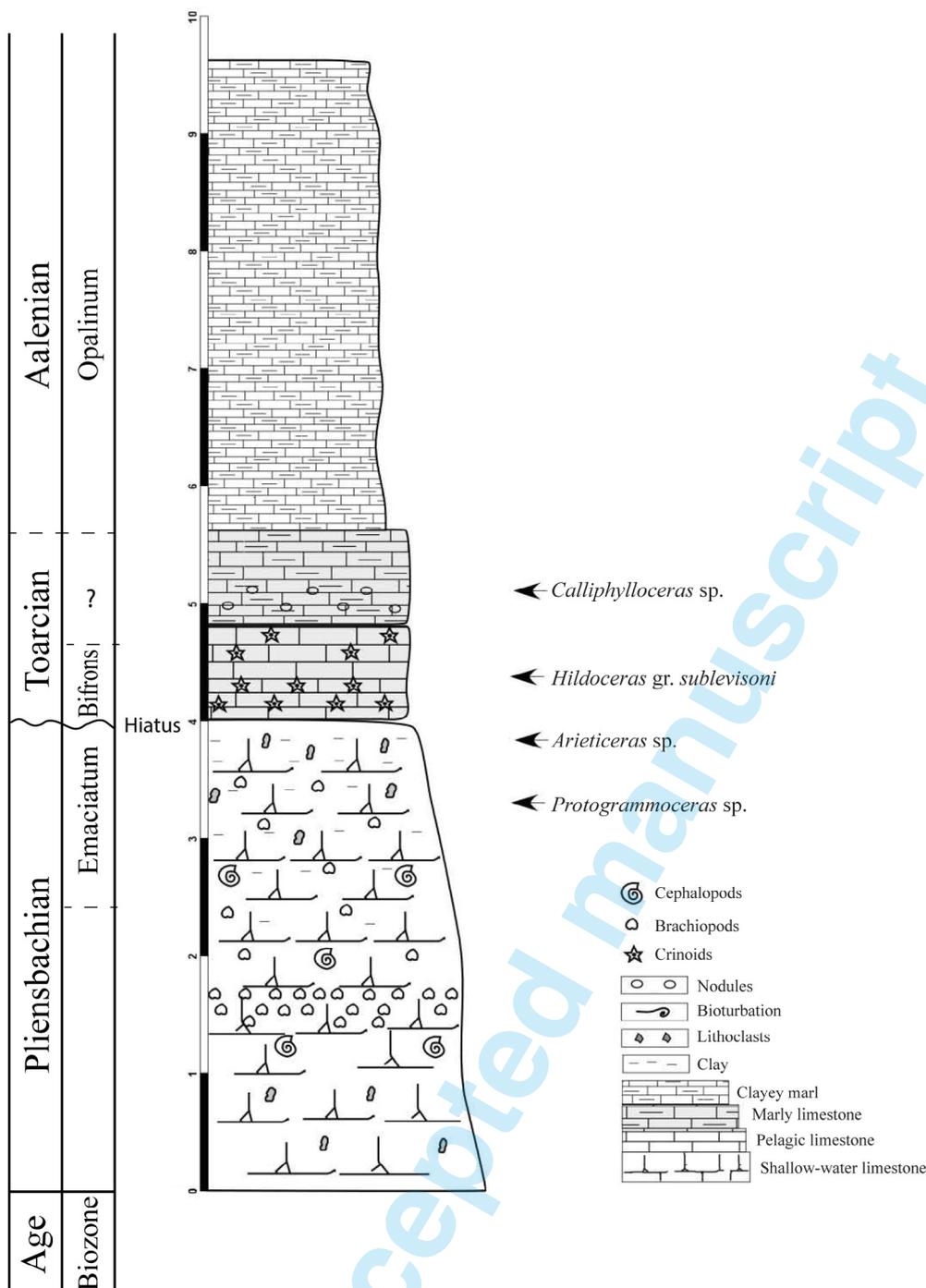


Fig. 16. Stratigraphic log of the Brulline section.

The Bifrons Zone is well documented in all the studied sections except for the Cava Gabbiano section, and has been chosen as the reference level for stratigraphic correlation (Fig. 17). This biozone is regionally characterized by a decrease in the clayey fraction in the Rosso Ammonitico facies, with beds showing a typical nodular marly appearance. Generally, the biozone thickness is between 2 and 4 m, but in the Monte Serrone section, it is characterized by alternations of calcarenite with marl and clay marl and reaches a thickness of about 32 m.

The sections which cover the entire Toarcian, up to the first Aalenian layers of the Opalinum Zone, are Pettino and Gorgo a Cerbara. In the Pettino section, it was possible to identify the Gradata Zone and the base of the Bonarellii Zone, while the Gorgo a

Cerbara section is the only complete section, allowing observation of the thickness of all the biozones from Gradata to Aalenis. The total measured thickness from the base of the Gradata Zone to the top of the Aalenis Zone is about 8 m at Pettino and about 4.5 m at Gorgo a Cerbara. In both sections, it is possible to observe an increase in  $\text{CaCO}_3$  content, as well as a significant increase in bioturbations.

Overall, the Monte Serrone section exhibits the thickest succession due to the development of greater accommodation space during the Toarcian. This led us to consider it the deepest portion of the investigated basin.

The successions of Gorgo a Cerbara and Pettino are thinner, with a total thickness of the Toarcian of 10 m and about 15 m,

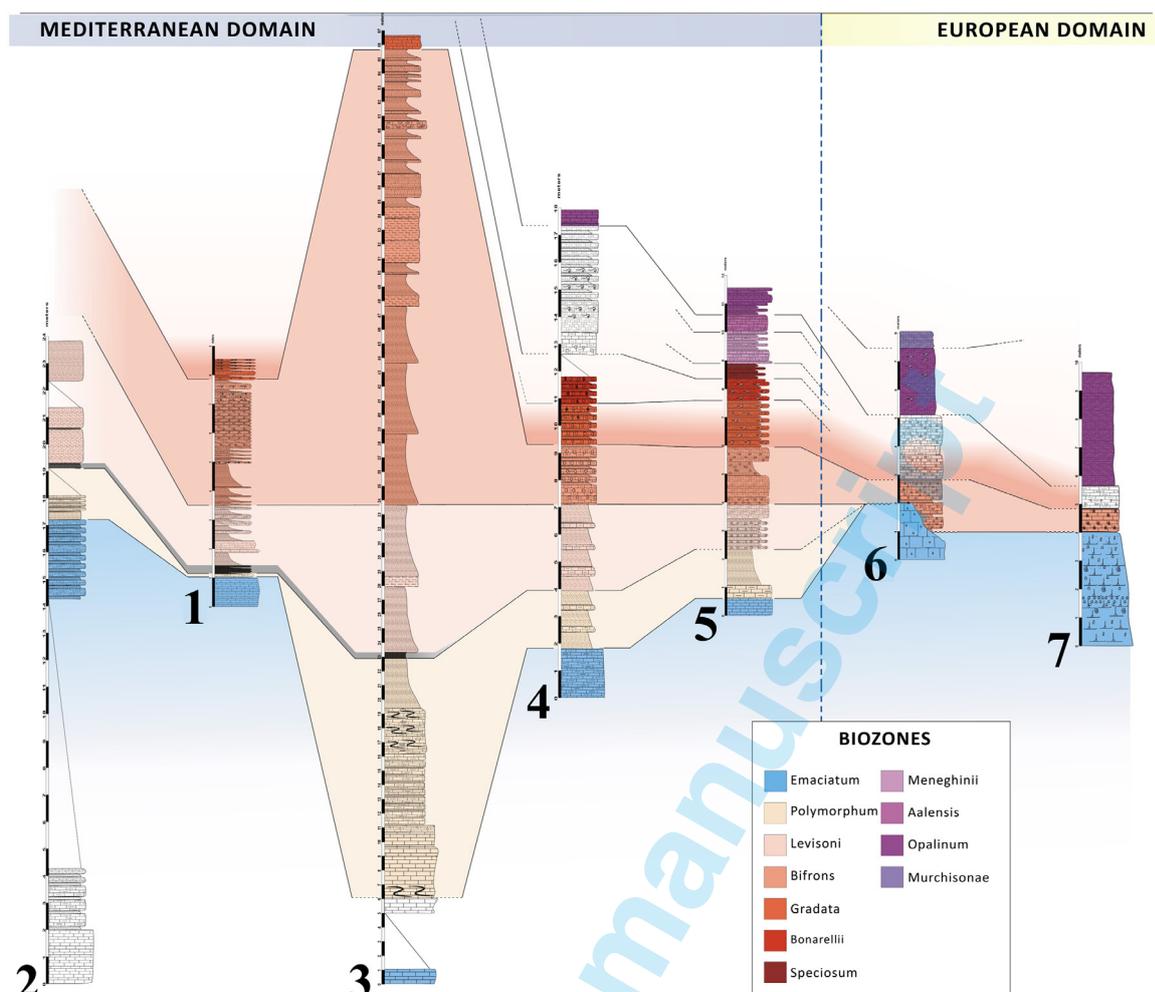


Fig. 17. Correlation panel of the studied sections. Numbers are the same of Figs. 3a and 4a: 1, Eremo delle Carceri; 2, Cava Gabbiano; 3, Monte Serrone; 4, Pettino; 5, Gorgo a Cerbara; 6, Cozzo di Mastro Pasquale; 7, Brulline.

respectively. This indicates a smaller accommodation space, which is due to the proximity of Jurassic structural highs. It is known that successions closer to structural highs are thinner than those farther away, partly because of differential compaction which produces different amounts of accommodation space (Carminati & Santantonio, 2005).

The “Eremo delle Carceri” and Cava Gabbiano sections are incomplete, but stratigraphic observations in neighboring outcrops suggest a total Toarcian thickness of about 20 m. They represent an intermediate setting, that is, a basinal setting in a distal position with respect to Jurassic structural highs, but with a moderate development of accommodation space if compared with the Mt. Serrone section. This is indicated by the dominant Rosso Ammonitico facies rather than the Marne di Monte Serrone facies.

The two sections belonging to the European Domain (Carito and Cozzo di Mastro Pasquale) have been correlated to the others through ammonite biozonation, which is fully comparable in the European and Tethyan (or Mediterranean) domains (Elmi et al., 1997; Gradstein et al., 2004).

It is worth noting that certain species of ammonites, such as *Hildoceras bifrons*, are typical of the European domain. This species is commonly used in the middle Toarcian of the Mediterranean

domain, although it is very rare, and similar taxa have to be referred to as “*Hildoceras gr. bifrons*” instead.

The base of both sections is referred to the uppermost Pliensbachian beds belonging to the Emaciatum Zone, which consists of bioclastic carbonates coming from a shallow-water carbonate setting and bearing abundant siliciclastic grains of the Lower Caloveto fm., disconformably resting on rugged metamorphic basement. At Brulline, the upper Pliensbachian is a drowning unconformity characterized by distinctive facies with a brachiopod coquina (Fig. 14f). The beginning of marly sedimentation in correspondence to the upper portion of the drowning unconformity, indicates the deepening of the sedimentary environment.

The Pliensbachian-Toarcian boundary in the Cozzo di Mastro Pasquale and Brulline sections is characterized by hiatuses corresponding to the Polymorphum and Serpentinum (Levisoni) Zones, although the second has been documented elsewhere in the Caloveto area (Santantonio & Fabbi, 2020). In both sections, the base of the Toarcian belongs to the Bifrons Zone. In the nearby Longobucco basin, however, several hundred meters of turbidites correspond to the Polymorphum and Serpentinum Zones.

The Bifrons Zone at “Cozzo di Mastro Pasquale” is made up of about 2 m of nodular marls, while at Brulline it consists of about 1

m of red marly limestones rich in crinoid fragments. Unfortunately, the successions of the Caloveto area were not particularly fossiliferous, and the base of the Gradata Zone was only inferred in both sections. It was impossible to detect the other Toarcian biozones. The Aalenian was documented by ammonites belonging to the Opalinum and Murchisonae Zones, but the base marked by the Opalinum/Aalensis Zones boundary was tentatively placed in correspondence with the lithological shift to red *Zoophycos* and *Posidonia* marls.

Assuming this boundary, a total Toarcian thickness of about 4 m has been inferred for the Cozzo di Mastro Pasquale section, and only 2 m for the Brulline section.

The Brulline section, considering the reduced thickness of the Toarcian sediments and the condensed pliensbachian facies characterized by benthic faunas (brachiopods, gastropods and crinoids) mixed with nectonic ones (cephalopods), can be referred as to the top of a morphostructural high, while the Cozzo di Mastro Pasquale section which has a double thickness of Toarcian sediments is referred to a deeper sedimentary environment (a lowered step – Santantonio & Fabbi, 2020).

## CONCLUSIONS

Based on the analysis of the stratigraphic sections, several conclusions can be drawn that help to improve our understanding of the geological history of the studied areas:

- 1) The Emaciatum Zone of the Apennines successions occurs within pelagic limestones or marly limestones/clayey alternations typical of the Marne of Monte Serrone. The Marne di Monte Serrone begins below the Polymorphum Zone, where the rate of accommodation space creation is higher, resulting in a slightly diachronous base. The Marne di Monte Serrone could be thus partly heteropic to the Corniola.
- 2) The Pliensbachian/Toarcian boundary (Emaciatum/Polymorphum Zone) in the Umbria-Marche area is characterized by continuity of sedimentation when it occurs in “Marne di Monte Serrone” facies. In contrast, an abrupt contact is observed where the boundary occurs between the Corniola and Rosso Ammonitico. This abrupt contact suggests a possible hiatus at the boundary, occasionally marked by a hardground.
- 3) In the Basal Toarcian (Polymorphum Zone), the Marne di Monte Serrone is heteropic to the first lithofacies of the Rosso Ammonitico.
- 4) The thickness of the T-OAE, identified at the base of the Levisoni Zone, is variable and sometimes not directly observable. However, the distinctive faunal change that corresponds to this horizon allows its detection.
- 5) The end of the Bifrons Zone is marked in all the analyzed sections by a facies change, characterized by a greater CaCO<sub>3</sub> content.
- 6) The Bifrons Zone is usually found within nodular marly facies, with the only exception of the Monte Serrone section where the middle Toarcian consists of calcarenites/marls alternations.
- 7) The Pliensbachian (Emaciatum Zone) of the Caloveto area is characterized by platform limestones and is completely different from the Umbria-Marche successions, characterized by pelagic limestones and clayey marls. Despite this facies difference, the two areas yielded fully correlable faunas.
- 8) The Pliensbachian-Toarcian passage at Caloveto records a hiatus corresponding at least to the Polymorphum Zone. The Serpentinum Zone has not been detected in the present study but documented in literature.

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