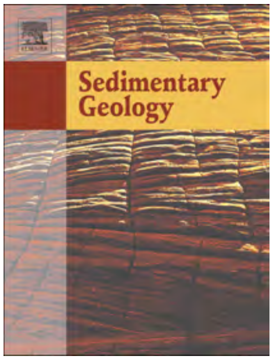

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Early Cretaceous tectonic rejuvenation of an Early Jurassic margin in the Central Apennines: the "Mt. Cosce Breccia"

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Abstract

Evidence for an extension-dominated tectonic phase in the late Early Cretaceous has been identified for the first time at Mt. Cosce in the Narni Ridge (60km N of Rome, Central Apennines) as a result of geological mapping. There, the Umbria-Marche-Sabina pelagic succession overlies shallow-water carbonates (Calcare Massiccio Formation, Hettangian). The Mt. Cosce area represents a Jurassic pelagic carbonate platform-basin system, the inheritance of Early Jurassic Tethyan rifting, hosting a remarkable stratigraphic unit named the "Mt. Cosce Breccia". This is a sedimentary breccia, bearing clasts of Calcare Massiccio and of pelagic units and forming sparse to laterally continuous outcrops, which rests unconformably on the horst-block Calcare Massiccio. The polygenic breccia is chaotic and displays heterometric clasts made of rocks not younger than the Early Cretaceous, white pebbly mudstones with radiolarian- and calpionellid-rich (Maiolica Formation) elements and a Maiolica-type matrix. The lithoclasts were clearly sourced locally and represent formations from the Calcare Massiccio to the Jurassic basinal and condensed pelagic carbonate platform units. The age of the polygenic breccias is assigned to the "middle" Barremian due to the youngest age detected within the clasts, the occurrence of *Hedbergella* cf. *H. luterbacheri* in the matrix, and calcareous nannofossils. The unconformity and breccia indicate an episode of exhumation of an original Jurassic paleoescarpment tract that had by then been buried by the lower part of the Maiolica Formation. The clasts were sourced from the exhumed vestiges of the Jurassic onlap wedge (hangingwall-basin succession), the peritidal pre-rift substrate and its condensed drape (pelagic carbonate platform-type deposits), as a product of escarpment rejuvenation, erosion, and displacement along an Early Cretaceous fault.

Keywords: Synsedimentary tectonics; Cretaceous faults; pelagic carbonate platform-basin system; limestone breccias; Narni-Amelia Ridge, Umbria-Marche-Sabina Succession.

1. Introduction

Deep-water carbonate breccias are the result of gravity-driven sedimentation, which can be triggered by an array of processes, ranging from changing sea-level to tectonic activity. Limestone breccias are typically found at the toe of productive carbonate platforms as well as of drowned platforms, in aseismic to tectonically active settings, and are the common products of collapse of steep submarine margins (Flügel, 2010). Spence and Tucker (1997) have also described calciclastics produced along low-angle slopes of productive carbonate platforms and ramps, triggered by pore-water overpressure related to high sedimentation rates, sea-water oscillations, compaction and seismicity. Examples of calciclastics put in relation with eustatic change within a sequence stratigraphic framework are reported in a number of studies, including Spence and Tucker (1997), Bice et al. (2007), Basilone (2009a), Rusciadelli et al. (2009) and Reijmer et al. (2015).

Spectacular examples of syn-tectonic limestone breccias have been reported from the Lower Jurassic of Western Tethys. Rift-related normal faults dismembered a super-regional Bahamian-type carbonate platform and led to a differentiation into fault-bounded shallow- and deep-water paleogeographic domains (see Santantonio and Carminati, 2011 for further details). Gravitational collapses could affect the faulted margins of both productive carbonate platforms and intrabasinal structural highs (often drowned platforms). Rock-fall and rock-avalanching were the main processes involved, causing the accumulation of exotic blocks and megabreccias at the toes of the steep escarpments (e.g., Flügel, 2010). Carbonate breccias related to the Early Jurassic rifting, made of shallow water limestones embedded within basinal pelagites, are documented from the Southern Alps (e.g., Bernoulli and Jenkyns, 1974; Eberli, 1987), the Apennines (e.g., Cantelli et al., 1978; Bice and Stewart, 1990), the buried margins of the Apulia Platform (Santantonio et al., 2013), the Sicilian fold-and-thrust belt (e.g., Di Stefano et al., 1996; Santantonio, 2002; Basilone, 2009b), the Tunisian (e.g., Tlig et al., 2013), Algerian (e.g., Marok and Reolid, 2012) and Moroccan (e.g., Merino-Tomé et al., 2012) Atlas Mountains, the Rif Cordillera (e.g., Vitale et al., 2014), the Betic

Cordillera (e.g., Ruiz-Ortiz et al., 2004), the Carpathians (e.g., Aubrecht and Szulc, 2006) and the Hellenides (e.g., Bernoulli and Renz, 1970). Syn-rift clastic gravity flows made of limestone, phyllite and granite blocks have also been described from the southern margin of the European plate (i.e. Calabria - Innamorati and Santantonio, 2018). Breccia deposits can also be found embedded in post-rift pelagic successions, Middle-Late Jurassic (e.g., Galdenzi, 1986; Basilone et al., 2014; Cipriani et al., 2016; Paparella et al., 2017), Early Cretaceous (e.g., Pierantoni et al., 2013; Basilone et al., 2016; Cipriani, 2016; Fabbi et al., 2016, and references therein) and Late Cretaceous (e.g., Capotorti et al., 1997; Marchegiani et al., 1999) in age, of the Umbria-Marche-Sabina Domain and of the Lombardy Basin (Castellarin, 1972, 1982) and are related to local post-rift synsedimentary extension.

While the occurrence of breccias with clasts composed of the pre-rift shallow-water limestone in Jurassic basin-fill successions is clearly related to the existence of pronounced submarine relief between footwall- and hangingwall-blocks, the Lower Cretaceous occurrences are puzzling, as the regional rift topography was levelled with the deposition of the Maiolica Formation (Tithonian *p.p.*-early Aptian) (Centamore et al., 1971; Farinacci et al., 1981; Santantonio, 1993). The presence of megaclasts of Calcare Massiccio within the uppermost Maiolica, paired with the existence of paleoescarpment tracts onlapped by uppermost Lower Cretaceous deposits is therefore an anomaly which requires an explanation. Regional geologists have long associated the deposition of Maiolica facies in the Umbria-Marche-Sabina Domain with a phase of thermal subsidence and tectonic quiescence. However, there is growing evidence supporting a super-regional phase of post-rift extension during the late Early Cretaceous (e.g., Castellarin, 1972, 1982; Graziano, 2000; Casabianca et al., 2002; Cipriani and Santantonio, 2014, 2016; Menichetti, 2016).

Spectacular evidence for Early Cretaceous synsedimentary tectonics was identified for the first time in the Mt. Cosce Ridge (Narni-Amelia Mountains, Central Italy) as a result of detailed geological mapping performed at 1:10,000 scale (Fig. 1). The “Mt. Cosce Breccia” represents the most notable feature of the study area and is the indirect evidence for Early Cretaceous normal faulting, along with ancillary evidence like neptunian dykes and soft-sediment deformation. The aims of this work are: (i) to describe the sedimentological characters of the “Mt. Cosce Breccia”, (ii) to assess its age on the basis of calcareous nannofossil biostratigraphy, in order to constrain the timing of tectonic event and (iii) to understand the role played by inherited Jurassic structures on the development and the geometries of the Early Cretaceous extension-dominated faults, in a region where Neogene orogenic and post-orogenic deformations have been severe.

2. Geological Setting

The Narni-Amelia Ridge represents the most internal structural unit of the central Apennine fold-and-thrust belt. The *circa* NW-SE-trending chain is characterized by calcareous/cherty/marly and siliciclastic rocks, Triassic-to-Neogene in age, of the well-known Umbria-Marche-Sabina sedimentary succession (e.g., Colacicchi et al., 1970; Galluzzo and Santantonio, 2002; Bollati et al., 2012). Mio-Pliocene orogenic and Plio-Pleistocene post-orogenic deformations caused uplift and shortening, followed by extension and exhumation of the Meso-Cenozoic succession (e.g., Doglioni, 1991; Pierantoni et al., 2013), which is then unconformably covered by Plio-Pleistocene marine-to-continental and volcanoclastic deposits.

2.1 Jurassic paleotectonic evolution of the Umbria-Marche-Sabina Domain

The stratigraphic and structural evolution of the Umbria-Marche-Sabina paleogeographic Domain was controlled by the Early Jurassic rift-related extension affecting the western and northern Tethys during the Early Jurassic (e.g., Bernoulli and Jenkyns, 1974; Santantonio and Carminati, 2011; Schettino and Turco, 2011). This rifting phase dismembered a wide carbonate platform (Calcare Massiccio carbonate platform) into fault blocks and caused the switch from a shallow-marine environment to an array of open marine environments. Benthic factories on the hangingwall blocks drowned at the Hettangian/Sinemurian boundary (Passeri and Venturi, 2005) due to tectonic subsidence (Marino and Santantonio, 2010), while on the morphostructural highs they survived until the early Pliensbachian (Morettini et al., 2002). Paleoceanographic and paleoecological perturbations rather than tectonic subsidence caused the drowning of the horst-blocks (Morettini et al., 2002; Marino and Santantonio, 2010), which postdated the acme of extension. After the early Pliensbachian the whole Umbria-Marche-Sabina Domain found itself in fully pelagic conditions when the post-rift phase started, and the structural highs became pelagic carbonate platforms *sensu* Santantonio (1994). According to Santantonio (1994, p. 122), pelagic carbonate platforms are "intrabasinal highs on continental crust, bordered by synsedimentary faults and […] sites of condensed and discontinuous pelagic carbonate sedimentation over drowned fragments of a former peritidal carbonate platform".

A complex pattern of pelagic carbonate platforms surrounded by deeper basins is recorded by facies and thickness variations of Jurassic to Lower Cretaceous pelagic deposits. The pre-rift Calcare Massiccio Formation was exposed along the submarine rift-fault scarps, which were by then inactive (paleoescarpments), and was onlapped by hundreds of meters of basin-fill pelagites and interbedded turbidites (Santantonio et al., 1996; Carminati and Santantonio, 2005), while the tops of pelagic carbonate platforms were the sites of deposition of thin, condensed and cephalopod-rich (locally also bearing a vertebrate fauna – Citton et al., 2019; Romano et al., 2019) successions (Bugarone Group – Galluzzo and Santantonio, 2002). This complex rift architecture was blanketed by the deposition of the Maiolica facies, although this work documents an exception to this "rule" (see also Fabbi et al., 2016), so that younger stratigraphic units display remarkable lateral continuity and facies homogeneity throughout the paleogeographic domain until the Neogene.

2.2. Lithostratigraphy of the Mt. Cosce Ridge

The stratigraphy of the whole Narni-Amelia Ridge is briefly described below (see Cipriani, 2016, 2017; for further details) (Fig. 2).

a) Calcare Massiccio Formation (Hettangian): more than 600 m of shallow-water peritidal, thick to faintly bedded limestones. The main textures are: bioclastic and peloidal grainstones, oncolitic rudstones, coral framestones (extremely rare in the whole Umbria-Marche-Sabina Domain), fenestral mudstones associated with cyanoalgal laminites and reddish levels due to emersion phases (Cipriani, 2016).

b) Corniola Formation (Sinemurian-Pliensbachian): up to 400 m of thin-bedded pelagic cherty limestones. The typical microfacies of the Corniola Formation include mudstones and wackestones bearing sponge spicules, crinoids and radiolarians, while floatstones with ammonites and brachiopods are less common. Peloidal-oncoidal grainstones and packstones change upwards to the fine-grained pelagites. These grainy intervals are interpreted as gravity flow (deposits prevailingly turbidity flows), and they characterize the lower two thirds of this unit (Cecca et al., 1990).

c) Rosso Ammonitico Formation (Toarcian): up to 30 m of red marls and nodular limestones, burrowed and rich in ammonites. Texturally these are ammonitiferous floatstones and mudstones/wackestones, with thin-shelled bivalves and radiolarians.

d) "Calcari e Marne a *Posidonia*" Formation (*sensu* Galluzzo and Santantonio, 2002) (Aalenian-late Bajocian): about 50 m of well-bedded limestones and cherty limestones; the lower part of the unit is largely made of marly limestones. Mudstones to packstones with thin-shelled bivalves and radiolarians are the main lithofacies, but locally ammonitiferous floatstones also occur.

e) "Calcari Diasprigni" Formation (*sensu* Galluzzo and Santantonio, 2002) (late Bajocian/Bathonian-early Kimmeridgian): from 0 to 60 m of thinly-bedded, greenish cherts and cherty limestones. Radiolarian wackestones/packstones are the most characteristic microfacies.

f) "Calcari ad aptici e *Saccocoma*" Formation (*sensu* Galluzzo and Santantonio, 2002) (late Kimmeridgian-early Tithonian): up to 30 m of pale, thin to well-bedded limestones and cherty limestones. Reddish, nodular and cephalopod-rich facies with hardgrounds and ferruginous crusts occur in proximity of pelagic carbonate platform margins. The crinoid genus *Saccocoma* characterizes this unit, the dominant microfacies being crinoidal mudstones to packstones, locally turbiditic.

g) Maiolica Formation (late Tithonian-early Aptian): up to 80 m of well-bedded, white cherty limestones. Mudstones and wackestones with radiolarians (and calpionellids in the lower part of the unit) represent the main microfacies. Slumps and clastic deposits ("Mt. Cosce Breccia" – see below) are found in the uppermost part the unit.

h) Marne a Fucoidi Formation (early Aptian-Albian): about 25 m of dark marls and interbedded whitish-gray, thin-bedded mudstones and wackestones rich in planktonic foraminifers and radiolarians. Foraminifer-rich grainstone to packstone beds, grading upward to burrowed wackestones, are interpreted as calciturbidites (Flügel, 2010). Pebbly mudstones with clasts of the Maiolica Formation embedded in laminated marls rich in planktonic foraminifers also occur locally.

2.3. The Mt. Cosce Jurassic pelagic carbonate platform-basin system

Mt. Cosce represents the southernmost tip of the Narni-Amelia Ridge and was a Jurassic pelagic carbonate platform, surrounded to the West and North (in present-day coordinates) by deeper water basins (Cipriani, 2016). The pelagic carbonate platform-top condensed succession is not preserved due to modern erosion, while NNW- and WSW-facing Jurassic paleoescarpments are well exposed. These are unconformity surfaces, being the sites of onlap of the Lower Jurassic basin-fill units (Corniola Formation, Sinemurian-earliest Toarcian) on the horst-block Calcare Massiccio. The occurrence of chert nodules and crusts in the Calcare Massiccio, an otherwise chert-free lithostratigraphic unit (silicification of the Calcare Massiccio *sensu* Santantonio et al., 1996), is a distinctive marker of such stratigraphic relationships. Interposed between the onlapping pelagites of the Corniola Formation and the horst-block Calcare Massiccio, limited patches (few square meters) of Sinemurian-Pliensbachian condensed pelagites (Bugarone Group), forming epi-escarpment deposits are locally found. This is also a typical feature of preserved paleoescarpment tracts (Galluzzo and Santantonio, 1994, 2002; Santantonio et al., 1996; Carminati and Santantonio, 2005).

Megaclasts of Calcare Massiccio and megabreccias characterize the onlap belt of the Corniola Formation, being the product of episodic collapse of the Jurassic escarpments. While the syn-rift and early post-rift (Sinemurian and Pliensbachian) basinal deposits of the Corniola Formation are rich in calciclastics, the Toarcian to Lower Cretaceous pelagic succession surrounding the Mt. Cosce pelagic carbonate platform is essentially resediment-free.

3. Materials and methods

Geological mapping was performed on a 1:10,000 scale (locally 1:5,000). Four stratigraphic sections (for a total of 85 m – Fig. 3) were measured at a cm-scale and 35 samples, representative of all the lithofacies of the limestone breccia, were collected for laboratory analysis. Microfacies description of the "Mt. Cosce Breccia" was performed on 20 thin sections using an Olympus CH-2 binocular microscope in the Micropaleontology Laboratory of Earth Sciences Department, "Sapienza" University of Rome. Dunham (1962) and Embry and Klovan (1971) classifications for carbonate rocks were used for the microfacies classification. Reference to the papers by Centamore et al. (1971), Cecca et al. (1990) and Chiocchini et al. (1994, 2008) for the Jurassic biostratigraphy, and to the papers by Coccioni et al. (1992, 2007), Erba et al. (1999) and Lakova and Petrova (2013) for the Cretaceous, was essential.

Calcareous nannofossils were investigated in three samples of the matrix of the "Mt. Cosce Breccia" and in four samples of Maiolica-type facies interbedded in the "Mt. Cosce Breccia". For each sample a simple smear slide was prepared by reducing a few grams of rock into a fine powder, suspended with distilled water and then smeared on the slide. The cover slide was fixed with the Norland Optical Adhesive.

Calcareous nannofossils were semi-quantitatively estimated by examining at least 200 fields of view of the smear slide under polarizing light microscope (cross polarized, transmitted light and quartz lamina) at 1250x magnification. The assemblages were typified for abundance and preservation. Total abundance was coded as: C: common, 10-20 specimens per field of view. F: few, 5-10 specimens per field of view. R: rare, 1 specimen per field of view. VR: very rare, less than 1 specimen per field of view. Abundance of individual taxa was coded as: C: common, 1 specimen in 1-10 fields of view. F: few, 1 specimen in 11-30 fields of view. R: rare, 1 specimen in > 30 fields of view. Preservation was coded as: M: moderate = little evidence of dissolution and/or overgrowth is present, primary morphological characteristics are sometimes altered. MP: moderate/poor = evidence of dissolution and/or overgrowth is present, primary morphological characteristics are sometimes altered, fragmentation has occurred. P: poor = most specimens exhibit dissolution or overgrowth, primary morphological characteristics are sometimes destroyed, fragmentation has occurred.

4. Results

4.1. Field evidence of the “Mt. Cosce Breccia”

The "Mt. Cosce Breccia" represents a unique feature of the study area. It forms sparse to laterally continuous outcrops along a *circa* N-S belt on the homonymous hill, for a total length of 3 km, while the original areal extension cannot be estimated due to dissection by Pliocene normal faults. The best outcrops are found in the Mt. Cosce-Cima Testone area, in the Pianastrina-Le Cese localities (Cima Boschetto area) and at Mt. Il Pago (1 km East of Vacone) (see Fig. 1). The "Mt. Cosce Breccia" rests unconformably, through an erosional surface (interpreted as a Cretaceous paleoescarpment – Cipriani & Bottini, 2018), on the Jurassic horst-block Calcare Massiccio and locally on the basinal Corniola Formation onlapping the Mt. Cosce pelagic carbonate platform (Fig. 4A-E). The bedrock presents cm- to m-scale fractures filled by “Mt. Cosce Breccia” and Maiolica-type deposits. These neptunian dykes cross-cut at various angles the master-bedding of the underlying units and, locally, cut across former Pliensbachian neptunian dykes. The relationships with the younger deposits, by contrast, cannot be appreciated due to modern erosion. As a consequence, the total thickness of the “Mt. Cosce Breccia” cannot be evaluated, but the maximum thickness identified in outcrop is about 40 m in the Cima Boschetto area.

The "Mt. Cosce Breccia" is a polygenic, chaotic, coarse-grained, pure carbonate breccia. While it overall constitutes a massive body, concave-upward erosional surfaces separate distinct mass-flow intervals forming meter-thick lenses up to tens of meters across. The lowermost levels of the “Mt. Cosce Breccia” show a clast-supported facies dominated by huge blocks (up to 5 m in diameter – Fig. 5A), while in the upper portions a gradual transition from matrix-poor to matrix-rich breccias can be observed (Fig. 5B-D). In the clast-dominated deposits the matrix is made of fine-grained debris dispersed in micrite, while for mud-supported facies the groundmass is a pure pelagic micrite. Locally, thinly-bedded Maiolica-type pelagites are interfingered with the matrix-supported deposits (Fig. 5E).

4.2. Petrographic composition of the “Mt. Cosce Breccia”

Texturally, the “Mt. Cosce Breccia” is a lithoclastic rudstone to floatstone, less commonly a wackestone to grainstone. The clasts are angular to sub-rounded, poorly-sorted and heterometric (millimetric to metric in diameter). In clast-supported facies, the fragments exhibit sutured contacts as a result of pressure-solution, forming a tightly packed breccia (polymictic stylobreccia *sensu* Flügel, 2010) (Fig. 6A-F). In mud-supported facies, rounded pebbles and cobbles floating in the matrix are abundant (Fig. 7A-F). Due to their pelagic mudstone nature, with no evidence whatsoever of any early lithification, rounded clasts are interpreted as being a product of their soft plastic state, rather than of physical abrasion. Thin oxide coats are locally observed at the periphery of the grains. Clasts display no apparent preferential orientation nor grading. This must be related to their almost null transport.

4.2.1. Clasts (Figs. 5, 6, 7)

As the micro-stratigraphical analysis of the clasts was one of the criteria for deriving their source and for constraining the minimum age and timing of emplacement of the breccia, the coarser facies of the "M. Cosce Breccia" were sampled for microfacies analysis. The main facies recognized in thin-section and in the field are:

a) white peloidal/oolithic/oncoidal grainstones to rudstones, locally with benthic foraminifers (valvulinids, textularids), algae (*Cayeuxia* sp.) and microproblematica (*Thaumatoporella parvovesiculifera; Lithocodium* sp.) (Calcare Massiccio Formation);
b) white peloidal grainstones with bird's eyes (Calcare Massiccio Formation);
c) microbial bindstones and mudstones with fenestral fabric (Calcare Massiccio Formation);
d) pale grey peloidal wackestones/packstones with micro-oncoids and undeterminable bioclastic debris, associated with siliceous sponge spicules, radiolarians and crinoids (Corniola Formation);
e) grey-brown mudstones to wackestones with radiolarians, siliceous sponge spicules, benthic foraminifers, brachiopods and crinoids (Corniola Formation);
f) reddish floatstones with thin-shelled bivalves of the genus *Diotis* sp., benthic foraminifers and siliceous sponge spicules. These lithofacies are typical of the upper Carixian deposits in the Umbria-Marche-Sabina Apennines (Monari, 1994) (Corniola Formation);
g) red and greenish mudstones and wackestones, marly in places, with thin-shelled bivalves (*Bositra buchii*), radiolarians and ammonite embryos (Rosso Ammonitico and "Calcari e Marne a *Posidonia*" Formations);
h) green, red, violet and dark chert made of radiolarian-rich wackestones to packstones ("Calcari Diasprigni" Formation);

i) pale green to yellowish bioclastic wackestones and packstones with fragments of *Saccocoma* sp., aptychi, ammonite embryos and radiolarians ("Calcari ad aptici e *Saccocoma*" Formation);

j) orange to hazelnut floatstones with ammonites (*Fuciniceras* sp., *Protogrammoceras* sp.), sponge spicules, brachiopods and crinoids. Locally, these deposits are thoroughly silicified including the ammonites, with chert in their phragmocones. These facies match the description of the condensed deposits of the Corniola-equivalent Formation (*sensu* Galluzzo and Santantonio, 2002 - Bugarone Group) (Pliensbachian *p.p.*), described in the pelagic carbonate platform condensed succession of the Sabina Plateau and exposed in the neighbouring Sabini Mountains (about 5 km to the east of the study area). The phenomenon of silicification of the ammonite shells suggests a pelagic carbonate platform-margin setting, where condensed epi-escarpment deposits were onlapped by cherty basinal units;

k) orange brachiopod coquina, with terebratulids and rhynchonellids, associated with sponge spicules and crinoid fragments (bioclastic floatstones). Cannata (2007) describes comparable deposits from the neighbouring Martani Mountains in the Corniola-equivalent Formation (*sensu* Galluzzo and Santantonio, 2002 - Bugarone Group) (Pliensbachian *p.p.*);

l) Hazelnut/orange bioclastic floatstones with ammonites (cm to dm in diameter), aptychi (*Laevaptychus* sp.), *Saccocoma* sp. and radiolarians. These facies are characteristic of the Bugarone superiore Formation (*sensu* Galluzzo and Santantonio, 2002 - Bugarone Group) (late Kimmeridgian-Tithonian *p.p.*), and are typical of pelagic carbonate platform-top successions, as well as of paleoescarpment settings (epi-escarpment deposits);

m) whitish mudstones and wackestones rich in calpionellids, radiolarians and *Saccocoma* sp. (Bugarone superiore/Maiolica Formations boundary - latest Tithonian);

n) white mudstones and wackestones rich in calpionellids and radiolarians (Maiolica Formation - late Tithonian-early Valanginian);

o) white mudstones and wackestones with only radiolarians (Maiolica Formation - late Valanginian-?Hauterivian/?Barremian).

Clast analysis has provided evidence for all the Jurassic to Lower Cretaceous lithostratigraphic units of the Umbria-Marche-Sabina sedimentary succession found in the study area. The occurrence of clasts belonging to the Bugarone Group is especially interesting as these deposits (Sinemurian-Pliensbachian in age) are locally preserved in small outcrops forming epi-escarpment deposits, while Middle-Upper Jurassic condensed facies (both of pelagic carbonate platform-top and margin) are no longer exposed in the Mt. Cosce Ridge due to Neogene-Quaternary faulting and modern erosion (see discussion in Cipriani, 2016).

One notable feature is the lack of facies younger than the Maiolica Formation in the clasts and in the matrix (i.e. Marne a Fucoidi Formation). The absence of Aptian-Albian clasts, coupled with the occurrence of clasts of Maiolica, allows to frame the “Mt. Cosce Breccia” within a pre-early Aptian time interval during the deposition of the uppermost levels of the Maiolica Formation.

4.2.2. Matrix

In the clast-supported facies the matrix displays a finely lithoclastic debris set in pelagic lime mud. The mud matrix of lithoclastic floatstones is a nannomicrite, whitish-to-greenish in color, comparable with the Maiolica Formation (Fig. 7A-D). It is sometimes hard to differentiate between the groundmass and the youngest Maiolica Formation lithoclasts, as their lithofacies is virtually identical. It is sometimes possible to differentiate macroscopically the Maiolica clasts (milk white color) from the Maiolica matrix (greenish color) due to the chromatic contrast (see Fig. 5B). In thin-section the two facies differ for their paleontological content (abundant microfauna with calpionellids and radiolarians in the pebbles *vs.* virtually barren matrix of the breccia, with only rare radiolarians) (Fig. 7E-F).

4.2.3. *Thinly-bedded pelagites interbedded with the rock-fall deposits*

At Le Cese and at Cima Testone thinly-bedded deposits are interfingered with the meter-thick lens-shaped breccias. Their facies include:

1. coarse grained, poorly-sorted, mud-supported polygenic floatstones, locally rudstones. Clasts are angular to sub-rounded and sand to pebble in size. The microfacies of the grains are comparable with those described for the “Mt. Cosce Breccia” as the lithostratigraphic units identified range from the Calcare Massiccio Formation to the Maiolica Formation, and also include the Bugarone Group. The matrix is a Maiolica-type micrite. These deposits are up to 30 cm thick, and are interbedded within pure pelagites;
2. laminated and graded lithoclastic microbreccias (texturally, lithoclastic wacke- to grainstones) (Fig. 8A);
3. white pelagic micrite. These deposits form thin chert-bearing beds. The microfauna is represented by rare radiolarians and very rare planktonic foraminifers (Fig. 8B and C).

4.2.4. *The Mt. Il Pago olistolith*

Correlative deposits to the “Mt. Cosce Breccia” in a more distal setting were found at Mt. Il Pago embedded in the upper part of the Maiolica Formation. There, a huge block (at least 450 m long x 350 m wide x 30 m high) made of silicified Calcare Massiccio with unconformable dark cherty radiolarites attached (“Calcari Diasprigni” Formation) is embedded in a typical Maiolica Formation mudstone lithofacies. This olistolith is an exotic block and represents a tract of the original western Jurassic escarpment of the Mt. Cosce horst-block detached and fallen into the Early Cretaceous basin.

4.3. Biostratigraphy

As the clasts have an age not younger than the early Valanginian, and the breccia clearly predates the Marne a Fucoidi Formation, this indicates that the age of the breccia must be bracketed between the post-early Valanginian and the pre-early Aptian. With reference to the matrix, the absence of calpionellids is notable. According to Lakova and Petrova (2013), the disappearance of calpionellids took place in the early Valanginian. Moreover, in the matrix of the breccia as well as in the interbedded pelagites, rare specimens of *Hedbergella* sp. were identified (Fig. 8D and E). A *circa* equatorial section of one specimen shows a circular periphery, slightly lobate, with 7 chambers. Chambers show drop-like sections, the sutures are radial and straight, and the umbilicus is wide. Hedbergellids are very low-trochospiral foraminifers and the presence of the umbilicus in thin section allows to identify the last whorl of the taxon, also characterized by a "deep" umbilicus. Unfortunately, a species-level taxonomic attribution cannot be defined in thin-section. However, the previously described characters of the study specimen are comparable with two species of pre-Aptian hedbergellids: *H. luterbacheri* (Longoria, 1974) and *H. kuznetsovae* (Banner and Desai, 1988). In equatorial section, *H. kuznetsovae* differs from *H. luterbacheri* by possessing a more inflated outline of the equatorial periphery and a shallower umbilicus. The characters described for the study specimen are more similar to those of *H. luterbacheri* rather than *H. kuznetsovae*, and this is why it has been tentatively referred to as *Hedbergella* cf. *H. luterbacheri*.

The fact that hedbergellid specimens are very rare, coupled with the lack of specific diversity in the planktonic foraminifer assemblage, suggests an age older than the bloom of planktonic foraminifers that occurred in the latest Barremian-earliest Aptian (Coccioni et al., 2007). The genus *Hedbergella* sp. has a wide biostratigraphic distribution, from the early Valanginian to the latest Albian (Coccioni et al., 2007). In particular, the first occurrence of the species *H. luterbacheri* Longoria 1974 was in the lower Barremian, and the taxon disappeared in the lower Aptian (data sourced from

Chronos database in http://www.mikrotax.org/pforams/). As a consequence, a Barremian age for the "Mt. Cosce Breccia" was firstly hypothesized.

4.3.1. Calcareous nannofossils

Calcareous nannofossil biostratigraphy was performed on samples of both the breccia matrix and the interbedded pelagites. Total nannofossil abundance, preservation and single taxa abundance are reported in Table 1 and the most common taxa are illustrated in Fig. 9. Calcareous nannofossil preservation is moderate to moderate-poor (Table 1), with signs of overgrowth. Four samples from the matrix of the breccia and from the embedded pelagites display the highest nannofossil abundance, whilst the other three are poorer. The nannofossil assemblages are characterized by relatively abundant narrow-canal nannoconids (*Nannoconus* sp., *Nannoconus steinmannii* and *Nannoconus colomii*) with respect to the wide-canal taxa (*Nannoconus* sp., *Nannoconus circularis*). The other nannofossil taxa detected are *Watznaueria barnesiae, Watznaueria britannica, Watznaueria manivitiae, Zeughrabdotus embergeri, Rhagodiscus asper, Lithraphidites carniolensis, Zeugrhabdotus embergeri, Cyclagelosphaera margerelii, Rucinolithus terebrodentarius* and pentaliths (*Micrantholithus hoschulzii* and *Micrantholithus obtusus*).

The presence of relatively more abundant narrow-canal than wide-canal nannoconids indicates an age not younger than the early Aptian, when wide-canal nannoconids became more abundant than narrow-canal ones (Erba 1994; Erba and Tremolada 2004). The presence of pentaliths and of *R. terebrodentarius* (first occurrence in the middle Hauterivian), coupled with the absence of *Calcicalathina oblongata* (last occurrence in the uppermost part of the early Barremian) and of typical markers of the latest Barremian (*Chiastozygus litterarius, Flabellites oblongus* - Bralower et al., 1995; *R. irregularis* - Erba et al., 1999), suggests a "middle" Barremian age for the "Mt. Cosce Breccia". This assemblage is characteristic of the nannofossil zone NC5D (following the biostratigraphic scheme of Bralower et al., 1995) and falls within the *Globigerinelloides blowi* Zone (planktonic foraminifers). This age corresponds with the deposition of the uppermost part of the Maiolica Formation.

5. Discussion

5.1. Genesis of the “Mt. Cosce Breccia” and relationships with the Mt. Cosce Jurassic pelagic carbonate platform-basin system

Widespread regional evidence suggests that the Jurassic rift-related paleotopography had to have been levelled with deposition of the Maiolica Formation in the latest Late Jurassic-earliest Early Cretaceous. Consequently, the unconformable contact, through an erosional surface, between the Barremian clastic/pelagic deposits and the Hettangian shallow-water limestones (with attached onlapping Pliensbachian pelagites) stands as a very unusual feature. At least three possible scenarios can be envisaged for an explanation: 1) a purely gravitative cause, 2) a deep-marine erosional phase or 3) a post-rift extensional tectonic phase.

In the first scenario, the Jurassic rift-related margin of the Mt. Cosce pelagic carbonate platform should be repeatedly affected by collapses during its Jurassic-Cretaceous evolution. The dominantly erosional regime would prevent the post-Corniola/pre-Maiolica basin-fill succession (the “Mt. Cosce Breccia” rests either on the Calcare Massiccio Formation or on the Corniola Formation) from being preserved. This hypothesis would not explain the presence of clasts of the Middle Jurassic succession in the breccia, because this would indicate that said succession was originally deposited but was later dismantled.

In the second scenario, a deep-marine erosion would imply the incision of deep (hundreds of meters) canyons in order to erode the Middle and Upper Jurassic part of the basin-fill sequence. However, no evidence whatsoever exists in the area for the existence of such canyons. While calciclastic deposits can be funneled downslope from a carbonate platform linear source through gullies (see Payros and Pujalte, 2008 and references therein), it is less probable that deep canyons formed in a pure pelagic carbonate domain, in a low sedimentary rate regime, and tens of kilometers away from the nearest productive carbonate platform (e.g., Lazio-Abruzzo carbonate platform). Moreover, the Mt. Cosce breccia contains no shallow-water material, with the exception of lithoclasts of the older pre-rift Calcare Massiccio Formation. This piece of negative evidence is consistent with a total disassociation of the Mt. Cosce depositional system from any carbonate source area potentially impacted by eustacy, like a bank subjected to subaerial exposure or a mobile shoreline, even in the form of a far-field effect, meaning that the breccia must be unrelated to changing sea-level.

The third scenario is represented by a post-rift extension-dominated tectonic phase. The presence of pre-Cretaceous units, like Middle-Upper Jurassic radiolarian cherts, in the clasts of the “Mt. Cosce Breccia” can only be explained by inferring that they found themselves topographically uplifted with respect to the Cretaceous basin. The clasts could be fed from the exhumed vestiges of the Middle/Late Jurassic onlap wedge, including the peritidal substrate and the former epi-escarpment and pelagic carbonate platform-top deposits (Bugarone Group), as a product of escarpment rejuvenation, erosion, and displacement along an Early Cretaceous fault. This scenario is the most conservative and accounts for the stratigraphic and sedimentological features previously described. This transtensional faulting (see Cipriani and Bottini, 2018, for further discussions; see also Basilone et al., 2016 for an example in Sicily) affected the study area during the late Early Cretaceous and led to the formation of a new paleotopography of the seafloor and to the formation of the Cretaceous unconformity surface mapped along the Mt. Cosce-Cima Boschetto slopes. Since no Mesozoic shear zones were directly identified in the field in the study area, which is severely deformed by Mio-Pliocene faults, activity along a single Cretaceous master fault is inferred here for simplicity.

5.1.1. Role of inherited Early Jurassic discontinuities

Geological mapping indicates that the strike of the inferred Cretaceous fault apparently runs parallel to the Early Jurassic fault, which constitutes the western boundary of the Mt. Cosce pelagic carbonate platform (Fig. 10). It is therefore conceivable to infer a Cretaceous reactivation of an inherited W-dipping, Jurassic rift-fault. It's worth noting that while the surface separating the Cretaceous breccia from the Lower Jurassic substrate must, in our interpretation, be taken as the evidence for an underlying fault, it is not quite the fault itself, but rather an unconformable contact. The presence in the "Mt. Cosce Breccia" (i.e. part of the hangingwall succession of the Cretaceous faults) of clasts referable to: i) the Jurassic-Lower Cretaceous succession of top of pelagic carbonate platform; ii) the margin of the Jurassic horst-block; and iii) the units of the basinal succession, implies that the footwall of the Cretaceous normal fault had to comprise both the upthrown-blocks (i.e. Mt. Cosce pelagic carbonate platform) and the hangingwall-successions of the Jurassic rift-faults. Moreover, field evidence demonstrates that the Cretaceous fault-related discontinuities displace the Jurassic escarpments (Cipriani and Bottini, 2018). According to Carminati and Santantonio (2005), Jurassic paleoescarpments are no more active fault scarps, heavily modified by submarine erosional processes as rock falling and avalanching. The resulting products are unconformity surfaces displaying lower angles with respect to their roots (i.e. paleofaults). The deformation of Jurassic paleoescarpments by post-rift discontinuities allows to speculate that the Cretaceous fault(s) were newly formed faults and had an angle higher than that of its Jurassic ancestor (Cipriani and Bottini, 2018). This means that the latter was not reactivated *per se* (Fig. 11). However, lacking constraining field evidence (i.e. exposure of Jurassic and Cretaceous faults) reactivation of inherited faults cannot be definitively excluded. Early (and locally Late) Cretaceous faults were described by Santantonio et al. (2013) based on 2D and 3D seismic data of the Adriatic Sea offshore. These normal faults back-stepped the eastern margin (formed during the Early Jurassic rifting stage) of the Apulia Carbonate Platform. The notable feature described by those authors is that the Jurassic discontinuities were not reactivated, but rather were displaced, as Cretaceous faults were at a higher angle than the Jurassic ones. The data obtained in the Narni-Amelia Ridge therefore match the elements described by Santantonio et al. (2013), and could represent the outcrop analogue of an interpreted seismic line.

Footwall and hangingwall blocks of the Cretaceous fault were separated by a steep fault scarp, which was subjected to submarine erosion and to gravitational collapses. The progressive erosional retreat of the new-formed margin cannibalized the vestiges of the former basin-fill onlap succession, eventually leading to the re-exhumation of the local Jurassic paleoescarpment tract of the Mt. Cosce pelagic carbonate platform, which had originally been buried by the Maiolica Formation (Figs. 10C, 11A). The sites where the breccia rests on the Corniola Formation correspond to the tectonically uplifted and eroded remnants of the onlap wedge. The final results of these processes were the formation of a younger, late Early Cretaceous paleoescarpment superimposed on the Jurassic margin of the Mt. Cosce pelagic carbonate platform and the accumulation of a megaclastic talus made of carbonate breccia on and at the toe of the newly formed escarpment (Fig. 11B).

The total displacement of the Cretaceous fault cannot be defined due to the lack of key correlative outcrops on both footwall- and hangingwall-blocks. A conservative estimate of the amount of displacement is provided by the thickness of the upper Lower Jurassic to Lower Cretaceous deposits, exposed at the footwall of the Cretaceous fault. While in pure basinal successions their thickness is about 600 m (e.g., Cecca et al., 1990), in basin-margin onlap successions the Pliensbachian (upper Corniola Formation) to Berriasian deposits can only be about 200 m due to pinch-out. This latter figure is conservatively taken as a tentative estimate for the displacement along the Cretaceous fault.

5.1.2. Submarine rockfall vs. debris-flow deposits

The “Mt. Cosce Breccia” can be crudely differentiated in two lithotypes.

1) The first lithotype is characterized by massive, coarse-grained and clast-supported deposits. These are poorly sorted to unsorted and are made of closely packed huge (meter-size) boulders. Larger clasts coexist with pebble-size fragments. The matrix consists of sand-size lithoclastic debris dispersed in typical fine-grained Maiolica facies. This first lithotype of the “Mt. Cosce Breccia” is the lowermost facies identified in the field at Pianastrina, and rests directly on the Calcare Massiccio and Corniola Formations through an irregular unconformity surface (Cipriani and Bottini, 2018). The composition of the blocks is here “oligotypic”, with clasts of the Calcare Massiccio and Corniola Formations dominating (>60% of total lithoclasts), which indicates local sourcing essentially through free-fall (submarine rockfall breccia *sensu* Flügel, 2010).
2) The second lithotype is coarsely bedded and is characterized by a matrix-supported breccia facies with interbedded thin pelagites. The clasts are angular to rounded and are polymictic, displaying the widest range of lithostratigraphic units. Millimetric to decimetric blocks are dispersed in the micrite matrix, a typical feature of high-concentration gravity flows. Most of the “Mt. Cosce Breccia” outcrops (i.e. Mt. Cosce, Cima Testone and Le Cese) are characterized by this lithofacies, interpreted as debris-flow deposits (Flügel, 2010).

5.1.3. Age of faulting

The “Mt. Cosce Breccia” has been interpreted as a syn-tectonic deposit. As a consequence, the bio- and lithostratigraphic data obtained from the analysis of this limestone breccia allow to constraint the timing of the extension, dated to the “middle Barremian”.

5.2. Regional overview and extra-Apennines occurrences

Stratigraphic and sedimentological evidence for Early Cretaceous extensional tectonic is widespread in Italy. This evidence includes clastic deposits embedded in pelagic successions, soft-sediment deformations and neptunian dykes. In analogy with Jurassic faults (see Santantonio et al., 2017, for further discussions), there are no Cretaceous faults exposed and described from Central Italy to date. They have however been described in the Gargano peninsula by Graziano (2000, 2001), in Sicily (Basilone et al., 2017) and in the subsurface (Santantonio et al., 2013) in the Adriatic offshore.

Fabbi et al. (2016) describe comparable features to those of the “Mt. Cosce Breccia” from the Mt. Primo Ridge (Umbria-Marche Apennines). There, polygenic breccias made of clasts of Calcare Massiccio Formation, of Jurassic pelagic carbonate platform-top condensed facies, of basinal units and of Maiolica Formation are found in the uppermost levels of the top of Maiolica Formation. These limestone breccias have been interpreted as the result of fault-related exhumation and backstepping of a Jurassic pelagic carbonate platform margin (i.e. Mt. Gualdo-Mt. Primo pelagic carbonate platform; Fabbi, 2015) during the Barremian-Aptian, and are associated with Lower Cretaceous lithoclasts and shallow water-derived loose material sourced by a productive carbonate platform.

Limestone breccias characterize the Mt. Cetona Ridge (Southern Tuscany – Jacobacci, 1962; Passerini, 1964). These very thin (up to 4 m) breccias are interposed between the Diaspri Formation (typical Tethyan radiolarites - Bathonian-Kimmeridgian) and the Brolio Shales (foraminifer-rich marls, equivalent to the Marne a Fucoidi Formation - Aptian-Albian), so they essentially replace the Maiolica Formation. Passerini (1964) relates the breccias to either a transgression or to submarine rock-falls. As discussed previously for the “Mt. Cosce Breccia”, any bedrock collapse solely due to sea-level change is highly unlikely in a distal pelagic domain, therefore it can be considered more conservative to infer that the limestone breccias in Tuscany were formed as a result of synsedimentary extension.

Neptunian dykes made of Maiolica facies and cutting across two pelagic carbonate platforms were described from the neighbouring Sabini Mountains (4 km E of Mt. Cosce - Farinacci, 1967; Galluzzo and Santantonio, 2002) and the Mt. Soratte Ridge (20 km SW of Mt. Cosce - Chiocchini et al., 1975). These Cretaceous submarine fractures affect the condensed succession of the Sabina Plateau-top (*sensu* Galluzzo and Santantonio, 2002) and the western margin of the Mt. Soratte Jurassic pelagic carbonate platform. The latter experienced tectonic back-stepping of its western margin during the Mesozoic. This is testified by Early Cretaceous fractures cross-cutting Pliensbachian deposits, and by the presence of Upper Cretaceous pelagites of Scaglia Formation in the form of neptunian dykes and epi-escarpment deposits (resting unconformably on the Calcare Massiccio Formation). The formation of the Lower Cretaceous neptunian dykes was referred to the same extensional tectonic phase described for the Mt. Cosce area.

Tectonically-triggered soft-sediment deformation was described by Menichetti (2016) from the top of the Maiolica Formation in the well-known Contessa Quarry (Gubbio anticline). Seismically-induced mass-transport deposits (i.e. slumps and calcidebrites) in the Maiolica Formation were largely described also from the Gargano Peninsula (e.g., Jablonská et al., 2016; Korneva et al., 2016) and from equivalent deposits (i.e. Lattimusa Formation) from Sicily (Basilone, 2017).

The most spectacular example of Early Cretaceous synsedimentary tectonics affecting a Jurassic pelagic carbonate platform-basin system was described by Castellarin (1972, 1982) from the Brenta Dolomites (Southern Alps). There, the western margin of the Trento Plateau (e.g., Clari et al., 2002) was dissected and backstepped by Early Cretaceous normal faults. Rock-falls caused the accumulation of the “Ballino Breccia” in the Lombardy basin, while submarine erosion formed the Cretaceous tracts of the Ballino escarpment. These clastic deposits characterize the top of the Maiolica Formation and are associated with slumps. Neptunian dykes are also abundant in the footwall-block of the Cretaceous faults. The Cretaceous faults are sealed by the “Ballino Breccia”, by few decimeters to few meters of Maiolica Formation and by the Aptian-Albian marly facies of the Scaglia Variegata Alpina Formation. All these deposits onlap the Cretaceous Ballino paleoescarpment (Cipriani and Santantonio, 2017).

Limestone breccias are important from an economic point of view, being potential hydrocarbon reservoirs (Casabianca et al., 2002). Lower Cretaceous megaclastic deposits as traps for hydrocarbon accumulation are reported from several Italian plays (Casero and Bigi, 2013). In the subsurface of the Po plain the "Cavone Breccia", a Lower Cretaceous megabreccia embedded in the Maiolica Formation and sealed by the Marne del Cerro Formation (Aptian-Albian, equivalent of the Marne a Fucoidi Formation), can be related to tectonic rejuvenation of the buried Bagnolo carbonate platform margin and is exploited for hydrocarbon production (Nardon et al., 1990). Lower Cretaceous breccias and paleoescarpments characterize the exposed margins of the Apulia carbonate platform (Maiella Ridge and Gargano peninsula – e.g., Bosellini and Morsilli, 1997; Casabianca et al., 2002; Rusciadelli, 2005; Graziano, 1999, 2000) and represent the outcrop analogues of its buried margins. Syn-sedimentary faults and breccias at the eastern and northern margins of the Ombrina-Rospo plateau (Ombrina oil and gas field), sealed by the Marne a Fucoidi Formation (Aptian-Albian), were identified by Santantonio et al. (2013) in the Adriatic offshore.

In the late Early Cretaceous an important phase of plate reorganization took place. According to Schettino and Turco (2011), the African and Eurasian plates started to converge due to the opening of the Southern Atlantic Ocean. Contemporaneously, the Iberian plate started its counterclockwise rotation with a left-lateral strike slip motion, as a result of the Northern Atlantic rifting and drifting. The rotation of Iberia produced rifting of the Biscay Bay, whose eastern arm was identified in the Briançonnais Domain (Bertok et al., 2012). While extension characterized the western boundaries of the lithospheric plates, compressional stress fields affected the western Tethys Ocean and the former passive margins of Africa, Eurasia and Iberia. The subduction of the Ligurian oceanic crust started in the late Early Cretaceous and led to the closure of Alpine Tethys and Neotethys oceans. Growing evidence, on a super-regional scale, for coeval lithospheric extension and shortening in the Cretaceous poses several kinematic questions. The far-field effect of the strike-slip kinematics related to rotation of the Iberian plate is invoked for the study area (e.g., Tavani et al., 2018). Inherited Jurassic heterogeneities could have played a role, in a strike-slip regime, in the development of pull-apart or partitioned transtensional basins. Similar described examples come from Sicily (Basilone et al., 2016). Another hypothesis regards arching of the lithosphere as a result of intraplate stress at convergent plate boundaries (Cloetingh, 1988), producing normal faults.

6. Conclusions

This study provides an insight into the sedimentological and tectono-stratigraphic features of the “Mt. Cosce Breccia”. The “Mt. Cosce Breccia” represents the stratigraphic and sedimentological evidence of a synsedimentary, post-rifting, normal faulting phase affecting the Central Apennines during the late Early Cretaceous. This Cretaceous normal faulting affected the western margin of the Mt. Cosce pelagic carbonate platform, re-utilizing or displacing a Jurassic rift-related fault. This tectonic phase locally rejuvenated the rift-related seafloor relief that had previously been blanketed by the deposition of Maiolica Formation during the lower part of the Early Cretaceous. The “Mt. Cosce Breccia” is a carbonate megabreccia which formed as a result of rock-falls affecting the uplifted footwall of the active Cretaceous fault, and was deposited at the toe of a submarine escarpment. The former onlap wedge of the Jurassic basin-fill succession on the Mt. Cosce pelagic carbonate platform, unroofed along the new fault, was subjected to intense submarine erosion. Catastrophic rock-falls also caused the emplacement of huge olistoliths (i.e. Mt. Il Pago olistolith), embedded in the uppermost part of Maiolica Formation. The youngest age detected within the clasts, the occurrence of *Hedbergella* cf. *H. luterbacheri* in the matrix and the calcareous nannofossil content allow us to identify a “middle” Barremian age for the breccia, which in turn can be taken as a constraint to the timing of faulting. Indirect evidence for late Early Cretaceous normal faulting is found from different pelagic successions in the Western Tethys, characterized by pelagic carbonate platform-basin systems. Although the displacement produced by the Early Cretaceous faults is not comparable with that of their Early Jurassic ancestors, this phase of tectonic instability was widespread and was related to the re-organization of lithospheric plates. It is believed that the results of the present study improve our understanding of the role played by inherited Jurassic discontinuities on the development of post-rift faults, and can be applied to paleogeographic domains having a comparable Jurassic history. The "Mt. Cosce Breccia" represents an outcrop analogue for Lower Cretaceous syntectonic deposits exploited as hydrocarbon plays.

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Figure and table captions

Fig. 1. Geographical localization and geological map of the Mt. Cosce—Vacone area (modified from Cipriani, 2016). The black boxes describe the a) Mt. Cosce-Cima Testone, b) Cima Boschetto and c) Mt. Il Pago areas. Legend*:* 1) Calcare Massiccio Formation; 2) "calcare massiccio C" lithofacies; 3) "calcare massiccio B" member; 4) Corniola Formation; 5) Rosso Ammonitico Formation; 6) "Calcari e Marne a *Posidonia*" Formation; 7) "Calcari Diasprigni" Formation; 8) "Calcari ad aptici e *Saccocoma*" Formation; 9) Maiolica Formation; 10) "Mt. Cosce Breccia"; 11) Marne a Fucoidi Formation; 12) Scaglia Bianca Formation; 13) Scaglia Rossa Formation; 14) Scaglia Variegata Formation; 15) Scaglia Cinerea Formation; 16) Chiani-Tevere unit; 17) alluvial and debris fan; 18) scree; 19) bed attitude and dip angle; 20) overturned bed attitude and dip angle; 21) lithostratigraphic unit boundary; 22) silicification of the Calcare Massiccio; 23) thrust fault; 24) normal fault; 25) inferred Cretaceous fault; 26) measured stratigraphic section. Spatial reference of the geological map: WGS84 Datum, UTM Projection, Zone 33N.

Fig. 2. Mesozoic lithostratigraphic and paleotectonic scheme of the study area. Legend: ADB) Anidriti di Burano Formation; CET) Mt. Cetona Formation; CMA) Calcare Massiccio Formation; CMC) "Calcare Massiccio C" lithofacies; COR) Corniola Formation; RSA) Rosso Ammonitico Formation; CMP) "Calcari e Marne a *Posidonia*" Formation; CDA) "Calcari Diasprigni" Formation; SAC) "Calcari ad aptici e *Saccocoma*" Formation; MAI) Maiolica Formation; MAF) Marne a Fucoidi Formation; SBI) Scaglia Bianca Formation; SRO) Scaglia Rossa Formation.

Fig. 3. Measured stratigraphic sections of the "Mt. Cosce Breccia", with position of the samples analyzed for nannofossil biostratigraphy. Legend: 1) Calcare Massiccio Formation; 2) Corniola Formation; 3) Rosso Ammonitico Formation; 4) "Calcari e Marne a *Posidonia*" Formation; 5) "Calcari Diasprigni" Formation; 6) "Calcari ad aptici e *Saccocoma*" Formation; 7) Bugarone Group; 8) Maiolica Formation; 9) massive limestone; 10) well bedded limestone; 11) "Mt. Cosce Breccia"; 12) chert.

Fig. 4. Field view and line drawing of the unconformable contacts between the “Mt. Cosce Breccia” and the Jurassic bedrock. (A) Unconformity “Mt. Cosce Breccia” - Calcare Massiccio Formation at Cima Testone; note the interbedded strata of Maiolica Formation (geographic coordinates: 42°24'6.83"N; 12°38'12.96"E). (B) Unconformity “Mt. Cosce Breccia” - Corniola Formation at Cima Testone (geographic coordinates: 42°24'4.87"N; 12°38'21.24"E). (C) Coarse facies of the “Mt. Cosce Breccia” resting directly on the Calcare Massiccio Formation at Pianastrina (geographic coordinates: 42°23'29.42"N; 12°38'40.84"E). (D) Matrix-rich facies of the “Mt. Cosce Breccia” onlapping the Calcare Massiccio Formation at Pianastrina (geographic coordinates: 42°23'29.28"N; 12°38'40.62"E). (E) Unconformable contact between the “Mt. Cosce Breccia” and the Corniola Formation at Le Cese (geographic coordinates: 42°23'38.86"N; 12°38'40.45"E). Hammer as scale.

Fig. 5 Mesoscopic features of the “Mt. Cosce Breccia”: (A) meter-size boulder of Calcare Massiccio embedded in the coarsest facies of the limestone breccia at Pianastrina; (B) mud-supported facies at Cima Testone; (C) coarse-grained facies at Le Cese. Note the Maiolica-type matrix of the breccia, shiny light grey in color, surrounding the brownish clasts; (D) chaotically arranged mud-supported facies at Cima Testone, with decimeter-size clasts of chert; (E) thin beds of Maiolica type embedded in and incised by chaotic, coarse-grained, facies of the “Mt. Cosce Breccia” at Le Cese. Hammer as scale.

Fig. 6. (A-F) Photomicrographs showing the petrographic features of the clast-supported “Mt. Cosce Breccia”. Clasts of: *Cma)* Calcare Massiccio Formation; *Cor)* Corniola Formation; *Cmp)* “Calcari e Marne a *Posidonia*” Formation; *Cda)* “Calcari Diasprigni” Formation*; Sac)* “Calcari ad aptici e *Saccocoma*” Formation; *Bug)* Bugarone Group; *Mai)* Maiolica Formation Abbreviations: *sty)* stylolitic contact; *ch)* chert. Scale bar: 1 mm.

Fig. 7. (A-F) Microfacies of mud-supported “Mt. Cosce Breccia” lithofacies. Clasts of: *Cmp)* “Calcari e Marne a *Posidonia*” Formation; *Sac)* “Calcari ad aptici e *Saccocoma*” Formation; *Mai)*

Maiolica Formation Abbreviations: *sty)* stylolitic contact; *ch)* chert; *ox)* Fe oxides; *mat*) Maiolica-type matrix. Scale bar: 1 mm.

Fig. 8. (A) Intra-litho-bioclastic wackestone/floatstone. Microbreccia lithofacies of the Maiolica Formation embedded in the “Mt. Cosce Breccia”. Scale bar: 1 mm. (B-C) Nannomicritic mudstones with traces of Fe oxides, sampled for calcareous nannofossil analysis. In particular: (B) sample AC187a; (C) sample AC1028. Scale bar: 0,5 mm. (D) Specimen of *Hedbergella* sp. Scale bar: 0,5 mm. (E) *Hedbergella* cf. *H. luterbacheri*. Scale bar: 0,5 mm.

Fig. 9. Calcareous nannofossils identified in the “Mt. Cosce Breccia”. (A) *W. barnesiae* (sample AC187A). (B) *C. margerelii* (sample AC187A). (C) *W. manivitiae* (sample AC187A). (D) *L. carniolensis* (sample AC187A). (E) *M. obtusus* (sample AC187A). (F) *Z. embergeri* (sample AC187A). (G) *N. steinmannii* (sample AC187A). (H) *N. colomii* (sample AC1026). (I) *N. circularis* (sample AC187A). (J) *Nannoconus* sp. (sample AC187A). (K) *Nannoconus* sp. (sample AC187A). (L) *R. terebrodentarius* (sample AC1026). Scale bar (reported in microphotograph A): 5 µm.

Fig. 10. (A-C) Tridimensional and (A’-C’) bidimensional block diagrams illustrating (A, A’) the rift-related paleotectonic setting of the Mt. Cosce area, with stripped off post-Calcare Massiccio deposits; (B, B’) the Middle Jurassic Mt. Cosce pelagic carbonate platform-basin system and (C, C’) the rift architecture buried by the Maiolica Formation, with the possible traces of Barremian faults (not to scale). 1) Anidriti di Burano + Mt. Cetona Formations; 2) Calcare Massiccio Formation; 3) Corniola Formation; 4) Rosso Ammonitico Formation; 5) “Calcari e Marne a *Posidonia*” Formation; 6) “Calcari Diasprigni” Formation; 7) “Calcari ad aptici e *Saccocoma*” Formation; 8) Bugarone Group; 9) Maiolica Formation.

Fig. 11. (A, B) 3D and (A’, B’) 2D block diagrams of the Early Cretaceous faulted blocks summarizing the reconstruction of the “Mt. Cosce Breccia” origin (not to scale). 1) Anidriti di Burano + Mt. Cetona Formations; 2) Calcare Massiccio Formation; 3) Corniola Formation; 4) Rosso Ammonitico Formation; 5) “Calcari e Marne a *Posidonia*” Formation; 6) “Calcari

Diasprigni" Formation; 7) "Calcari ad aptici e *Saccocoma*" Formation; 8) Bugarone Group; 9) Maiolica Formation;10) Barremian unconformity surface; 11) syn-tectonic Maiolica facies infilling neptunian dykes.

Table 1. Calcareous nannofossil range chart of the "Mt. Cosce Breccia". The chart reports the distribution and semi-quantitative abundance of all taxa observed, as well as the total abundance and preservation of each investigated sample.

Taxonomic list of calcareous nannofossils

Cyclagelosphaera margerelii Noël, 1965

Lithraphidites carniolensis Deflandre, 1963

Micrantholithus hoschulzii (Reinhardt, 1966) Thierstein, 1971

Micrantholithus obtusus Stradner, 1963

Nannoconus steinmannii Kamptner, 1931

Nannoconus circularis Deres and Achéritéguy, 1980

Nannoconus colomii (de Lapparent 1931) Kamptner 1938

Rhagodiscus asper (Stradner, 1963) Reinhardt, 1967

Watznaueria barnesiae (Black in Black & Barnes, 1959) Perch-Nielsen, 1968

Watznaueria britannica (Stradner, 1963) Reinhardt, 1964

Watznaueria manivitiae Bukry, 1973

Zeugrhabdotus embergeri (Noël, 1959) Perch-Nielsen, 1984

Sample	Lithology	Locality	Preservation	Total nannofossil abundance	*C. margerelii*	*L. carniolensis*	*M. obtusus*	*N. circularis*	*N. colomii*	*N. steinmannii*	*Nannoconus* sp.	Narrow canal *Nannoconus* sp.	*R. asper*	*R. terebrodentarius*	*W. barnesiae*	*W. britannica*	*W. manivitiae*	Wide canal *Nannoconus* sp.	*Z. embergeri*
AC 182	Matrix of the “Mt. Cosce Breccia”	Eastern slope of Cima Testone	MP	R						R					R				
AC 184	Matrix of the “Mt. Cosce Breccia”	Eastern slope of Cima Testone	MP	R						R					R				
AC1029	Matrix of the “Mt. Cosce Breccia”	Le Cese (North of Cima Boschetto)	M	F		R		R		R	R				F	R			
AC 187A	Maiolica-type facies interbedded in the “Mt. Cosce Breccia”	Eastern slope of Cima Testone	M	F/C	R	R	R	R/F	R/F	R/F	R/F	F	R	R	F/C		R	R	R
AC187C	Maiolica-type facies interbedded in the “Mt. Cosce Breccia”	Eastern slope of Cima Testone	M	F		R	R	R		R/F		F			F	R		R	R
AC1026	Maiolica-type facies interbedded in the “Mt. Cosce Breccia” and onlapping the Calcare Massiccio Fm.	Le Cese (North of Cima Boschetto)	M	F/C		R	R	R		R	R	F		R	F				R
AC1028	Maiolica-type facies interbedded in the “Mt. Cosce Breccia”	Le Cese (North of Cima Boschetto)	M	R/F			R								R/F				R

Highlights

- The “Mt. Cosce Breccia” is a synsedimentary tectonic-related deposit;
- Calcareous nannofossil biostratigraphy indicates a “middle” Barremian age;
- Cretaceous normal faulting displaced a Jurassic rift architecture;
- Rock falls backstepped the Cretaceous scarp and rejuvenated a Jurassic margin.

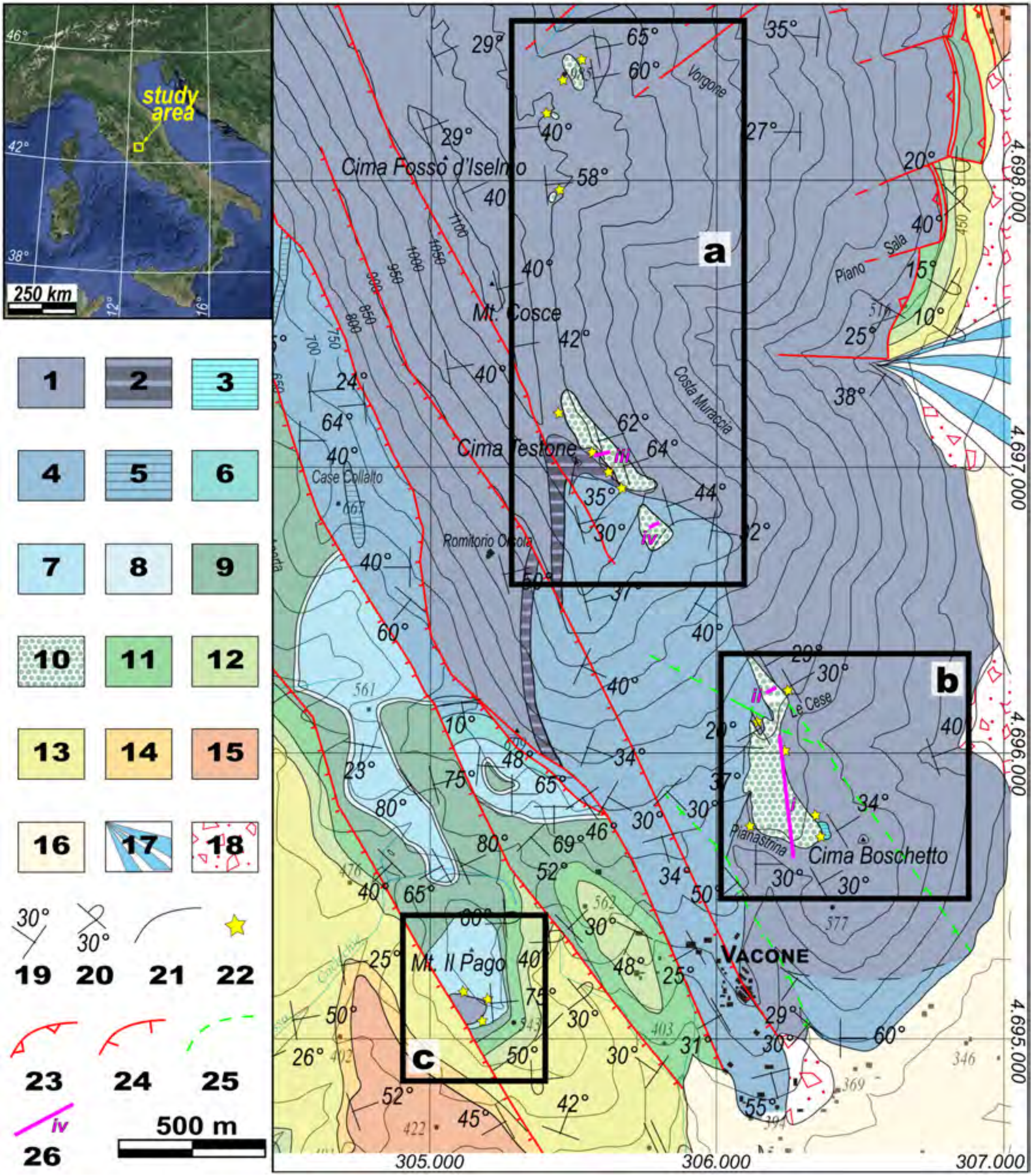
46°
42°
38°
study area
250 km
12°
16°
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
30°
19
30°
20
21
22
23
24
25
iv
26
500 m
a
b
c
Cima Fosso d'Iselmo
Mt. Cosce
Cima Testone
Case Collalto
Romitorio Ciciola
Vorgone
Costa Muraccia
Piano Sala
Le Cese
Pianastrina
Cima Boschetto
VACONE
Mt. Il Pago
i
ii
iii
iv
305.000
306.000
307.000
4.698.000
4.697.000
4.696.000
4.695.000

Figure 1

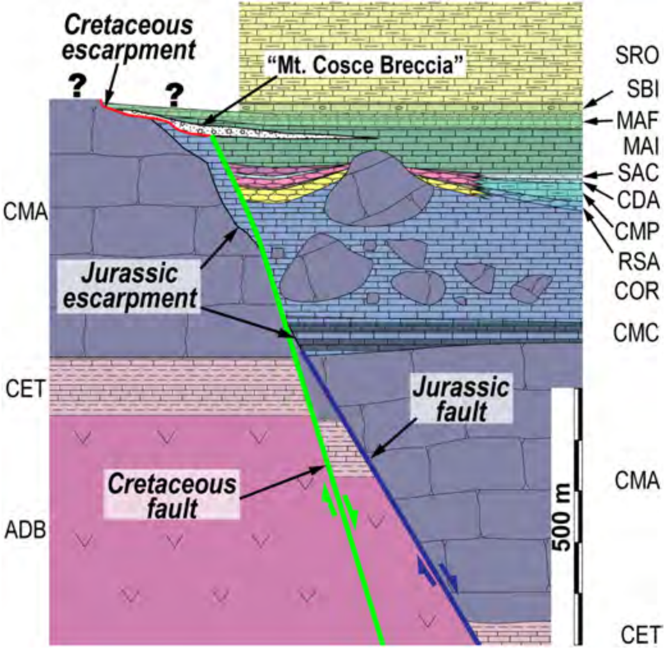
Cretaceous escarpment
?
?
"Mt. Cosce Breccia"
SRO
SBI
MAF
MAI
SAC
CDA
CMP
RSA
COR
CMC
CMA
Jurassic escarpment
CET
Jurassic fault
Cretaceous fault
ADB
500 m
CMA
CET

Figure 2

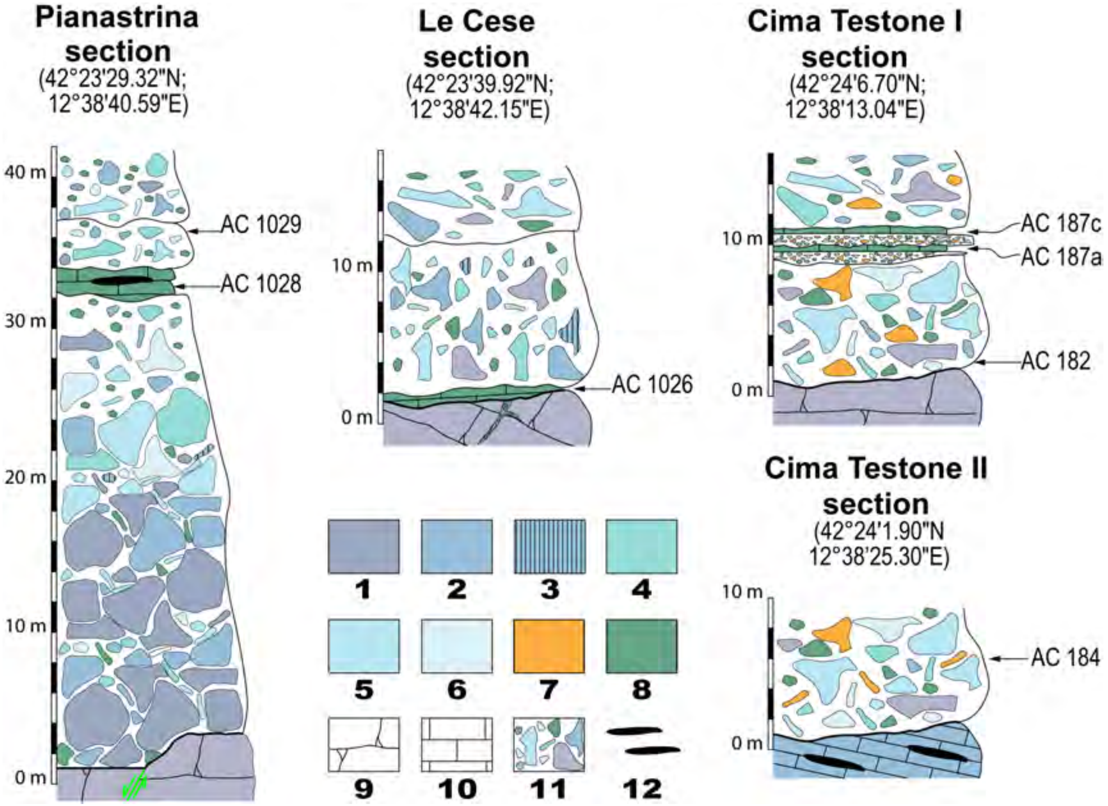
Pianastrina section
(42°23'29.32"N;
12°38'40.59"E)
40 m
30 m
20 m
10 m
0 m
AC 1029
AC 1028
Le Cese section
(42°23'39.92"N;
12°38'42.15"E)
10 m
0 m
AC 1026
Cima Testone I section
(42°24'6.70"N;
12°38'13.04"E)
10 m
0 m
AC 187c
AC 187a
AC 182
Cima Testone II section
(42°24'1.90"N
12°38'25.30"E)
10 m
0 m
AC 184
1
2
3
4
5
6
7
8
9
10
11
12

Figure 3

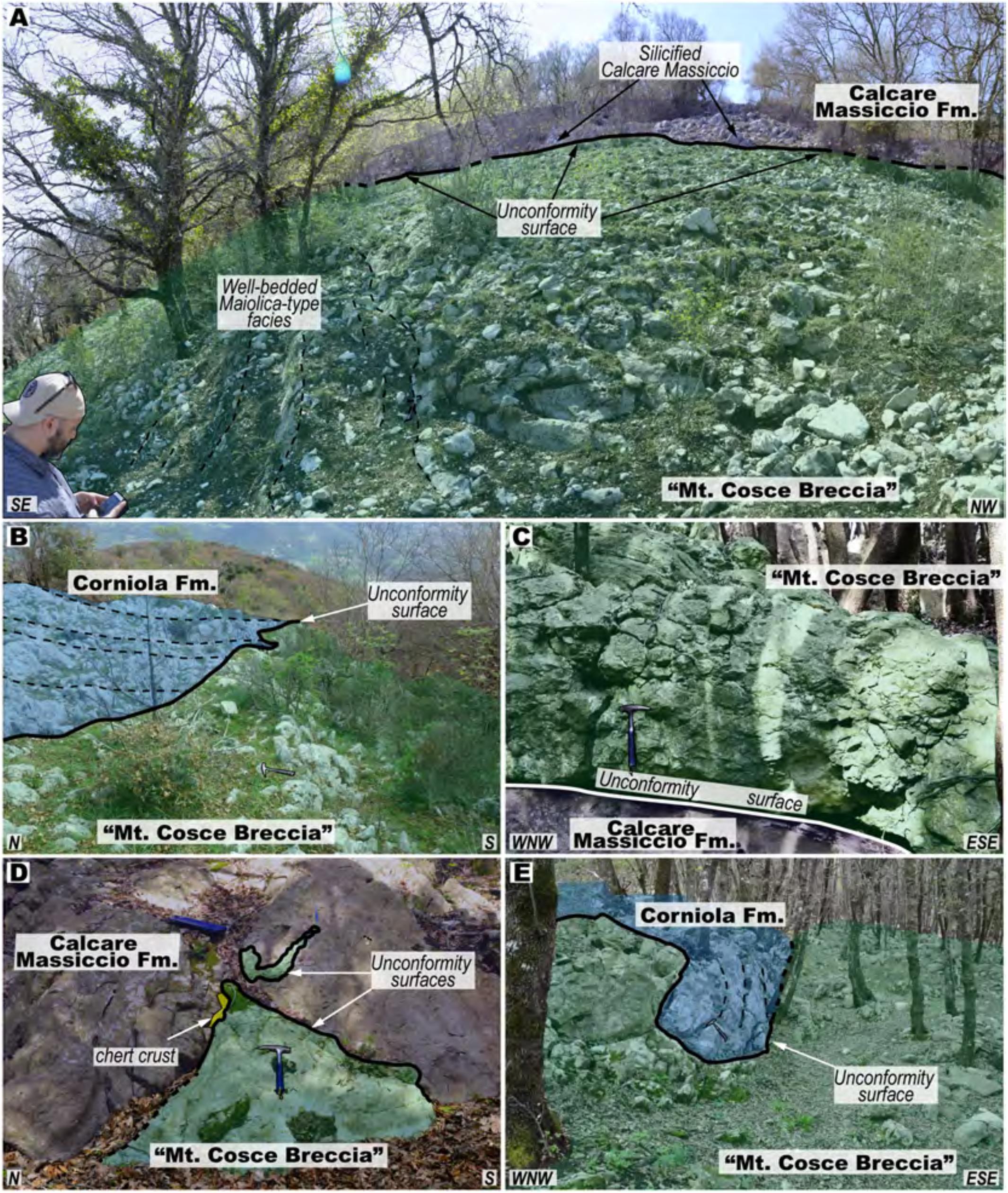
A
Silicified
Calcare Massiccio
Calcare
Massiccio Fm.
Unconformity
surface
Well-bedded
Maiolica-type
facies
"Mt. Cosce Breccia"
SE
NW
B
Corniola Fm.
Unconformity
surface
"Mt. Cosce Breccia"
N
S
C
"Mt. Cosce Breccia"
Unconformity
surface
Calcare
Massiccio Fm.
WNW
ESE
D
Calcare
Massiccio Fm.
Unconformity
surfaces
chert crust
"Mt. Cosce Breccia"
N
S
E
Corniola Fm.
Unconformity
surface
"Mt. Cosce Breccia"
WNW
ESE

Figure 4

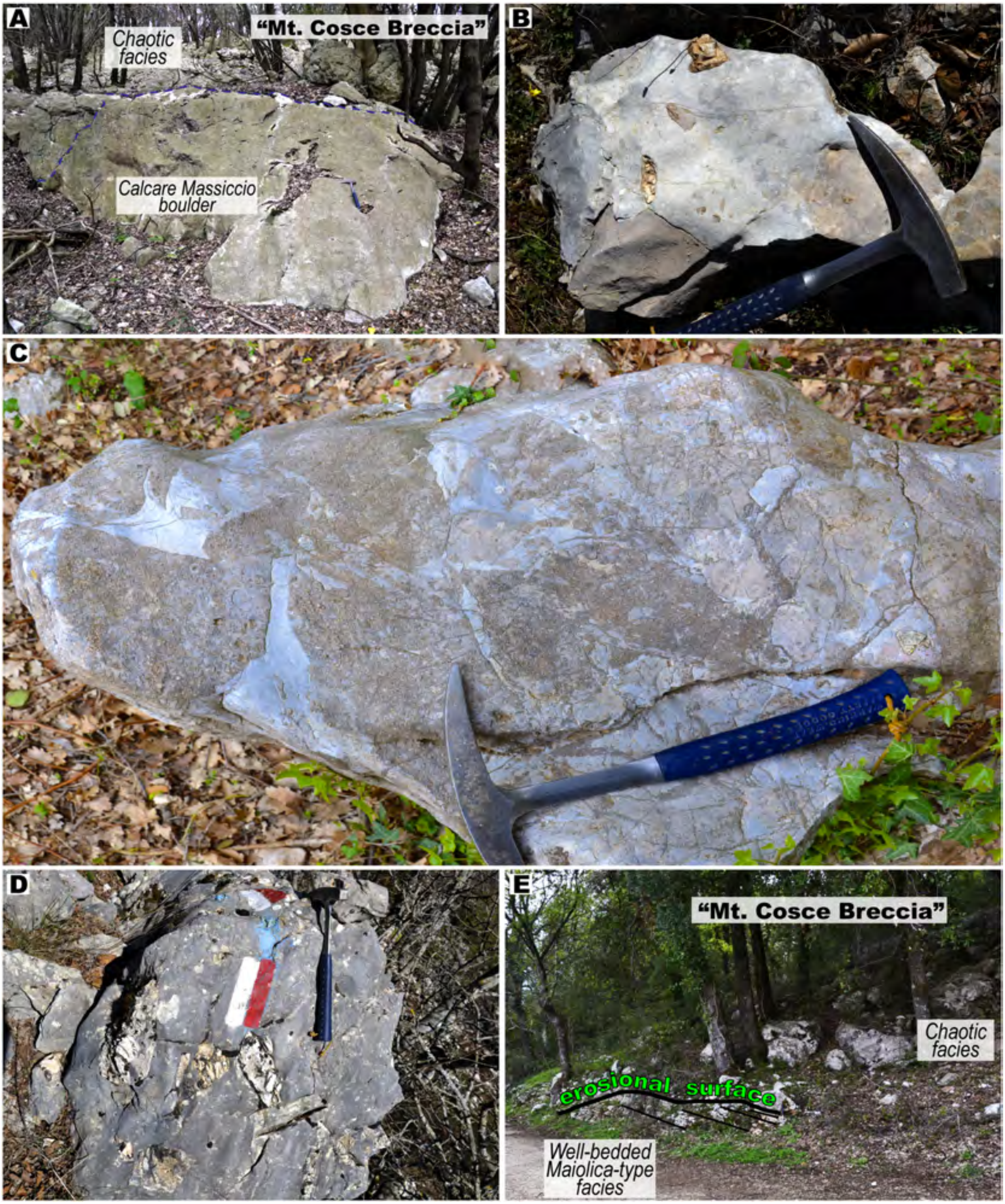
A
"Mt. Cosce Breccia"
Chaotic facies
Calcare Massiccio boulder
B
C
D
E
"Mt. Cosce Breccia"
Chaotic facies
erosional surface
Well-bedded Maiolica-type facies

Figure 5

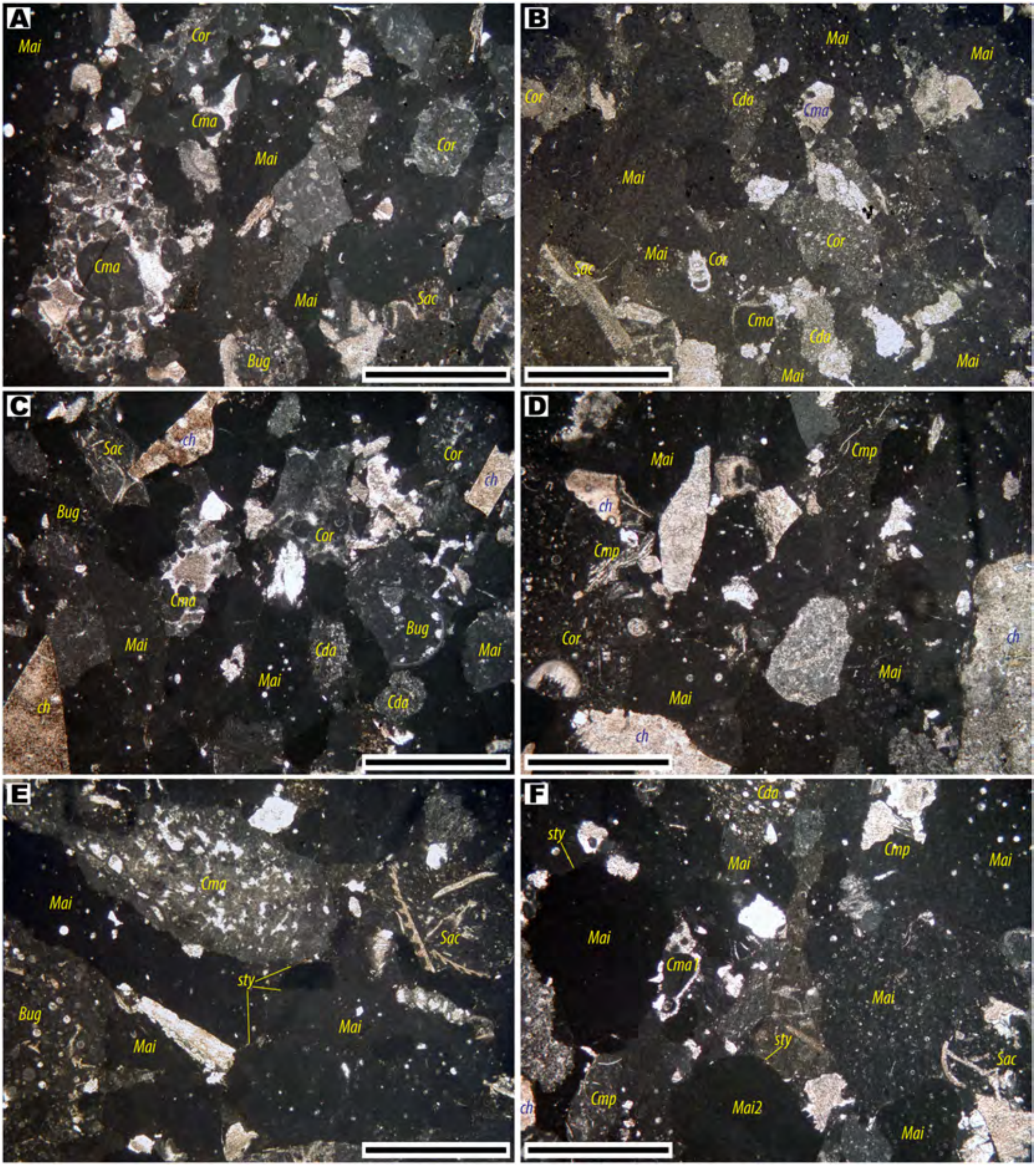
A
Mai
Cor
Cma
Mai
Cor
Cma
Mai
Sac
Bug
B
Mai
Mai
Cor
Cda
Cma
Mai
Cor
Sac
Mai
Cor
Cma
Cda
Mai
Mai
C
ch
Sac
Cor
ch
Bug
Cor
Cma
Bug
Mai
Cda
Mai
Mai
ch
Cda
D
Mai
Cmp
ch
Cmp
Cor
ch
Mai
Mai
ch
E
Cma
Mai
Sac
sty
Bug
Mai
Mai
F
Cda
sty
Cmp
Mai
Mai
Mai
Cma1
Mai
sty
Sac
Cmp
Mai2
ch
Mai

Figure 6

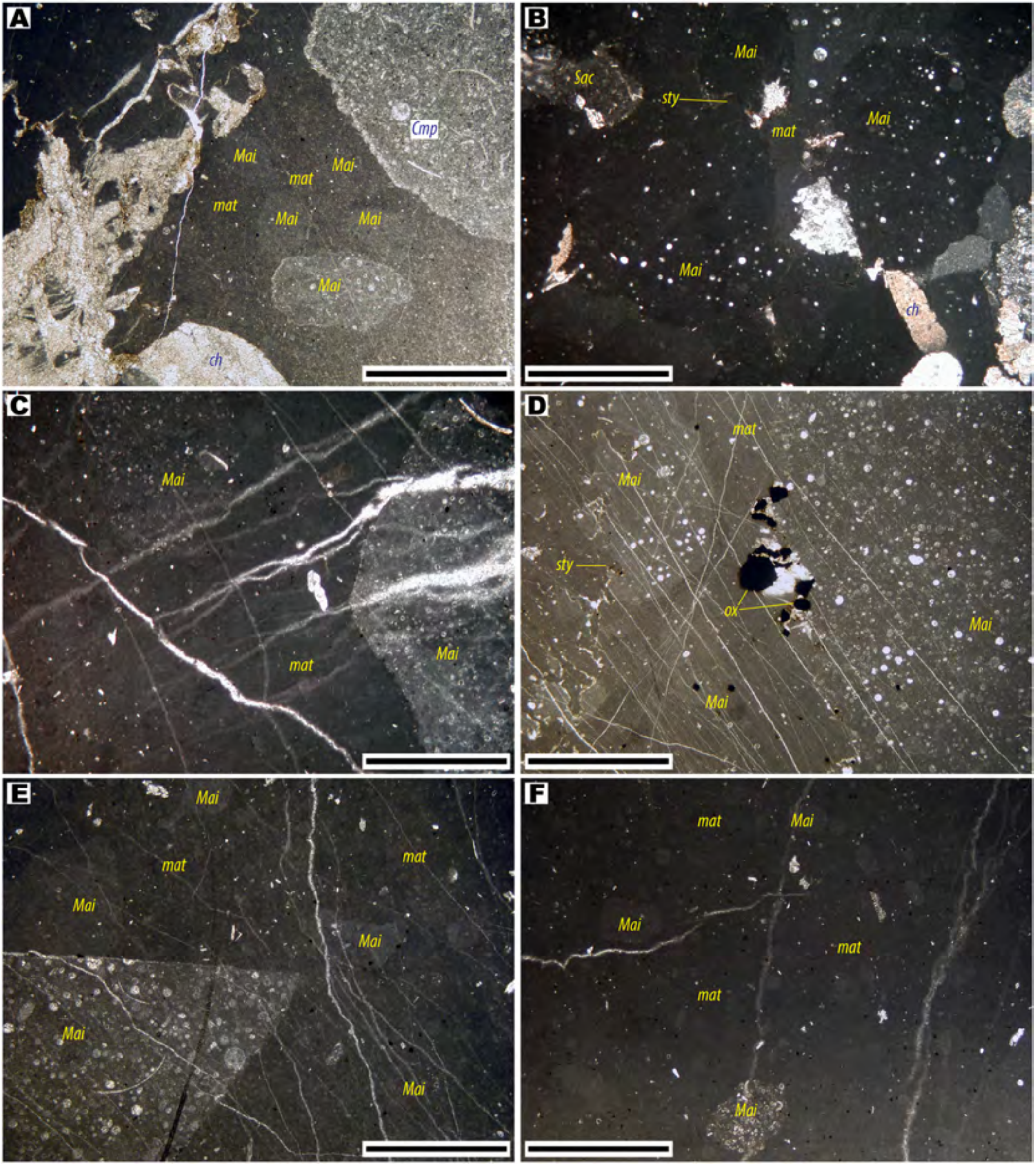
A
Cmp
Mai
mat
Mai
mat
Mai
Mai
Mai
ch
B
Mai
Sac
sty
mat
Mai
Mai
ch
C
Mai
mat
Mai
D
mat
Mai
sty
ox
Mai
Mai
E
Mai
mat
mat
Mai
Mai
Mai
Mai
F
mat
Mai
Mai
mat
mat
Mai

Figure 7

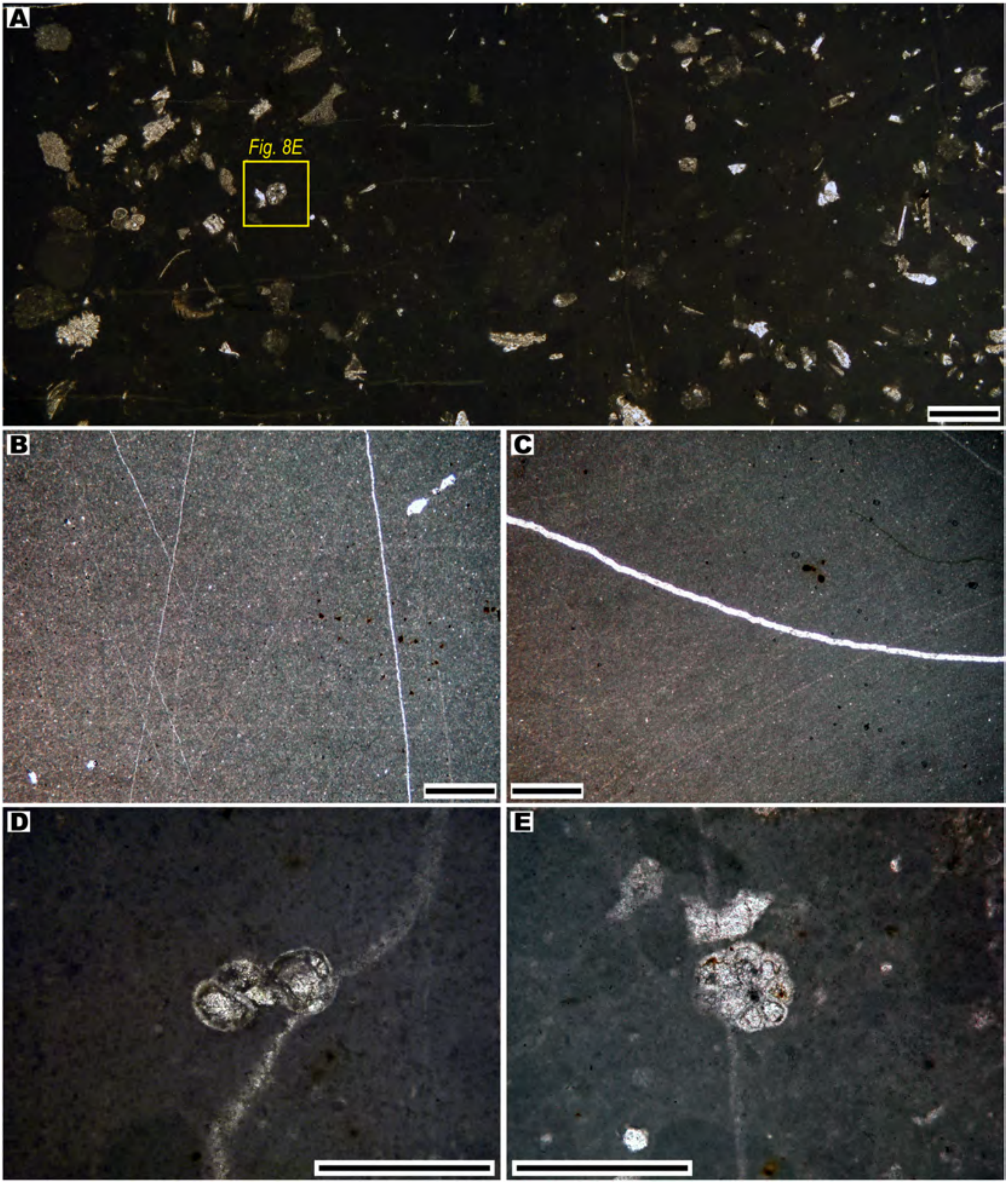

Figure 8

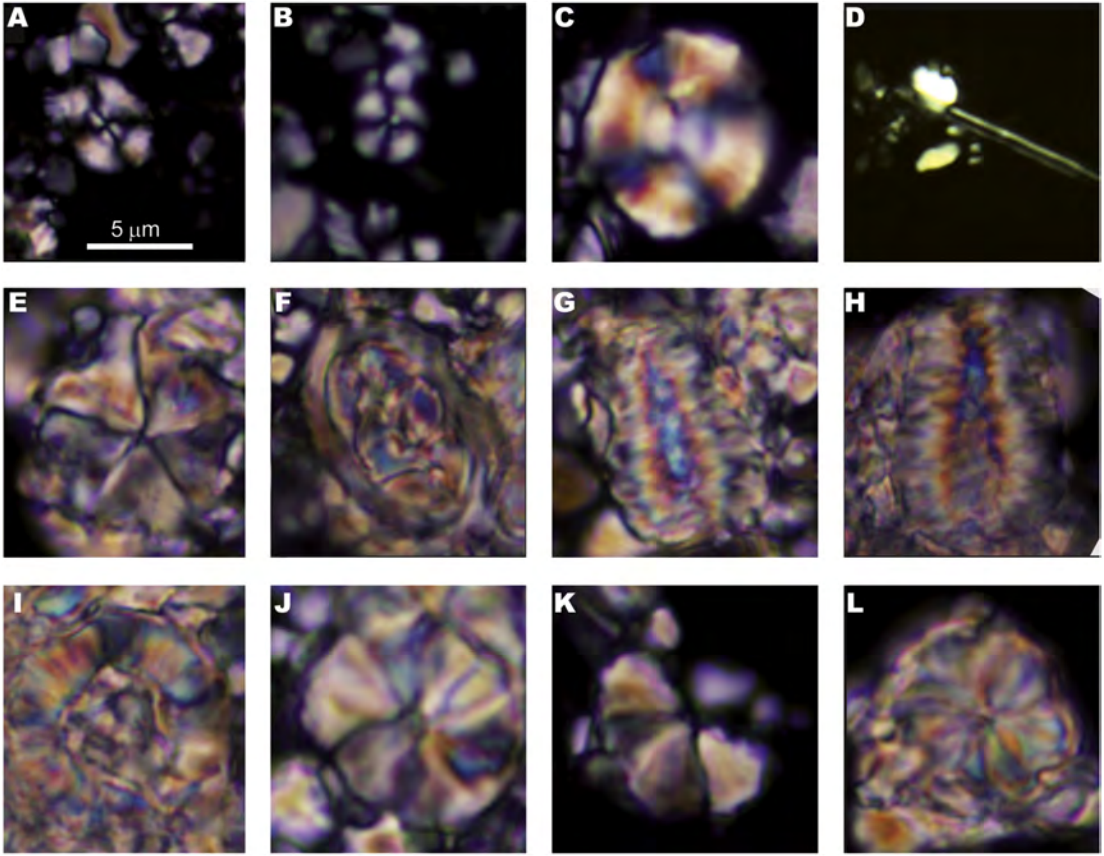

Figure 9

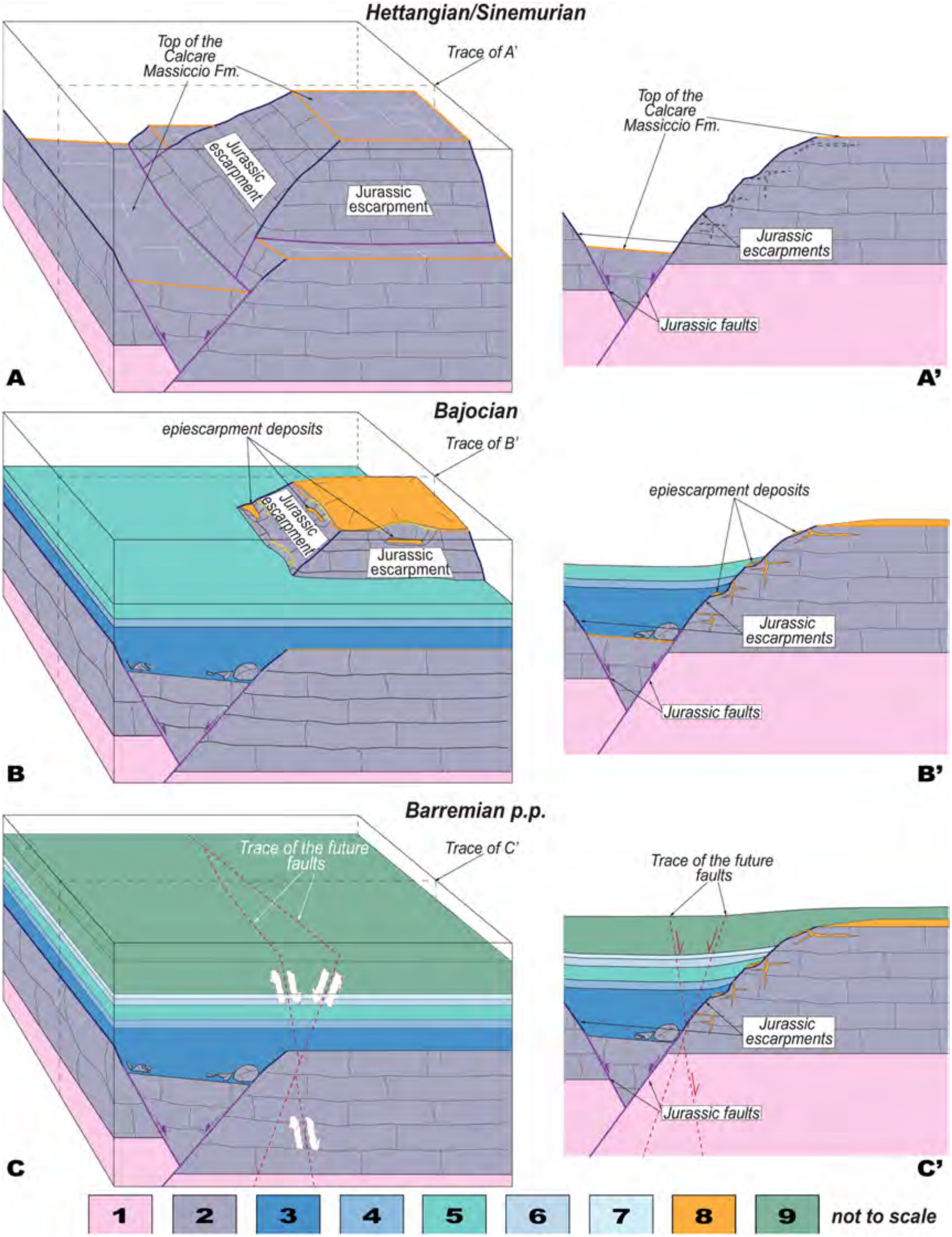
Hettangian/Sinemurian
Top of the Calcare Massiccio Fm.
Trace of A'
Jurassic escarpment
Jurassic escarpment
A
Top of the Calcare Massiccio Fm.
Jurassic escarpments
Jurassic faults
A'
Bajocian
epiescarpment deposits
Trace of B'
Jurassic escarpment
Jurassic escarpment
B
epiescarpment deposits
Jurassic escarpments
Jurassic faults
B'
Barremian p.p.
Trace of the future faults
Trace of C'
C
Trace of the future faults
Jurassic escarpments
Jurassic faults
C'
1
2
3
4
5
6
7
8
9
not to scale

Figure 10

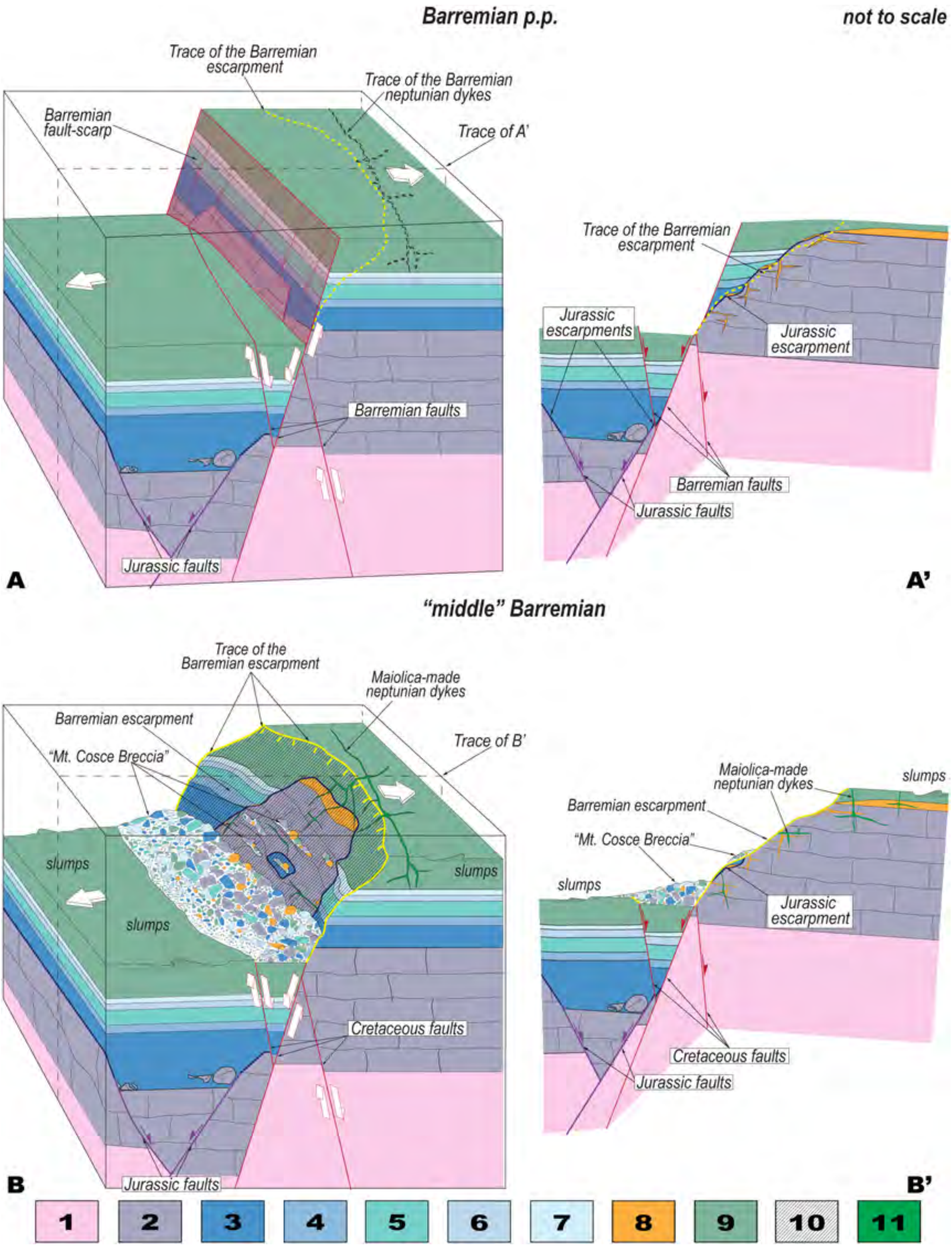
Barremian p.p.
not to scale
Trace of the Barremian escarpment
Trace of the Barremian neptunian dykes
Barremian fault-scarp
Trace of A'
Barremian faults
Jurassic faults
Trace of the Barremian escarpment
Jurassic escarpments
Jurassic escarpment
Barremian faults
Jurassic faults
A
A'
"middle" Barremian
Trace of the Barremian escarpment
Maiolica-made neptunian dykes
Barremian escarpment
"Mt. Cosce Breccia"
Trace of B'
slumps
slumps
slumps
Cretaceous faults
Jurassic faults
Maiolica-made neptunian dykes
slumps
Barremian escarpment
"Mt. Cosce Breccia"
slumps
Jurassic escarpment
Cretaceous faults
Jurassic faults
B
B'
1
2
3
4
5
6
7
8
9
10
11

Figure 11