





Q2 The Monterey Event in the Mediterranean platform to basin transition: The Guadagnolo Formation (Miocene, Prenestini Mountains, Central Apennines)

 The corrections made in this section will be reviewed and approved by a journal production editor.

Q3 Q4 Marco ^a marco.brandano@uniroma1.it, Irene ^{b,*} irene.comacchia@igg.cnr.it, Rita ^b rita.catanzariti@igg.cnr.it, Laura ^a laura.tomassetti@uniroma1.it

^aDipartimento di Scienze della Terra, Sapienza Università di Roma, P.le Aldo Moro 5, 00185 Roma, Italy

^bIstituto di Geoscienze e Georisorse IGG-CNR, Via G. Moruzzi 1, 56124 Pisa, Italy

*Corresponding author.

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Abstract

The stratigraphic evolution of the Guadagnolo Fm, developed on the transition between the Latium-Abruzzi Platform and the Umbria Sabina Basin (central Apennines), was studied through facies and stable isotope analysis. Calcareous nanofossil biostratigraphy allows to identify the Burdigalian-Langhian boundary, constraining the sections to the lower to middle Miocene. This interval consists of marly deposits forming the intermediate member of the formation dominated by sponge spicules, molluscs, bryozoans, benthic and planktonic foraminifers. This member is deposited in a distal outer ramp where the abundance of siliceous sponges has been attributed to the high seawater fertility coinciding with the Monterey event, enhanced by regional nutrient flux due to continental runoff and volcanism. The upper member is Serravallian and consists of bryozoan-dominated cross-bedded calcarenites deposited in a shallower environment of the outer ramp. A positive carbon isotope excursion was correlated with the Monterey event recorded in the Central Apennines carbonate ramps and from ODP sites. Five carbon maxima belonging to the Monterey Carbon Isotope Excursion have been identified. Four carbon isotope peaks fall in the spongolitic member, one in the upper member. The Carbon Maxima recorded within the spongolitic member show an attenuate isotope excursion compared with the pelagic and the carbonate platforms record. The weaker signal is due to the fractionation effect of primary producers of the photic zone and to the sponge release of ¹²C-enriched CO₂ deriving from the oxidation of organic matter. Conversely, the largest positive carbon isotope excursion is recorded in the upper member, representative of a shallower environment, and it is due to the absence of sponges and the increased contribution of photosynthetic biota. The shoaling of the depositional environment is related to the global cooling recorded after 14 Ma, as evident also from the δ¹⁸O positive shift at the base of the upper member of the Guadagnolo Fm.

Keywords: Carbon isotope stratigraphy;  Biostratigraphy; Latium-Abruzzi platform; Siliceous sediments

1 Introduction

Silica-rich sediments accumulated between the early and the middle Miocene both in neritic and pelagic environments of the Mediterranean (Moret, 1924; Guerrero, 1977; Carboni et al., 1982; Civitelli et al., 1987; Amorosi et al., 1994, 1995), of the Pacific (Flower and Kennett, 1993; Minoura et al., 1996) and Atlantic margins (Maurrasse, 1993; Pisera et al., 2006). During this time interval, the Mediterranean area was affected by major paleogeographic changes. The relative movements between the Arabian and African plates led to the shoaling and intermittent closure of the Indian gateway, which was definitely sealed in the Langhian (Rögl, 1999; Popov et al., 2004). The eastward migration of the Apennine orogenic system was associated with an eastward extensional wave, which induced the opening of Valencia trough, Provençal basin and Tyrrhenian basin (Carminati et al., 2012). The extensional wave was associated with the subduction-related volcanism that influenced the seawater chemistry of the Mediterranean (Lustrino et al., 2009; Kocsis et al., 2008; Comacchia et al., 2018), potentially affecting carbonate production as well.

At global scale, the end of early Miocene was characterized by the onset of a long-lasting global carbon cycle perturbation known as the Monterey Event, recorded by the occurrence of large amounts of organic carbon stored in

the locality of Monterey (California, USA; Vincent and Berger, 1985; Woodruff and Savin, 1991). Six carbon maxima form the Monterey Carbon isotope excursion. These peaks are orbitally paced and occurred between 17 and 13.6 Ma (Woodruff and Savin, 1985, 1991; Holbourn et al., 2004, 2007). The Monterey Event was associated with the Middle Miocene Climatic Optimum (MMCO, 17–14.7 Ma, Zachos et al., 2001), which represents the warmest time interval of the Cenozoic icehouse climate (Woodruff and Savin, 1991; Holbourn et al., 2015).

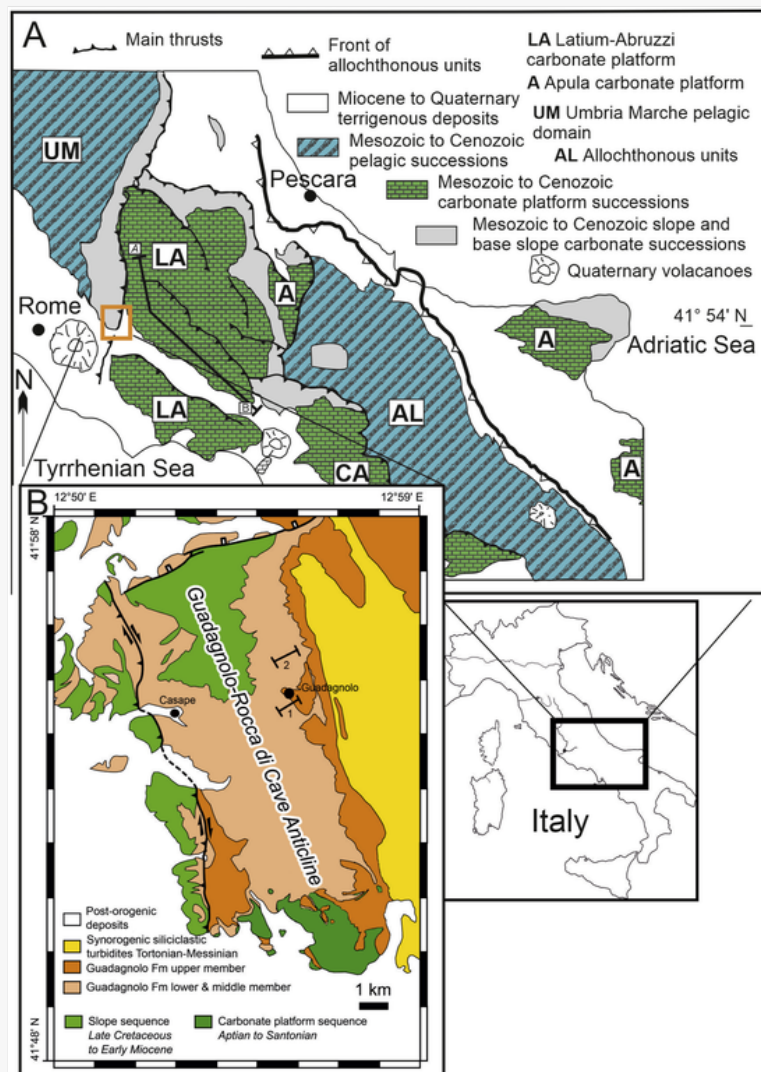
The Monterey Carbon Isotope Excursion has been identified in the Mediterranean record of hemipelagic successions (Jacobs et al., 1996; John et al., 2003; Kocsis et al., 2008), as well as in platform settings (Brandano et al., 2017; Salocchi et al., 2018). In the platform domains of the Central Apennine (Latium-Abruzzi and Apulian platforms), the positive carbon isotope shift related to the Monterey Event is twice as wide as in the deep pelagic settings of the Mediterranean and up to four times wider than the ODP sites.

During the time coinciding with the Monterey event, the shallow-water carbonate production was dominated by coralline algae (Halfar and Mutti, 2005). They occur frequently as rhodolith pavements within the mesophotic and oligophotic zones in mesotrophic, inner- and middle ramp environments (Bourrouilh-Le Jan and Hottinger, 1988; Carannante et al., 1988; Braga, 2017; Brandano et al., 2017). In the Mediterranean, the carbonate ramps during this interval suffered a deterioration of trophic conditions and a consequent expansion of the mesophotic factories (Pomar et al., 2012; Brandano et al., 2017), with the spreading of bryozoans facies in the aphotic zone linked to increased nutrient availability in surface waters (Brandano et al., 2017). The highest carbon isotope peaks of Monterey recorded in the Latium-Abruzzi platform coincide with facies changes and a huge spreading of the bryozoan-dominated factory, which in turn controlled the geometry of these ramps (Brandano et al., 2010, 2017).

In this work, the lower to upper Miocene siliceous deposits represented by the Guadagnolo Fm have been investigated. This Formation deposited in the transition zone between the Latium-Abruzzi (LA) carbonate platform domain and Umbro-Sabina pelagic domain (Fig. 1). The stratigraphic framework of this formation has never been extensively analysed, only few attempts have been made based on strontium isotopes performed on sediment bulk (Madonna, 1996; Barbieri et al., 2003/2004).

alt-text: Fig. 1

Figure 1: Fig. 1



This paper aims to i) propose a revised stratigraphic framework of Guadagnolo Fm; ii) identify the Monterey Carbon Isotope Excursion in the transitional platform to basin setting; iii) discriminate global and regional factors which concurred in controlling carbonate production changes; iv) correlate the deep carbon isotope signal with the shallower record of the Latium-Abruzzi Platform to provide new insights into the carbon cycle dynamics during this global perturbation.

2.2 Geological Setting

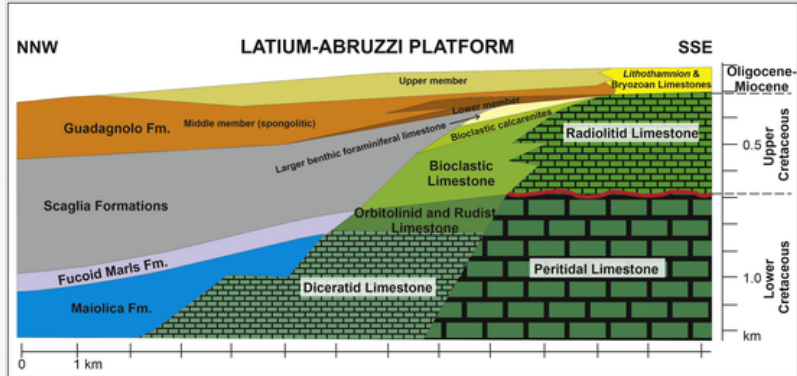
The Apennine orogeny is the result of a west-directed subduction linked to the inversion of the Alpine-Betic subduction after the late Eocene (Doglioni, 1991; Lustrino et al., 2009; Carminati et al., 2012). The Apennine orogeny developed mostly from the Neogene to the Quaternary, with the east-directed migration of the accretionary wedge and front, and the contemporary extension in the western back-arc area (Gueguen et al., 1998). Volcanism related to the Apennine subduction characterizes the Western Mediterranean from the Oligocene to the present, but with a peak, with respect to the volumes erupted, in the early Miocene between 21 and 18 Ma (Lustrino et al., 2009).

The sedimentary succession of the Central Apennines comprises two platform and basinal domains, respectively the Latium-Abruzzi Platform and the Apulian Platform, and the Monte Genzana-Molisano Basin that separated the platforms, as well as the Umbria-Marche Basin, extended northward (Fig. 1, Bernoulli, 2001; Parotto and Praturlon, 2004).

The Latium Abruzzi Platform consists of Triassic to Miocene shallow water carbonates. The Mesozoic carbonates represent the deposition of a flat-topped open shelf platform on which was superimposed a carbonate ramp system in the lower Miocene, represented by the *Lithothamnion* and Bryozoan Limestones (LBL) Fm (Fig. 2). Between the Upper Cretaceous platform and the lower Miocene ramp, a Paleogene long-lasting hiatus occurs (Accordi et al., 1967; Brandano, 2017). This hiatus has its maximum duration within the inner Mesozoic platform, while along the margins discontinuous Cenozoic deposits occur (Tomassetti et al., 2016; Tomassetti and Benedetti, 2020). These deposits were fed by the productive internal areas of the platform and accumulated locally on the margin, mainly at the toe of the slope where they interfingered with the basinal deposits of the Umbro-Sabina Basin represented by the detritic Cenozoic Scaglia and by Bisciaro Fms (Civitelli et al., 1986a; Brandano et al., 2015; Tomassetti and Benedetti, 2020). At the end of the Oligocene the sedimentation between the Latium Abruzzi platform and the Umbro-Sabina Basin, the transitional zone sensu Carboni et al. (1982), was represented by the Guadagnolo Fm (Fig. 1; 3). The Guadagnolo Fm consists of three informal members (Civitelli et al., 1986b). The lower member is 100 m thick, and consists of alternating rudstone, packstone to grainstone and planktonic wackestone with cherty nodules. The coarse bioclastic beds represent turbidites and other gravity-flow deposits containing lithic and bioclastic sand and gravel transported downslope from the shelf (Civitelli et al., 1986b; Brandano et al., 2005). The middle member (Burdigalian-Langhian in age), which is the main focus of this study, known also as “spongolitic member” due to dominance of sponge spicules, is up to 600 m-thick and consists of an alternation of marls, calcareous marls and bioclastic calcarenites. Carboni et al. (1992) recognized in this member two main genera of hexactinellid siliceous sponge: *Aphrocallistes* and *Loacaetis*. The marly deposits are abundantly bioturbated and dominated by planktonic foraminifera and sponge spicules, whilst the calcarenitic portion is dominated by skeletal debris of echinoids, bryozoans and molluscs (Civitelli et al., 1986b; Barbieri et al., 2003/2004). The upper member (Langhian-Tortonian in age) of the Guadagnolo Fm consists of coarse bryozoan rich floatstones to grainstones and rests unconformably on the underlying spongolitic member (Civitelli et al., 1986b; Barbieri et al., 2003/2004; Brandano et al., 2015). The sedimentation of the Guadagnolo Fm ended when the Latium-Abruzzi Platform faced the deepening of the area due to the migration of the Apennines foredeep system, as testified by the onset of the hemipelagic sedimentation of the *Orbulina* Marls (upper Tortonian) followed by the turbiditic flysch deposition in the Messinian (Cipollari and Cosentino, 1992; Vezzani et al., 2010).

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Figure 2: Fig. 2



Stratigraphic architecture of the Latium-Abruzzi Platform Domain (modified and redrawn from [Brandano et al., 2015](#)).

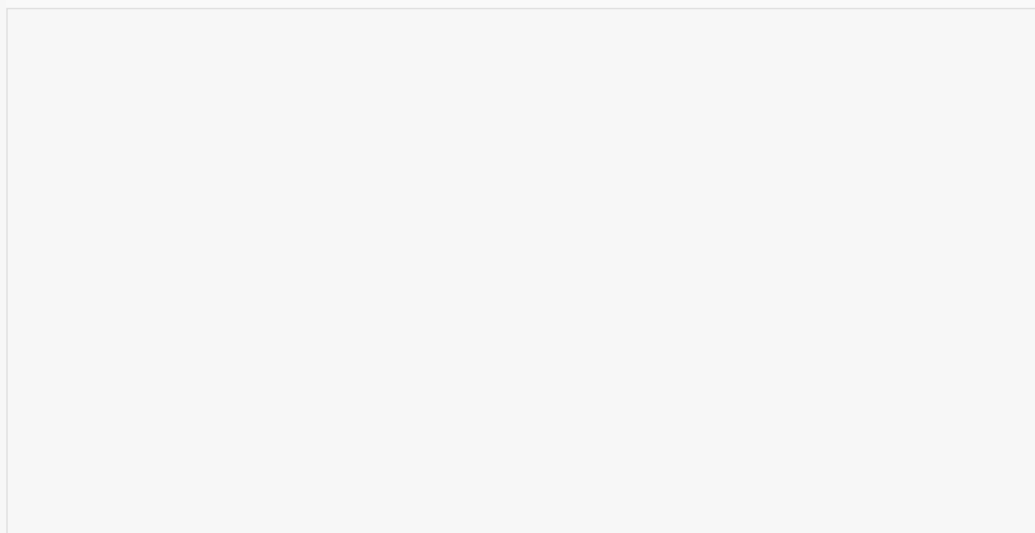
3.3 Methods

Two stratigraphic sections (named Cerella and Guadagnolo sections) belonging to the Guadagnolo Fm have been logged and sampled for isotope analysis. Thin section examination was conducted for textural characterisation and identification of skeletal components.

Carbon and oxygen stable isotopes have been measured on eighty-five bulk-rock samples, with a Finnigan Mar 232 RPQ multicollector mass spectrometer of the Istituto di Geologia Ambientale e Geoingegneria (IGAG-CNR). All the results have been calibrated against the international standard for carbonate rocks NBS19. The oxygen and carbon isotope compositions are reported as deviation in part per mil relative to the PDB (Pee DeeBelemnite) standard. The analytical error is $\pm 0.05\%$ based on replicate analyses of the standard.

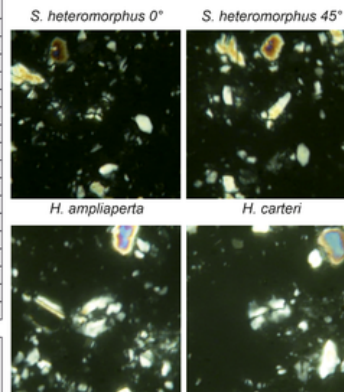
Calcareous nannofossil assemblages have been analysed on twenty smear-slides belonging to different marly interlayers of the Guadagnolo stratigraphic section to provide new age-constraints of the Guadagnolo Fm. Smear-slides have been prepared from unprocessed material following the standard techniques suggested for simple smear slide preparation by [Bown and Young \(1998\)](#). Observations have been performed using a polarising light microscope at 1250~~x~~~~x~~ magnification. Data have been collected with semi-quantitative methods, the relative frequencies of index species have been defined counting them in term of specimens in a prefixed area of the slide (200 FOV-fields of view, roughly corresponding to 4 mm²), and then normalized to 1 mm². The total abundances have been reported as letters, using R (Rare, <5 forms per FOV), F (Few, 5-10 forms per FOV), C (Common, >10 forms per FOV). The occurrence of non-index species has been evaluated only as mere presence (P), on account of the fact that it would be difficult to discriminate between reworked and not-reworked specimens. The taxa considered in the nannofossil assemblages are referenced in [Young et al. \(2017\)](#). The zonal assignment follows the scheme proposed by [Di Stefano et al. \(2008\)](#), as implemented by [Iaccarino et al. \(2011\)](#), for the early to middle Miocene time interval of the Mediterranean area ([Table 1](#)).

Distribution of the calcareous nannofossils ~~recognised~~~~recognized~~ in the Cerella and Guadagnolo stratigraphic sections. R_i=Rare, F_i=Few, C_i=Common, P_i=Present and not counted. The subzones are referred to the biostratigraphic scheme proposed by [Di Stefano et al. \(2008\)](#) as implemented by [Iaccarino et al. \(2011\)](#). The microphotographs of the main markers recognized (*H. ampliaperta*, *H. carteri* and *S. heteromorphus*) are shown next to the table.



Guadagnolo		Total abundance	N°/mm ²					Occurrence					Calcareous nannofossil tubercle	Age	meter
Sample	lithology		C. premonchyloni	H. ampliaperla	H. carteri	S. heteromorphus	C. pelagicus	Diphycooides + Reticulolamella (small)	Sphaerulites spp.	Paleogenic reworking	Calcareous nannofossil tubercle				
GN15bis	R	0.5	0.0	2.0	1.0	P	P	P	P	P					89.0
GN15	R	0.0	0.0	0.0	0.0	/	/	/	/	/					88.0
GN14bis	R	0.0	0.0	0.0	0.0	/	/	/	/	/					87.75
GN14bis	R	0.0	0.0	0.0	0.0	/	/	/	/	/					87.75
GN13	Barenen	0.0	0.0	0.0	0.0	/	/	/	/	/					74.33
GN12	Barenen	0.0	0.0	0.0	0.0	/	/	/	/	/					71.5
GN11	R	0.0	0.0	0.0	0.0	P	P	P	P	P					65.9
GN10	F	0.0	0.0	0.0	0.3	P	P	P	P	P					63.5
GN9	C	0.0	0.0	5.0	4.0	P	P	P	P	P					48.7
GN8	F	0.0	0.0	0.0	0.0	P	P	P	P	P					46.00
GN7	F	0.0	0.0	0.0	0.0	P	P	P	P	P					29.4
GN6	F	0.0	3.0	0.5	0.0	P	P	P	P	P					9.35
GN5	F	0.0	0.0	0.0	0.0	P	P	P	P	P					8.22
GN4	F	0.0	0.0	0.0	0.0	P	P	P	P	P					5.75
GN3	F	0.0	1.5	0.5	4.0	P	P	P	P	P					5.00
GN2	F	0.0	1.0	0.0	3.0	P	P	P	P	P					4.66
GN1	F	0.0	0.0	0.0	0.0	P	P	P	P	P					3.75

Cerella		Total abundance	N°/mm ²					Occurrence					Calcareous nannofossil tubercle	Age	meter
Sample	lithology		C. premonchyloni	H. ampliaperla	H. carteri	S. heteromorphus	C. pelagicus	Diphycooides + Reticulolamella (small)	Sphaerulites spp.	Paleogenic reworking	Calcareous nannofossil tubercle				
CN3	R	0.0	0.0	0.5	0.5	P	P	P	P	P					117.0
CN2	F	0.0	0.0	1.0	3.0	P	P	P	P	P					100.0
CN1	C	0.0	8.0	7.0	53.0	P	P	P	P	P					75.0



1 Please delete bis from the first GN14. The samples are GN14 and GN14bis

4.4 Results

4.1.4.1 Stratigraphic sections

This study focuses on the middle and upper members of the Guadagnolo Fm, analyzing the carbon isotope record of whole-rock samples belonging to two different stratigraphic sections: the Cerella and the Guadagnolo sections (Fig. 1; 44; 55). In the following paragraph a brief description of the stratigraphic sections will be shown.

4.1.1.4.1.1 The Cerella stratigraphic section

The Cerella stratigraphic section (N 41° 55' 03.15", E 12° 55' 50.18") (Fig. 1B; 44A-B; 55A) is 118 m-thick and consists of the middle member of the Guadagnolo Fm here represented by monotonous stack of calcareous marly deposits. Three main lithofacies have been recognized (Fig. 5A). The first lithofacies is represented by bioclastic calcarenites texturally constituted by packstones to grainstones with small benthic foraminifers (rotaliids, textularids), bryozoans and abundant echinoid fragments (Fig. 4B; 55A; 66A). The second lithofacies consists of bioturbated marly limestones, characterized by a packstone texture with rotaliids, buliminaceans, *Lenticulina*, echinoid fragments, sponge spicules and planktonic foraminifers (Fig. 4B; 55A). The last lithofacies is represented by bioturbated marls, from a textural point of view they range from packstone to wackestone rich in planktonic foraminifers and sponge spicules (Fig. 5A; 66B). Glauconite and phosphate grains are frequent in this lithofacies.

4.1.1.1.4.1.1.1 The Cerella carbon and oxygen isotope records

The overall $\delta^{13}\text{C}$ curve of the Cerella stratigraphic section spans from +0.14‰ to +1.20‰ (Fig. 5A). From the base of the section to 31 m, the $\delta^{13}\text{C}$ shows a trend towards lighter values, followed by an opposite trend toward heavier values up to 55 m. Upwards, the $\delta^{13}\text{C}$ curve shows a long-term trend towards heavier values, punctuated by a short-term cyclic pattern where five heavier peaks alternate with lighter carbon isotope values up to the end of the section.

The overall $\delta^{18}\text{O}$ record of the Cerella section spans from -0.63‰ to +0.80‰ (Fig. 5A). From the base of the section to 38 m, the $\delta^{18}\text{O}$ curve shows a short-term cyclic pattern, followed by a more stable signal up to 70 m. Upwards, the $\delta^{18}\text{O}$ curve shows a tenue trend towards heavier values, punctuated by sharp opposite spikes towards lighter isotope values.

4.1.2.4.1.2 The Guadagnolo stratigraphic section

The Guadagnolo stratigraphic section (N 41° 54' 40.74", E 12° 55' 42.61") (Fig. 1B; 44C-D; 5B) is 92 m-thick and comprises the upper portion of the middle member and the lower part of the upper member of the Guadagnolo Fm.

The boundary between the middle and upper members of the Guadagnolo Fm crops out at 74.5 m (Fig. 4C; 5B) and is marked by a major unconformity. The basal and middle portion of the section are characterized by the same lithofacies recognized in the Cerella stratigraphic section, in particular these parts are organized with an alternation of bioclastic calcarenites (packstone to grainstones) with benthic foraminifers, bryozoans, echinoid fragments, marly limestones and marls dominated by sponge spicules and planktonic foraminifers (Fig. 6C). The upper portion of the

Guadagnolo section is characterized by coarse, cross-bedded bioclastic calcarenites dominated by bryozoans, echinoid fragments and small benthic foraminifers, mainly rotaliids and textularids (Fig. 4D; 66D).

4.1.2.1:4.1.2.1 The Guadagnolo carbon and oxygen isotope records

The overall $\delta^{13}\text{C}$ curve of the Guadagnolo stratigraphic section spans from +0.17‰ to +1.76‰ (Fig. 5B). From the base of the section to 54 m, the $\delta^{13}\text{C}$ curve shows a trend towards lighter values, followed by a long-term trend towards heavier values up to the end of the section. This long-term trend is interrupted only by a short-term opposite trend towards lighter values, attested between 67 and 73 m.

The overall oxygen isotope ratios of the Guadagnolo stratigraphic section span from -0.70‰ to +1.10‰ (Fig. 5B). From the base of the section to 54 m, the $\delta^{18}\text{O}$ curve shows a trend towards lighter values, followed by an opposite trend towards heavier values up to 84 m. Lastly, the uppermost portion of the sections shows the $\delta^{18}\text{O}$ values decreasing again towards lighter isotope ratios.

4.1.2.2:4.1.2.2 Calcareous nannofossil biostratigraphy

Five on seventeen samples collected in the Guadagnolo stratigraphic section were found to be barren in calcareous nannofossils, matching very well with lithologies unsuitable to contain this fossil group. The other samples, three of which coming from the Cerella section (CN1-CN3), contain assemblages characterized by scarce and poor preserved specimens, referable to the genera *Coccolithus*, *Cyclicargolithus*, *Dictyococites*, *Reticulofenestra*, *Sphenolithus* (partly represented by Paleogene reworked forms) and to the species *Calcidiscus premacintyreii*, *Helicosphaera ampliaperta*, *Helicosphaera carteri*. However, on the presence of marker and index species it was possible to identify the lower to middle Miocene time interval (Fig. 7). In fact, the Burdigalian MNN4a Subzone was detected in the CN1 sample, at 75 m of the Cerella section, on the co-occurrence of *Sphenolithus heteromorphus* and *H. ampliaperta* (Table 1). The interval sampled from 100 m to 117 m in the Cerella section and the interval sampled from 3.75 m to 5 m in the Guadagnolo section were assigned to the Burdigalian-Langhian MNN4b Subzone because of the low abundance or absence of *H. ampliaperta* above its last common occurrence (Table 1). The Langhian MNN4c Subzone was detected in the Guadagnolo section from 5.75 to 46 m, in samples where the absence of *S. heteromorphus* allows the identification of its paracme interval. Taking into account the events Paracme Beginning (PB) and Paracme End (PE) of *S. heteromorphus*, recognizable in the stratigraphic succession, and their calibration in the Mediterranean according to Turco et al. (2017), ages around 15.56 Ma and 15.24 Ma, may be supposed for the sediments where they occur. In addition, the occurrence of *H. ampliaperta*, detected at 9.35 m of the Guadagnolo section, in sample GN6, during the *S. heteromorphus* paracme interval, may be interpreted as the *H. ampliaperta* Abundance Spike (AS) event (firstly defined in Fornaciari et al., 1996), corresponding to the Influx_2 of Turco et al. (2011) and calibrated to 15.42 Ma in Turco et al. (2017). Finally, the base of the Langhian MNN5a Subzone was supposed at 48.7 m in the Guadagnolo section, on the re-occurrence of *S. heteromorphus* above its paracme interval (Table 1). Above this level, samples are barren or depleted in calcareous nannofossils so that the upper part of the section cannot be dated confidently. However, the occurrence of *S. heteromorphus* in sample GN15Bbis, at 88 m, constrains the upper part of the Guadagnolo Fm below the last occurrence (LO) of *S. heteromorphus*, calibrated to 13.34 Ma in Abdul Aziz et al. (2008).

5.5 Discussion

The stable isotope study coupled with the nannofossil biostratigraphic analysis performed on the Guadagnolo Fm in the investigated sections, allowed to identify the main isotopic excursion at the Burdigalian-Langhian boundary coinciding with the Monterey event. Furthermore, the isotope excursion has been correlated with the coeval signatures of nearby carbonate platform successions in order to discriminate global and regional factors controlling the type of sediment produced and isotope record in the basin to platform transitional environment.

5.1.5.1 The siliceous benthic factory

Paleoceanographic changes occurring during early to middle Miocene were frequently associated with increase of upwelling intensity (White et al., 1992; Holbourn et al., 2014), accompanied by large-scale organic-carbon-rich sedimentation that affected the global carbon cycle and climatic change (Flower and Kennett, 1993). Extensive marine calcareous-siliceous deposition characterizes at global level many costal and pelagic areas during the time interval coinciding with the Monterey event (Keller and Barron, 1983; Flower and Kennett, 1993; Maurrasse, 1993; Pisera et al., 2006; Holbourn et al., 2014). These evidences originated analyzing the strata of Monterey Fm throughout the California, which were characterized by high biogenic silica and generally high organic carbon contents (White et al., 1992; Flower and Kennett, 1993). Generally, the siliceous sedimentary deposits are commonly interpreted as products of high surface water fertility conditions produced by nutrient-rich subsurface waters supported by upwelling activity (Keller and Barron, 1983; Holbourn et al., 2014). Classically, the main components of this siliceous deposits are diatoms, in fact the increased photosynthesis by diatom activity facilitates transfer of atmospheric carbon dioxide to the ocean, hence connecting silicon to carbon cycles. The Miocene siliceous deposits of the outer ramp environments of Mediterranean area, in particular of Guadagnolo Fm, are typically dominated by sponge spicules. Sponges are

benthonic and opportunistic suspension feeders that process rapidly large volumes of water and incorporate particulate and dissolved nutrients. Even if the uptake of dissolved siliceous rates by sponges are clearly lower on average than those of diatoms, it has been recently demonstrated that siliceous sponges give an important contribute in sinking silica on continental margins (Maldonado et al., 2011, 2012). The siliceous sponges utilize dissolved silicate to construct their opaline skeleton, therefore need access ~~the~~ constant input of silica supplied by rivers runoff, upwelling of oceanic waters onto continental shelves and volcanism. Consequently, the sponges can expand with increasing availability of silica, however differently from diatoms, which are photosynthetic organisms, the sponges ingest and remove substantial amounts of organic matter from the passing water (Maldonado et al., 2012). These organisms have an important role in organic matter processing and benthic–pelagic coupling, therefore they enter anyway in the carbon cycle.

The deposits of the Guadagnolo Fm, in particular the middle “spongolitic” member, accumulated during a long lasting interval (Burdigalian–Langhian) of global high seawater fertility, and enhanced regional nutrient flux due to continental ~~Q6~~ run-off and volcanism related to the Alps and Apennines orogeneses (Carminati et al., 2012, Brandano et al., 2010, 2015). The evolution of the different orogenesis systems of the Mediterranean area strongly influenced the seawater circulation, favoring the development of coastal upwellings (Föllmi et al., 2008, 2015; Brandano et al., 2016). Under an enhanced nutrient flux, in this context particularly enriched in silica, phytoplankton blooms increased the surface water turbidity, thus reducing the light available for the bottom-dwelling organisms, such as zooxanthellate corals, calcareous algae or larger benthic foraminifers. The primary production represents a very good resource for filter feeder biota. Photo-independent organisms, such as bryozoans and molluscs, proliferate in the outer ramp of the Apennine platforms (Latium-Abruzzi platform and Apulian platform, Brandano et al., 2017). In the most external environment of the outer ramp and in the platform to basin transition, the dominant bottom-dwelling organisms were the siliceous sponges. These organisms were thriving under favorable conditions represented by high availability of silica and other nutrients, such as N and P, essential for their metabolisms and overall organic matter. The suspension-feeding activity of sponges (bacterioplankton, microphytoplankton, nanoplankton and picoplankton) established thus a significant trophic link between the benthos and the overlying water column during the Burdigalian and Langhian in the distal outer ramp and in the platform to basin transition of central Apennines (~~c/E~~. Maldonado et al., 2012).

5.2.5.2 Significance of C and O stable isotope records

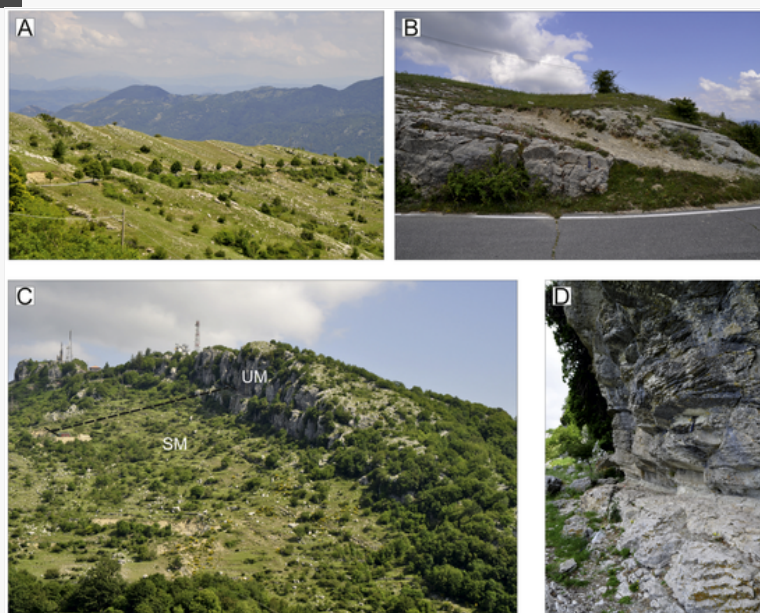
Bulk-rock carbon isotope ratios have been widely studied to identify carbon cycle perturbations since they are a proxy of the ambient seawater isotopic composition (Shackleton, 1987; Hayes et al., 1999; Weissert et al., 2008; Saltzman and Thomas, 2012 and reference therein). Carbonate producing organisms precipitate CaCO_3 in isotopic equilibrium with the Dissolved Inorganic Carbon (DIC), while temperature has a negligible effect (Emrich and Vogel, 1970). For this reason, carbon isotope ratios of bulk rock samples can be identified as a proxy of the composition of waters during carbonate precipitation, once major diagenetic effects can be ruled out. Meteoric diagenesis, in fact, tends to lower accordingly C and O isotope ratios due to the influence of freshwaters, isotopically light, and soil derived carbon, extremely negative with respect of the DIC (Burla et al., 2008). At the same time, burial diagenesis might as well lead to the dissolution of pristine carbonates and precipitation of cements at higher temperatures, which are characterized by negative oxygen isotope ratios (Colombié et al., 2011). Lastly, when analyzing bulk-rock samples the mineralogy of carbonates (aragonite vs calcite) has to be carefully considered. Among carbonate minerals, low-Mg calcite is the most stable form and therefore the less affected by diagenesis (Morse and Mackenzie, 1990). The skeletal components of the Guadagnolo Fm. are dominated by calcitic organisms, therefore less affected by diagenetic alteration. Furthermore, the carbon isotope record of the measured sections are entirely positive, while the minimum oxygen isotope ratios are ~~0.63‰~~ ~~and~~ ~~0.70‰~~ for the Cerella and Guadagnolo sections respectively. Despite being negative ratios, these values are not as negative as the typical oxygen isotope values affected by burial diagenesis. Lastly, carbonate diagenesis tends to lower C and O isotope ratios accordingly. In the analysed sections, C and O isotope ratios show a very low correlation (Pearson correlation $r = 0.39$ for a number of samples $n = 85$; Fig. 8), which argues for a negligible diagenetic effect on these bulk-rock samples.

5.3.5.3 The record of Monterey Event in the Guadagnolo Fm

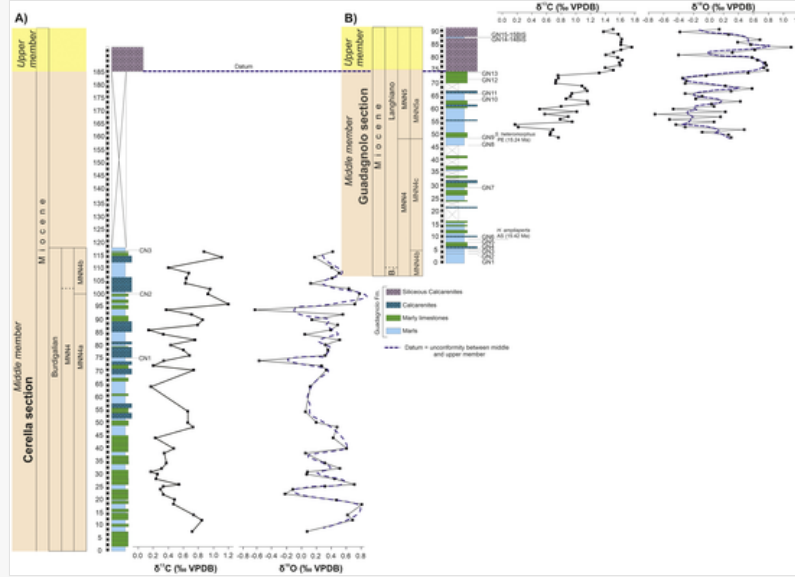
The revised stratigraphy, based on calcareous nannofossil assemblages, allow ~~s~~ to constrain the Cerella section to the Burdigalian-Langhian, with the boundary falling in the uppermost portion of the section (Fig. 5A). Accordingly, the Guadagnolo stratigraphic can be ascribed to the uppermost Burdigalian-Langhian. These new biostratigraphic constraints corroborate the physical correlation between the two sections, based on the the middle to upper member transition marked by a major unconformity and abrupt facies change recognized on the entire formation. According to new biostratigraphic tie point, the sedimentation rate for the middle member of the Guadagnolo Fm results in 3.2 cm/kyr, which would place the base of the Cerella section at ~~~18.1~~ ~~Ma~~, which is consistent with the biostratigraphic data available for the upper portion of the section. Therefore, the middle member of Guadagnolo Fm results younger than previously assessed (Barbieri et al., 2003/2004) (Fig. 3), and coinciding with the Middle Miocene Climatic Optimum and the Monterey Carbon Isotope Excursion (Zachos et al., 2001; Holbourn et al., 2004, 2007).

Serie	Stage	Guadagnolo Fm (This work)	Guadagnolo Fm Brandano & Corda (2011)	Guadagnolo Fm (Barbieri et al., 2003/04)	LA Platform (Brandano et al., 2017)
		Tor	Orbulina Marls	Orbulina Marls	Orbulina Marls
Miocene	Ser	Upper Member	Upper Member	Upper Member	Lithothamnion and Bryozoan Limestones
	Lan	Middle Member	Middle Member	Middle Member	
	Bur				
	Aq	Lower Member	Lower Member	Lower Member	
Oligoc.	Ch				

Chronostratigraphic framework of the Guadagnolo and *Lithothamnion* and Bryozoan Limestones Fms. A) Chronostratigraphic framework of the Guadagnolo Fm proposed in this work. The lower member has been dated by Brandano and Corda (2011) thanks to Larger Benthic Foraminifera (LBF) biostratigraphy (SBZ 23–25 of Cahuzac and Poignant, 1997). The middle member has been dated by calcareous nanofossil biostratigraphy (this work). B) The chronostratigraphic framework proposed by Brandano and Corda (2011) relies on LBF biostratigraphy for the lower member and to Strontium Isotope Stratigraphy (SIS) for the middle member. C) The chronostratigraphic framework proposed by Barbieri et al. (2003/2004) is based on SIS. D) The chronostratigraphic framework of the *Lithothamnion* and Bryozoan Limestones Fm is based on Brandano et al. (2017).



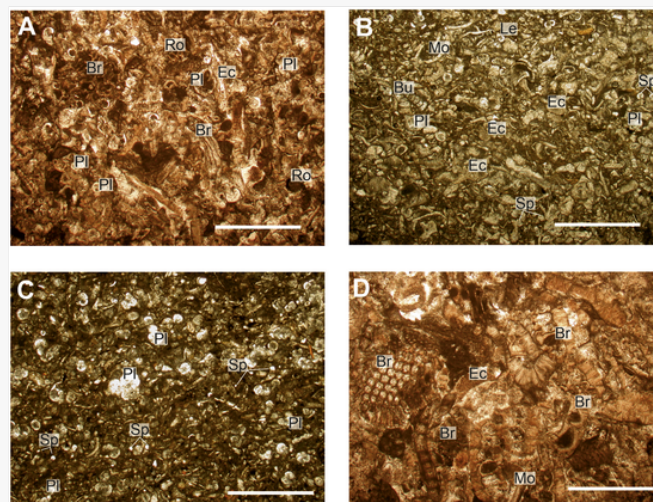
Outcrop photos. A) Cerella stratigraphic section. B) Particular of the Cerella stratigraphic section showing the alternation of limestone calcarenites and marls of the middle member of the Guadagnolo Fm. C) Guadagnolo stratigraphic section. D) Top of the Guadagnolo stratigraphic section showing the contact between the middle member and the coarse calcarenites belonging to the upper members of the Guadagnolo Fm. SM = Spongolitic member (intermediate member); UM = upper member.



Carbon and Oxygen isotope records of the measured sections plotted against stratigraphic depth. A) Cerella stratigraphic section; B) Guadagnolo stratigraphic section. The age constraints are provided by calcareous nannofossil biostratigraphy. The biostratigraphic schemes of [Fomaciani et al. \(1996\)](#); and [Di Stefano et al. \(2008\)](#), as implemented by [Iaccarino et al. \(2011\)](#) are reported. The correlation between the two stratigraphic sections is based on the identification of the calcareous nannofossil subzone MNN4b of [Iaccarino et al. \(2011\)](#), and is consistent with physical correlation between the two sections, taking as tie point the middle to upper member transition marked by a major unconformity and abrupt facies change recognized on the entire formation. For the Oxygen isotope record, a moving average is plotted with a dashed line.

alt-text: Fig. 6

Figure 6: Fig. 6

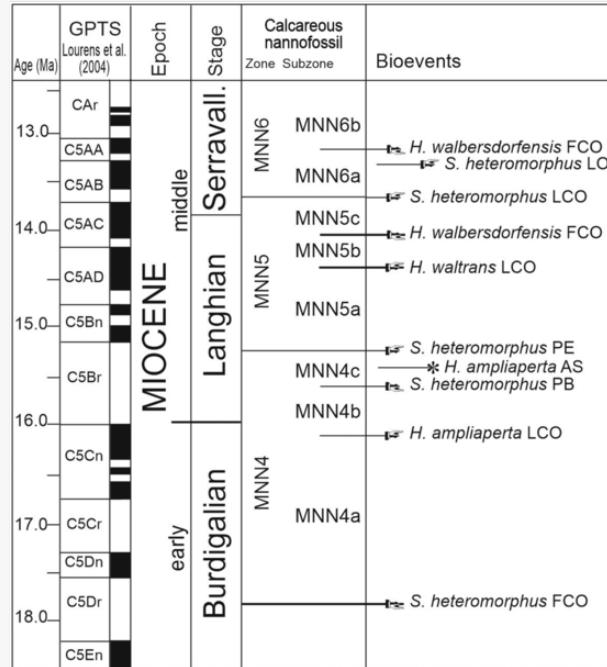


Photomicrographs of microfacies of the three informal members forming the Guadagnolo Fm. A) Bioclastic packstone from the intermediate member, the sediment consists of bryozoans, echinoid plates, small benthic foraminifers and undetermined skeletal

debris (Cerella stratigraphic section). Scale bar is 500 μm . B) Bioturbated marly limestones (middle member of Guadagnolo Fm) characterized by a packstone texture with small benthic foraminifers (rotaliids, buliminids, *Lenticulina*) echinoid fragments, sponge spicules and planktonic foraminifers (Guadagnolo stratigraphic section). Scale bar is 500 μm . C) Bioturbated marls (middle member of Guadagnolo Fm) dominated by sponge spicules and planktonic foraminifers and texturally characterized by a wackestone to fine packstone (Cerella stratigraphic section). Scale bar is 500 μm . D) Coarse bioclastic calcarenite (upper member of Guadagnolo Fm) texturally constituted by packstones to grainstones with small benthic foraminifers (rotaliids), bryozoans and abundant echinoid fragments. Scatter planktonic foraminifers occur (Guadagnolo stratigraphic section). Scale bar is 500 μm . Pl-planktonic foraminifers; Sp-sponge spicules; Ec-echinoids; Br-bryozoans; Mo-molluscs; Ro-rotaliids; Le-*Lenticulina*; Bu-buliminids.

alt-text: Fig. 7

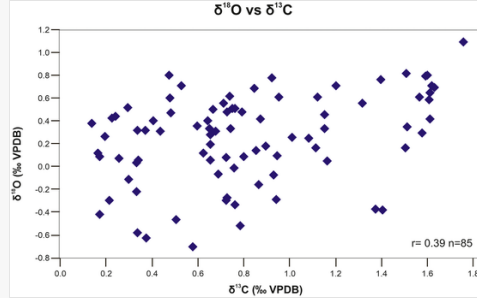
Figure 7: Fig. 7



Adopted calcareous nannofossil biostratigraphic scheme for dating the Guadagnolo Fm, plotted versus the Geomagnetic Polarity Time Scale (GPTS, Lourens et al., 2004). Biozonation is from Di Stefano et al. (2008, emended from Fornaciari et al., 1996) as implemented by Iaccarino et al. (2011). Calibration of the events is after Abdul Aziz et al. (2008); Backman et al. (2012); Turco et al. (2017). FCO = First Common Occurrence, PB = Paracme Beginning, AS = Abundance Spike, PE = Paracme End, LO = Last Occurrence.

alt-text: Fig. 8

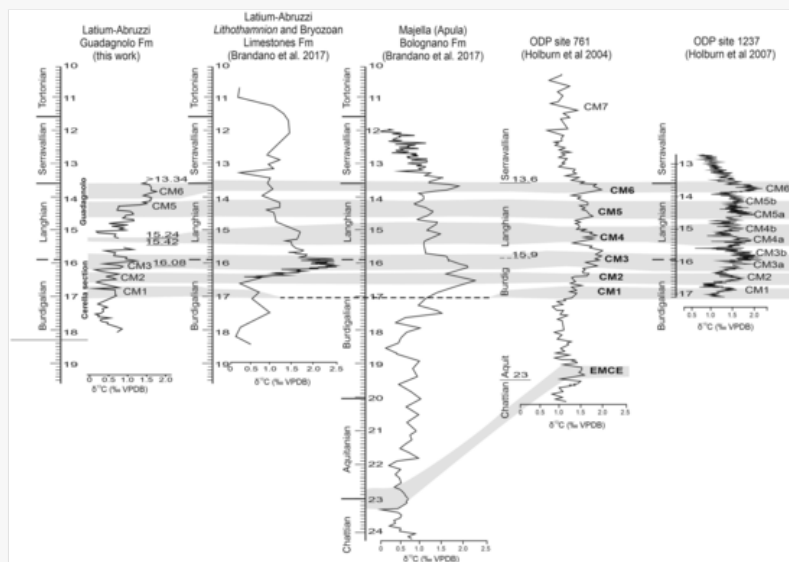
Fig. 8: Fig. 8



Cross-plots O vs C isotope records of the composite Cerella-Guadagnolo stratigraphic section. The $r = 0.39$ based on a number of samples $n = 85$ attests for the poor correlation among C and O isotope records.

alt-text: Fig. 9

Fig. 9, Fig. 9



Correlation of the carbon isotope curves of the studied composite section with the contemporary carbon isotope record of the Central Apennines Platforms (Latium-Abruzzi and Majella Mountain) and the middle Miocene global carbon isotope curves of the ODP sites 1237 and 761. The correlation proposed is based on the revised stratigraphy of the middle member of the Guadagnolo Fm, provided by calcareous nannofossil biostratigraphy, and related sedimentation rates estimated for the Cerella stratigraphic section. The age constraints used as tie points are plotted next to the Guadagnolo carbon isotope curve, them being, 16.08 Ma = MNN4a/MNN4b limit (referred to Di Stefano et al., 2008 as implemented by Iaccarino et al., 2011); 15.42 Ma = the *H. ampliaperta* Abundance Spike (AS) event (firstly defined in Fomacieri et al., 1996) calibrated to 15.42 Ma in Turco et al. (2017); 15.24 Ma = The base of the Subzone MNN5a (Di Stefano et al., 2008; Iaccarino et al., 2011). The top of the section is >13.34 Ma in age, since it is below the LO of *S.heteromorphus* (Abdul Aziz et al., 2008). The dashed line plotted at 17 Ma on the Majella (Apulian) platform carbon isotope curve represents the fact that the CM1 is not represented in this record.

The carbon isotope record of the analysed portion of the Guadagnolo Fm has been correlated with the Monterey Carbon Isotope signal of the Central Apennines carbonate ramps (LBL and Bolognana Fms; Brandano et al., 2017), and with two carbon isotope records from ODP sites of the Pacific and Indian Oceans (Fig. 9). The latter are the reference sites for the Monterey Carbon Isotope Excursion, where all the six carbon maxima have been identified and tuned (Holbourn et al., 2004, 2007).

A first carbon isotope peak, 0.5‰ wide, is recorded between 17 Ma and 16.7 Ma, according to the newly estimated sedimentation rates of the Guadagnolo Fm, and correlated with the CM1 of the oceanic record (Fig. 9). This $\delta^{13}\text{C}$ peak is followed by a second one of the same amplitude, correlated with the CM2 (Fig. 9). The record of the first two carbon maxima in the Guadagnolo Fm is not marked by carbon isotope excursions as wide as in the deep ocean record of the ODP sites (Fig. 9). Furthermore, the CM2 carbon isotope shift is marked by a huge positive spike in the LBL and Bolognana Fms record, while is not as abrupt in the deeper setting here analysed. This weaker signal is not surprising. First, carbon maxima are related to the fractionation effect of primary producers and therefore, tend to have a wider signal in the photic zone or near it. Secondly, the sponges use the carbon for biomass production and generation of energy. Respiration is the metabolic process through which organic matter is oxidized with release of energy. The

oxidation of organic matter for energy coincides with the release of carbon dioxide under aerobic conditions in the sponge. Consequently, the sponges release CO₂ deriving from organic matter, most of it produced by photosynthetic organisms. This CO₂ results progressively enriched in ¹²C. This light carbon enrichment of deep waters is recorded in the deep benthic calcareous shells of carbonate organisms such as echinoids, molluscs and benthic foraminifers. As we analysed the bulk sediment, we obtained a mix of signals of photic zone and of benthic aphotic zones, and this balance produced a lighter signal.

A two stepped positive carbon isotope shift is recorded between 16.2 and 15.8 Ma. Overall, it is represented by a more than 1‰ positive excursion, twice as wide as the previous peaks. The onset of this positive excursion falls at ~16.2 Ma according to the new age model proposed, and correlated with the CM3 record of the Central Apennine records as well as ODP sites (Fig. 9). Furthermore, it corresponds to a global peak in the CO₂ atmospheric content (Foster et al., 2012). The long-lasting carbon isotope positive excursion at the Burdigalian-Langhian boundary attests an excess of primary producers, which might be sustained the development of the explosive volcanism in the Sardinia-Corsica Block (Lustrino et al., 2009). Comacchia et al. (2018) analysed the Sr isotope record of well age-constrained hemipelagic sections belonging to the Umbria-Marche domain and correlated it with the global ocean Sr isotope curve for the Miocene. The authors show how the Central Mediterranean Sr isotope record deviates from the global signal towards lighter Sr isotope values in the upper Burdigalian-lower Langhian. The main controlling factors on Sr isotopes in seawater are volcanism and weathering. Among them, the first one tends to lower the overall ⁸⁷Sr/⁸⁶Sr isotope ratios, entering into the waters huge amounts of light ⁸⁶Sr. Therefore, the deviation attested by Comacchia et al. (2018) is a clear evidence of the influence of regional volcanism on the Central Mediterranean waters. The influence of volcanism was attested also by Kocsis et al. (2008), who analyzed/analysed the Sr and Nd isotope signals on different pelagic and hemipelagic Miocene successions of the Mediterranean area. Furthermore, several volcanoclastic layers are distributed in the Umbria-Marche basinal succession between the early and middle Miocene, and in particular between 17 and 15 Ma (Piero della Francesca level, Deino et al., 1997; Aldo Level, Mader et al., 2001; Hüsing et al., 2010). Furthermore, volcanism affects carbon cycle not only due to the input of CO₂, but also because volcanic ashes bring into surface waters macro- and micro-nutrients, among which Fe, which have a strong fertilization potential and can trigger primary productivity blooms (Duggen et al., 2010; Olgun et al., 2011). In this time interval, a bryozoan-dominated skeletal assemblage spreads in the proximal outer ramp of the LBL ramp (Brandano et al., 2017). Bryozoans are filters-feeding organisms which were favored by the increased nutrient availability sustained by global warming and enhanced by regional volcanism (Brandano et al., 2017). In the basin to platform setting, bryozoans are replaced by siliceous sponges. The CM4 peak of the Monterey Carbon Isotope Excursion is not clear in the Guadagnolo Fm record, where the onset of a carbon isotope positive trend in the uppermost portion of the Cerella section might represent the beginning of this carbon maximum. An overall 1‰ positive carbon isotope peak is recorded between 14.4 and 14.2 Ma, according to the new age model, and correlates with the CM5 as showed in the ODP records (Holbourn et al., 2004, 2007; Fig. 9). Interestingly, the amplitude of this positive excursion is wider in the Guadagnolo succession than in the other Central Apennines records as well as in the ODP sites.

Lastly, the widest positive carbon isotope excursion of the analysed record falls in the upper Langhian and correlates with the CM6 (Fig. 9, Holbourn et al., 2004, 2007). Interestingly, the CM6 peak is expressed more clearly than the previous peaks in the Guadagnolo Fm records. The CM6 falls in the upper member of the Guadagnolo Fm, the amplification of this carbon isotope excursion with respect to underlying CMs can be ascribed to the shallower depositional environment of this member. This member represents deposition in the outer ramp where the carbonate production is dominated by bryozoans with the contribution of oligophotic biota such as larger foraminifers, while the sponges are absent. The absence of the sponges drastically reduces the contribution of the CO₂ progressively enriched in ¹²C, producing a wider positive carbon isotope excursion. Interestingly, on the basis of the presented correlation the transition between the middle and the upper member falls around 14 Ma and is marked by a shoaling of depositional environment. According to Holbourn et al. (2014), the interval between 14.5 Ma and 13.5 Ma is characterized by a new pattern of climate variability and it is known as Middle Miocene Climate Transition. The MMCO was followed by high-latitude sea-surface temperature cooling and Antarctic ice sheet expansion (Holbourn et al., 2014; Super et al., 2018). A salient feature of the δ¹⁸O record is the massive increase at 13.9–13.8 Ma that has been attributed to Antarctic ice-sheet expansion and deep-water cooling (Shackleton and Kennett, 1975; Miller et al., 1991; Woodruff and Savin, 1991; Holbourn et al., 2014) and coincides with the onset of the CM6 that is well recorded in the upper member of Guadagnolo Fm. Interestingly also, the transition between the middle and the upper member is marked by a relevant positive shift of δ¹⁸O, even if the O isotope record on bulk carbonate sediments has to be considered with caution. Therefore, the marked lithofacies and depositional environmental changes occurring at the transition between these members represent the sedimentary record of the significant climate change-cooling step preceding the CM6 peak.

6.6 Conclusions

The isotope record of the Guadagnolo Fm in the Central Apennines, associated with calcareous nannofossil biostratigraphy, allowed to identify the main isotopic excursion of the Monterey event and to understand the controlling factors of the development of the dominant biota producing sediment.

The Guadagnolo Fm is deposited in the transitional platform to basin zone, in particular in a distal outer ramp environment where the benthic faunula was dominated by siliceous sponge. They accumulated during a long lasting interval of global high seawater fertility, coinciding with the Monterey event, and an enhanced regional nutrient flux due to continental run-off and volcanism related to the Alps and Apennines orogenesis. Under an enhanced nutrient flux, in this context particularly enriched in silica, phytoplankton blooms increased the surface water turbidity, thus reducing the light available for the bottom dwelling organisms, such as zooxanthellate corals, calcareous algae or larger benthic foraminifers.

The overall carbon isotope record of the Guadagnolo Fm correlates with the global signal but it is influenced by other controlling factors as well. The carbon isotope record of the Guadagnolo Fm well correlates with the Monterey Carbon Isotope signal of the Central Apennines carbonate ramps and from ODP sites. Five of the six carbon maxima have been identified and correlated with the global signal. Four of the carbon isotope peaks are in the spongolitic member and characterized by an attenuate isotope excursion when compared with the deep ocean record of the ODP sites and the marked spikes of the adjacent carbonate platform domains. This weaker signal has been linked to the fractionation effect of primary producers of the photic zone and secondly to the release of ^{12}C -enriched CO_2 by sponges, due to oxidation of organic matter in the water column. The widest positive carbon isotope excursion (CM6) falls in the upper member of the Guadagnolo Fm. In this case, the amplification of the carbon isotope excursion can be ascribed to the shallower depositional environment of this member characterized by the absence of the sponges. The absence of the sponges drastically reduces the contribution of the CO_2 progressively enriched in ^{12}C , producing a stronger positive carbon isotope excursion.

Finally, the transition from the middle to the upper member of the Guadagnolo Fm represents a shoaling of the depositional environment related to the global cooling step recorded after 14 Ma and before the onset of the CM6. This cooling step is also evident in the $\delta^{18}\text{O}$ isotope curve of the Guadagnolo section, characterized by a shift towards heavier values at the base of the upper member.

Q9 Uncited reference

Pagani et al., 1999

Declaration of Competing Interest

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


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Q10 ~~Appendix A~~ [Appendix A](#) Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.palaeo.2020.110177>.

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 The corrections made in this section will be reviewed and approved by a journal production editor. The newly added/removed references and its citations will be reordered and rearranged by the production team.

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Highlights

- The Monterey Event was recorded in the Guadagnolo Fm (Central Apennines, Italy).
 - New nannofossil data constrained the Guadagnolo Fm during the Monterey Event.
 - In the distal outer ramp, siliceous sponges dominated the benthic factory.
 - Sponges thrived due to high seawater fertility due to global and regional factors.
 - Release of ¹²C- enriched CO₂ by sponges affected the signal of the Monterey.
-

Supplementary material 1

alt-text: Image 1

[Multimedia Component 2](#)

Supplementary material 2

alt-text: Image 2

[Multimedia Component 3](#)

Supplementary material 3

alt-text: Image 3

[Multimedia Component 4](#)

Supplementary material 4

alt-text: Image 4

Queries and Answers

Q1

Query: Citation "Tavani et al., 2015" has not been found in the reference list. Please supply full details for this reference.

Answer: Tavani, S., Vignaroli, G., Parente, M. 2015. Transverse versus longitudinal extension in the foredeep-peripheral bulge system: Role of Cretaceous structural inheritances during early Miocene extensional faulting in inner central Apennines belt. *Tectonics*, 34 (7), 1412-1430.

Q2

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