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G. Del Viscio
G. Frijia
R. Posenato
P. Singh
Daniel J. Lehrmann

*Trinity University*

See next page for additional authors

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Proliferation of *Chondrodonta* as a proxy of environmental instability at the onset of OAE1a: Insights from shallow-water limestones of the Apulia Carbonate Platform

GABRIELLA DEL VISCIO*, GIANLUCA FRIJIA*, RENATO POSENATO*, PULKIT SINGH†, DANIEL J. LEHRMANN‡, JONATHAN L. PAYNE†, KHALID AL-RAMADAN§, ULRICH STRUCK¶, KLAUS P. JOCHUM** and MICHELE MORSILLI*

* Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Ferrara, 44122, Italy (E-mail: mrh@unife.it)
† Department of Geological Sciences, Stanford University, Stanford, CA, 94305, USA
‡ Department of Geosciences, Trinity University, San Antonio, TX, 78212, USA
§ College of Petroleum Engineering & Geosciences, King Fahd University of Petroleum & Minerals, Dhahran, 31261, Saudi Arabia
¶ Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science, Berlin, 10115, Germany
** Climate Geochemistry Department, Max Planck Institute for Chemistry (Otto-Hahn-Institute), Mainz, 55020, Germany

ABSTRACT

*Chondrodonta* is an opportunistic, oyster-like bivalve, common in shallow-water carbonates of the Cretaceous Tethyan Realm. Despite its high abundance and widespread geographic distribution, the precise relationship between the early Aptian proliferation and environmental perturbations resulting from the Oceanic Anoxic Event 1a (OAE1a), has not been investigated. Stratigraphic and geochemical analyses of the lower Aptian *Chondrodonta* bedsets within the inner platform limestones of the Apulia Carbonate Platform (Gargano Promontory, southern Italy) are conducted to assess the environmental controls on the *Chondrodonta* proliferation and its timing and causal relationship to OAE1a. *Chondrodonta* occurs with sparse to common individuals within requieniid rudist floatstone–rudstones, forms monospecific biostromes during the early phase of stressed environmental conditions and then rapidly disappears at the peak of OAE1a. It proliferates in dysoxic seawater with relatively increased trophic sources, which correlate to increasing nutrient levels in the nearby pelagic realm. *Chondrodonta*-rich beds are associated worldwide with the onset of OAE1a and occur in a transitional context between a stable and a strongly stressed environment, where the opportunistic behaviour of *Chondrodonta* is rather efficient. Increasing nutrient load and unstable environmental conditions right below the peak of OAE1a created an environmental ‘window’ favourable for *Chondrodonta* to proliferate, outplaying the less tolerant benthos (for example, rudists). The occurrence, duration and position of the environmental window were controlled by local palaeogeographic and hydrodynamic settings (i.e. low energy, decreased seawater oxygenation and circulation). Further increase in inhospitable conditions, leading to OAE1a, constituted an upper threshold for *Chondrodonta* and allowed mesotrophic taxa like *Bacinella–Lithocodium* and orbitolinids to dominate the benthic
communities. The present study suggests that the proliferation of *Chondrodonta* in shallow-water platform carbonates can be used as proxy for the initial phase of ecological stress related to OAE1a.

**Keywords** Apulia Carbonate Platform, *Chondrodonta*, early Aptian, OAE1a, Tethys.

**INTRODUCTION**

*Chondrodonta* Stanton, 1901, is an epifaunal, filter-feeding, oyster-like bivalve, common in shallow-water carbonates of the Cretaceous Tethyan Realm. It has a gregarious and cemented life-habit with a ‘mud-sticker’ strategy of bottom stabilization (Posenato et al., 2020). Its dense aggregates (bivalve bouquets, thickets and carpets) influenced the sedimentation rates and dynamics of carbonate platform systems (Gili et al., 1995; Skelton & Gili, 2012). *Chondrodonta* has a discontinuous distribution spanning from the ?Berrianian (Masse et al., 2015) to the ?Campanian (Freneix & Lefèvre, 1967) and an abundance peak during the Aptian – Cenomanian interval (Posenato et al., 2018, 2020). *Chondrodonta* accumulations occur worldwide (Dhondt & Dieni, 1993) in a set of marine sub-environments including tidal flats, lagoons, back-reefs and platform margins. The bivalve occurs both in monospecific biostromes (Phelps et al., 2014; Posenato et al., 2018) and associated with rudists (Bover-Arnal et al., 2010; Posenato et al., 2020). *Chondrodonta* is considered an r-strategist and its proliferation around the Cretaceous Oceanic Anoxic Events (OAEs) has been interpreted as evidence of population blooms in response to environmental instability (Graziano, 2013; Posenato et al., 2018, 2020; Núñez-Useche et al., 2020).

During the early Aptian, *Chondrodonta* beds are reported in several shallow-water carbonate platforms bordering the Tethys Ocean (e.g. Masse, 1993; Császár et al., 1994; Malchus et al., 1995; Immenhauser et al., 2004; Gili et al., 2016; Graziano & Raspini, 2018; Posenato et al., 2018, among others) and the proto-North Atlantic (e.g. Phelps et al., 2014; Núñez-Useche et al., 2020).

The early Aptian represents a period of considerable climate and environmental change (Föllmi, 2012) primarily linked to the emplacement of the Ontong Java Large Igneous Province (LIP) in the Pacific Ocean (Larson & Erba, 1999; Tejada et al., 2009). The large amount of CO₂ released into the atmosphere and dissolved in seawater mainly by submarine and subaerial volcanic activity (Föllmi, 2012; Erba et al., 2015) and, secondly, by methane hydrate dissociation (Mehay et al., 2009), triggered a sequence of climate disturbances that caused crises in carbonate production in both the pelagic and neritic domains (e.g. Erba, 1994; Weissett et al., 1998). The resulting early Aptian OAE1a (i.e. Selli Event – Schlanger & Jenkyns, 1976; Jenkyns, 2010) is associated with a negative δ13C spike linked to increased volcanism, followed by a positive δ13C excursion (Menegatti et al., 1998; Tejada et al., 2009). The onset of the δ13C excursion coincides with widespread black shale deposition in basinal settings and with the nannoconid crisis (Erba, 1994; Erba & Tremolada, 2004).

In shallow-water settings, there is global evidence for a profound environmental change before and during the C-cycle perturbation corresponding to OAE1a. Carbonate platforms within and outside the Tethys underwent significant phases of ecological stress, primarily due to enhanced nutrient input, that resulted in biotic turnovers from oligotrophic to mesotrophic and even to eutrophic communities (e.g. Millán et al., 2009; Skelton & Gili, 2012; Stein et al., 2012).

The shallow-marine carbonate platform ecosystems along the Northern Tethyan margin (e.g. Föllmi et al., 2006; Bover-Arnal et al., 2009; Huck et al., 2013) and in the proto-North Atlantic (e.g. Millán et al., 2011; Huck et al., 2014) drowned, resulting in the deposition of condensed sequences and extensive formation of hardgrounds immediately before and during OAE1a (Godet, 2013). Conversely, carbonate platforms of the Central and Southern Tethys (for example, Croatia and Oman) continued to grow under highly stressed conditions, as indicated by episodes of *Bacinella–Lithocodium* and orbitolinid mass occurrences replacing coral–rudist associations (Huck et al., 2010; Rameil et al., 2010; Schröder et al., 2010; Godet et al., 2014; Hueter et al., 2019, 2020).

The proliferation of the opportunistic *Chondrodonta* in the early Aptian has been interpreted as an indication of unstable environmental conditions during OAE1a, with episodic increases in
food sources and ocean temperature coupled with acidification (Graziano, 2013; Posenato et al., 2018). Despite the high abundance and widespread geographic distribution of *Chondrodonta* (Posenato et al., 2018), a clear cause–effect relationship between its flourishing and OAE1a has yet to be established. Further, it is still unclear whether and how the environmental disturbances linked to the mass release of CO₂ may have played a role in its proliferation and dominance over other bivalve groups (for example, rudists).

The lower Aptian *Chondrodonta* beds of the inner platform facies of the Apulia Carbonate Platform (ACP) are here analysed to determine the temporal relationship between their deposition and the onset of OAE1a. Sedimentological, petrographic and biostratigraphic analyses of stratigraphic sections are integrated and coupled with analyses of geochemical environmental proxies. Results are correlated with the major environmental perturbations recorded in the adjacent Adriatic/Ionian Basin. The stratigraphic position of the *Chondrodonta* beds is further compared to other coeval *Chondrodonta* accumulations to highlight the precise stratigraphic position and the ecological significance of *Chondrodonta* accumulations in relation to the biotic turnovers from oligotrophic to mesotrophic associations recorded during OAE1a.

**STRATIGRAPHIC SETTINGS**

The Gargano Promontory (Fig. 1A) represents the north-eastern margin of the ACP, a major Mesozoic palaeogeographic domain in the central Tethys (Eberli et al., 1993; Bernoulli, 2001). The Promontory was partially involved in the Neogene southern Apennines and Dinaric thrust belts and is currently interpreted as a deformed foreland (Bosellini et al., 1999a; Borgomano, 2000; Morsilli et al., 2017). It is folded in a gentle and broad north-west/south-east anticline and dissected by Miocene – Pliocene reverse and normal faults, and by Pleistocene strike-slip faults (Bertotti et al., 1999; Brankman & Aydin, 2004). The outcropping carbonate succession records a suite of depositional environments from inner platform and peritidal settings to relatively deep-water pelagic environments (Morsilli & Bosellini, 1997; Borgomano, 2000).

The studied succession belongs to the lower Cretaceous inner platform facies of the San Giovanni Rotondo Limestone (SGRL) (Luperto Sinni & Massé, 1986; Di Palma, 1995; Claps et al., 1996; Graziano et al., 2013). The SGRL crops out in the eastern and south-eastern Gargano Promontory (Fig. 1A) and changes eastward to margin facies of the Montagna degli Angeli Limestone and to slope and basin deposits of the Mattinata and Maiolica formations, respectively (Bosellini et al., 1999a).

The SGRL is a 500 to 600 m thick, shallow-water carbonate succession spanning the upper Valanginian *p.p.* – Aptian *p.p.* Claps et al. (1996) divided this unit into three members, namely members 1 to 3, from the base to the top (Fig. 2). Member 1 (140 m thick) consists of a non-cyclic subtidal succession of mudstone–wackestones and scattered skeletal or oolitic packstone–grainstones. Member 2 (ca 310 m thick), is a cyclic succession of ‘loferitic’ beds with layers of green shales and stromatolites, commonly with dinosaur footprints on the bed surfaces (Petti et al., 2008). Member 3 (ca 100 m thick) contains a variety of facies, ranging from subtidal high-energy thin-bedded calcarenites to domal stromatolites. The present study focuses on the upper Barremian *p.p.* – lower Aptian *Chondrodonta* accumulations which mark the base of member 3 and crop out in lagoon to tidal flat settings (Posenato et al., 2018).

**METHODS**

The following methods have been integrated to define the precise stratigraphic position and the ecological significance of the lower Aptian *Chondrodonta* accumulations on the ACP. The stratigraphic framework around the *Chondrodonta* beds was built using biostratigraphic and chemostratigraphic (δ13C and 87Sr/86Sr) data. Sedimentological and petrographic analyses were coupled with spectral gamma ray measurements and trace element concentrations to infer early Aptian palaeoenvironmental changes associated with the proliferation of *Chondrodonta*.

**Fieldwork and lithofacies analysis**

Well-exposed outcrops along road-cuts (Fig. 1B and C) were used to measure two stratigraphic sections. Seven polished slabs of *Chondrodonta*-bearing samples were studied for sedimentological analyses. One hundred and seventy-six thin sections, integrated with outcrop observations, were used for microfacies and biostratigraphic analyses.

Textures were classified based on Dunham (1962), Embry & Kovan (1971), Insalaco (1998)
and Lokier & Al Junaibi (2016). Depositional textures for lithofacies definition were analysed semi-quantitatively and expressed in terms of relative abundance. The biostratigraphic schemes proposed in Claps et al. (1996) for the SGRL were updated based on more recent reviews of dasycladales (Carras et al., 2006) and of benthic foraminifera (Velić, 2007; Schröeder et al., 2010; Chiocchini et al., 2012).

The Chondrodonta accumulations are here defined as ‘bedsets’ (Campbell, 1967) because they are composed of superimposed levels forming a unique set of Chondrodonta beds, about or more than 1 m thick and laterally continuous (see Posenato et al., 2018, for the detailed taphonomic description).

The classification of oligotrophic, mesotrophic and eutrophic associations is based on the nutrient gradients in modern low latitude waters reported in milligrams of chlorophyll $a$ per cubic metre of seawater (see fig. 2 in Mutti & Hallock, 2003) and estimated for the Lower Cretaceous dominant benthos (see fig. 10 in Rameil et al., 2010). Rudist limestones are here considered...
indicative of oligotrophic to mesotrophic conditions and the replacement of rudists by mesotrophic taxa like orbitolinids and Bacinella–Lithocodium is considered indicative of elevated nutrient levels (Vilas et al., 1995; Huck et al., 2010; Rameil et al., 2010; Najarro et al., 2011; Núñez-Useche et al., 2020). Spectral gamma-ray measurements were made with a hand-held spectrometer (Radiation Solutions model RS-125) to measure relative variations in the concentration of organic matter in the bulk rocks.

Geochemical methods
A total of 140 samples were analysed for δ¹³C and δ¹⁸O ratios within the micritic portion of the rock matrix. The polished slabs were studied under a binocular microscope and checked with the respective thin sections to identify areas free from large bioclasts or recrystallization. Some samples underwent duplicate analyses to assess reproducibility within a given sample but across potential variation in microfabric. All results are reported in per mil (‰), in the conventional δ notation with reference to the Vienna Pee Dee Belemnite (VPDB) standard.

Fourteen samples from the San Giovanni section were analysed for the elemental concentration through Laser Ablation – Inductively Coupled Plasma – Mass Spectrometry (LA-ICP-MS). The purest micritic fraction of all samples was chosen to measure the concentration of phosphorous and of a selected group of Redox-Sensitive Trace Elements (RSTE) comprehensive of vanadium, arsenic, molybdenum and uranium. Results were normalized to the concentration of aluminum (Al) on the assumption that Al represents the clay mineral detrital input (e.g. Pearce et al., 2009; Westermann et al., 2013; Hueter et al., 2019).

A total of 12 shell fragments of Chondrodonta and rudists was measured for ⁸⁷Sr/⁸⁶Sr chemostratigraphy. To assess the preservation of the original microstructure, shells were screened petrographically using visible light and, where possible, analysed for elemental concentration of magnesium, strontium, manganese and iron (see Brand & Veizer, 1980; Steuber et al., 2005; Frijia et al., 2015). The numerical ages were then translated into the chronostratigraphic ages of the GTS2012 (McArthur et al., 2012). For details on the geochemical methods, see the Supporting Information section.

RESULTS

Lithofacies and lithofacies associations
Based on sedimentological and petrographic analyses of outcrops and thin sections, eleven lithofacies were identified (Table 1, Fig. 3). Textures change from mud to grain-supported to even bindstones; the benthic fauna is mainly represented by bivalves (requieniids and Chondrodonta), foraminifera and dasycladales. Micro-encrusters (for example, Bacinella–Lithocodium) are particularly concentrated in some stratigraphic intervals. The eleven lithofacies were grouped into three lithofacies associations (LA) (Table 1) and interpreted in terms of depositional environment.

Lithofacies association 1 (LA1) consists of mud-supported and bioturbated bioclastic wackestone (BW) and bioturbated mudstone (MD) facies episodically interbedded with beds of PP and BF (Fig. 3). Microbialites form both stromatolitic bindstones (ST) and discontinuous laminar microstructures in MD, BW and peloidal–bioclastic packstone (PP). Chondrodonta boundstones (CH) also occur. The benthic fauna is composed by scattered bivalves (for example, requieniids and Chondrodonta) and by common micro-encrusters like Thaumatoporella and Cayeuxia. This mud-dominated lithofacies association is interpreted to have been deposited in low-energy protected subtidal settings with a mostly restricted marine...
Table 1. Summary of the main sedimentological characters of the lithofacies associations and of the 11 lithofacies recognized in the studied sections. Components considered are, in order; skeletals, micro-encrusters and non-skeletal grains. Their relative abundance is expressed as: a, abundant, c, common, r, rare. Laminar and patchy cloudy shapes of *Bacinella–Lithocodium* bindstones are from Huck et al. (2010).

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<th>Bed features and thickness</th>
<th>Components</th>
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<td>MD - Bioturbated mudstone</td>
<td>Massive and tabular centimetre to metre-thick beds</td>
<td><em>Chondrodonta</em> and requieniid fragments (r), dasycladales (r), foraminifera (r), small-sized oncoids (r), solitary corals (r), echinoderm spines (r); <em>Thaumatoporella</em> (c-r), <em>Cayeuxia</em> talli (r); peloids (c-r)</td>
<td>Bioturbation, burrows, discontinuous microbial laminae, peloidal-grainstone pockets</td>
<td>LA1 Low-energy protected lagoon passing to tidal flat</td>
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<tr>
<td>BW - Bioclastic wackestone</td>
<td>Massive and tabular centimetre to metre-thick beds</td>
<td>Foraminifera (a-c), <em>Salpingoporella</em> sp. (a-c), small-sized oncoids (c-r), solitary corals and echinoderm spines (r), bivalve and gastropod fragments (r), ostracods (r); <em>Thaumatoporella</em> (c); peloids (c-r)</td>
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<td>Horizontal shell layers, rare discontinuous microbial laminae</td>
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<td>CH - <em>Chondrodonta</em> boundstone</td>
<td>Boundstone; mudstone–wackestone or wackestone–packstone matrix</td>
<td>Tabular and nodular decimetre-thick beds forming a unique bedset; shells both horizontally oriented (i.e. topped) or in life-position</td>
<td><em>Chondrodonta</em> (a), requieniids (r), foraminifera (r), dasycladales (r); <em>Thaumatoporella</em> (r), <em>Cayeuxia</em> talli (c-r), microbial crusts (c-r); peloids (r)</td>
<td>Horizontal shell layers, microbial crusts</td>
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<td>PG – Peloidal–foraminiferal packstone–grainstone</td>
<td>Packstone–grainstone; grainstone</td>
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<td>Micritization, microencrustations</td>
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<td>RF – Bivalve floatstone–rudstone</td>
<td>Floatstone–rudstone; packstone–grainstone matrix</td>
<td>Massive, tabular, and occasionally lens-shaped centimetre to metre-thick beds</td>
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<td>Floatstone–rudstone; packstone–grainstone matrix</td>
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circulation, as indicated by the poorly differentiated biotic assemblages. Inter-supratidal facies and sedimentary structures (i.e. stromatolite lithofacies – ST – fenestrae and exposure surfaces) indicate occasional shifts to tidal-flat settings. Subtidal cycles prevail whereas peritidal cycles, capped by stromatolites or by exposure surfaces, are less common. Apart from the singular occurrence of CH, all lithofacies of LA1 are typical of inner platform settings documented in many adjacent Tethyan carbonate platforms (e.g. Husinec & Read, 2011, 2018; Di Lucia et al., 2012; Amodio & Weissert, 2017, among others).

Lithofacies association 2 (LA2) consists of grain-supported facies [peloidal–foraminiferal packstone–grainstone (PG), bivalve floatstone–rudstone (RF) and oncoid floatstone–rudstone (OF)] with high skeletal content and diversity (Fig. 3). The benthic fauna is composed of common to abundant bivalves (requieniids and Chondrodonta), nerineid gastropods, foraminifera and dasycladales. Based on textures and skeletal components, as well on the absence of exposure surfaces or inter-supratidal sedimentary structures (common in LA1), LA2 can be interpreted as deposited in a typical subtidal environment or protected lagoon. The latter is characterized by a more open circulation with episodic high-energy events (PG and OF) and by short-term transgressive phases during the accumulation of RF. A similar interpretation of this type of lithofacies has been given in other inner platform settings (e.g. Husinec & Read, 2018).

Lithofacies association 3 (LA3) is based on the occurrence of Bacinella–Lithocodium both as bindstones (BL) and as micro-encrustations in floatstone–rudstones (LB) (Fig. 3). These micro-encrusters are concentrated in specific intervals of the stratigraphic succession, in which they predominate over other biota. BL and LB facies alternate with LA2 grain-supported lagoon facies and, less commonly, with mud-supported beds of LA1. Bacinella–Lithocodium facies have been considered as indicative of environmental stress on the platform top (Immenhauser et al., 2005). LA3 can be therefore interpreted as deposited in moderate-energy lagoon settings under environmentally stressed conditions. In other lower Aptian shallow-water platforms (for example, Arabian and Adriatic Carbonate Platforms) the occurrence of these micro-encrusters, also in the form of small patchy bioherms, is associated with the

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<td>Tabular decimetre-thick beds</td>
<td>Requieniids (a-c), oncoids (a-c), nerineids (c-r), Chondrodonta (c-r), solitary corals (c-r), echinoderm spines (r); foraminifera (c), dasycladales (c-r); Thaumatoporella (r), Bacinella–Lithocodium (c), Cayeuxia talli (r); peloids (a), mudclasts (c-r), aggregate grains (r)</td>
<td>Micro-encrustations</td>
<td>LA3 Moderate-energy lagoon under stressed conditions</td>
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<tr>
<td>BL – Bacinella–Lithocodium bindstone</td>
<td>Bindstone</td>
<td>Centimetre to decimetre-thick nodular beds</td>
<td>Undetermined bivalve fragments (c-r), foraminifera (r), echinoderm spines (r), solitary corals (r), small-sized oncoids (r); Thaumatoporella (r), Bacinella–Lithocodium (a); peloids (c-r)</td>
<td>Laminar to patchy cloudy micro-encrustations</td>
<td>LA3</td>
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Table 1. (continued)
environmental instability related to OAE1a (e.g. Immenhauser et al., 2005; Huck et al., 2010; Rameil et al., 2010; Hueter et al., 2019).

**Stratigraphy and geochemical results**

*The San Giovanni section*

The San Giovanni stratigraphic section (Figs 1C and 4) is 23.8 m thick and records low-skeletal, mud-supported facies gradually passing to grain-supported rudist beds with Bacinella–Lithocodium micro-encrustations. The lower part (0 to 15.9 m, SGRL, uppermost member 2 to lowermost member 3) is mostly composed of LA1 metre-thick massive mudstones (MD), miliolid–algal wackestones (BW) and peloidal packstones – locally wackestones (PP). Microbial activity generates both decimetre-thick tabular and
domal stromatolites (ST) and discontinuous peloidal – microbial laminae in MD, BW and PP. All of these beds are abundantly bioturbated and show common ephemeral emersion-related features like breccias, vugs and fenestrae. Less common LA2 thin-bedded peloidal packstone–grainstones (PG) and oncoid floatstone–rudstones (OF) are intercalated and gradually increase upward in thickness and frequency. Chondrodonta and nerineids, oncoids, miliolids and micro-encrusters (for example, Caleyuxia and Thaumatoporella) are common; ostracods are locally abundant and horizontally oriented in thin layers (4.0 to 5.4 m). The Chondrodonta bedset (base of member 3, CH and locally BF) occurs between 7.1 m and 9.25 m, on top of a tabular stromatolite, and is overlain by BW, PP and OF beds rich in oncoids and Thaumatoporella and barren in molluscs, foraminifera and dasycladales (10.0 to 13.5 m). The uppermost occurrence of Salpingoporella muehlbergii is at the base of the section and the micro-component association of Cuneolina sp., Debarina sp., Praechrysalidina infracretacea, Pseudolithonella sp. and Salpingoporella sp. occurs above the Chondrodonta bedset (ca 10 m from the base).

The upper part of the section (15.9 to 23.8 m, SGRL, member 3) lacks stromatolites and is mainly composed of LA2 and LA3 facies. The base of the section is a metre-thick peloidal–packstone (PP) overlain by thin-bedded peloidal–foraminiferal packstone–grainstones (PG) interbedded with centimetre-thick requieniid beds (RF) and metre-thick oncoid floatstone–rudstones (OF). Requieniids increase upward in size and abundance and are locally arranged in lenticular accumulations. Chondrodonta occurs as common bioclasts with nerineids, dasycladales (Salpingoporella sp.) and foraminifera (miliolids, P. infracretacea and Cuneolina sp.); orbitolinds are scattered within requieniid facies (17.5 to 21.0 m from the base). Bacinella–Lithocodium micro-encrustations (LB) occur commonly across the upper part of the section; a Bacinella–bindstone (BL) occurs between 18.5 m and 19.3 m in association with requieniid fragments and orbitolinids. The first occurrence of Salpingoporella dinarica is at 18.5 m above the base.

The δ13C curve in the San Giovanni section (Fig. 4) records an overall upward decreasing trend from +0.1‰ to −1.1‰ and a range of values between +0.7‰ and −4.8‰, with a mean of −1.3‰. Above the Chondrodonta bedset, a sharp negative shift from −0.6‰ to −2.4‰ (9.8 to 10.1 m) marks the onset of a negative plateau that extends up to 15.9 m and contains the most negative values of the entire δ13C curve. The overall decreasing trend in δ18O is less marked and does not show abrupt positive or negative shifts; δ18O values decrease from −2.7‰ to −4.6‰, with an average of −3.9‰.

The concentration of Al in the San Giovanni section averages around 500 ppm and shows a sharp positive peak of 3000 ppm right above the Chondrodonta bedset (ca 10 m), in correspondence of an oncoid–floatstone with ephemeral emersion-related features (Fig. 5). The P/Al ratio averages around 0.1, with a weak increase within the Chondrodonta bedset, followed by a sharp decrease immediately above it.

The Redox-Sensitive Trace Elements (RSTE)/Al ratios show generally low values. Within the Chondrodonta bedset, both the V/Al and the Mo/Al ratios show short fluctuations, between 0.01 and 0.02 and between 0.001 and 0.002, respectively. The As/Al and the U/Al ratios show sharper positive peaks, up to 0.003 and up to 0.01, respectively. At the top of the bedset, all of the RSTE/Al values abruptly decrease, and their curves flatten.

In the uppermost part of the section (ca 11.5 m), both the P/Al and the RSTE/Al ratios culminate in positive peaks at an exposure surface.

The Borgo Celano 1 section
The Borgo Celano 1 stratigraphic section (Figs 1B and 6A) is 25.3 m thick (SGRL, members 2 and 3) and consists of lime mud-rich beds interbedded with grain-supported and bioclastic deposits. Bacinella–Lithocodium micro-encrustations occur in the uppermost part of the section.

Most of the section consists of alternating LA1 and LA2 facies associations with rare LA3. The lowermost 13.5 m are characterized by metre-thick and decimetre-thick foralgal–Thaumatoporella wackestones (BW), bioturbated mudstones (MD) and molluscan floatstones with common Chondrodonta, requieniids and nerineids (BF). These lithofacies are intercalated with decimetre-thick, thin-bedded peloidal–foraminiferal packstones and grainstones (PP and PG) and bioclastic–oncoid rudstones and floatstones (OF and RF). The abundance of skeletal material is moderate, especially for foraminifera and dasycladales; ostracods are locally common and micro-encrusters, except for scattered Thaumatoporella, are rare.
Chondrodonta at the onset of OAE1a

Fig. 4. San Giovanni stratigraphic log (base: 41°40′19.90″N, 15°43′44.30″E; top: 41°40′13.85″N, 15°43′46.05″E) including biostratigraphy and stable isotope results ($\delta^{18}$O, $\delta^{13}$C, $\delta^{18}$O/$^{16}$Sr). Rock-components are analysed semi-quantitatively and their abundance is expressed relative to the rock texture. The Chondrodonta bedset is highlighted in orange; see text and Table 1 for the description of lithofacies and lithofacies associations.

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Higher in the section (13.5 to 22.5 m) the bioclastic content, especially requieniids, decreases gradually. Microbial activity generates discontinuous microbial–peloidal laminae in MD and BW as well as decimetre-thick domal and tabular stromatolites (ST), interlayered with mudstones and grain-supported facies. Ephemeral emersion-related features like vugs and fenestrae are common. The Chondrodonta bedset (15.5 to 16.1 m, SGRL, base of member 3, CH and locally BF) overlies a tabular stromatolite and is followed by ca 3 m of limestones depleted in molluscs, foraminifera and dasycladales, and relatively enriched in Thaumatoporella and other micro-encrusters (for example, Cayeuxia thalli). The last occurrence of S. muehlbergii is recorded 11 m above the base of the section.

Cuneolina sp., P. infracretacea, Nezzazzatids, Debarina sp. and Pseudolituonella sp. gradually appear upward; Mayncina sp., Salpingoporella heraldica and Actinoporella podalica occur around the Chondrodonta bedset.

The uppermost part of the section (22.5 to 25.3 m) consists of LA2 and LA3 facies associations and starts with a massive peloidal packstone-grainstone (PG) rich in foraminifera (miliolids, Cuneolina sp. and P. infracretacea) and dasycladales (Salpingoporella sp.). It is followed by oncoid floatstone–rudstone beds (OF) and bivalve (requieniids and Chondrodonta) floatstones with scattered orbitolinids and common Bacinella–Lithocodium micro-encrustations (LB).

The $\delta^{13}C$ curve in the Borgo Celano 1 section (Fig. 6B) records an overall slightly upward increasing trend from $-2.1\%$ at the base to $-0.9\%$ at the top, with a mean of $-0.9\%$. In the lower part of the section, the positive trend is punctuated at 11 m by a negative shift from $+0.1\%$ (the highest value of the $\delta^{13}C$ curve) to about $-3.0\%$. This shift marks the base of a negative plateau occurring up to 18 m, with values averaging around $-0.9\%$. The $\delta^{18}O$ curve exhibits a similar, slightly increasing trend from $-4.6\%$ at the base to $-3.8\%$ at the top, with an average of $-3.7\%$ and no sharp positive or negative shifts.

The total gamma ray intensity is generally below 20.0 API units in the first 13 m of the Borgo Celano 1 section (Fig. 6B). It shows an overall increase up-section, with peaks up to 40.0 (8.0 to 11.5 m) and 50.0 API units (at 19.8 m). The concentration of uranium is lower than 2 ppm in the first 13 m and increases upward with peaks of more than 5 ppm (at 18.4 m and 20 m, respectively). Above 20 m, signals of both total gamma ray and uranium

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Fig. 6A. Borgo Celano 1 stratigraphic log (base: 41°40′31.38″N, 15°39′58.40″E; top: 41°40′27.35″N, 15°40′01.85″E) including biostratigraphy. Rock-components are analysed semi-quantitatively and their abundance is expressed relative to the rock texture. The *Chondrodonta* bedset is highlighted in orange; see text and Table 1 for the description of lithofacies and lithofacies associations and Fig. 4 for the legend.
Fig. 6B. Borgo Celano 1 stratigraphic log including stable isotope (δ¹⁸O, δ¹³C, ⁸⁷Sr/⁸⁶Sr) results and gamma ray data (Total API, uranium, thorium and potassium). The Chondrodonta bedset is highlighted in orange; see text and Table 1 for the description of lithofacies and lithofacies associations and Fig. 4 for the legend.
Fig. 7A. Borgo Celano 2 stratigraphic log (lower part) (base: 41°40′31.7″N, 15°40′07.55″E; top: 41°40′24.30″N, 15°40′04.70″E) including biostratigraphy and stable isotope results ($\delta^{18}$O, $\delta^{13}$C). Rock-components are analysed semi-quantitatively and their abundance is expressed relative to the rock texture. The *Chondrodonta* bedset is highlighted in orange; see text and Table 1 for the description of lithofacies and lithofacies associations and Fig. 4 for the legend.

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Fig. 7B. Borgo Celano 2 stratigraphic log (upper part) (base: 41°50’31.7”N, 15°40’07.55”E; top: 41°40’24.30”N, 15°40’04.70”E) including biostratigraphy and stable isotope results (δ¹³C, δ¹⁸O). Rock-components are analysed semi-quantitatively and their abundance is expressed relative to the rock texture. The Chondrodonta bedset is highlighted in orange; see text and Table 1 for the description of lithofacies and lithofacies associations and Fig. 4 for the legend.

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decrease. The concentration of thorium ranges around 2 ppm throughout the section, with peaks of 4 ppm between 8.0 m and 11.5 m. Values decrease to 1 ppm only in the upper part (17 to 20 m from the base). The concentration of potassium varies between 0% and 0.4% throughout the section and shows sharp concentration peaks at 10 m, 17 m and 20 m from the base.

The Borgo Celano 2 section

The Borgo Celano 2 stratigraphic section (Figs 1B, 7A and 7B) is 56.8 m thick (SGRL, member 2 and 3) and shows lime mud-rich facies alternating with grain-supported and bioclastic beds. Bacinella–Lithocodium micro-encrustations are common in the lower-middle part of the section and stromatolites predominate in the upper part.

The lowermost 7.6 m are composed of alternating LA1 and LA2 facies successions, with a generally low skeletal abundance. It is marked at the base and at the top by tabular stromatolites (ST) and contains bioturbated mudstones (MD) and Thaumatoporella–wackestones and packstones (BW and PP). These are interbedded with massive decimetre-thick peloidal–foraminiferal packstone–grainstones (PG) and mollusc–oncoid floatstone–rudstones (OF and RF) with requieniids and nerineids. The Chondrodonta bedset (1.7 to 2.0 m, base of member 3, CH) occurs within both mud-supported and grain-supported facies.

In the middle part of the section (7.6 to 31.1 m) stromatolites are absent and the skeletal abundance generally increases. This part consists mostly of interbedded LA2 and LA3 skeletal-rich facies, arranged in massive decimetre to metre-thick requieniid–oncoid floatstone–rudstones, in both granular and muddy matrices (RF, OF and BF). Requieniids increase upward in size and abundance. These skeletal-rich facies are interbedded with thin-beded peloidal–foraminiferal packstones and grainstones (PG and PP) and, commonly, with lithofacies LB. Bacinella–Lithocodium micro-encrustations form bindstones (BL) between 9.5 m and 14.3 m. Common constituents of this middle part include requieniids, small benthic foraminifera (miliolids, P. infracretacea, Cuneolina sp. and Debarina sp.) and dasyycladales (Salpingoporella sp.). Thaumatoporella is locally abundant and orbitolinids occur within the rudist and Bacinella–Lithocodium facies. Bacinella–Lithocodium micro-encrustations (LB) eventually disappear in favour of muddy strata (MD and BW) and, up-section, of grain-supported strata (OF and RF).

The upper part of the section (31.1 to 56.8 m) records the complete disappearance of the LA3 facies association and of rudist limestones. It is composed of LA1 facies with interbedded thin LA2 intervals and is characterized by predominant stromatolites (ST). These occur either as centimetre-thick wavy laminae within MD, as tabular decimetre-thick beds alternating with PP, PG, OF and BW, or as tabular and dome-shaped decimetre to metre-thick beds (between 46.1 m and 56.8 m). The abundance of macrofossils, especially requieniids, is generally low in the upper part of the section; exceptions are noted for S. dinarica, which reaches its highest concentration between 38.7 m and 38.9 m, and for the occurrence of an orbitolinid-rich wackestone (Mesorbitolina lotzei and Praeorbitolina cormyi) at 50.0 to 51.5 m.

The δ13C values in the Borgo Celano 2 section (Fig. 7A and B) increase up-section, from −1.9‰ at the base to −0.7‰ at the top, with an average of −0.2‰. The lower part (0 to 7.6 m) contains a negative peak of −2.2‰ (7 m). Values slightly increase in the middle part (7.6 to 31.1 m) and a short negative shift, from +0.3‰ to −0.1‰, occurs around the Bacinella-rich level (12.0 to 15.8 m). In the upper part of the section (31.1 to 56.8 m) two negative peaks, of −1.7‰ and of −1.9‰, occur respectively at 33.4 m and at 44.6 m, in correspondence with beds with ephemeral-emersion related features. The most positive peak of the stratigraphic section, of +2.8‰, occurs at 46.35 m. The δ18O curve also increases up-section, rising from −4.0‰ at the base to −3.5‰ at the top.

Chondrodonta bedsets

The Chondrodonta bedsets occur in the lower-middle part of the studied sections (see Fig. 8A to G), interbedded with carbonate mud-rich facies and stromatolites. The bivalves belong to the species C. glabra Stanton (Posenato et al., 2018), form parachothonous to autochothonous accumulations and occur in an almost monospecific association with subordinate requieniids: C. glabra shells, 8 to 12 cm long on average, are mostly articulated, present a generally low degree of breakage and show a variable orientation and distribution throughout the bedsets. The outer calcite shell layer is preserved whereas the inner aragonitic one is dissolved (see Posenato et al., 2018).
The Chondrodonta bedset in the Borgo Celano 1 section (Fig. 8A) is composed of nodular beds in which chaotically oriented shells and small bouquet-like aggregates (see Fig. 3I) are scattered between dense sheets of sub-horizontal individuals (Fig. 8C). The upper bed surface (Fig. 8A) shows three sub-circular reliefs (cf. ‘knobs’; see Posenato et al., 2018) with shells in upright position forming bouquet-like or thicket aggregates (Fig. 8G). In the Borgo Celano 2 section, a few hundred metres eastward, the same Chondrodonta bedset is half the thickness and directly overlies subtidal oncid beds.

In the San Giovanni section, the bedset is composed of two sub-sets (Fig. 8B). The lower sub-set, arranged in decimetre-thick tabular beds, shows locally common Chondrodonta in small patches, with sub-horizontal or, less commonly, upright shells. In the upper sub-set, composed of nodular and undulating beds, shells are more abundant and occur either horizontally oriented in dense sheets or chaotically oriented with common bouquet-like aggregates (Fig. 8D).

**INTERPRETATION AND DISCUSSION**

**Reliability of the stable isotope geochemistry**

In the last decades, high-resolution δ^{13}C stratigraphy has been successfully applied to the correlation of Cretaceous shallow-water platform carbonates and hemipelagic deposits (e.g. Parente et al., 2007; Burla et al., 2008; Vahrenkamp, 2010; Huck et al., 2011; Schmitt et al., 2020). Syn-depositional and post-depositional diagenetic alteration (Allan & Matthews, 1982; Oehlert & Swart, 2014, 2019) as well as biological fractionation and local palaeoeceanographic conditions may cause the δ^{13}C composition of shallow-water carbonates to deviate from the global open ocean value (Patterson & Walter, 1994; Immenhauser et al., 2008; Huck et al., 2017). A positive covariance between δ^{13}C and δ^{18}O bulk values is often used to infer either decreasing alteration in the freshwater phreatic zone (Swart & Oehlert, 2018) or diagenetic alteration under the meteoric water influx in the mixing zone (Allan & Matthews, 1982). As a result, several studies proposed the lack of covariance between δ^{13}C and δ^{18}O values as indicative of the unaltered nature of samples (e.g. Grotzinger et al., 2011). Nevertheless, recent studies point out that a lack of correlation between δ^{13}C and δ^{18}O alone cannot be used as proof for sample preservation, and that changes in sediment source through time can also produce paired shifts in δ^{13}C and δ^{18}O values (Swart & Oehlert, 2018; Oehlert & Swart, 2019).

In the studied sections, scatterplots of δ^{13}C and δ^{18}O show no significant correlation for individual lithofacies or for lithofacies associations (Fig. 9A and B), suggesting that variations in δ^{13}C are not the result of facies changes. In the analysed samples, most of the isotope bulk values are coherent with the rudist and Chondrodonta shells isotope values.

The analysed samples partly overlap the Aptian isotopic field of the Apennine Platform shallow-water carbonates (Di Lucia et al., 2012; Schmitt et al., 2020) and plot within the lower range of Barremian – Aptian seawater (‘low-latitude’) biotic calcite field of Prokoph et al. (2008) (Fig. 9C). With respect to the field of the Aptian Apennine Platform shallow-water carbonates, an important tail of more depleted δ^{13}C and δ^{18}O values is observed. The moderate inverted ‘J’ stable isotope pattern (more visible
Fig. 9. Scatterplots of the C and O isotopic values of the San Giovanni and Borgo Celano sections. (A) C and O correlation for the bulk of each lithofacies association and for Chondrodonta and requieniid shells. (B) C and O average correlation for single lithofacies and lithofacies associations. (C) Scatterplots of the studied sections against the isotopic range of both the Barremian – Aptian shallow-marine tropical–subtropical carbonates by Prokoph et al. (2008) and the Barremian – lower Aptian shallow-water carbonates of the Apennine Platform (Di Lucia et al., 2012; Schmitt et al., 2020). (D) Correlation between the concentration of Sr (ppm) and the $^{87}$Sr/$^{86}$Sr value in Chondrodonta and requieniid shells, compared to Borgo Celano shell samples analysed by Guerzoni (2016).
for the San Giovanni section; see Fig. 9A and C) indicates an impact of meteoric diagenesis (Allan & Matthews, 1982; Lohmann, 1988), mainly affecting LA1 and LA2 facies. In the presented dataset, LA1 and, subordinately, LA2 facies, contain frequent exposure-related features like spar-filled fenestrae, micro-vugs and thin intraformational brecciated levels (Fig. 9A and C). Despite this evidence of meteoric alteration, not all samples located below emersion surfaces have negative δ13C values and also not all samples with negative δ13C values are associated with exposure surfaces. These findings confirm the complexity of the stable isotopes’ behaviour in shallow-water carbonates associated with exposures (e.g. Immenhauser et al., 2003; Thickling et al., 2007; Christ et al., 2012) and suggest that some negative excursions may be related to changes in the primary marine carbon isotope signal.

Considering the potential for diagenetic effects, a conservative approach was chosen for the use of δ13C profiles for stratigraphic correlations (e.g. Huck et al., 2017). All samples with evidence of exposure/dissolution features at the outcrop or microscope scale were discarded and a smoothing procedure was run to highlight low-order trends and excursions in δ13C. The general trend of δ13C values is more likely to record the long-term global variations of the open ocean than higher-order fluctuations; the latter are more likely to result from variations in local environmental conditions on the shallow platform (Colombie et al., 2011).

The overall isotope trends and excursions, which extend across multi-metre-thick intervals at both San Giovanni and Borgo Celano, can be traced and correlated across the two sections (for example, the positive δ13C peak at the top of the *Chondrodonta* bedsets, which precedes a decreasing trend of the curve). This evidence suggests that isotopic patterns in the smoothed data are, therefore, significant and reflect a control overriding the local-scale diagenetic processes.

The outer low-Mg calcite layer of Cretaceous rudist and oyster shells has been widely recognized as a suitable archive for the Sr-isotope composition of ocean waters (e.g. Steuber et al., 2005; Boix et al., 2011; Frijia et al., 2015; Huck & Heimhofer, 2015). The concentration of strontium, iron and manganese in shells is commonly used for estimating the degree of diagenetic alteration (e.g. Ullmann & Korte, 2015) and several elemental threshold values have been suggested for both rudists (Fe < 100 ppm, Mn < 50 ppm, Sr > 700 ppm; Steuber et al., 2005; Frijia et al., 2015) and *Chondrodonta* (Mn < 250 ppm, Sr > 500 ppm; Damas Mollá et al., 2006). Considering that diagenesis is usually associated with a decreased Sr concentration coupled with increased Fe–Mn concentrations and increased 87Sr/86Sr ratios, only shells with low iron and manganese concentrations in skeletal calcite and high strontium concentrations are, usually, considered suitable for Strontium Isotope Stratigraphy (SIS).

In the presented dataset, all shell samples have Fe and Mn concentrations below the conventional thresholds indicative of diagenetic resetting and they show no covariance with Sr concentrations (Table 2). The Sr content is higher in rudist shells (558 to 1109 ppm) than in *Chondrodonta* shells (57 to 708 ppm), as also observed by Schmitt et al. (2020) in samples from the Apennine Platform. No correlation between decreasing Sr content and increasing/decreasing 87Sr/86Sr in rudists and *Chondrodonta* shells (Fig. 9D) as well as no covariance of Sr concentration with δ13C or δ18O values, were observed. Only one sample from the *Chondrodonta* bedset of San Giovanni, despite its high Sr concentration, yields an 87Sr/86Sr value higher than the isotope composition of the sample matrix (sample DPG11-A; see Table 2). On the other hand, a few samples with low Sr concentration also have low 87Sr/86Sr values (Table 2). This evidence indicates that strict thresholds in Fe, Mn and Sr concentrations are not perfect screening mechanisms for identifying samples with primary isotope ratios.

Internal consistency of Sr isotopic values among different components within the same bed or nearby beds is, instead, considered as strong evidence for preservation of the original signal (McArthur et al., 2004, 2012). Therefore, samples with elemental concentrations below the published elemental threshold values (for example, Sr > 500 ppm for *Chondrodonta* and Sr > 700 ppm for rudists) were considered for SIS only when their Sr-isotope values were within the analytical error (8 × 10^-6 in average) with respect to other shells from the same bed or from the nearby beds. Only one sample (SG14-D; see Table 2), despite its internal consistency of the Sr isotopic value, was discarded for the SIS due to a lower Sr concentration with respect to the one measured in the matrix.
Table 2. Elemental concentrations and Sr-isotope ratios of the studied rudist and *Chondrodonta* samples collected from the San Giovanni and the Borgo Celano 1 sections. Sr-isotopes values have been corrected for interlaboratory bias (see text for further details). Preferred numerical ages have been derived from the look-up table of McArthur *et al.* (2001, version 5: 04/2013), which is calibrated to the Geological Time Scale of Ogg & Hinnov (2012). See the text for details on the precision estimation and on the calculation of minimum and maximum ages. In italics, samples discharged from the Strontium Isotope Stratigraphy (SIS); in bold, the mean value of the Sr isotope ratio for each sample set and the preferred numerical age derived from it. Minimum and maximum ages were obtained by combining the statistical uncertainty (2 SE) of the mean values of the Sr-isotope ratios with the uncertainty of the seawater curve (see Frijia *et al.*, 2015, for details on the procedure).

<table>
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<th>Location</th>
<th>Sample</th>
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<th>(^{87}\text{Sr}/^{86}\text{Sr} \text{ measured} )</th>
<th>(+2 \text{ SE} \left( \times 10^{-6} \right))</th>
<th>(^{87}\text{Sr}/^{86}\text{Sr} \text{ corrected} )</th>
<th>(+2 \text{ SE} \left( \times 10^{-6} \right))</th>
<th>Mg (µg/g)</th>
<th>Sr (µg/g)</th>
<th>Fe (µg/g)</th>
<th>Mn (µg/g)</th>
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Correlation of the stratigraphic sections

The integrated high-resolution framework based on biostratigraphy, SIS and δ¹³C segments enables correlation of lithofacies and lithofacies associations. The benthic foraminiferal assemblage at the base of the three sections (Figs 4, 6A and 7A), including Cuneolina sp., P. infracretacea, Mayncina sp. and the last occurrence of the dasycladacean alga S. muehlbergii (0.5 m at San Giovanni and 11 m at Borgo Celano), indicates a lowermost Aptian age (Chiocchini et al., 2012). Above the Chondrodonta bedsets, the co-occurrence of Debarina sp., Pseudolituonella sp. and S. dinarica indicates either an early (Chiocchini et al., 2012) or early – late (Di Lucia et al., 2012) Aptian age. The co-occurrence of M. lotzei and P. cormyi within the uppermost part of the Borg Celano 2 section (see also Claps et al., 1996) suggests a late early Aptian or, possibly, an early late Aptian age, according to the most recent review of Schröder et al. (2010).

The mean ⁸⁷Sr/⁸⁶Sr from the Chondrodonta bedset at San Giovanni (0.707415) and at Borgo Celano (0.707410) are statistically indistinguishable (see Table 2), suggesting that the two Chondrodonta bedsets are roughly coeval. The first occurrence of Debarina sp. a few metres above the top of the Chondrodonta bedsets, supports this interpretation. The isotopic values indicate an estimated age of 125.87 ± 0.6 Ma at San Giovanni and of 125.65 ± 1 Ma at Borgo Celano, corresponding to the lower part of the early Aptian, consistent with the biostratigraphic data. Samples of a bivalve floatstone 5 m below the Chondrodonta bedset at Borgo Celano have an ⁸⁷Sr/⁸⁶Sr mean value of 0.707419, calibrated to an age of 125.98 Ma ± 0.1. A rudist floatstone 12 m above the Chondrodonta bedset at San Giovanni has a value of 0.707412, calibrated to an age of 125.75 Ma ± 1. The similar ⁸⁷Sr/⁸⁶Sr values among sections constrain the age of the Chondrodonta bedsets within the early Aptian at the boundary between Globigerinelloides...
blowi and Leuoldina cabri planktonic foraminiferal zones, according to the GTS2012 (Ogg & Hinnov, 2012).

The negative excursions in δ¹³C above the Chondrodonta bedsets are interpreted to be correlative, as are the negative excursions around the Bacinella-rich interval. The Chondrodonta bedsets have therefore been used as stratigraphic datum to correlate the stratigraphic sections (Fig. 10).

Both stratigraphic sections are characterized by a benthic community dominated by Chondrodonta and micro-encrusters in the lower part and by Bacinella–Lithocodium in the upper part. These
biotic changes reflect a stressed platform ecosystem during the deposition of the lower Aptian San Giovanni Rotondo Limestone, preventing the thriving of a diversified macro-benthic and micro-benthic fauna. Similar biotic turnovers, indicative of environmental stress, have been documented worldwide during the early Aptian (Huck et al., 2010; Rameil et al., 2010; Skelton & Gili, 2012; Stein et al., 2012; Huck et al., 2014; Nuñez-Useche et al., 2020, among others).

Relative sea-level fluctuations in the stratigraphic sections are indicated by both ephemeral emersion-related features in the lower part and by a facies shift towards open shelf deposits in the middle-upper part. These fluctuations can be attributed either to decreased carbonate production or to eustatic changes.

Along the margin of the Apulia Carbonate Platform (ACP), a pronounced lower Aptian backstepping of at least 5 km landward is indicated by pelagic facies (Marne a Fucoidi formation) overlying the slope and margin succession. This backstepping, interpreted as a drowning unconformity (Bosellini et al., 1999a; Graziano, 2013) or as a partial drowning (Morselli et al., 2017), is coeval with the drowning phase documented in many other lower Aptian Tethyan platforms (Bover-Arnal et al., 2012; Husinec et al., 2012; Maurer et al., 2013; Pictet et al., 2015, among others). However, no high-resolution sequence stratigraphic studies of the lower Aptian inner platform facies on the ACP have been carried out to date and the short stratigraphic interval analysed in this study prevents a broader scale comparison to track sea-level changes at a regional or global scale.

**Platform-to-basin correlation**

The δ13C record of the studied sections can be used in combination with biostratigraphic markers and SIS to achieve a chemostratigraphic correlation with the δ13C curves of the Cismon Apticore in southern Alps (Menegatti et al., 1998; Erba et al., 1999) and of the Adriatic Basin adjacent to the ACP (Luciani et al., 2001, 2006) (Fig. 11).

The beginning of the negative δ13C trend in the studied sections (1.6 m at San Giovanni and 11.1 m at Borgo Celano) is correlatable with the top of the magnetochron M0 of Malinverno et al. (2010), right below the onset of the C3 segment in the Cismon section. The chemostratigraphic Selli Event (C3–C6 segments, cf. Erba et al., 1999; Malinverno et al., 2010) is here placed within the middle-upper part of the San Giovanni section and in the lower part of Borgo Celano composite. The beginning of the C3–C4 segments within the Cismon Apticore is correlated with the negative shift right above the *Chondrodonta* beds (Fig. 11). The positive shift of the C6 segment in the Cismon Apticore is tentatively correlated with the *Bacinella*-rich level. Higher in the Borgo Celano composite section, the increasing δ13C values associated with thick stromatolite beds are tentatively correlated to the C7 segment. According to this interpretation, the San Giovanni and the Borgo Celano δ13C curves would capture the entire perturbations of the global carbon cycle associated with OAE1a, including their prelude in the upper C2 segment.

This chemostratigraphic correlation places the *Chondrodonta* beds within the uppermost C2 segment, making them coeval with the *Chondrodonta* accumulations of the Monte degli Angeli Limestone margin facies (see Graziano, 2013; Guerzoni, 2016) exposed along the southern Gargano Promontory (Fig. 1A).

The San Giovanni section and the lower part of the Borgo Celano composite have been further correlated to the δ13C curve of the Coppitella section in the Adriatic Basin. This section represents the pelagic deposits of the ‘Marne a Fucoidi’ (Fig. 1A). Black shales occur at Coppitella only in the C6–C7 segments (cf. ‘lower’ and ‘upper’ black shales in Luciani et al., 2001, 2006), are absent in the C3–C4 segments and not exposed in the C5 segment (see Fig. 11).

The quantitative micropaleontological analysis carried out by Luciani et al. (2001) on planktonic and small benthic foraminifera, calcareous nannofossils and radiolarians indicates oligomesotrophic conditions in the C3–C5 tract, suggesting that Coppitella did not record the eutrophication affecting the global oceans during most of OAE1a (Menegatti et al., 1998; Jenkyns, 2003; Erba & Tremolada, 2004). Moderate and high fertility conditions have been interpreted for the ‘lower’ (C6 segment) and ‘upper’ (middle C7 segment) black shales, respectively (see figs 6 to 9 in Luciani et al., 2001).

Both the micropaleontological associations and the stratigraphic position of black shales in basinal settings suggest that eutrophication occurred only from the upper part of OAE1a interval in the Adriatic Basin (i.e. from the C6 segment). The same time interval was characterized by biotic turnovers in the shallow-water settings of the ACP. Indeed, the gradual
disappearance of rudists in favour of orbitolinids and *Bacinella–Lithocodium* assemblages would indicate a gradual shift from oligotrophic to mesotrophic conditions across OAE1a, according to the nutrient gradients for benthic communities proposed by Mutti & Hallock (2003) and Rameil *et al.* (2010).

The chemostratigraphic C3–C4 segments (Fig. 11) correlate in the studied sections with an interval of peloidal packstone–grainstones and lime mud-rich facies with scarce to absent skeletal components like molluscs, foraminifera and dasyycladales (see Figs 4, 6A and 7A). This decreased abundance of organisms indicates deposition under stressed conditions during the first part of OAE1a, as also suggested by the trace element concentrations in the San Giovanni section (Fig. 5). A suite of RSTE (V, As, Mo and U) has been used to better reconstruct the palaeo-redox conditions (see Tribovillard *et al.*, 2006; Hueter *et al.*, 2019) and the P/Al ratio has been used to track the nutrient content of the seawater (e.g. Föllmi, 1995; Westermann *et al.*, 2013). The changes in concentration of RSTE should be observed at different temporal scales due to their variable residence time in the oceans (from few kyr to hundreds of kyr; Sholkovitz & Schneider, 1991; Shields & Stille, 2001; Bodin *et al.*, 2007). Nevertheless, due to the different solubility of V, Mo and U in waters with variable levels of oxygen, decreases in the RSTE concentration in marine deposits are commonly assigned to an oxygen deficiency phase favouring the enrichment of RSTE in organic-rich sediments (Algeo & Maynard, 2004; Tribovillard *et al.*, 2006; Bodin *et al.*, 2007; Hueter *et al.*, 2019). The decrease of the RSTE/Al ratios in the San Giovanni section within the chemostratigraphic C3–C4 segments suggests dysaerobic conditions during the first part of OAE1a, thus reinforcing the sedimentological data. A similar decrease in RSTE from the base of the C3 segment has been observed in the Adriatic Platform (Hueter *et al.*, 2019). The decreased RSTE correlate with a decrease of the P/Al ratio (Fig. 5), indicative lower nutrient content. Dysaerobic seawater and lower nutrient levels may explain, therefore, the impoverished fauna in the C3–C4 segments.

Stressed conditions on the ACP in the lower part of OAE1a are further suggested by the gamma ray profiles of the Borgo Celano 1 section (see Fig. 6B). The increase in the total API (%) and, particularly, in uranium (ppm) across the C3–C4 tract may indicate a progressive enrichment in organic matter. Similar trends, with a marked gamma ray peak caused by an increased concentration of uranium, have been observed in the lower part of the Shu‘aiba Formation in northern Oman (Vahrenkamp, 2010). The OAE1a interval in the Shu‘aiba Formation (cf. ‘Maximum Flooding Interval’; see Vahrenkamp, 2010) is marked by a gamma ray peak caused by the uranium, interpreted as indicative of an enrichment in organic matter.

The enrichment in organic matter at Borgo Celano also correlates with a global biocalcification crisis (Weissett & Erba, 2004; Erba *et al.*, 2010; Giraud *et al.*, 2018), carbonate platform drowning in northern Tethys, and biotic turnover (from rudist-dominated to *Bacinella–Lithocodium*-dominated) on carbonate platforms of the Southern Tethys (e.g. Skelton & Gili, 2012; Huck *et al.*, 2014).

Upward in the studied sections, the *Bacinella*-rich level correlates to the chemostratigraphic C6 segment, characterized by mesotrophic conditions (i.e. moderate fertility peak, see above) and the deposition of the ‘lower’ black shale in the Adriatic Basin (Fig. 11). Increased nutrient input on the ACP in this tract is also suggested by the more open-shelf facies of the coeval Coppa di Pila limestones (northern Gargano; Fig. 1A). Here, orbitolinid-rich mudstones with subordinate *Bacinella–Lithocodium* micro-encrustations are overlain by foraminifera-rich and bivalve-rich beds, indicative of restoration of normal-marine conditions (Guerzoni, 2016).

Transient peaks in the abundance of *Bacinella–Lithocodium*, coeval with black shale deposition during OAE1a, also occur on the Arabian and Adriatic platforms (Huck *et al.*, 2010; Rameil *et al.*, 2010) and have been interpreted to reflect meso-eutrophic conditions on the platform top.

The smaller magnitude bloom of *Bacinella–Lithocodium* on the ACP, with respect to the Arabian and Adriatic platforms, can be attributed to moderate nutrient levels on the platform top, coeval to the only moderate fertility conditions in the Adriatic Basin.

A transgressive and deepening-up trend is further interpreted at the base of the *Bacinella–Lithocodium* interval on the Arabian and Adriatic platforms (Huck *et al.*, 2010). On the ACP, a transgressive episode at the base of the *Bacinella–Lithocodium* facies is suggested by the deepening-up trend interpreted from open shelf LA2 deposits progressively replacing restricted subtidal LA1 facies in the C5–C6 segments (see Figs 4, 6A and 10).
Proliferation of Chondrodonta: proxy of ecological stress in shallow-water communities prior to OAE1a?

Regional occurrence of Chondrodonta accumulations

Few studies on Berriasian – lower Barremian shallow-water carbonates report Chondrodonta accumulations in the Southern Tethys (e.g. Pratt & Smewing, 1990; Zaghibb-Turki, 2003; Massé et al., 2015) and in the proto-North Atlantic (e.g. Phelps et al., 2014). In contrast, upper Barremian – lower Aptian Chondrodonta accumulations have been extensively documented worldwide. With few exceptions (Posenato et al., 2018, 2020), only limited attention has been given to the palaeoecological significance of Chondrodonta accumulations. Only a few authors (e.g. Phelps et al., 2015; Posenato et al., 2018; Nuñez-Useche et al., 2020) have interpreted Chondrodonta as an indicator of ecological stress in a mesotrophic domain. Other authors (e.g. Leonide et al., 2012; Bonin et al., 2016) consider it as a component of oligotrophic (cf. ‘Urgonian’) communities.

Determining the precise stratigraphic position of every Chondrodonta bed reported worldwide...
is challenging. Only by integrating recent high-resolution studies on the stratigraphic, environmental and ecological evolution of worldwide carbonate platform successions spanning OAE1a, a synthesis of the global accumulations was feasible (Fig. 12).

In the Helvetic domain (Switzerland) of the Northern Tethys, *Chondrodonta* occurs within oligotrophic coral–rudist limestones (Wissler et al., 2003) of the uppermost Barremian – lower Aptian succession, below the drowning interval associated with mesotrophic associations (Föllmi et al., 2006). *Chondrodonta* also occurs both in rudist limestones and in monospecific biostromes in the (?) upper Barremian – lower Aptian carbonates of Hungary (Császárv et al., 1994), below an interval with abundant *Bacinella–Lithocodium* and orbitolinids. In the Maestran Basin (south-east Spain), *Chondrodonta* occurs in monospecific biostromes prior to OAE1a (Malchus et al., 1995) but is interpreted as recording ‘normal marine conditions’ (Bonin et al., 2016). In the Vocontian Basin and Provence Platform domains (south-east France), stepwise drowning events prior to OAE1a (Masse & Feneciry-Masse, 2013; Giraud et al., 2018) are characterized by Urgonian limestones with episodic orbitolinid levels. Leonide et al. (2012) report local chondrodontids in Urgonian rudist facies, extending to the uppermost chemostratigraphic C2 segment.

In the Central and Southern Tethyan realm, the upper Barremian – lower Aptian Apennine Platform (Amodio & Weissert, 2017) is characterized by a shift towards mesotrophic conditions with *Bacinella–Lithocodium* and *Palorbitolina lenticularis*. Graziano & Raspini (2018) interpret abundant *Chondrodonta*, both in monospecific biostromes and in association with *Bacinella–Lithocodium* and *P. lenticularis*, as an indication of mesotrophic conditions. Orbitolinid-rich rocks of earliest Aptian age and extensive *Bacinella–Lithocodium* intervals at the turn of OAE1a occur in Oman (Pittet et al., 2002; Huck et al., 2010; Rameil et al., 2010); here *Chondrodonta* floatstones are interpreted as oligotrophic communities proliferating probably up to the uppermost C2 segment, although ‘abundant oysters’ (cf. Immenhauser et al., 2004) are also reported within *Bacinella–Lithocodium* facies. Rudist–*Chondrodonta* limestones interbedded with orbitolinid-rich beds occur in the (?) lower Aptian shallow-water successions of Ethiopia (Bosellini et al., 1999b) and Somalia (Barbieri et al., 1979) and in the (?) Barremian – Aptian limestones of Afghanistan (Abdullah et al., 2008).

In the proto-North Atlantic, Najarro et al. (2011) report *Chondrodonta* within oligotrophic assemblages of the Basque–Cantabrian Basin that underlie and overlie OAE1a. Conversely, in the Lusitanian Basin (Portugal), Huck et al. (2014) interpret the replacement of oligotrophic rudist–coral limestones by orbitolinid–oyster-rich facies with subordinate *Bacinella–Lithocodium*, as a result of palaeoenvironmental perturbations and incipient drowning associated with OAE1a. In the Gulf of Mexico, *Chondrodonta* occurs in association with *Bacinella–Lithocodium* in (?) Barremian – lower Aptian limestones of the Atima platform in Honduras (Scott & Finch, 1999). In the Comanche Platform (Texas) Phelps et al. (2014, 2015) report *Chondrodonta* within upper Barremian rudist limestones and as lower Aptian monospecific biostromes (up to the top of the C2 segment) and interpret them as a response to increased detrital clay input, preceding sea-level transgression and platform drowning during OAE1a. Similarly, in the Cupido Platform (Mexico) which drowned after OAE1a, Núñez-Useche et al. (2020) interpret the occurrence of lowermost Aptian orbitolinid-rich and *Chondrodonta*-rich beds as a short mesotrophic event caused by both sea-level transgression and increased continental weathering due to a more humid climate. *Chondrodonta* in the Cupido Platform occurs also within oligotrophic assemblages at the onset of OAE1a, below an extensive *Bacinella–Lithocodium* interval recording environmental instability and mesotrophic conditions during the anoxic event.

Globally (Fig. 12), *Chondrodonta* thrived both within coral–rudist associations (as a subordinate component) as well as in fully mesotrophic conditions (where it predominates) and, except for the Apennine Platform, its accumulations generally pre-date the strong environmental stress that affected shallow-water carbonates deposition during OAE1a.

**Palaeoenvironmental controls on the Chondrodonta proliferation**

During OAE1a, environmental disturbances triggered by the Barremian–Aptian climate warming (Larson, 1991; Larson & Erba, 1999; Tejada et al., 2009) caused biotic stress in the shallow-water and deep-water domains (e.g. Pancost...
et al., 2004; Dumitrescu et al., 2006; Föllmi et al., 2006; Najarro et al., 2010). Ocean eutrophication (i.e. ‘nannoconid crisis’; Erba, 1994, 2004) and carbonate platform demise (Weissert et al., 1998; Wissler et al., 2003) are widely documented. Intensified precipitation and continental weathering due to a warmer and more humid climate, combined with increased upwelling near coastlines due to intensified atmospheric and oceanic circulation, increased the nutrient (for example, phosphorous) input to shallow-water areas (Föllmi, 1996, 2012). The latter resulted in biotic turnover from oligotrophic to mesotrophic benthic communities on the platform top during OAE1a (e.g. Immenhauser et al., 2005; Skelton & Gili, 2012; Huck et al., 2014; Amodio & Weissert, 2017; Hueter et al., 2019). Nevertheless, biotic changes in the shallow-water benthic communities occurred also in the prelude phase of the anoxic event.

_Chondrodonta_ is considered an opportunistic and r-strategist taxon and a relatively high nutrient availability has been suggested as a prerequisite for its thriving (Posenato et al., 2018, 2020). This interpretation is supported by the stratigraphic occurrence of the studied _Chondrodonta_ bedsets on the ACP, in an interval of transition from oligo-mesotrophic (i.e. rudists) to fully mesotrophic (i.e. _Bacinella_–_Lithocodium_, orbitolinids) assemblages. A relative increase in the P/Al concentration and its trend within the _Chondrodonta_ bedset of the San Giovanni section (see Fig. 5) suggest higher and fluctuating trophic levels during its deposition. These nutrient fluctuations, which occur just below the onset of OAE1a, correlate with the oligo–mesotrophic regime in the Adriatic Basin (see Platform-to-basin correlation section) and with increasing eutrophication in the nearby pelagic Cismon Apticore (Fig. 13; see Bottini et al., 2020).
et al., 2015). The latter correlation suggests a local to regional scale increase of trophic sources, as also confirmed by the stratigraphic position of the worldwide lower Aptian Chondrodonta beds, placed in a transitional phase between oligotrophic and mesotrophic communities (Fig. 12). Stratigraphic evidence on the major sources of P on the ACP during the deposition of the Chondrodonta beds sets, however, still needs to be investigated.

Most worldwide Chondrodonta accumulations can be correlated to a short interval preceding the onset of OAE1a; in some cases, the accumulations extend also within the anoxic event and even slightly above (for example, Apennine Platform; Graziano & Rasolini, 2018), whereas in other areas they have not been reported (for example, Adriatic Platform; Huck et al., 2010). These observations suggest that the proliferation of Chondrodonta, mainly triggered by increased nutrient availability, would have been favoured or prevented by other local and/or regional environmental fluctuations during the early Aptian.

The facies analysis of the Chondrodonta bedsets on the lower Aptian ACP indicates a low-energy and restricted subtidal environment during their deposition. The redox proxies at San Giovanni show fluctuating trends within the Chondrodonta bedset (Fig. 5), suggesting that rapid changes in the local redox conditions and in nutrient levels did not exclude it. This finding indicates that Chondrodonta was resilient to variations in the seawater oxygenation. This hypothesis is confirmed by literature, where most Cretaceous monospecific (or oligo-) Chondrodonta biostromes are documented in low-energy, protected areas of the inner platform (Malchus et al., 1995; Leonide et al., 2012; Millán et al., 2014; Phelps et al., 2014; Núñez-Useche et al., 2020, among others). Although recent studies question anoxia as a driving mechanism for the demise of rudist–coral ecosystems in the prelude of OAE1a (see Hueter et al., 2020), fluctuating seawater redox conditions enabling Chondrodonta to outpace less tolerant benthic communities, at least at a local scale, cannot be excluded.

The stratigraphic position of the Chondrodonta bedsets on the ACP corresponds also to an interval of increasing water temperature in pelagic settings, far below the cooling episodes recorded within OAE1a (see Jenkyns, 2018). Although the bivalve occurs also in cooler-water settings in the Aptian (e.g. Millán et al., 2014), warmer waters could have enhanced its proliferation before the onset of the Selli Event.

In addition to warmer and more humid conditions of the early Aptian (Erba, 1994; Weissert & Erba, 2004), changes in water chemistry (for example, salinity and pH variations) may have facilitated the Chondrodonta proliferation by excluding other benthic competitors and potential predators. The early dissolution of the aragonitic inner shell layer in the Chondrodonta bedsets of Borgo Celano has been interpreted by Posenato et al. (2018) as possible consequence of a different aragonite saturation state related to seawater acidification during OAE1a. Because major changes in CO2 concentrations did not apparently result in any prolonged surface ocean acidity below or during OAE1a (see Naafs et al., 2016), the seawater acidification as a cause co-favouring the flourishing of Chondrodonta cannot be determined nor excluded.

The geochemical proxies of the San Giovanni section (Fig. 5) also show changes towards the top of the Chondrodonta bedset (i.e. towards the onset of OAE1a). The relative decrease in the concentration of the RSTEs is accompanied by a dramatic drop in the P/Al ratio and by a concentration peak of Al, indicative of a terrigenous input and land-derived material (Pearce et al., 2009; Westermann et al., 2013; Hueter et al., 2019). These combined geochemical fluctuations may reflect the exacerbation of the environmental stress on the ACP at the onset of the anoxic event, which resulted in conditions that excluded Chondrodonta.

Combining the stratigraphic position of the worldwide lower Aptian Chondrodonta accumulations below the onset of OAE1a (Fig. 12) with the increasing environmental deterioration prior to the anoxic event, it is conceivable that the proliferation of this bivalve took place in a short and confined environmental ‘window’. This window was triggered by the changing climate leading to OAE1a, which resulted in nutrient pulses promoting biotic turnover from oligotrophic to mesotrophic benthic communities in shallow-water carbonate platforms. The worldwide Chondrodonta accumulations occupied an environmental niche between rudist-dominated and Bacillaria–Lithocodium–orbitolinid-dominated assemblages, right below the onset of OAE1a. The opportunistic behaviour of Chondrodonta was rather efficient in this transitional context between more stable,
CONCLUSIONS

*Chondrodonta* is a Cretaceous oyster-like bivalve occurring in Tethyan shallow-water carbonates, commonly found in lower Aptian strata that record considerable climate and environmental changes peaking during Oceanic Anoxic Event 1a (OAE1a). The lower Aptian *Chondrodonta* bedsets of the Apulia Carbonate Platform (ACP) can be correlated to the uppermost chronostratigraphic C2 segment of C-isotope curve straddling OAE1a. *Chondrodonta* appears within rudist limestones and reaches a brief phase of maximum proliferation in monospecific biostromes (*Chondrodonta* bedsets) that terminate abruptly right before the negative δ¹³C excursion (C3 segment) of OAE1a. *Chondrodonta* accumulations precede the environmental stress related to the anoxic event and occupy an environmental niche between the oligo-mesotrophic (rudist-dominated) and fully mesotrophic (*Bacinella–Lithocodium–orbitolinid-dominated*) communities, as also reported worldwide.

The interval of proliferation of *Chondrodonta* on the ACP is characterized by variable nutrient levels and seawater oxygenation, and correlates also to an oligo-mesotrophic regime in the nearby pelagic realm.

Increasing nutrient loading preluding the onset of OAE1a created an environmental ‘window’ favourable for *Chondrodonta* in protected areas of the inner platform. Low energy, dysoxic seawaters and restricted circulation controlled the worldwide occurrence and duration of the environmental window. Other local to regional environmental fluctuations (for example, seawater temperature and acidification) likely contributed to the dominance of *Chondrodonta*. Further increase of inhospitable conditions leading to OAE1a inhibited the proliferation of *Chondrodonta*, allowing *Bacinella–Lithocodium* and orbitolinids to dominate within the benthic communities. The opportunistic behaviour of *Chondrodonta* was, therefore, rather efficient in the transitional context between more stable, stenotopic biotic assemblages, that occurred below the onset of OAE1a.

The proliferation of *Chondrodonta* in lower Aptian shallow-water carbonates resulted from unstable environmental conditions at the onset of OAE1a and the same is likely to apply to other Cretaceous oceanic anoxic events.

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DATA AVAILABILITY STATEMENT

Data used for this study are available upon request to the corresponding author (mrh@unife.it).

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Chondrodonta at the onset of OAE1a


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Supporting Information

Additional information may be found in the online version of this article:

Supporting Information. Procedures and analytical methods for the geochemical analyses performed in this study. The entire geochemical dataset, of both stable isotopes and trace elements, is also included.