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Paleoceanographic evolution and chronostratigraphy of the Aptian Oceanic Anoxic Event 1a (OAE1a) to oceanic red bed 1 (ORB1) in the Gorgo a Cerbara section (central Italy)

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A B S T R A C T

We performed a detailed study of the stratigraphic transition of Oceanic Anoxic Event 1a (OAE1a) to oceanic red bed 1 (ORB1) from the classic Gorgo a Cerbara section in the Umbria region of central Italy. We focused on a 25.5-m-thick stratigraphic succession, from which we analyzed 305 samples for total organic carbon (TOC), $CaCO_3$, magnetic susceptibility, diffuse reflectance spectrophotometry and the stable carbon and oxygen isotopic composition of both bulk samples and organic matter. In the Gorgo a Cerbara section, the Selli Level of OAE1a (~1.81 m thick) consists of laminated to bioturbated dark gray to black mudstones and shales with medium to dark gray radiolarian-rich silty to sandy layers and a maximum TOC content of 20.22%. The carbon isotopic values show a negative excursion (C3 stage, ~0.14 m) at the base of the Selli Level, followed by a stepwise positive excursion (C4–C6 stages, ~1.67 m) in the upper part of the Selli Level. The transition from OAE1a to ORB1 (~3.19 m thick) is characterized by bioturbated greenish gray cherty limestones and marly limestones with subordinate marls, corresponding to stable carbon isotopic C7 stage and lasts for ~0.75 Ma. The ORB1 interval (~13.15 m) consists of reddish marly claystones, dark-red marlstones, red marly limestones and red calcareous shales which indicate a highly oxic environment. Our results reveal a stepwise transition from a predominantly mesotrophic and dysoxic to anoxic environment at the time that the OAE1a black shales were deposited to an oligotrophic and oxic environment during the transitional interval and finally to highly oxic conditions during the ORB1 interval. The nannoconid crisis occurs at the top of the C2 stage, just 0.34 m below the negative excursion in $\delta^{13}C$ isotopic values. The massive $CaCO_3$ dissolution phase occurs 0.25 m above the negative excursion; it persisted for 0.85 Ma and probably resulted from excess CO_2, ocean acidification, and carbonate compensation depth (CCD) shoaling. Deposition of massive black shales occurs at the base of the C6 stage and lasted for 0.4 Ma.

1. Introduction

The early Aptian was marked by major perturbations in the global carbon cycle associated with considerable environmental change (Leckie et al., 2002; Jenkyns, 2003; Wagreich et al., 2011). These perturbations are expressed by positive excursions in the $\delta^{13}C$ values of both carbonates and organic carbon, and they may be coeval with the widespread deposition of laminated organic-rich sediments that represent oceanic anoxic events (OAEs; Schlanger and Jenkyns, 1976). The early Aptian includes one of the most significant and intensively studied of these events, OAE1a, which is also called the "Selli Event" (Arthur et al., 1990; Erba, 1994; Menegatti et al., 1998; Mehay et al., 2009; Tejada et al., 2009; Erba et al., 2010). Geologic evidence suggests that OAE1a was characterized by the deposition of organic-rich sediments in pelagic basins, extreme greenhouse conditions (Dumitrescu et al., 2006), increases in continental weathering and runoff (Najarro et al., 2011), and a negative excursion in the carbon isotopic values of carbonate and organic carbon material, followed by a pronounced positive excursion (Menegatti et al., 1998). Further, OAE1a is coeval with significant sea-level rise and a major change in nannofossil assemblages (Erba, 1994; Menegatti et al., 1998), which may indicate a period of ocean acidification (Erba et al., 2010). The mechanism that triggered OAE1a is thought to be a phase of intense

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volcanism that included the emplacement of the Ontong-Java Plateau, a large igneous province (LIP; Weissert and Erba, 2004; Mehay et al., 2009; Tejada et al., 2009).

Most previous studies have examined the OAE1a black shales or the record preceding OAE1a (Kuhnt et al., 2011; Stein et al., 2011 and references therein). Less attention has focused on the changes after OAE1a, with the exception of studies of the Yenicesihlar section in central Turkey. Oceanic red beds (ORBs) were formed in the Tethyan Ocean during the late Aptian shortly after OAE1a (Hu et al., 2006, 2012; Wang et al., 2011). To date, the environmental changes associated with the transition between the OAE1a black shales and the ORBs have not been well documented (Patruno et al., 2015). To better understand the paleoenvironmental changes during the transition from OAE1a to the first reddish limestones of ORB1 (Hu et al., 2006), this study examines a classic pelagic stratigraphic section in central Italy and compares it to the Yenicesihlar section.

2. Geologic setting

The Cretaceous pelagic sequence of the Umbria-Marche Basin was deposited near the northern edge of a "promontory" of the African plate (the "Adria continental microplate"; Satolli et al., 2007; Patruno et al., 2015). The basement of the Umbria-Marche Apennines is continental, with Upper Jurassic to lower Miocene pelagic strata overlying a Triassic to Lower Jurassic carbonate platform. During the latest phase of the Alpine-Himalayan orogeny during the Miocene (Centamore et al., 2002), the basin was involved in tectonic compression and became part of the Alpine-Apennine orogen.

The Lower Cretaceous sedimentary succession that crops out in the Umbria-Marche Basin has been subdivided into two discrete formations based on color changes, carbonate content and the presence or absence of chert and black shales: the Maiolica (upper Tithonian-lower Aptian) and Marne a Fucoidi (lower Aptian-upper Albian) formations. The Maiolica Formation consists primarily of whitish to medium-gray pelagic limestones; near the top of the formation, these include beige to black chert nodules to layers and dark-gray to black, organic-rich horizons with variable carbonate content. The overlying Marne a Fucoidi Formation is a more shale-rich sequence of dark-gray to black calcareous shales, light-green-gray marly limestones containing intervals of interbedded red and green marlstones, as well as calcareous mudstones.

3. Stratigraphy and sedimentary petrology

The Gorgo a Cerbara section is located in the Umbria Marche Basin in the northern Apennines of central Italy, 4 km east of the town of Piobbico along the Candigliano River (Fig. 1). It is a key reference section for the Tethyan domain, and the proposed GSSP stratotype for the Barremian/Aptian boundary (Channell et al., 2000; Gradstein et al., 2012). There is detailed and integrated magnetostratigraphy, chemostratigraphy and cyclostratigraphy for the entire section (Herbert et al., 1995; Channell et al., 2000; Speranza et al., 2005; Tejada et al., 2009; Stein et al., 2011). In addition, a calcareous nannofossil and planktic foraminiferal biostratigraphic framework has been established, along with ammonites, calpionellids, palynomorph and radiolarians (Coccioni et al., 1992; Erba, 1994; Coccioni et al., 2006; Coccioni et al., 2012; Patruno et al., 2015; Unida and Patruno, 2015).

The measured section is approximately 25.5 m thick, and the sequence encompasses the transition between the Maiolica and Marne a Fucoidi formations, as well as between OAE1a and ORB1. Detailed descriptions of the section's lithostratigraphy can be found in Patruno et al. (2015) and Unida and Patruno (2015) (Fig. 2). The uppermost part of the Maiolica can be divided into lithozones I and II, which consist of rhythmic alternations of white-grayish medium pelagic limestones with black clay layers, greenish-gray marly limestones and dark cherts (Fig. 3a). The lowermost part of the Marne a Fucoidi can be divided into seven lithozones (lithozones III–IX) according to Patruno et al. (2015). Lithozone III is the lowermost part of the Marne a Fucoidi and is characterized by whitish pelagic limestone. Subsequently, the Lower Transition Interval of lithozone IV is 0.26 m (Patruno et al., 2015) or 0.34 m thick (this study) and is dominated by white-grayish cherty limestones. Lithozone V (the Selli Level) is 1.81 m thick and consists of black or dark-gray shales intercalated with gray marlstones and silty-sandy beds (Fig. 3b); the black shales lie within the *Leupoldina cabri* planktic foraminiferal biozone (early Aptian) and have been correlated to OAE1a (Patruno et al., 2015). Lithozones VI and VII are 3.19 m thick and include greenish-gray bioturbated limestones with very thinly bedded gray calcareous marls or shales. In some areas, centimeter-thick brownish-gray, parallel-laminated, silty limestones occur; these may be calci-turbidites (Fig. 3c). Lithozone VIII mainly consists of reddish marly claystones; lithozone IX is dominated by bioturbated dark-red marlstones, red marly limestones and red calcareous shales with subordinate gray marlstones and marly limestones that occur in beds from 1 to 30 cm thick (Fig. 3d). The reddish lithozones VIII-IX are assumed to be equivalent to the late Aptian ORB1 (Hu et al., 2006).

4. Analytical methods

This section was described at the centimeter scale in the field. A total of 305 samples were collected for laboratory analysis at a resolution of 10–20 cm. We follow the lithozones proposed by Patruno et al. (2015), setting meter 0 to correspond with the top of the highest Maiolica-like bed, which is thick and whitish (Bed A). However, we use our own thickness measurements.

4.1. Total organic carbon (TOC)

Samples for TOC analysis were first treated with 10% HCl at 60 °C to remove carbonate, then washed with distilled water to remove HCl. Next, the samples were dried overnight at 50 °C and measured using a LECOCS-200 carbon-sulfur instrument at the Wuxi Research Institute of Petroleum Geology at SINOPEC, China. The standard deviation of the TOC measurements is lower than ±0.10%.

4.2. Calcium carbonate

Calcium carbonate analyses were performed on 83 bulk rock samples that were powdered from polished surfaces using a dental drill. The calcium carbonate content was measured using an NFP18-508 calcimeter at the State Key Laboratory of Marine Geology of Tongji University, China. The method measures the CO_2 volume produced by the complete dissolution of pre-weighed samples (100 ± 1 mg each) in 10% vol. HCl. The total carbonate content (wt.% $CaCO_3$) was computed with a precision of 1% using formulas that take into account the pressure and temperature of the laboratory, the amount of bulk sample used, and the volume of CO_2 evolved in the calcimeter. Pure calcium carbonate standards were measured every ten samples to ensure proper calibration.

4.3. Bulk stable carbon and oxygen isotopic compositions

The carbon and oxygen stable isotopic compositions of 253 whole rock samples were determined using a Finnigan MAT Delta