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Review

The end-Triassic mass extinction: A new correlation between extinction events and $\delta^{13}C$ fluctuations from a Triassic-Jurassic peritidal succession in western Sicily

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ABSTRACT

A new $\delta^{13}C_{carb}$ curve was obtained from an expanded peritidal succession in western Sicily and was used to investigate the relationships between isotopic signatures and biological events on carbonate platforms across the Triassic-Jurassic boundary (TJB). The resulting curve shows two main negative carbon isotopic excursions (CIEs) that fit well with the "Initial" and "Main" CIEs that are recognized worldwide and linked to the End-Triassic Extinction (ETE). In the studied section, the first negative CIE marks the disappearance of the large megalodontids, which were replaced by small and thin-shelled specimens, while the "Main" CIE corresponds to the last occurrence (LO) of the megalodontids and, approximately 50 m upsection, to the total demise of the Rhaetian benthic foraminifer community. Upward, the carbon curve shows a positive trend (ca. +1‰) and a gradual recovery of the benthic communities after an approximately 10 m-thick barren interval populated only by the problematic alga *Thaumatoporella parvovesiculifera*.

A comparison between the Mt. Sparagio $\delta^{13}C_{carb}$ curve and other coeval C_{carb} and C_{org} curves from carbonate platform, ramp and deep basin successions indicates similar isotopic trends; however, the diverse magnitudes and responses of benthic communities confirm that the carbon cycle perturbations have been globally significant, and were influenced by external forces such as CAMP volcanism. The multiphase nature of the extinction pulses could have been caused by local environmental changes related to transgression/regression phenomena. Overall, this study adds new data and a new timing to the effect of the acidification process on carbon productivity and benthic communities in different environments across the TJB.

1. Introduction

The End-Triassic Extinction (ETE) is one of the Big Five mass extinction events that occurred in the Phanerozoic, with a faunal turnover that involved both marine and terrestrial taxa (Flügel, 2002; Hesselbo et al., 2002; Kiessling et al., 2007). During Rhaetian time, a series of climate and environmental changes occurred, such as rapid climate change towards a global warming of 3°- 4 °C (McElwain et al., 1999), stratification of the ocean with consequent decreased water circulation (e.g., Huynh and Poulsen, 2005), an increase in atmospheric pCO_2 inducing a perturbation in the carbon cycle (e.g., Schaller et al., 2011), a sea level fall (e.g., Hallam, 1981), and a decline in the carbonate productivity with a decrease in the wt% carbonate content (e.g., van de Schootbrugge et al., 2007; Greene et al., 2012).

Several causes have been put forward for the ETE, however, the emplacement of the Central Atlantic Magmatic Province (CAMP), which is subsequent to the break-up of the Pangea supercontinent, is indicated as the main triggering factor (e.g., Wignall, 2001; Hesselbo et al., 2002; Marzoli et al., 2004; Nomade et al., 2007; Greene et al., 2012). The CAMP in fact released a huge amount of greenhouse gases, inducing anoxia and biotic crises (e.g., Hallam and Wignall, 1999; Pálfy et al., 2001; Greene et al., 2012). Although the duration of CAMP volcanism is still debated, several authors agree that it could have contributed to the perturbation of the global carbon cycle through pulsed volcanic phases (e.g., Marzoli et al., 2004; Deenen et al., 2010; Schaller et al., 2011; Ruhl and Kürschner, 2011; Davies et al., 2017). The interaction between the atmosphere and ocean may have led to a more superficial dissolution of CO_2, resulting in acidification of oceanic water (Hautmann et al., 2008; Greene et al., 2012). This process particularly affected the biomineralized organisms such as molluscs, corals and sponges, leading to the demise of the sponge and coral reefs at the end of the Triassic (Flügel, 2002; Kiessling et al., 2009; Črne et al., 2011).

The increase in volcanogenic CO_2 caused an alteration of the carbon cycle that resulted in negative shifts/trends of the $\delta^{13}C$ curve. The

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negative CIEs across the TJB are considered global in shape but not in absolute value (Greene et al., 2012; Pálfy and Kocsis, 2014). The different values recorded from correlatable sequences depend on the early diagenetic imprint that has influenced the isotopic signature (Clémence et al., 2010). The same consideration concerns the increase in $\delta^{13}C$ during the Hettangian time, which has a global signature but with different values recorded in different sections (Bachan et al., 2012). Recently, several time calibrations of the volcanic CAMP units were attempted to correlate the magmatic activity with the CIEs and ETE (Deenen et al., 2010; Davies et al., 2017). However, these calibrations are debated due to the regional variations of the events recorded across the TJB.

The TJB biotic crisis has been fully described from Tethyan deep-water successions (e.g., Hesselbo et al., 2002; Ciarapica, 2007; Pálfy and Zajzon, 2012; Hillebrandt et al., 2013). Concerning the shallow-water settings, several sections across the TJB were studied (McRoberts et al., 1997; Romano et al., 2008; Tunaboylu et al., 2014; Todaro et al., 2017), however in some cases they suffered lithological and/or facies variations (Southern Alps, Galli et al., 2005) or were affected by discontinuities (i.e., the reef margins in Sicily, Zarcone and Di Stefano, 2010).

The biostratigraphical signature across the TJB has been described in detail from some Tethyan peritidal successions (De Castro, 1990; Mancinelli et al., 2005; Romano et al., 2008; Tunaboylu et al., 2014). Al-Suwaidi et al. (2016) also analysed the carbon curve oscillations across the TJB in an equatorial carbonate platform succession from the Ghalilah Formation (United Arab Emirates). They documented a negative $\delta^{13}C$ shift at the end of the Triassic that did not seem to affect the reef biota. This could suggest the persistence of aragonite supersaturation at the equatorial latitude, in contrast to the acidification processes at higher latitudes that were likely responsible for the extinction of biomineralized biota (Al-Suwaidi et al., 2016).

With the aim of better discriminating the relationship between isotopic signatures and biological events across the TJB, we attempted a chemostratigraphic correlation of the $\delta^{13}C_{carb}$ values from an expanded peritidal succession from western Tethys with the $\delta^{13}C_{carb}$ values from carbonate platforms (Mt. Cefalo, Bachan et al., 2012; Wadi Milaha, Al-Suwaidi et al., 2016), ramps (Val Adrara, Bachan et al., 2012) and deep basin successions (Csóvar basin, Pálfy et al., 2007). Moreover, we extended our correlation to the $\delta^{13}C_{org}$ curves recorded in southwest England at Doniford (Clémence et al., 2010) and St. Audrie's Bay (Hesselbo et al., 2002).

2. The Mount Sparagio section

The studied section belongs to the Mt. Sparagio tectonic unit, an element of the Maghrebian fold and thrust belt in northwestern Sicily, cropping out in the southern part of the San Vito Lo Capo Peninsula near the village of Custonaci (38°05′N, 12°51′E) (Fig. 1).

The Triassic-Jurassic succession in this tectonic unit consists of peritidal limestones belonging to a wide carbonate shelf from the southwestern Tethys (Ionian Tethys, sensu Di Stefano et al., 2015) that was located at low latitude (15°–20°, according to Muttoni et al., 2015). During Late Triassic, extensive lagoons rimmed by sponge and coral reefs developed on the shelf, while the interior zones of the platform were transitioning to sabkha environments. As in many other rimmed platforms, the reefs experienced a drastic demise at the end of Triassic and were replaced by sandy margins during the lowermost Jurassic. The shallow-water carbonate sedimentation lasted during the Hettangian and Sinemurian ages, while during the Pliensbachian, the carbonate platform experienced a general drowning.

2.1. Sedimentological and stratigraphical characteristics

The Mt. Sparagio section consists of approximately 800 m of Upper Triassic-Lower Jurassic limestones, the lowermost part of which is hidden along the slope by a thick detrital cover that prevented its study. For this reason, only the upper 430 m were studied in detail to analyse the sedimentology and biostratigraphy across the TJB (Todaro et al., 2017). Petrographic characterization differentiated 14 facies types. These facies are organized in asymmetric, shallowing upward cycles that consist of repetitions of subtidal, intertidal and supratidal facies (D'Argenio, 1974; Strasser, 1991).

On the basis of the macro- and microfossil record in the subtidal facies, the Mt. Sparagio section was subdivided into three informal units in stratigraphic order (Unit A, Unit B and Unit C) (Todaro et al., 2017) (Fig. 2). The oldest unit (Unit A, 111 m thick) records the common occurrence of large and thick-shelled megalodontids that alternate, in some cycles, with coral patch reefs (*Retiophyllia* sp.). Benthic foraminifers such as *Triasina hantkeni* Majzon and aulotortids are common constituents of the microfacies. In Unit B (179 m thick), the large megalodontids disappear and only rare, small and thin-shelled specimens occur; however, the microfossil content does not differ from that of Unit A. In the upper part of this unit, the megalodontids became extinct, while the last occurrence of benthic foraminifers, 50 m upward, marks the top of this unit. A zone 10 m thick follows upward. It consists of barren subtidal facies almost totally formed by calcisphere particles (50–150 μm). Its top is marked by the appearance of thinner subtidal facies with oligospecific assemblages of *Thaumatoporella parvovesiculifera* and rare *Aeolisaccus* sp. (Unit C, approximately 140 m thick).

2.2. Biostratigraphic considerations

The macrofossil content of subtidal facies in the units A and B is linked to a very diversified association of benthic foraminifers dominated by *Triasina hantkeni*, *Auloconus permodiscoides*, *Duotaxis birmanica*, *Tetrataxis inflata*, *Aulotortus* sp., *Glomospira* sp., *Glomospirella friedli*, *Glomospirella pokornyi*, *Trochammina* sp., *Frondicularia woodwardi*, *Nodosaria* sp., *Textularia* sp. and nodular thalli of calcareous algae "Porostromata" (*Cayeuxia* sp., *Orthonella* sp.). In addition, *Thaumatoporella parvovesiculifera* and fragments of dasycladalean algae such as *Griphoporella curvata* are rarely observed.

Aware the limit of the biostratigraphic resolution in shallow water settings, we have considered all the biostratigraphic schemes that are available for the shallow-water Tethyan Triassic. In particular, the extinction of *Triasina hantkeni* is considered as the most reliable biomarker for the end of the Triassic System (De Castro, 1990; Chiocchini et al., 1994).

The FO of *Triasina hantkeni* is reported in the *Rabdoceras suessi* zone (Gazdzicki, 1983) corresponding to the uppermost Norian (Dagys and Dagys, 1994; Krystyn et al., 2007). Gazdzicki (1983) defines as Rhaetian a foraminifer association composed by *Triasina hantkeni* along with *Glomospirella friedli*, *Glomospirella pokornyi*, *Glomospirella parallela*, *Trochammina alpina*, *Tetrataxis inflata*, *Agatammina austroalpina*, *Miliopora cavillieri*, *Planiinvoluta carinata*, *Nodosaria ordinata*, *Aulotortus communis*, *Aulotortus gaschei*, *Aulotortus tumidus*, *Aulotortus sinuosus*.

Chiocchini (2008) defines at Mt. Cefalo (Italy) a *Triasina hantkeni* and *Griphoporella curvata* assemblage zone, characterized by foraminifers such as *Auloconus permodiscoides*, *Aulotortus sinuosus*, *Aulotortus tenuis*, *Aulotortus friedli*, *Aulotortus communis*, *Aulotortus impressus*, *Gandinella falsofriedli*, *Trochammina alpina*, Duostominidae, *Gyroporella vesiculifera*, *Asterocalculus heraci* and Megalodontidae.

Megalodontids are reported in association to *Triasina hantkeni* and other Upper Triassic benthic foraminifers (e.g. aulotortids) in very thick (up to 500 m) peritidal successions that are ascribed to the uppermost Norian and Rhaetian (De Castro, 1990; Romano et al., 2008; Tunaboylu et al., 2014).

A comparable association was found at Mt Sparagio, where Megalodontids are associated to a foraminiferal assemblage with *Triasina hantkeni*, *Glomospirella friedli*, *Glomospirella pokornyi*, *Auloconus permodiscoides*, *Aulotortus communis* that, according to several biozonal schemes from Upper Triassic shallow water carbonate successions, is