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The Eocene–Oligocene transition in the C-isotope record of the carbonate successions in the Central Mediterranean

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ABSTRACT

The Eocene-Oligocene transition marks a fundamental step in the evolution of the modern climate. This climate change and the consequent major oceanic reorganisation affected the global carbon cycle, whose dynamics across this crucial interval are far from being clearly understood. In this work, the upper Eocene to lower Oligocene $\delta^{13}C_{Carb}$ and $\delta^{13}C_{TOC}$ records of a shallow-water and a hemipelagic carbonate settings within the Central Mediterranean area have been studied and discussed. The shallow-water carbon isotope signal has been analysed in the northern portion of the Apula Platform, cropping out in the Majella Mountain, Central Apennines (Santo Spirito Formation). A coeval Umbria-Marche basinal succession has been investigated in the Massignano section (Conero area, Central Italy). The purposes of this work are: to discriminate between the global and the local (Mediterranean) signature of C-isotope record during the Oi-1 event, to correlate the regional C-isotope signal with the global record, and to evaluate the carbon cycle dynamics across the greenhouse-icehouse transition through the integration of complementary records (shallow-water vs pelagic settings, $\delta^{13}C_{Carb}$ vs $\delta^{13}C_{TOC}$). The upper Eocene carbon isotope record of the analysed successions matches with the global signal. The overall trend shows a decrease of the $\delta^{13}C_{Carb}$ and a contemporary increase of the $\delta^{13}C_{TOC}$. The decoupling of the two curves is consistent with a reduced fractionation effect by primary producers that characterised the interval between the Middle Eocene Climatic Optimum and the onset of the Oi-1 event. However, regional factors superimposed the global signal. In fact, the upper Eocene basinal $\delta^{13}C_{TOC}$ record is marked by short-term negative spikes, which possibly represent times of higher productivity triggered by the westward subtropical Eocene Neotethys current entering from the Arabian-Eurasian gateway. On the contrary, the shallow-water record does not display these short-term productivity pulses. A change in the carbonate factory is only recorded at the Eocene-Oligocene transition, marked by a reduction of the larger benthic foraminifera and the spread of seagrass and corals. Moreover, in the shallow-water record of the Santo Spirito Formation, no major carbon isotope shift related to the Oi-1 event is recorded due to the presence of extensive slumps that disrupt the bedding. These slumps are the main evidence of the sea-level drop that occurred concomitantly with the onset of the Antarctica ice-sheet, which caused the deepening of the storm wave base and increased the instability over the entire ramp.

1. Introduction

The Eocene-Oligocene transition (EOT) represents the most important step in the evolution of the modern icehouse climate. It marks the transition from the warm 'greenhouse world' when the atmospheric pCO_2 was higher than 1000 ppm (Beerling and Royer, 2011; Pagani et al., 2014) and only transient ice-sheets could develop at low latitudes (Carter et al., 2017), to the modern 'icehouse' climate that is characterised by stable polar ice caps and lower CO_2 concentrations (Pearson et al., 2009; Beerling and Royer, 2011). The EOT (Houben et al., 2012) culminates with a $\delta^{18}O$ peak recorded in the lower Oligocene (33.55 Ma) deep-sea successions (Miller et al., 1991). This positive oxygen isotope shift, named Oi-1 event (Miller et al., 1991; Zachos et al., 1996, 2001; Coxall and Pearson, 2007; Lear et al., 2008), marks the development of a permanent ice sheet in Antarctica as much as 50% in volume of the present one (DeConto and Pollard, 2003; Liu et al., 2009; Miller et al., 2009; Bohaty et al., 2012). Several studies testify for a very dynamic and unstable polar ice cap in Antarctica from the early Oligocene to the late Miocene (Pekar and Deconto, 2006; Cook et al., 2013; Liebrand et al., 2017; Sangiorgi et al., 2018). Pekar and

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Deconto (2006) report different records showing that the ice-volume fluctuated between 50% and 125% of the present Eastern Antarctic ice sheet, while Liebrand et al. (2017) state a minimum waxing and waning of 85% to 110% of the present-day volume. However, it is overall accepted that an ice sheet persisted in Antarctica since the Oi-1 event.

Both the causes and the effects of the glaciation in Antarctica are still under debate. Overall, the main theories approaching this problem rely on two different hypotheses e.g. the isolation of Antarctica due to plate reorganisation, or the decrease of the atmospheric CO_2 during late Eocene. The opening of the Tasmanian and Drake Passages during late Eocene was assumed as the main triggering cause of the glaciation since it led to the development of the Antarctic Circumpolar Current and therefore the thermal isolation of Antarctica (Kennet et al., 1975; Kennet, 1977). However, more recently, the decrease of pCO_2 is considered the main controlling factor on the ice-growth in Antarctica (DeConto and Pollard, 2003; Pagani et al., 2011; Egan et al., 2013; Goldner et al., 2014; Galeotti et al., 2016). Regardless of the debate on the triggering causes, both the opening of the Drake Passage (Scher and Martin, 2004) and the onset of an Antarctic ice sheet (Goldner et al., 2014; Wright et al., 2018) altered the ocean circulation resulting in a general global ocean reorganisation that affected the carbon cycle, as marked by a positive $\delta^{13}C$ isotope excursion recorded in the deep-sea successions (Zachos et al., 1996, 2001; Cramer et al., 2009) associated with a major deepening of the Calcite Compensation Depth (CCD) (Coxall et al., 2005). Different hypotheses have been suggested to explain this positive carbon isotope excursion, most of which are related to changes in the oceanic trophic regime and the associated primary productivity induced by sea level changes or changes in the global oceanography (Salamy and Zachos, 1999; Zachos and Kump, 2005; Coxall et al., 2005; Coxall and Pearson, 2007; Miller et al., 2009; Coxall and Wilson, 2011; Plancq et al., 2014).

The carbon cycle perturbation related to the Oi-1 event has been clearly identified in the deep-sea record of all the oceans at different latitudes (Zachos et al., 1996, 2001; Cramer et al., 2009), whereas little is known about the response of the shallow-water carbonate systems' to this carbon cycle perturbation (Jaramillo-Vogel et al., 2013, 2016). Notwithstanding that, even if often discontinuous, shallow-water carbonates are significantly more sensitive to temperature and trophic changes than deep-se-a successions. In fact, during the transition from the warm Eocene to the Oligocene 'icehouse', these major changes in climate, ice volume, and ocean circulation deeply influenced the composition and production of the carbonate factory (Nebelsick et al., 2005; Brandano et al., 2009, 2017a; Pomar et al., 2017).

The larger benthic foraminifera, which dominated the Eocene carbonate platforms (Racey, 2001, and references therein; Bassi, 2005; Beavington-Penney et al., 2005), experienced a major decline. In turn, zooxanthellate corals and coralline algae spread as main biota-producing sediment, and seagrass environments expanded strongly in the euphotic zone, influencing the facies association of the Cenozoic carbonate platforms (Nebelsick et al., 2005; Pomar and Kendall, 2008; Brandano et al., 2017a).

In this work, the carbon isotope record is studied in the EOT interval in two different contexts from the Central Mediterranean area. The first case study refers to sedimentary succession from the Apula Carbonate Platform (Central Apennines, Central Italy), in which the main lithofacies of the Santo Spirito Formation and $\delta^{13}C$ of the whole-rock signal are analysed and discussed. This shallow-water carbon isotope signal is correlated with the $\delta^{13}C$ record obtained in the Massignano section (Scaglia Variegata and Scaglia Cinera Fm, Conero area, Central Italy), which is the well-known Global Stratotype Section and Point (GSSP) of the Eocene-Oligocene boundary (Premoli Silva and Jenkins, 1993), and represents the Umbria-Marche basinal succession.

Through a precise correlation of the C-isotope records of the Mediterranean area with the global signal, we aim (i) at assessing the impact of C-cycle perturbations on shallow- and deep-water successions, and (ii) at evaluating the relationships between carbon cycle and shallow carbonates across this major greenhouse-icehouse transition.

2. Geological setting

The Apennine fold-and-thrust belt is the result of the collision of the Adria plate with the southern margin of Europe (Alvarez et al., 1974; Bally et al., 1986; Dewey et al., 1989; Doglioni, 1991; Rosenbaum et al., 2002a; Devoti et al., 2008; Carminati et al., 2012). The Apennine subduction started in the late Eocene (Lustrino et al., 2009), and it continued through Neogene until today (Boccaletti et al., 1990; Rosenbaum et al., 2002b; Doglioni et al., 1998; Carminati et al., 2010, 2012). The westward-dipping Apennine slab led to an eastward migration of the deformation fronts and related foredeeps, and subsequent extensional tectonics in the back-arc area where several basins opened during the Oligocene-Miocene interval on thin continental (the València Through) and oceanic (Alborán, Provençal and Thyrrenian Basin) crust (Carminati et al., 2012 and references therein). The Central Apennine consists of Triassic to Miocene deposits that can be ascribed to three different paleogeographic domains: the Apennine carbonate platforms (Latium-Abruzzi and Apula platforms), the Umbria-Marche basin, and the Molisano basin (Colacicchi, 1967; Crescenti et al., 1969; Parotto and Praturlon, 1975; Bernoulli, 2001; Vezzani et al., 2010). In this study, the northern extension of the Apula platform, represented by the Majella Mountain and the Marche basinal successions, are investigated (Fig. 1a).

2.1. The Majella Mountain

The Majella Mountain (Fig. 1b) is a 35 km-long anticline that is convex towards the northeast, and plunges both northward and southward (Patacca et al., 2008). Its outcropping succession consists of Upper Jurassic to upper Miocene limestones and dolostones (Crescenti et al., 1969). During the Mesozoic, a steep erosional escarpment separated the platform top from the basin, which extended northward (Fig. 1c). By the late Campanian, the platform prograded over the basin, that was filled up by onlapping sediments (Vecsei et al., 1998). Thus, the Paleogene evolution of the Majella carbonate platform, corresponding to the Santo Spirito Formation, is represented by a continuous sedimentation along the platform margin and the slope, while the platform top shows long-term hiatuses and discontinuous deposits. In the upper Rupelian a discontinuity surface occurs, separating the Santo Spirito Formation from the Bolognano Formation (upper Rupelian-lower Messinian), which represents a carbonate ramp developed above the former shallow deposits of the platform (Mutti et al., 1997; Brandano et al., 2012, 2016a). The evolution of the Oligocene-Miocene ramp ended in the Messinian with the deposition of the *Turborotalita multiloba* Marls (Carnevale et al., 2011), followed by the Gessoso-Solfifera Formation (Crescenti et al., 1969). Lastly, during the early Pliocene, the Majella Mountain was involved into the foredeep system of the Apennine orogeny (Cosentino et al., 2010).

2.2. The Umbria-Marche Domain

The Umbria-Marche Domain consists of an Upper Triassic-Miocene sedimentary succession deposited in the northern margin of the Tethys (Fig. 1a and d). During the Late Triassic, the rifting of the Tethys led to a marine transgression, testified by the evaporitic deposition of the Anidridi di Burano and, subsequently, by the development of the Calcare Massiccio carbonate platform (Pialli, 1971). During the Early Jurassic, the Calcare Massiccio platform drowned due to the rift-related extensional tectonics, and the Umbria-Marche domain evolved into a wide basin characterised by intrabasinal structural highs (Centamore et al., 1971; Bernoulli and Jenkyns, 1974; Brandano et al., 2016b) until the Late Jurassic.

This heterogeneous paleogeography ended with the deposition of pelagic mudstones (the Maiolica Formation, Titonian to Albian in age)