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The middle Toarcian cold snap: Trigger of mass extinction and carbonate factory demise

F.N. Krencker [a,*], S. Bodin [a], R. Hoffmann [a], G. Suan [b], E. Mattioli [b], L. Kabiri [c], K.B. Föllmi [d], A. Immenhauser [a]

[a] Ruhr-Universität Bochum, Institut für Geologie, Mineralogie und Geophysik, D-44870 Bochum, Germany
[b] UMR CNRS 5276 LGLTPE, Université Lyon 1, ENS Lyon, Campus de la Doua, Bâtiment Géode, F-69622 Villeurbanne Cedex, France
[c] Faculty of Science and Techniques Errachidia, University of Moulay Ismaïl, BP 509, 52000 Boutalamine-Errachidia, Morocco
[d] Institut des Sciences de la Terre, Quartier UNIL-Mouline, Bâtiment Géopolis, 1015 Lausanne, Switzerland

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ABSTRACT

The Pliensbachian and Toarcian (Early Jurassic) ages are characterised by several, relatively short-lived carbon cycle perturbations, climate change and faunal turnover. The cause(s) of biotic and abiotic disturbances remain unclear but most probably involved increased magmatic activity in the Karoo–Ferrar large igneous province. The Toarcian oceanic anoxic event (T-OAE) might represent the most extreme of these events, and as such, is becoming increasingly well documented worldwide. So far, other critical time intervals of the Pliensbachian–Toarcian have received considerably less attention. Here, the effects of the Middle Toarcian Variabilis event on the neritic–epeiric realm are explored making use of three well-exposed and extended stratigraphic sections in the Central High Atlas, Morocco. The carbon and oxygen isotopic compositions of 112 bulk micrite samples were analysed and placed against 39 data points from carefully screened brachiopod valves in order to differentiate between palaeo-environmental and diagenetic patterns. Additionally, the phosphorus concentrations of 109 micrite samples were determined to evaluate the P-cycling. In all studied sections, an upper middle Toarcian major change from carbonate- to clastics-dominated sedimentation is recorded, pointing to a first-order carbonate production crisis. Our results reveal that these major sedimentological patterns coincide with an increase of oxygen-isotope ratios as well as a decrease of phosphorous accumulation rates. This suggests that the late middle Toarcian carbonate ramp crisis was related to a transient cooling event, potentially triggered by pulsed massive SO_4 exhalation events in the context of the Karoo large igneous province. Short-term cooling was likely amplified by the drawdown of atmospheric CO_2 levels related to the coeval decline of neritic carbonate precipitation and the warm water mass circulation disruption between the Tethys and the continental shelf. The data shown here provide the first evidence for coupled changes in carbon cycling, continental weathering and neritic systems in the aftermath of the T-OAE.

1. Introduction

The Toarcian stage (Early Jurassic, 182.7 to 174.1 Ma, Gradstein et al., 2012) was punctuated by several major marine invertebrate extinction events (Little and Benton, 1995; Harries and Little, 1999; Cecca and Macchioni, 2004; Mattioli and Pittet, 2004; Mattioli et al., 2008, 2009; Suan et al., 2010, 2011). Previous work suggested that cephalopods in the Euro-boreal and Mediterranean realm, considered to be amongst the most environmentally sensitive marine organisms (Wang and Bush, 2008), were affected during four major Toarcian turnover events. Specifically, these took place (1) at the Pliensbachian–Toarcian boundary; (2) at the onset of the early Serpentinum ammonite zone; (3) around the Bifrons–Variabilis boundary and (4) during the Dispansum chronozone (Dommergues et al., 2009; Dera et al., 2010). Recently, these four extinction events were also recognised in northern panthalassic ammonites and foraminifera ecological patterns (Caruthers et al., 2013).

From a chemostratigraphical point of view, the Toarcian is characterised by several carbon isotope excursions (CIEs) recorded in bulk carbonate, bulk organic matter, brachiopod valves and fossil wood samples. The most intensively studied CIE is undoubtedly that characterising the Toarcian ocean anoxic event (T-OAE; Jenkyns, 1985, 1988; Harries and Little, 1999; McArthur et al., 2000; Jenkyns et al., 2001; Röhl et al., 2001; Bailey et al., 2003; van de Schootbrugge et al., 2005; Mailliot et al., 2006; Cohen et al., 2007; Hesselbo et al., 2007; Gómez et al., 2008; Mattioli et al., 2008; Sabatino et al., 2009). Chronologically, the T-OAE is the second Toarcian event. Indeed, this event is preceded by a pronounced negative CIE spanning the Pliensbachian–Toarcian boundary (Hesselbo et al., 2007; Bodin et al., 2010; Littler et al., 2010), hereafter referred to as the Pliensbachian–Toarcian

* Corresponding author. Tel.: +49 234 32 23256.
E-mail address: francois.krencker@rub.de (F.N. Krencker).

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boundary event (PTo-E). Interestingly, the PTo-E and the T-OAE broadly coincide with the Pliensbachian–Toarcian boundary and the early Serpentinum cephalopod turnover events, respectively. Records of these two events share important similarities including the association with organic matter-rich stratigraphic intervals (Jenkyns, 1988; Jenkyns et al., 2002; Cohen et al., 2007; Wignall and Bond, 2008) and carbonate productivity shutdown (Dromart et al., 1996; Blomeier and Reijmer, 1999; Wilmsen and Neuweiler, 2008; Bodin et al., 2010; Trecalli et al., 2012).

Both of these events are also associated with significant warming of surficial water masses, as reflected by a marked decrease in oxygen-isotope ratios of brachiopod valves (Suan et al., 2008), belemnite rostra (McArthur et al., 2000; Bailey et al., 2003; Gómez et al., 2008) and fish tooth apatite (Dera et al., 2009b). Coeval increase of belemnite strontium-isotope ratios ($^{86}Sr/^{87}Sr$; McArthur et al., 2000), changes in clay mineral spectra (Dera et al., 2009a; Hermoso and Pellenard, 2014) and increased phosphorus contents in bulk rock samples (Bodin et al., 2010) point to a concomitant increase in continental weathering and nutrient fluxes to coastal seas (Bodin et al., 2010; Jenkyns, 2010).

The above similarities of the PTo-E and T-OAE records caused previous workers (Suan et al., 2008; Littler et al., 2010) to suggest that similar processes triggered both events. Models invoked to explain concomitant atmospheric and oceanic change in carbon cycling during the PTo-E and the T-OAE all imply massive and relatively sudden input of an isotopically light carbon component in the ocean–atmosphere reservoirs. Hypotheses brought forward include gas hydrate release (Hesselbo et al., 2000) and the thermal metamorphism of carbon-rich sediments in the Karoo–Ferrar large igneous province (McElwain et al., 2005; Svensen et al., 2007), sustained injection of light carbon from a volcanogenic source (Suan et al., 2008), or a combination of these.

To date, only few studies have investigated the Bifrons–Variabilis (O'Dogherty et al., 2000; Bodin et al., 2010; Guex et al., 2012; Sandoval et al., 2012; Caruthers et al., 2013) and Dispansum events (Dera et al., 2010), both of which took place in the aftermath of the T-OAE. Despite their arguably global extent and significance (Caruthers et al., 2013), geochemical data covering the corresponding stratigraphic intervals are still scarce. Consequently the significance of these two events is mainly deduced from marine faunal turnovers. Nonetheless, recent carbon- and oxygen isotope analyses of belemnite rostra suggested that, in the case of the Bifrons–Variabilis event, a CIE and a rapid cooling event (Gómez et al., 2008; Dera et al., 2011a) have been recorded. Moreover, regressive pulses have been suggested as the main mechanisms driving shallow marine extinction events during the Bifrons–Variabilis and Dispansum intervals (Sandoval et al., 2001, 2002; Dera et al., 2010). Nevertheless, given the low resolution of the few available geochemical and sedimentological records, these mechanisms remain speculative and alternative causes remain feasible. Surprisingly, little attention has been paid to the impact of these perturbations on neritic carbonate ecosystems, which arguably react sensitively to changes in biotic and abiotic parameters (Hallock and Schlager, 1986; Mutti and Hallock, 2003; Föllmi et al., 2006, 2007; Halfar et al., 2006) and hence represent detailed, albeit complex, archives of past environmental changes.

In this paper, we first present new sedimentological and geochemical data for Pliensbachian–Aalenian sections in the High Atlas Mountain range of Morocco. By this, we second provide evidence on changes in carbon cycling, carbonate productivity, sea-surface palaeo-temperatures and nutrient discharge in Tethyan neritic environments in the aftermath of the T-OAE. Here, particular attention is given to the response of neritic carbonate ramps to the Bifrons–Variabilis event. Third, in the context of these palaeo-environmental patterns, the possible causes of the Bifrons–Variabilis and the Dispansum event are contrasted and compared. The data shown here are relevant for those concerned with the complex palaeo-environmental patterns in the aftermath of the T-OAE.

2. Geotectonic setting

The study area is located in the central High Atlas rift basin of Morocco (Fig. 1). The pre-orogenic history of the central High Atlas rift basin commences near the Permian-Triassic boundary. This time is

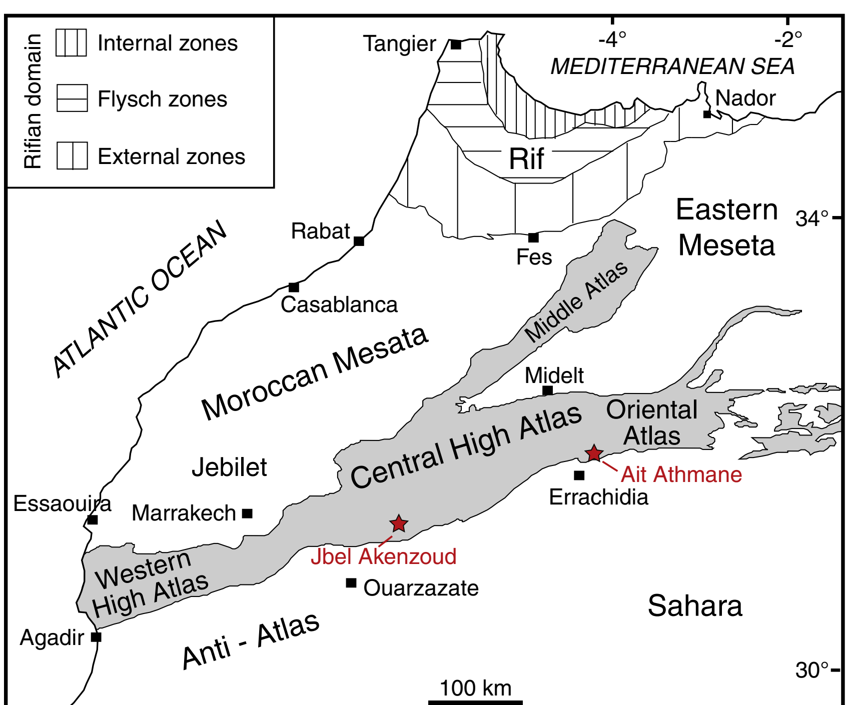

Fig. 1. Simplified structural map of Morocco indicating position of studied outcrops (modified after Lachkar et al., 2009). Atlas Mountain range is shaded grey.