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Synchronization of the astronomical time scales in the Early Toarcian: A link between anoxia, carbon-cycle perturbation, mass extinction and volcanism

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ABSTRACT

The Late Pliensbachian–Early Toarcian is a pivotal time in the Mesozoic era, marked by pronounced carbon-isotope excursions, biotic crises and major climatic and oceanographic changes. Here we present new high-resolution carbon-isotope and magnetic-susceptibility measurements from an expanded hemipelagic Late Pliensbachian–Early Toarcian section from the Middle Atlas Basin (Morocco). Our new astronomical calibration allows the construction of an orbital time scale based on the 100-kyr eccentricity cycle. The Early Toarcian Polymorphum Zone contains 10 to 10.5 repetitions of the 100-kyr eccentricity both in the carbon-isotope and the magnetic-susceptibility data, leading to an average duration of 1.00 ± 0.08 myr. We also show that the Late Pliensbachian–Early Toarcian global carbon-cycle perturbation has an average duration of 0.24 ± 0.02 myr. These durations are comparable to previous astrochronological time scales provided for this time interval in the most complete sections of the Tethyan area, and longer than what has been provided in condensed sections. Anchoring this framework on published radiometric ages and astrochronological time scales, we estimate that the carbon-cycle perturbation of the Late Pliensbachian–Early Toarcian corresponds with the early phase of the Karoo and Chonke Aike large igneous provinces. Likewise, our new age constraints confirm that the Toarcian oceanic anoxic event is synchronous to the main phase of the Ferrar volcanic activity. Thus, these successive and short phases of the volcanic activity may have been at the origin of the successive phases of the mass extinctions observed in marine biotas in the Pliensbachian and Toarcian times.

1. Introduction

The Early Toarcian (184.15–174.1 Ma) was a time of global warming events (Dera et al., 2011), mass extinctions (Little and Benton, 1995), and pronounced negative carbon-isotope excursions recorded in marine carbonates and organic matter, brachiopods, biomarkers and fossil wood (Hesselbo et al., 2007; Suan et al., 2008a; Ait-Itto et al., 2017). These events coincide with carbonate production demises (Bassoullet and Baudin, 1994; Wilmsen and Neuweiler, 2008) and widespread oceanic anoxia (Jenkyns, 1988; Hesselbo et al., 2007).

Although large amounts of data have been produced, the timing and rhythms of the environmental perturbations are still debated, leading to controversies on the mechanisms at the onset of the climatic changes in the Early Toarcian (e.g. Kemp et al., 2005; Suan et al., 2008b). For instance, Martinez et al. (2017) assess the duration of Pliensbachian–Toarcian event (P–To event) at 0.18 to 0.27 myr, while in the Peniche section (Lusitanian Basin, Portugal) the duration of this event is evaluated as 0.05 myr (Suan et al., 2008b). Similarly, the estimates of duration of the Polymorphum Zone vary from 90 kyr to 1.15 myr (Mattioli and Pittet, 2004; Suan et al., 2008b; Boulila et al., 2014; Huang and Hesselbo, 2014; Ruebsam et al., 2014; Martinez et al., 2017). The main reason of these differences is the occurrence of four discontinuity events identified by correlations of $\delta^{13}C$ and sedimentological features throughout the Tethyan margins, which are due to changes in the sea level observed in the earliest Toarcian (Pittet et al., 2014). The section studied here in Issouka, Morocco, is expanded compared to the sedimentary series from the northern Tethyan margin. It provides the opportunity to fill the gap in the time scale of the Toarcian Stage and to establish a detailed chronology of the suc-

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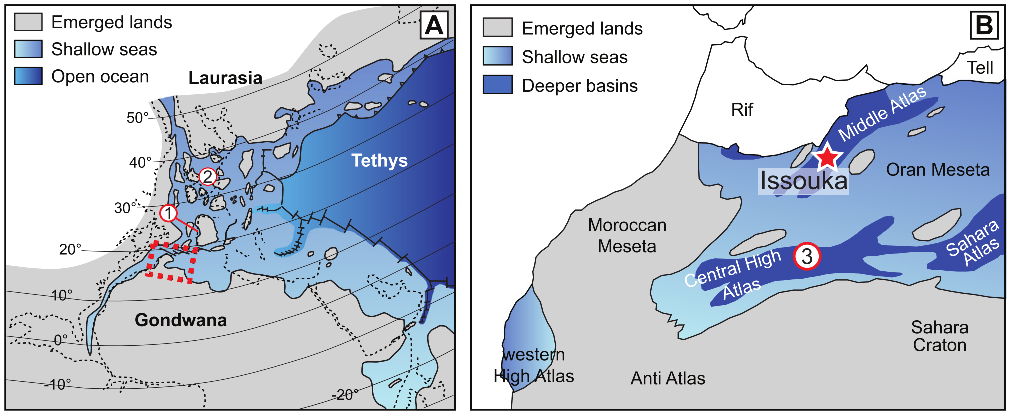

Fig. 1. Geological setting of the Issouka section. **A.** Palaeogeographic map of the western Tethys during the Early Jurassic. The red dash rectangle shows the limit of the second map. Label "1" indicates the location of the Peniche section. Label "2" indicates the location of Yorkshire area. **B.** Geographical map of Morocco and western Algeria showing the main geological provinces and the location of the Issouka section within the Middle Atlas. Label "3" indicates the location of the Foum Tillicht section (maps from Bodin et al., 2010).

cession of the environmental disturbances occurring in the Early Toarcian.

2. Geological setting

The geological history of Morocco was influenced by two important events, starting in the early Mesozoic with the opening of the north Atlantic and western Tethys and the collision of Africa and Europe during the middle Cenozoic (Michard, 1976). These events led to the formation of fault-bounded basins, which are made up of several smaller depocenters, separated by synsedimentary highs (Studer and Du Dresnay, 1980). The Middle Atlas is one of these small fault-bounded basins (Fig. 1). It constitutes a part of a Meso-Cenozoic intracontinental chain, namely the Moroccan Atlas (Michard, 1976). The Middle Atlas of Morocco is structurally dominated by four NE–SW trending anticlines and is mainly constituted of Lower and Middle Jurassic formations (Du Dresnay, 1971). The basin is bounded by the Saïs Plain and the front of the Rifian Nappes in the North, by the Guercif Basin in the northeast, by the Moulouya Plain to the southeast, and by the Hercynian Central Massif in the West.

The Middle Atlas Basin is deep in the center and shallows towards the northern and southern basin margins (Du Dresnay, 1971). The study area during the Early Toarcian was located at a palaeolatitude of ∼20°N (Bassoulet et al., 1993) (Fig. 1A). The sedimentary evolution and palaeogeographic differentiation is controlled by tectonic activity, combined with the rate of sedimentation and global eustatic variations (Wilmsen and Neuweiler, 2008). The rapid transition from shallow marine carbonates to hemipelagic marls has been taken to reflect a major deepening phase across the entire Middle and High Atlas area (Wilmsen and Neuweiler, 2008). The Pliensbachian–Toarcian transition coincides with a dislocation of the Lower Jurassic carbonate platform (Lachkar et al., 2009; Ait Addi and Chafiki, 2013) with Toarcian deposits dominated by marls lying upon Upper Pliensbachian shallow marine limestones and calcareous marls. This drowning episode is linked to the eustatic sea-level rise of the Early Toarcian described in Europe and Africa (e.g. Hallam, 1997).

The biostratigraphy in the Middle Atlas has been established with ammonites (El Hammichi et al., 2008) with further biostratigraphic data provided by benthic foraminifera (Bejjaji et al., 2010). The ammonite zonation in the Issouka section is based on the Mediterranean zonation. Notably, the ammonites *Emaciaticeras emaciatum* of the Emaciatum Zone, *Dactylioceras polymorphum* of the Toarcian Polymorphum Zone and *Hildaites* in the Semicelatum Zone have been identified (e.g. El Hammichi et al., 2008). Furthermore, the occurrence of the benthic foraminifera *Lenticulina sublaevis* in the Issouka section is correlated by Bejjaji et al. (2010) to the Emaciatum ammonite zone of the Pliensbachian, whilst *Lenticulina bochardi* and *Lenticulina toarcense* are correlated with the Toarcian Polymorphum Zone and *Lenticulina obonensis* with the Serpentinus Zone.

The Issouka section is situated near the village of Issouka, ∼25 km southwest of Immouzer Marmoucha, in the Middle Atlas (N33° 26′55.56″; W4° 20′33.83″; Fig. 1). The section begins with centimeter thick limestone–marl alternations (Fig. 2). The limestone beds contain a rich ammonite fauna, with also belemnites, echinoids and brachiopods. Foraminifera suggested a Late Pliensbachian age (Bejjaji et al., 2010; Fig. 2A). The early Toarcian succession starts with green marls and marl–limestone alternations, rich in foraminifera, belemnites, echinoids and gastropods. The Toarcian deposits are generally hemipelagic and correspond to deep marine environments (Bejjaji et al., 2010; Fig. 2B).

3. Material and methods

A total of 430 bulk-rock samples were collected with an even sample distance of 10 cm in the Issouka section. The samples were recovered from up to 15 cm below the surface, to minimize the effects of surface weathering. The sampled interval encompasses the end of the Pliensbachian Stage to the lowermost part of the Levisoni ammonite Zone. Such a range allows the Polymorphum Zone to be entirely sampled. The bulk-rock samples were then powdered using a metal ring grinder and analyzed for stables isotopes, magnetic susceptibility and calcium carbonate contents.

3.1. Carbon isotopes

A total of 430 samples were analyzed for stable isotopes at the University of Plymouth. Using 200 to 300 micrograms of carbonate, stable isotope data were generated on a VG Optima mass spectrometer with a Gilson autosampler. Isotope ratios were calibrated using NBS19 standards and are given in δ notation relative to the Vienna Pee Dee Belemnite (VPDB). Reproducibility was generally better than 0.1‰ for samples and standard material.

3.2. Magnetic susceptibility

The magnetic susceptibility (MS) of the 430 powdered samples was measured with a Kappabridge KLY-3. The samples are placed in small plastic cubes of 10 cm^3 and then introduced inside the instrument using the "pick-up" unit. We measured the cube empty