The Triassic–Jurassic boundary event from an equatorial carbonate platform (Ghalilah Formation, United Arab Emirates)

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Abstract: The Ghalilah Formation, UAE provides a complete and continuous equatorial shallow-water carbonate sequence through the Upper Triassic to Lower Jurassic interval. In higher latitudes, this interval is frequently associated with widespread ocean acidification evidenced by a lack of carbonates or a hiatus in deposition. The data presented here in contrast show evidence for aragonite supersaturation at the Triassic–Jurassic boundary in the equatorial Tethys. δ13C_carb shows a characteristic negative excursion with values as low as −2.8‰ just below the boundary. Deposition of fossiliferous limestones in this location persisted into the latest Rhaetian through the initial negative carbon isotope excursion.

Supplementary material: δ13C_carb data from bulk rock and a detailed stratigraphic log with sample locations are available at https://doi.org/10.6084/m9.figshare.c.3277283.

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The Triassic–Jurassic (T–J) transition was a period of extreme environmental crisis, associated with major extinction of marine and continental biota, a biocalcification crisis, and major perturbations in the carbon cycle, possibly including an episode of ocean acidification during the T–J transition. The Ghalilah Formation varies in thickness from 140 to 190 m and comprises the Asfal, Sumra, Sakhra and Shuba members (Maurer et al. 2008). The Asfal and Sumra members contain a characteristic Late Triassic fauna of brachiopods, megalodontid and wallowaconchid bivalves, sphinctozoan and inozoan sponges, hydrozoans and solitary as well as branching corals, indicating the subtidal zone of an outer shelf environment (Senowbari-Daryan & Maurer 2008). These members contain varying amounts of carbonates and siliciclastic material; no siliciclastic rocks occur in the upper 3 m of the Sumra Member. The Sakhra Member is 25 m thick and consists predominantly of lager- and cross-bedded oolitic limestones without macrofossils, and intercalated rudstones with decimetre-sized intraclasts, indicating a subtidal, high-energy platform-margin environment. Considering these sharp facies changes, Maurer et al. (2008) tentatively drew the T–J boundary at the base of the Sakhra Member, and above a Retiophyllia framestone at the top of the Sumra Member, but no additional evidence supported this assumption. Detailed sedimentological examination of the section shows no evidence of a hiatus or subaerial exposure in the Sumra and Sakhra members of the section although subaerial exposure is apparent in the upper part of the overlying Shuba Member, which consists of Lower Jurassic intertidal dolostones with intercalated siliciclastic rocks.

Methods

We sampled a continuous section from the top of the Sumra Member starting with the lowermost accessible limestone bed above an alternation of limestones and siliciclastic rocks covered by scree. The top of the sampled section is located in the middle part of the Sakhra Member, which locally forms a vertical cliff.

Samples for isotope analysis were collected at c. 20 cm intervals, cleaned and cut, then drilled for carbon isotope analysis using a hand-held microdrill and avoiding areas of the samples that contain predominantly cement or large diagenetically altered components. Approximately 120 μg of powdered sample were reacted with 100% phosphoric acid on a Gasbench II and the resulting CO₂ was
transferred to a ThermoFinnigan Delta Plus XP ratio mass spectrometer at the University of Texas at San Antonio. Samples were corrected to the V-PDB scale using in-house and international standards. External precision was determined through repeated analyses of an in-house standard (belemnite from the Sundance Formation) and was ±0.1‰ for carbon and oxygen. Thin sections were prepared for the characterization of carbonate microfacies.

\[ \delta^{13}C_{\text{carb}} \] results and interpretation

Bulk-rock carbonate \( \delta^{13}C \) values from Wadi Milaha range from −2.8 to 5.7‰. Values fluctuate by ±1‰ in the lower 2 m of the section but trend toward more negative values, with the lowest value (−2.8‰) occurring at the 1 m mark in the Sumra Member (Fig. 2). This negative excursion is followed by a gradual increase and a broad positive excursion with values as high as 5.7‰ through the Sakhra Member (lower Hettangian). Values fluctuate between 2 and 4.5‰ in the upper half of the section. The amplitude of fluctuations in \( \delta^{13}C \) in the basal Sakhra Member is larger than previously reported in T–J boundary sections (Figs 2 and 3).

The carbon isotope curve from the Ghalilah Formation shows a similar pattern to that of other T–J boundary sections with \( \delta^{13}C_{\text{carb}} \) records (Fig. 3; e.g. Galli et al. 2007; Pálffy et al. 2007; Clémence et al. 2010; Haas et al. 2010; Čme et al. 2011; Bachan et al. 2012), although these sections are from basinal or toe-of-slope environments (Pálffy et al. 2007; Haas et al. 2010; Čme et al. 2011), or have carbonate-poor deposits in the T–J boundary interval (Clémence et al. 2010; Bachan et al. 2012). In the Alps of northern Italy, depositional environments change from a mixed calcareous–siliciclastic ramp to outer ramp, deep subtidal micrites in the interval that has recorded the negative carbon isotope excursion (Galli et al. 2007). The new record presented here contrasts with previously published upper Rhaetian–lower Hettangian sections as it contains a continuous shallow-water carbonate record.

Based on the similarity to other carbon isotope records, we place the onset of the T–J boundary interval (TJB, Figs 2 and 3) at a minor negative excursion within the overall increase of \( \delta^{13}C_{\text{carb}} \) values from the initial negative Rhaetian CIE to the peak values in the Hettangian (see Clémence et al. 2010; Korte et al. 2009; Ruhl et al. 2009; Hillebrandt et al. 2013). This is a level within the basal oolites. In other T–J boundary sections with \( \delta^{13}C_{\text{carb}} \) records, the initial negative CIE marking the boundary is typically found in carbonate-poor marl or shale, with reefal biota disappearing before the onset of the excursion (e.g. Greene et al. 2012). In the Ghalilah Formation, the initial negative CIE corresponds to a level with abundant characteristic Rhaetian reefal biota. At the Kuhjoch Global Stratotype Section and Point (GSSP) section in Austria, the
initial negative excursion also occurs in the Rhaetian strata, below the first appearance of the ammonite *Psiloceras spelae*, which marks the base of the Jurassic in that section.

Petrographic study results and interpretation

The basal Sakhra Member contains rounded grains with inferred original aragonite mineralogy, now consisting of sparry calcite. Other bioclasts are rare in the basal Sakhra Member, although fragments of bivalve shells are preserved as coated grains of calcite spar, evidence of their originally aragonitic mineralogy. Ooids are micritic, with very few skeletal nuclei. Neomorphic formation of microspar in ooid cortices (Fig. 4) indicates that the original mineralogy of the micritic ooids was also aragonite (Lasemi & Sandberg 1984; Melim et al. 2002). In the few cases where bioclasts formed the nuclei of ooids, the original mineralogy was aragonite, and concentric bands of calcite spar in some micritic ooids also argue for aragonite as the original mineralogy. The Ghalilah Formation is thus unique, as the characteristic Late Triassic reefal biota persists 2 m above the main negative CIE, indicating that typical Late Triassic fossil associations persisted longer in equatorial settings than in higher latitudes (Figs 1–3). Equatorial waters of the southern Tethys appear to have remained supersaturated with respect to aragonite, contrary to the hypothesis of global ocean acidification that has been invoked as one of the

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**Fig. 3.** Comparison of rock types, $\delta^{13}$C$_{carb}$, and inferred position of the T–J boundary or boundary interval from Wadi Milaha with other time-equivalent sections from the Southern Alps (Galli et al. 2007; Felber et al. 2015) and the UK (Korte et al. 2009; Clémence et al. 2010). Note continuous carbonate sedimentation across the T–J boundary at Wadi Milaha, contrasting with other notable T–J localities.

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**Fig. 4.** Thin-section micrographs of pseudospar within cortices of micritic ooids, interpreted as neomorphic formation of calcite in originally aragonitic ooids: (a) plane-polarized light; (b) cross-polarized light.
driving forces of marine extinction at the T–J boundary (e.g., Hautmann et al. 2008; Greene et al. 2012).

Discussion

The results presented here provide important information about the timing of the demise of Late Triassic reefal biota, and evidence that earliest Hettangian seawater was supersaturated with respect to aragonite in shallow equatorial regions. The observation that the demise of aragonite-dominated Late Triassic reefal ecosystems occurred earlier in higher latitudes than at the equator supports the hypothesis of a gradual decrease in aragonite supersaturation. This decrease in aragonite reached critical levels for acid-sensitive bimineralizing biota in cooler waters at higher latitudes, where aragonite supersaturation is typically lower, whereas low-latitude seawater maintained aragonite supersaturation that was sufficiently high for these taxa to survive.

Greene et al. (2012) summarized the evidence for ocean acidification at the T–J transition and emphasized that such an event may have been short-lived, with long-term effects on marine ecosystems. Although we see no evidence of a hiatus in carbonate deposition at the top of the Sumra Member, we cannot rule out a short-term acidification event. It remains to be demonstrated if the final demise of aragonite-dominated Late Triassic reefal biota as observed in the Ghalilah Formation was the result of a short-lived acidification event, extreme variations in global temperature (Bonis & Kürschner 2012), variations in nutrient availability and water chemistry, and/or possibly a consequence of a shrinking latitudinal range of affected taxa (Jablonski 2005) owing to a latitudinal contraction of aragonite supersaturation.

Similar to the record from the Ghalilah Formation, ooliths have been observed above the Triassic–Jurassic boundary in the Western Calcareous Alps (Fig. 3; e.g. Lorünns, Austria; Felber et al. 2015) and the Lombardy Basin (Southern Alps, Italy; Galli et al. 2007; Bachan et al. 2012). The common occurrence of these oolitic facies in the Hettangian post bio-calcification crisis suggests that owing to the extinction of skeletal calcifiers, the shallow marine depositional system switched to inorganic and/or microbial carbonate precipitation in shallow, warm seawater. This pattern appears to be similar to that for the Permian–Triassic boundary, where oolites are common globally and are considered to be a post-extinction and probably post-acidification phenomenon, typically associated with regression, elevated atmospheric CO2 associated with volcanism, and possible CH4 release from methane clathrate destabilization, as well as elevated global temperatures of 4–8°C (McElwain et al. 1999; Korte & Kozur 2010). Given the large number of studies conducted on the Permian–Triassic boundary and specifically on the oolites associated with this event (see Li et al. 2013; Woods 2013; Tian et al. 2015) it would be of interest to examine and explore further the occurrence of ooids at the T–J boundary and the mechanisms driving their formation and distribution in equatorial regions.

The emerging temporal and latitudinal pattern of demise of an aragonite-dominated reefal ecosystem as a response to inferred ocean acidification at the T–J boundary owing to massive release of CO2 is remarkably similar to events recorded around the Early Aptian oceanic anoxic event 1a. During this event, high-latitude carbonate platforms drowned during a negative CIE (Wissler et al. 2003), whereas aragonite-dominated platforms persisted in equatorial latitudes (Skelton & Gili 2012), leading to a contraction of carbonate platforms to low latitudes during a period of injection of CO2 into the atmosphere–ocean system. The final demise of early Aptian carbonate platforms and their characteristic aragonite-dominated biota occurred in equatorial palaeo-latitudes only during the recovery from an initial negative CIE followed by a positive CIE in the late early Aptian, a pattern again remarkably similar to that emerging for the T–J boundary. Although the exact timing and duration of the T–J CIEs are not yet known in sufficient detail to allow for a more detailed comparison with the early Aptian event, the pattern of a short-lived negative excursion followed by a more extended positive excursion appears to be the same.

Conclusions

The T–J boundary section presented here has important implications for the understanding of the effects of major environmental change related to high atmospheric CO2 on mass extinction, the timing of such events, and their relation to palaeogeography. The Ghalilah Formation provides a record of continuous shallow-water carbonate sedimentation across the T–J boundary and shows the characteristic CIEs known from other locations in higher palaeo-latitudes. In the Ghalilah Formation, the initial negative CIE, associated with injection of CO2 into the atmosphere–ocean system, hypothesized to result in widespread ocean acidification and mass extinction among marine biota, is found in limestones with an abundant and diverse fauna of characteristic reefal Rhaetian aragonite-dominated marine calcifiers. This indicates that aragonite supersaturation was sufficiently high in equatorial waters at that time. These limestones are overlain by ooliths with few bioclasts with inferred original aragonite mineralogy, also supporting aragonite supersaturation during the Triassic–Jurassic mass extinction event. Although we cannot rule out that a short-lived acidification event caused the final demise of late Rhaetian aragonite-biomineralizing biota, it appears that earliest Hettangian equatorial waters remained aragonite supersaturated. Perhaps Central Atlantic Magmatic Province related injection of CO2 into the atmosphere–ocean system lowered aragonite supersaturation in high to intermediate latitudes to an extent that caused the interruption of carbonate sedimentation and demise of many acid-sensitive taxa of marine calcifiers, whereas warmer equatorial waters maintained a level of aragonite supersaturation that allowed survival beyond the initial negative CIE.

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