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# The Early Toarcian revisited: Redox-state-specific uranium isotopes reveal earlier onset of global anoxia

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The Toarcian Oceanic Anoxic Event (TOAE) represents one of the most profound perturbations of the Mesozoic carbon cycle, marked by global warming, ocean acidification, intensification of the hydrological cycle, enhanced continental weathering, and widespread marine deoxygenation. This crisis has been linked to massive $CO_2$ and $CH_4$ release associated with emplacement and degassing of the Ferrar large igneous province (LIP). Carbonate-based uranium isotope records ($\delta^{238}U_{carb}$) have previously documented a ~0.4‰ negative excursion preceding the characteristic negative carbon isotope excursion (CIE) of the TOAE, suggesting an early expansion of global anoxia. However, recent work shows that bulk carbonate $\delta^{238}U$ reflects a mixture of primary $U^{6+}$ and diagenetically incorporated $U^{4+}$, raising concerns about the fidelity of these records as tracers of seawater redox conditions. Here we present a redox-state-specific uranium isotope record ($\delta^{238}U^{6+}$) from open-marine platform limestones of the southeastern Tethys, providing a more robust archive of seawater composition.

Our data show that diagenetic $U^{4+}$ can account for up to 70% of total uranium in these limestones, with isotopic values ranging from −0.2 to +0.7‰. In contrast, $\delta^{238}U^{6+}$ values are consistently lower than modern carbonate values (−0.17‰), confirming significant diagenetic overprinting in bulk carbonate records. Stratigraphically, $\delta^{238}U^{6+}$ exhibits a pronounced ~0.6‰ negative excursion beginning at the onset of the Pliensbachian–Toarcian CIE, followed by a prolonged recovery toward modern carbonate values throughout the TOAE. This pattern indicates that the expansion of global marine anoxia began synchronously with the initial phases of Karoo LIP activity and coincided with the broad positive TOAE CIE, in excellent agreement with independent thallium isotope constraints. Together, these results establish $\delta^{238}U^{6+}$ as a more faithful proxy of seawater redox conditions and reveal an earlier and larger-scale expansion of marine anoxia than previously recognized. The redox-specific approach resolves longstanding uncertainties associated with bulk carbonate records and provides a clearer temporal link between initial carbon cycle perturbation and global deoxygenation. This refined chronology offers new constraints on the sequence of environmental changes during the TOAE and improves our ability to assess causal relationships among volcanism, climate change, and marine redox evolution.