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Thallium Isotopes Uncover Deep Ocean Anoxia One Million Years Before the End-Permian Mass Extinction

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Widespread ocean anoxia played a key role in the End-Permian Mass Extinction, the most severe biotic crisis in Earth's history. Despite extensive research on the redox history of this event, the spatial distribution and extent of anoxia remain poorly constrained. The most commonly applied global-scale paleoredox proxies, uranium and molybdenum, mainly capture redox changes in shallow-marine environments, providing limited insight into oxygen availability on the deep ocean floor. Furthermore, these proxies are insensitive to short-lived fluctuations in oxygenation due to their long (~400 kyr) seawater residence times. Consequently, reconstructions of oxygenation through the end-Permian Mass Extinction have lacked a proxy capable of tracking deep-water oxygen loss and resolving a high-resolution global redox history. Thallium isotopes, which track global deep ocean oxygenation through the burial of manganese oxides, have emerged as a potential solution to this challenge due to the much shorter residence time of Tl in the ocean (~20 kyrs). In this study we present the first combined carbonate-shale Tl-isotope record, one that covers four geographically distant regions and provides a near-continuous record of global-scale redox change during the extinction interval. Using an inverse model, we interpret a composite record of Permian-Triassic Tl isotopes, providing evidence that ocean anoxia was already prevalent one million years before the extinction, challenging the prevailing view of a well-oxygenated Late Permian ocean. Oxygen depletion likely remained largely constrained to the deep ocean and was distinct from the shelf- and slope-depth euxinia of the Early Triassic that was central to the loss of animal diversity.