

Constraining the Rate of Ocean Deoxygenation Leading to the End-Permian Mass Extinction: Toward a Multi-Isotope Tracer Approach

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The end-Permian mass extinction (EPME), which occurred approximately 252 million years ago, represents the most severe biotic crisis of the Phanerozoic, resulting in the mortality of more than 81% of marine species. While the expansion of oceanic anoxia has been commonly cited as a proximate cause of the EPME, the rate of ocean deoxygenation in the latest Permian oceans remains poorly quantified. In this study, we integrate multiple Permian-Triassic records from widely spaced sections—Meishan, Dajiang, and Lengqinggou in South China, and the Abadeh section in Iran—to construct high-resolution $\delta^{238}\text{U}$, $\delta^{142}\text{Ce}$, and $\epsilon^{205}\text{Tl}$ profiles. These profiles provide new quantitative constraints on the rate and extent of ocean deoxygenation during the EPME. The sections were temporally correlated using a combination of $\delta^{13}\text{C}$ records and conodont biostratigraphy.

The correlated sections demonstrate excellent agreement, with an average $\delta^{238}\text{U}$ value of -0.23‰ before the End-Permian Mass Extinction (EPME), which drops to -0.80‰ during the EPME interval and stabilizes around -0.55‰ into the earliest Triassic. An inversion mass balance model indicates that global anoxia expanded from approximately 1% to 6% during the EPME. Thallium isotope records reveal an average $\epsilon^{205}\text{Tl}$ value of $-5.4 \pm 3 \text{‰}$ (2SD, $n=7$) during the end-Permian, decreasing to a minimum of -7.2‰ before rising to -2.0‰ prior to the EPME and remaining stable around this value into the earliest Triassic. A detailed comparison of the $\delta^{238}\text{U}$ and $\epsilon^{205}\text{Tl}$ profiles shows that the positive excursion in $\epsilon^{205}\text{Tl}$ occurred approximately 71 kyr before the $\delta^{238}\text{U}$ signal, suggesting that global ocean deoxygenation began ~ 71 kyr earlier than previously indicated by $\delta^{238}\text{U}$ studies. Furthermore, considering the differences in residence time and isotopic behavior in the oceans, the comparisons among the $\delta^{238}\text{U}$, $\delta^{142}\text{Ce}$, and $\epsilon^{205}\text{Tl}$ profiles document that anoxic waters affected both shallow marine environments and deep seafloors. Since over 95% of marine species inhabit shallow marine environments, our study offers a more comprehensive understanding of the connection between marine deoxygenation and the EPME event.