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Ocean redox structure and trace-metal cycling during the Paleoproterozoic Cuddapah Basin sedimentation: constraints using trace metals, iron speciation, and Mo-W isotope systematics

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Reconstructing redox conditions in the Earth's geological past remains challenging because of complex interplay between water column processes, sediment-water interactions, and basin-scale controls. Many commonly used proxies including trace-metal (TM) enrichments (Mo, U, V, and Mn) and Fe speciation ratios (Fe_{HR}/Fe_T, and Fe_{py}/Fe_{HR}) rely on rigid threshold-based interpretations, and they can record overlapping depositional and diagenetic influences. Similarly, metal isotope signatures ($\delta^{98}Mo$ and $\delta^{186}W$) require appropriate environmental context to be interpreted meaningfully in terms of basin redox conditions. This study presents TM enrichments (V/Al ~ 4.323 to 20.405; Mo/Al ~ 0.02 to 2.864; and U/Al ~ 0.236 to 2.204), iron speciation (Fe_{HR}/Fe_T ~ 0.228 to 0.793, and Fe_{py}/Fe_{HR} ~ 0.308 to 0.760), and Mo-W isotope data ($\delta^{98}Mo$ ~ -1.533 to 2.130 and $\delta^{186}W$ ~ -0.246 to 0.272) of siliciclastic sedimentary rocks of Papaghni sub-basin, Cuddapah Supergroup, India. Conventional proxy thresholds suggest a predominantly sub-oxic to ferruginous water column with limited indications of euxinia in some samples. Further, to move beyond deterministic interpretations, we apply an integrated probabilistic framework that combines iron speciation, TM systematics, and Mo-W isotope data to evaluate redox structure, basin restriction, and sulfide availability within the basin. Instead of assigning discrete redox states, individual proxies are treated as uncertainty-bearing constraints, allowing individual samples to express mixed or transitional redox signatures and enabling quantitative assessment of ferruginous, euxinic, and oxygenated influences. Analytical uncertainties in Mo-W isotope data are incorporated through simulation-based evaluation against conceptual process fields, allowing consistency checks with basin-scale redox conditions. The combined results indicate a redox structure dominated by ferruginous conditions, variably influenced by basin restriction and limited, spatially heterogeneous sulfide development, rather than sustained euxinia. This study highlights the importance of probabilistic, multi-proxy approaches for investigating redox heterogeneity in Proterozoic basins.