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Quantifying subglacial meltwater-driven oxygenation during Snowball Earth periods

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The Cryogenian period witnessed the most severe glaciation events in Earth's history. How life survived during the globally ice-covered state—known as the "Snowball Earth"—remains a long-standing question. Among the potential refugia for Cryogenian life, subglacial meltwater habitats have been identified from geochemical and sedimentological evidence. However, the magnitude of input fluxes and the extent of oxygenation during meltwater flushing remain poorly constrained. Here we report a siltstone sequence interlayered within Sturtian-aged diamictites in Gucheng Formation, Shennongjia area, South China. This interlayered siltstones are interpreted as an interval deposited during a single meltwater flushing event, as suggested by variations in pyrite sulfur isotopes ($\delta^{34}S_{py}$) and salinity proxies (Sr/Ba). Based on sedimentary molybdenum concentrations and Mo isotope ($\delta^{98}Mo$) variations, we apply a Monte Carlo–based two-dimensional kernel density estimation within a Mo mass balance framework. The modeling results reveal a dramatic increase in Mo input flux (~40-fold) and an expansion of oxygenated conditions (~30% of the basinal seafloor area) during the meltwater flushing. These first quantitative constraints reveal a dynamic and pulsating Snowball Earth, reveals how expansive oxygenated refugia and high-magnitude nutrient pulses may facilitate the taxonomic diversification of eukaryotic algae and primed the marine biosphere for its subsequent ecological revolution.