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Constraining fluctuations in atmospheric oxygen in the wake of the Great Oxidation Event(s)

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The accumulation of atmospheric oxygen, during the so-called Great Oxidation Event (GOE), is envisaged to have initiated a series of biogeochemical transformations that set the trajectory for the emergence of complex life. The disappearance of mass-independent sulfur isotope fractionation (S-MIF) within the *c.*2.33-billion-year-old (Ga) Rooihoogte Formation has been used as a chemostratigraphic marker to define the tipping point in the irreversible rise of oxygen. However, recent reports of S-MIF in the overlying Timeball Hill Formation question this narrative [1], leaving significant uncertainties surrounding the timing, tempo, and trajectory of Earth's oxygenation. Herein, presenting a new bulk quadruple S-isotope record from core KEA-4, we return to the South African Transvaal Basin in search of support for these putative oscillations in atmospheric oxygen beyond 2.33 Ga. Here, although we capture the expected Rooihoogte-housed demise of S-MIF, we fail to identify *any* vestige of younger S-MIF [2], despite scrutinizing the Timeball Hill Formation at unprecedented resolution. Precluding a non-atmospheric explanation for the Timeball-Hill-housed S-MIF identified by Poulton et al. [1], the dichotomy we expose between cores separated by less than 5 km (i.e., KEA-4 *vs.* EBA-1/-2) requires that any "reappearance" of S-MIF must be stratigraphically isolated and, therefore, difficult to resolve by typical sampling campaigns. To better constrain these fluctuations, we further present a series of statistical experiments, which we combine with new targeted data from core EBA-2, to argue that any return to an oxygen-impoverished atmospheric state capable of S-MIF production after 2.33 Ga was ephemeral, potentially lasting on the order of tens-of-thousands of years. Such rapidity distinguishes these "young" oscillations in pO_2 from their earlier proposed counterparts (i.e., 2.45–2.33 Ga), implicating fundamentally different drivers while exposing an unrecognized sensitivity to feedbacks at the dawn of atmospheric oxygenation. [1] Poulton et al. (2021) *Nature* **592**; [2] Izon and Luo et al. (2022) *PNAS.*