Goldschmidt 2025 Abstract
https://doi.org/10.7185/gold2025.32317

Where Life Meets Minerals: Insights on Manganese Oxidation and Reduction based on Single Cell Analysis of Pseudomonas putida GB-1

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The oxidation and reduction of manganese underpin numerous processes, from photosynthesis and defense against oxidative stress to the biogeochemical cycling of trace metals and organic matter. Microbial manganese oxidation, which typically leads the formation of MnO_2(s), was documented more than a century ago. However, its physiological function remains elusive. Also lacking is knowledge of the factors that control the regulation and transcription of the enzymes leading to manganese biomineralization. Recently, we developed a novel reporter gene fusion system to study the activation of the genes encoding two manganese oxidases in the common bacterium, *Pseudomonas putida* GB-1. This system has enabled the first temporally and spatially resolved analysis of manganese oxidase promoter activation at the single cell level. Additionally, the integration of optical and fluorescence microscopy with X-ray based spectro-microscopy allows us to correlate gene activation with mineral precipitation and Mn redox state across a range of spatial scales and environmental conditions. The mechanism of manganese biomineralization that emerges is one regulated at the population-level and not at the single cell level. Further, the two manganese oxidases are regulated by specific chemical cues that expand the ecological niches for manganese biomineralization. This work provides a new framework to investigate how microbial communities orchestrate the extent, location and timing of metal oxidation and reduction, while providing new insights on the dynamics of electron transfer at the life-mineral interface and the the application of biominerals in treatment systems.