

Early earth marine oxygen oases sustained by abiotically produced hydrogen peroxide

LUKAS MIKSA^{1,2}, REZA FAHIM GUILANY³, WOLFGANG BACH⁴, DIRK DE BEER⁵, GUNTER WEGENER⁶ AND JUDITH KLATT⁷

¹Microcosm Earth Center

²University of Bremen & Max Planck Institute for Marine Microbiology

³Microcosm Earth Center, Philipps-University Marburg & Max Planck Institute for Terrestrial Microbiology, Marburg, Germany

⁴Faculty of Geosciences, University of Bremen, Germany

⁵Max-Planck-Institute for Marine Microbiology

⁶MARUM, Center for Marine Environmental Sciences, University of Bremen

⁷Microcosm Earth Center, University of Marburg & Max Planck Institute for Terrestrial Microbiology

Abstract

Early Earth marine oxygen oases sustained by abiotically produced hydrogen peroxide

Lukáš Mikša¹, Reza Fahim Guilany², Wolfgang Bach³, Dirk De Beer¹, Gunter Wegener³, Judith Klatt²

¹Max Planck Institute for Marine Microbiology, 28359 Bremen, Germany

²Microcosm Earth Center, Max Planck Institute for Terrestrial Microbiology & Philipps University Marburg, 35032, Marburg, Germany

³MARUM - Zentrum für Marine Umweltwissenschaften der Universität Bremen, Leobener Str. 8, 28359 Bremen, Germany

The Great Oxidation Event (GOE) marks one of the most pivotal transitions in Earth's history. While the initial rise in atmospheric oxygen paved the way for complex life, it also triggered what may have been Earth's largest mass extinction, as O₂ is lethal to many anaerobic organisms. This raises the question if survivors had the chance of an early adaption. The geological record and phylogenetic analyses suggest that reactive oxygen species, such as hydrogen peroxide (H₂O₂), and molecular oxygen (O₂), existed transiently and locally before the GOE, despite early Earth being predominantly reduced. Abiotic sources of ROS may have thus preconditioned life for oxidative stress, and aerobic metabolic processes may have emerged long before our planet's surface became oxygenated.

In this study, we experimentally simulated coastal and open ocean conditions, exploring interactions between solar radiation, pre-paleoproterozoic seawater chemistry, and mineral surfaces representative of early Earth. Our results confirm light-driven but also light-independent H₂O₂ production, enabling the oxidation of various reduced compounds. Notably, in the presence of polymetallic sulfide, we observed substantial H₂O₂ production and subsequent O₂ formation exhibiting strong pH dependency. Minerals bearing Eu, and Mn also displayed tendencies for oxygen evolution. Additionally, the presence of microaerophilic iron-oxidizing bacteria equipped with catalase enhanced the

conversion of H₂O₂ to O₂, thus amplifying the oxygen accumulation.

These findings suggest that abiotic processes could have indeed sustained oxygenated microenvironments, thus supporting the emergence of early aerobic metabolisms before the widespread oxygenation of Earth's atmosphere. Such localized O₂ sources may have primed some life forms – including the ancestors of cyanobacteria – for the eventual advent of biogenic oxygen production via oxygenic photosynthesis.

Keywords: early Earth, hydrogen peroxide (H₂O₂), oxygen (O₂), abiotic, evolution, mineral, polymetallic sulfide