Evolution of oxygenic photosynthesis triggered the rise of oxygen

LEWIS M. WARD*[1], JAMES HEMP[1], PATRICK M. SHIH[23], JOSEPH L. KIRSCHVINK[1] AND WOODWARD W. FISCHER[1]

[1]Division of Geological and Planetary Sciences, California Institute of Technology, 1200 E. California Blvd, Pasadena, CA 91125 (*Correspondence: lward@caltech.edu) (jim.hemp@caltech.edu, kirschvink@caltech.edu, wfischer@caltech.edu)

[2]Joint BioEnergy Institute, 5885 Hollis St, Emeryville, CA 94608 (pmshih@gmail.com)

[3]Physical Biosciences Division, Lawrence Berkeley National Laboratory, One Cyclotron Rd, Berkeley, CA 94720

It is widely accepted that Cyanobacteria invented oxygenic photosynthesis, and that this was a necessary precondition for the rise of oxygen by ~2.3 Gya, but it is debated whether this occurred immediately following the evolution of Cyanobacteria or whether they originated far earlier in Archean time.

New molecular clock analyses reveal the divergence between Cyanobacteria and recently discovered nonphotosynthetic relatives ~2.5 Ga, marking an upper limit for the origin of oxygenic photosynthesis; furthermore the radiation of crown group Cyanobacteria is placed after the rise of oxygen, ~2.0 Ga, potentially coincident with the acquisition of aerobic respiration.

To test these results and assess whether the evolution of oxygenic photosynthesis could be directly responsible for the rise of oxygen, we constructed a biogeochemical model to estimate the characteristic timescales for fluid Earth oxygenation. This framework accounts for major pools and fluxes of compounds that might buffer oxygenation, demonstrating that these are insufficient to delay oxygenation for more than tens to hundreds of thousands of years. Calculations suggest that oxygenation proceeds rapidly upon evolution of oxygenic photosynthesis. These buffers are regenerated over geological timescales, while gross primary production acts orders of magnitude faster. The only O_2 sink that responds on a comparable timescale is aerobic respiration. Insights from comparative biology suggest a delay between the evolution of oxygenic photosynthesis and aerobic respiration—a scenario with consequences for organic carbon burial and climate.

These data support a consistent scenario in which Cyanobacteria diverged from nonphotosynthetic ancestors and evolved oxygenic photosynthesis shortly before 2.3 Gya, triggering the relatively rapid oxygenation of the atmosphere.