Biogeochemical modeling perspective on the role of phosphorus cycle in the Great Oxidation Event

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The Earth’s early atmosphere was reduced, but remarkable oxygenation has occurred during the Paleoproterozoic, ca. 2.4-2.1 billion years ago. This marked transition of atmospheric redox state is called Great Oxidation Event (GOE), representing one of the largest environmental changes in the history of Earth’s chemical evolution. However, the puzzle of when and how the GOE occurred remains a topic of vigorous debate.
A previous modeling study[1] suggests that the GOE with a transient oxygenation of the atmosphere—the so-called oxygen overshoot[2]—would have occurred as a consequence of the Snowball Earth event. However, recent stratigraphic correlations[3] make the causal linkage between the Snowball Earth event and the GOE unclear. If the Snowball Earth event is not responsible for the occurrence of GOE, it raises a question of what drives the oxygen overshoot. To answer this question, it is necessary to consider the coupled, redox-dependent biogeochemical dynamics in Earth’s surface system.
Here we employ the biogeochemical model of global C, P, S, and O_2 cycles to investigate the biogeochemical dynamics associated with the GOE. We focus particularly on the role of phosphorus (P) cycle, because P is an essential nutrient controlling global biospheric activity on geologic timescales. The model consists of three reservoirs: the atmosphere, the surface ocean, and the deep ocean. In the atmosphere, oxygen (O_2), carbon dioxide (CO_2), and methane (CH_4) are considered as chemical species, and in the ocean, dissolved O_2, dissolved inorganic carbon (DIC), alkalinity (Alk), calcium ion (Ca^{2+}), phosphate (PO_4^{3-}), sulfate (SO_4^{2-}) are simulated. In this study, we conducted sensitivity experiments with respect to the riverine P input flux from the continent to the ocean and the initial value of atmospheric CO_2 levels in order to investigate the conditions for the occurrence of the GOE and the biogeochemical consequences during the GOE.
Our results demonstrate that both the riverine P flux and atmospheric CO_2 levels play a critical role not only in the occurrence of the GOE and but in the biogeochemical dynamics. More specifically, we found that the condition for the GOE are sensitive to the P availability in the ocean: the GOE tends not to occur when the riverine P flux is reduced by a few % from the reference value, highlighting the fundamental role of P availability on global O_2 budget. Our model also demonstrates that the occurrence of oxygen overshoot requires a relatively high initial value of atmospheric CO_2 (>~0.2 atm) and that the timescale of oxygen overshoot is sensitive to the riverine P flux. Based on the systematic sensitivity experiments, we conclude that the P cycle exerts a primary control on the O_2 dynamics during the GOE.

References

[1] Harada et al., 2015, *EPSL*, 419, 178-186.
[2] Bekker & Holland, 2012, *EPSL*, 317-318, 295-304.
[3] Poulton et al., 2021, *Nature*, 592, 232-236.

