

Modeling a rise of atmospheric oxygen after the Paleoproterozoic snowball Earth event

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Understanding the evolution of atmospheric oxygen is one of the fundamental issues in the history of life on earth, as the evolution of higher life, such as eukaryotes and metazoans, is dependent on the oxidation state of the atmosphere-ocean system. Atmospheric oxygen levels are considered to have increased largely (from $<10^{-5}$ of present atmospheric level (PAL) to ~ 0.01 PAL) in early Paleoproterozoic, although the cause of this rise has been controversial.

Previous studies have suggested a hypothetical causal linkage between the Paleoproterozoic snowball glaciation at 2.22 Ga and a rise in atmospheric oxygen based on evidence of depositions of manganese and iron oxides immediately after the glaciation found widespread in South Africa and North America [1,2]. These records imply that a global warming in the glacial aftermath enhanced chemical weathering on land and provided nutrients to the ocean, which lead to a cyanobacterial bloom [1]. In order to assess the hypothesis quantitatively, we developed a simple atmosphere-ocean biogeochemical cycle model. In the model, we simulate biogeochemical perturbations in the atmosphere-ocean system in response to a climate jump to an extreme greenhouse condition immediately after the Paleoproterozoic snowball glaciation. We calculate a consequent rise in oxygen due to the perturbations and evaluate timescale from the glacial termination to the initiation of cap carbonate depositions with the aim of comparing with the geological records [1].

The model consists of two boxes; atmosphere-surface ocean box, and deep ocean box. In each box, we calculate chemical and biological reactions relate to the global CO₂ methane, and oxygen cycles. We consider the inputs of phosphorous and Ca²⁺ from land into surface ocean via chemical weathering, and also calculate the diffusion of dissolved components (e.g. DIC, Alk and H₃PO₄) between the ocean boxes. Considering the Paleoproterozoic snowball deglaciation, high atmospheric pCO₂ (~ 0.7 atm) is assumed as an initial condition. Chemical weathering rate is given as a function of temperature and atmospheric pCO₂, multiplied by weathering efficiency f ($f = 1$ at present). We change f given the uncertainty in soil biological activity and continental area at that time. Nutrient supply is represented by riverine phosphorous input via chemical weathering, which is fully consumed by photoautotrophs (cyanobacteria) via photosynthesis. To calculate oxygen and methane levels in the atmosphere for given production fluxes, we adopt a redox balance model given by Goldblatt et al. [3].

The results indicate that, immediately after the glaciation, global temperature rises as high as 330 K, resulting in extremely high levels of riverine phosphorous input to the oceans due to the enhanced chemical weathering (~ 10 - 20 times higher than that of today). Assuming all the phosphorous are consumed by cyanobacteria via oxygen-producing photosynthesis, the total amount of oxygen generation reaches $\sim 10^{23}$ mol during the first 10^5 years after the glaciation. The atmospheric oxygen level increases from $< 10^{-5}$ PAL to ~ 1 PAL during the first 5×10^6 years, and then gradually decreases to ~ 0.01 PAL. These results are consistent with the oxygen levels reconstructed by the depositions of manganese and iron oxides [1,2].

We also found that the ocean becomes highly undersaturated with respect to carbonates after the glaciation due to high atmospheric CO₂ concentrations. Such a situation prevents carbonates from precipitating during the first 10^5 years after the glaciation, which is also consistent with the geologic records of the depositions of iron and manganese oxides followed by cap carbonate in the oceans [1].

[1] Kirschvink et al. (2000) *Proc. Natl. Acad. Sci. USA*, **97**, 1400-1405. [2] Sekine et al. (2011) *Earth Planet. Sci. Lett.* **307**, 201-210. [3] Goldblatt et al. (2006) *Nature* **443**, 683-686.