Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)
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BAO01-10 Room:301A Time:May 21 14:15-14:30

Modeling the rise of oxygen after the Snowball earth: implications for the Paleoproterozoic manganese and iron formation

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Earth's atmosphere and oceans are considered to have experienced stepwise and irreversible oxidation through its history (e.g. [1]), which may have paved the way to the complicated life such as eukaryotes and metazoans [2]. It is interesting to note that geological evidence suggests that a remarkable increase of oxygen concentration has occurred shortly after the Paleoproterozoic Snowball Earth event, based on widespread depositions of manganese and iron oxides immediately above the glacial diamictites found in the Paleoproterozoic sedimentary sequences from the Transvaal Supergroup, South Africa, and the Huronian Supergroup, Canada [3,4]. Carbonate precipitation occurs above the deposition of manganese and iron in both the Transvaal and Huronian Supregroups [3,5], which may represents a climate recovery from the greenhouse condition in the Snowball earth aftermath [3]. In this study we numerically investigated the linkage between a global-scale glaciation and an oxygenation of the atmosphere-ocean system, in the aim of comparing our results to the geological records.

The results of our numerical experiments with a biogeochemical cycle model indicate that the super greenhouse conditions (pCO_2˜0.7 atm and T˜320 K) in the aftermath of the Paleoproterozoic Snowball Earth event significantly enhance the chemical weathering of continents, causing ˜10 times as high as the present levels of nutrient input and the biological productivity. In the consequence of high levels of biological productivity together with a positive feedback in the atmosphere among a rise in oxygen, ozone formation, and UV shielding of methane, the atmospheric oxygen levels rapidly rise from $< 10^{-5}$ PAL to 0.01 PAL (PAL: the present atmospheric level) after the glaciation. The oxygen levels then overshoot to ˜1 PAL in ˜10^6 years after the glaciation due to the high levels of biological productivity sustained by a long-term global warming. Atmospheric oxygen then gradually decreases by oxidizing reducing materials from Earth's interior. Eventually, a steady state of atmospheric oxygen of ˜0.01 PAL is achieved in 10^8 years. Such an irreversible rise in atmospheric oxygen (i.e., from $< 10^{-5}$ PAL to ˜0.01 PAL) is explained by a transition between different steady state of atmospheric oxygen levels [6] caused by a Snowball Earth glaciation and the subsequent perturbations of biogeochemical cycles.

We found that the rapid oxygenation causes the deposition of manganese and iron in the shallow marine environments. Manganese and ferrous iron in the anoxic deep water are driven by thermohaline circulation, immediately oxidized in the shallow marine water within 10^4 years after the glaciation. Assuming deep water is initially saturated with respect to Mn-carbonates, we derive 10^{15} mol of manganese deposition, which would be sufficient to form manganese ore in the Hotazel formation, Transvaal Supergroup (˜8Gt, ˜10^{14} mol of manganese [7]). We also found that calcite precipitation is prevented in the ocean during 10^5 years after the glaciation owing to high atmospheric pCO_2. Our results imply that manganese and iron oxides deposition might precede the carbonate deposition, which is consistent with the geological records found both in the Transvaal and Huronian supergroups [3,4].

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