Mantle data imply that secular oxidation can drive oxygenation of the atmosphere

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One of the major components of the modern Earth's atmosphere is O_2, which is produced by photosynthesis and is necessary for aerobic lifeforms, including humans. However, according to geological evidence, such as mass-independent sulfur isotope fractionation, O_2 levels in the atmosphere were low during the Archean, even after the emergence of oxygenic photosynthesis around 3.2 - 2.8 Ga. It took several hundreds of millions of years before the O_2 level increased around 2.4 Ga, which is the start of the Great Oxidation Event (GOE) from ~2.4 to ~2.1 Ga.

In a majority of the literature, a delay of atmospheric oxygenation has been attributed to a secular decrease in O_2 sinks rather than a secular increase in O_2 sources. However, the actual mechanism for the decrease in O_2 sinks is still uncertain. One possibility is the secular oxidation of the mantle, which decreases the proportion of reducing gases in volcanic emissions and therefore, lowers the O_2 sinks relative to CO_2 fluxes, where CO_2 is a substrate for O_2 production. Although secular mantle oxidation has been long dismissed, two new studies reveal that the oxygen fugacity of the mantle increased by ~ 1.3 $\log_{10}$ units from the Archean onward. These studies qualitatively suggest that the new trend of the mantle redox state would cause the oxygenation of the atmosphere.

Here, we quantitatively examine the possibility of atmospheric oxygenation caused by mantle oxidation using the data from the new studies. We calculate a ratio of O_2 sources to rapid O_2 sinks: the oxygenation parameter, K_{oxy}. As explained in the previous studies, K_{oxy} less than unity indicates a reducing atmosphere, while K_{oxy} larger than unity indicates an oxic atmosphere. The effect of secular mantle oxidation increases K_{oxy} with time: K_{oxy} shifts from < 1 to > 1 at ~ 2.5 Ga. Hence, mantle oxidation would trigger the GOE around 2.5 Ga. On the other hand, if we model the mantle with a constant oxidation state, a shift of K_{oxy} from < 1 to > 1 never occurs.

These results do not exclude the possibility that other processes proposed previously contributed the GOE, such as a shift from the submarine to subaerial volcanoes, a secular increase in the degassing ratio of carbon and/or sulfur to hydrogen, and/or a decrease in hydrogen flux via serpentinization. The exact timing of the GOE (~2.4 Ga) is probably explained by combining these processes with the effect of mantle oxidation on the atmosphere. However, our results show that mantle oxidation alone could drive the oxygenation of the atmosphere.

If secular oxidation of the mantle ultimately controlled the timing of the GOE, then the cause of mantle oxidation is ultimately important for setting the tempo of biological evolution. Possible drivers of mantle oxidation are the mixing of a redox heterogeneous mantle and/or the escape of hydrogen to space. Such processes could also apply to other Earth-like planets and would determine whether such planets could be habitats for aerobic lifeforms.

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