Redox Revolutions on Earth and Beyond

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The molecule O_2 looms large in the search for life on extrasolar planets, because Earth's O_2-rich atmosphere is a consequence of biology. Commonly, it is assumed that an Earth-like planet on which oxygenic photosynthesis evolves will inevitably accumulate O_2 in its atmosphere and pervasively alter the surface environment –that biological redox innovations inexorably lead to environmental redox revolutions. However, close examination of Earth's environmental redox history challenges this assumption.

Increasingly, it appears that evolution of the solid Earth played a key role in modulating the oxygenation of Earth's surface environment. Multiple lines of evidence now suggest that O_2 was being produced biologically hundreds of millions of years before its accumulation in the atmosphere during the Great Oxidation Event (GOE), ca. 2.4 Ga, and hence that Earth's surface redox revolution was substantially delayed. This delay can be accounted for by interactions between the atmosphere and the solid planet, because the biological production of O_2 is ultimately balanced by consumption through reaction with reductants derived from Earth's interior. In particular, recent examinations of oxygen fugacity during the formation of Precambrian basalts and komatiites suggest that large volumes of the mantle underwent a secular increase of oxygen fugacity through the Archean and early Proterozoic. The cause(s) of this secular shift remain unclear, but when translated into a secular evolution of the redox state of volcanic gases, the observed mantle trend can account for a shift from net O_2 consumption to net O_2 production at about 2.4 Ga.

This emerging understanding of Earth's redox revolution raises important questions about the likelihood of similar revolutions on other worlds even in the presence of large biospheres powered by oxygenic photosynthesis. Even modest differences in mantle compositions or tectonics might substantially alter the timing of surface oxygenation. On some worlds, atmospheric O_2 accumulation might be impossible. This realization highlights the need for far better understanding of solid Earth processes - and how these processes might operate on other nominally "Earth-like" worlds - as a key part of a new science of living worlds.