FALSE NEGATIVES FOR REMOTE LIFE DETECTION ON OCEAN-BEARING PLANETS: LESSONS FROM THE EARLY EARTH.

C. T. Reinhard[1,2], S. L. Olson[1,3], E. W. Schwieterman[1,3,4,5], T. W. Lyons[1,3], [1]NASA Astrobiology Institute, [2]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA (chris.reinhard@eas.gatech.edu), [3]Department of Earth Sciences, University of California, Riverside, [4]NASA Postdoctoral Program, USRA, Columbia, Maryland, [5]Blue Marble Space Institute of Science, Seattle, WA

Introduction: Ocean-atmosphere chemistry on Earth has undergone dramatic evolutionary changes through its long history, with potentially significant ramifications for the emergence and long-term stability of atmospheric biosignatures. Though a great deal of work has centered on refining our understanding of 'false positives' for remote life detection, much less attention has been paid to the possibility of 'false negatives' – i.e., cryptic biospheres that are widespread and active on a planet's surface but are ultimately near or below detection in the planet's atmosphere. Here, we summarize the potential for remote detectability of O_2/O_3, CH_4, and O_2-CH_4 disequilibrium throughout Earth's history based on recent proxy results and coupled Earth system models.

Results: During the Archean (~3.8 – 2.5 Ga), currently available proxy and model constraints indicate that atmospheric CH_4 levels may have been generally within or above the range that would be remotely detectable. In contrast, atmospheric O_2 levels were many orders of magnitude below detection in terms of both O_2 or O_3, with the possible exception of pulsed pO_2 increases during the late Archean [e.g., 1]. During the mid-Proterozoic (~ 2.0 to 0.8 Ga), combined proxy and model results indicate that both O_2 and CH_4 would have been undetectable and that O_3 would have been challenging to detect. An interesting exception to this Proterozoic pattern may have occurred during the Paleoproterozoic, between ~2.2 – 2.0 Ga, when atmospheric pO_2 may have been elevated to detectable levels before decreasing again for over a billion years. Following possibly dynamic upheavals in ocean-atmosphere redox during the late Proterozoic, atmospheric O_2/O_3 was present at levels that should have been readily detectable for most of the last ~500 million years. However, results from Earth system models indicate that detection of atmospheric CH_4 would have been problematic with low- to moderate-resolution spectroscopy during this same period.

Conclusions: Although our results should be broadly applicable to Earth-analog planets orbiting Sun-like stars, additional work will be necessary to determine the extent to which differences in the stellar environment may impact the buildup of O_2 and CH_4 [2], while also considering the effects of ocean chemistry, as we have done here. Nevertheless, our work further stresses the importance of including and refining UV observations for exploration of potentially habitable exoplanets, since it is quite plausible that Proterozoic Earth analogs would have detectable O_3 without spectrally apparent O_2. Moreover, high-resolution spectroscopy ($R > 20{,}000$), coupled with high-contrast imaging, may provide a promising avenue for detecting modern Earth-like CH_4 abundances on an exoplanet [e.g., 3], though the feasibility of this technique has yet to be conclusively demonstrated. More broadly, our analysis highlights the importance of including a rigorous understanding of ocean biogeochemistry in models of biosignature production and preservation on exoplanets and affirms that critical insights into the evolution of atmospheric biosignatures can be provided by better understanding Earth's dynamic history.

References:

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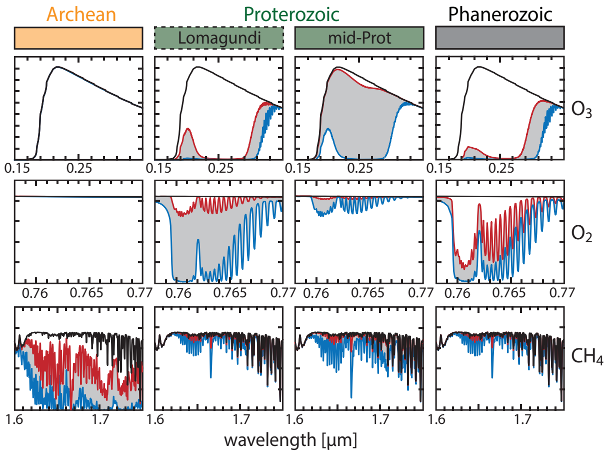

Figure 1. Reflectance spectra of selected O_2, O_3, and CH_4 bands as a function of geologic epoch. Lower abundance limits are given in red, upper limits are given in blue. The black line represents the case with no absorption. The resolution of each spectrum is 1 cm^{-1}, which is approximately $\Delta\lambda = 6.25 \times 10^{-6}$ μm at 0.25 μm, $\Delta\lambda = 5.78 \times 10^{-5}$ μm at 0.76 μm, and $\Delta\lambda = 2.62 \times 10^{-4}$ μm at 1.65 μm. We used a solar zenith angle of 60° to approximate a disk-average. Note that reflectances are arbitrarily scaled to provide a qualitative assessment of potential detectability.