National Aeronautics and Space Administration

NASA Astrobiology Institute
2016 Annual Science Report
Team Report:

Alternative Earths,
University of California, Riverside

ALTERNATIVE EARTHS

Lead Institution:
University of California, Riverside

Team Overview

Principal Investigator:
Timothy Lyons

A single question drives the research of the Alternative Earths Team: How has Earth remained persistently inhabited through most of its dynamic history, and how do those varying states of inhabitation manifest in the atmosphere? It is conceivable that each of Earth's diverse planetary states translates to a particular atmospheric composition that could one day be detected on an exoplanet—and that one of these "Alternative Earths" could help prove the presence of life elsewhere in the universe.

Defining these atmospheric compositions and their potential for remote detectability relies on teamwork among Co-Investigators at UC Riverside (UCR), Yale, Georgia Tech (GT), Arizona State University (ASU), Oregon Health and Science University (OHSU), and the J. Craig Venter Institute (JCVI), as well as with our collaborators at home and abroad. No matter what time slice of Earth history we tackle, our vertically integrated approach spans from a comprehensive deconstruction of the geologic record to a carefully coordinated sequence of modeling efforts to assess our own planet's relevance to exoplanet exploration. These efforts, from empirical evidence to complementary theory, require unique interdiscplinarity that bridges one perspective to the next:

- Composition of the oceans and atmosphere: proxy development
- Gas fluxes and ecological impacts: 3D Earth system models
- Stability and remote detectability of biosignature gases:1D photochemical and radiative transfer models that define synthetic spectra for evaluation using telescope simulators

Team Website: https://astrobiology.ucr.edu

2016 Executive Summary

Simply put, the Alternative Earths Team is unraveling the evolving redox state of Earth's early atmosphere as a guide for exoplanet exploration. Atmospheric redox and the abundance of associated gases are fingerprints of the complex interplay of processes on and within a host planet that point both to the presence and possibility of life. Redox-sensitive greenhouse gases, for example, can expand the habitable zone well beyond what is predicted from the size of a planet's star and its distance from that energy source alone. Conversely, the absence of obvious biosignature gases such as oxygen does not necessarily mean a planet is sterile: cyanobacteria were producing oxygen on Earth long before it accumulated to remotely detectable concentrations in the atmosphere.

Our latest findings are pushing us in novel directions toward previously unconsidered biosignatures, because, as Earth is teaching us, the traditional approaches are not likely to be straightforward or necessarily correct. Our latest modeling of biosignature gases in Earth's early atmosphere is revealing intriguing implications for climate stability and 'false negatives' in remote life detection—despite the earliest emergence of complex life in the oceans below. Indeed, our overarching conclusion from the past year's research is that ocean-bearing planets may not be clear-cut candidates for remotely detectable atmospheric biosignatures (Reinhard et al., 2017). Yet, our search for life is typically guided by the search for oceans, and so we must better balance the special challenges with the obvious motivations that come from distant seas.

Reaching these conclusions required a careful and arguably unprecedented vertical integration of research efforts, anchored by the core strengths of our Team: development of geochemical proxies that reveal the composition of the ancient oceans and atmosphere. In general, our Team is pursuing a comprehensive deconstruction of the geologic record from the earliest biological production of oxygen to its permanent accumulation in large amounts almost three billion years later. In this past year, we focused largely on the mid-Proterozoic Eon, from 1.8 to 0.8 billion years ago. A highlight in our ongoing proxy development is the most complete record to date of very low oxygen during this time period (Cole et al., 2016; Hardisty et al., 2017)—in both the atmosphere and within the essential biological habitats of the surface oceans.

Black shale sequences on Baffin Island, Canada.
Credit: Devon Cole

Comprehensive numerical modeling of mid-Proterozoic relationships among low atmospheric oxygen, methane instability, and low and heterogeneous shallow marine oxygen reveal a direct impact on the biosphere (Olson et al., 2016b; Reinhard et al., 2016; Reinhard and Planavsky et al., 2017)—and its potential for remote detection.

Ongoing research efforts are boosted by several recent sampling missions to the Ediacaran stratigraphy of South Australia, alkaline lake sediments in the Green River Formation of Central Utah, and Precambrian sections in Botswana, Norway, and Northwest Canada. We also have expanded our Team's breadth with the addition of new faculty and postdoctoral scholars and by continuing to foster synergisms with other NAI Teams, in particular the Virtual Planetary Laboratory. We are also pleased to have elevated the profile of astrobiology in southern California through two community-wide public lectures series, one in Riverside and the other in Palm Desert, both exploring the theme "Are We Alone."

Institutional PIs Chris Reinhard (Georgia Tech, left) and Noah Planavsky (Yale) sample marine sedimentary rocks deposited billions of years ago.

Astrobiology lecture series advertising displayed at Ontario Airport, California.

UNIVERSITY OF CALIFORNIA UCRIVERSIDE | Science Lecture Series

ARE WE ALONE?

THURSDAY, DECEMBER 8, 2016
Our Cosmic Origins

THURSDAY, JANUARY 12, 2017
Alternative Earths

WEDNESDAY, FEBRUARY 1, 2017
Ocean Worlds

THURSDAY, MARCH 23, 2017
Mars 2020 & Beyond

THURSDAY, APRIL 13, 2017
Alien Planets

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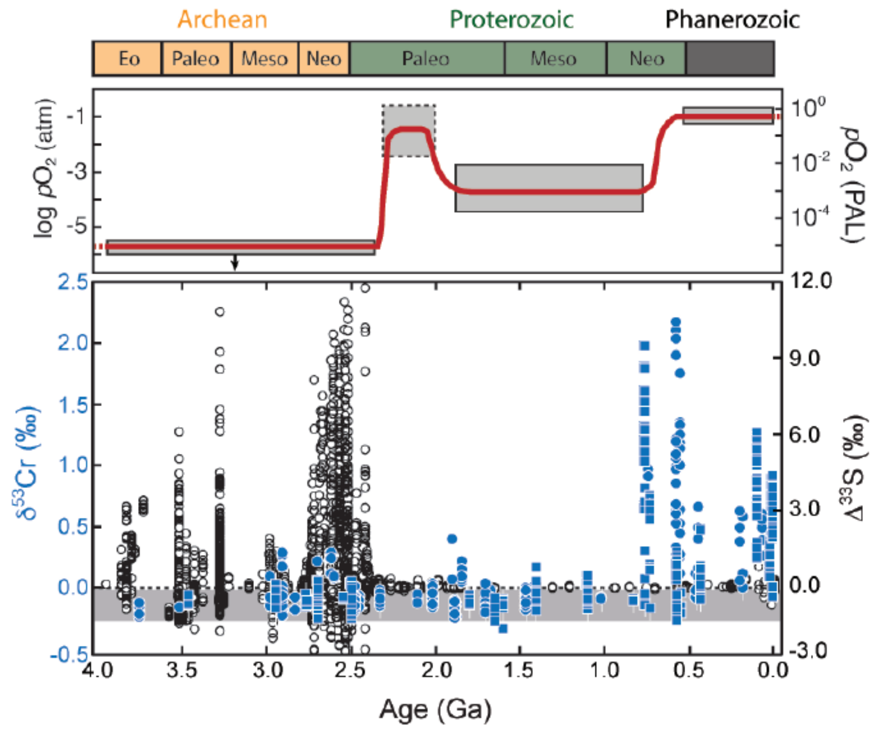
Project Reports

Composition of the Oceans and Atmosphere: Proxy Development

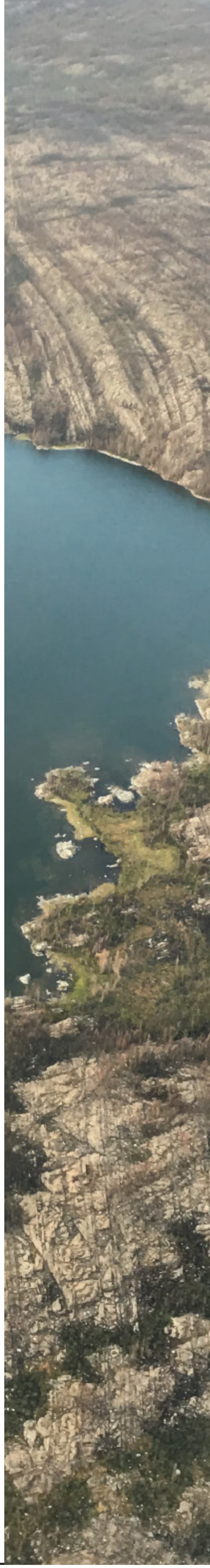
Building on the core strength of our Team, the highlight is the most complete record to date of very low oxygen—and its direct impact on the biosphere—during the mid-Proterozoic. Work led by graduate student Devon Cole (Yale) and Noah Planavsky (Yale), working together with Team members at GT and UCR, has produced a new and transformative chromium isotope record through Earth's early history (Cole et al., 2016). Comprising more than 300 new chromium isotope measurements from 20 rock formations around the world, this work suggests that prior to 800 million years ago, atmospheric O_2 levels were <1% of present atmospheric level (PAL)—contrasting sharply with previous estimates of O_2 concentrations as high as 40% PAL. If correct, oxygen was clearly low enough to have directly hindered the diversification of complex life (see Gas Fluxes and Ecological Impacts: 3D Earth System Models).

To refine estimates of the atmospheric oxygen levels required to induce oxidative Cr cycling and explain the sedimentary chromium isotope record, we have initiated experimental Cr-Mn oxidation studies in the lab. We also continue to calibrate the utility of the chromium isotope and other proxies through studies of modern systems (Hood et al., 2016), analyses of metamorphosed, weathered, and hydrothermally altered rocks (Gueguen et al., 2016; Wang et al., 2016), and careful comment on the work of others (Planavsky et al., 2016).

To constrain oxygen levels in the all-important surface ocean, UCR graduate student Dalton Hardisty and PI Tim Lyons led development and application of the iodine proxy for reconstructing oxygen levels in the surface ocean. Application of this technique to a large suite of carbonate samples spanning Earth's history suggests significant spatiotemporal variability of mostly low surface ocean oxygen levels for much of Precambrian time, including frequent upward mixing of O_2-poor deep waters during the mid-Proterozoic (Hardisty et al., 2017).



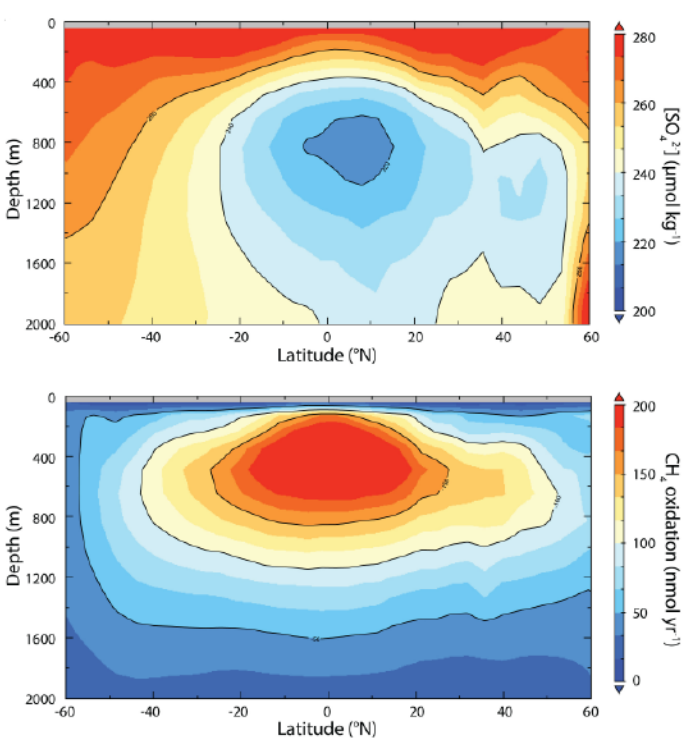
OXYGEN IN THE ATMOSPHERE: Atmospheric O_2 on Earth through time (upper) and select geochemical proxies for atmospheric pO_2 (lower). In the upper panel, shaded boxes show approximate ranges based on geochemical proxy reconstructions, while the red curve shows one possible trajectory through time. In the lower panel, open circles show the magnitude of non-mass-dependent sulfur isotope (NMD-S) anomalies, shown as Δ33S. Filled blue symbols show chromium (Cr) isotope fractionations from iron-rich and siliciclastic marine sedimentary rocks throughout Earth's history. Credit: Reinhard et al., 2017



Gas Fluxes and Ecological Impacts: 3D Earth System Models

Understanding of the ultimate mechanistic underpinnings and ecological consequences of very low pO_2 during the mid-Proterozoic remains a research focus for much of our Team. Work led by graduate student Stephanie Olson (UCR), together with Tim Lyons (UCR) and Chris Reinhard (GT), has focused on the development of 3D Earth system models designed to interrogate ocean-atmosphere chemistry on a mostly reducing planet. In particular, we incorporated parameterized O_2-O_3-CH_4 photochemistry and an explicit representation of a consortial microbial metabolism that oxidizes CH_4 anaerobically with dissolved sulfate, the latter being a consequence of the low but persistent oxygen levels in the biosphere. Results of this new model suggest that CH_4 would have been an ineffective climate stabilizer even on an Earth surface that was only weakly oxidizing with mostly anoxic oceans. Astrobiologists now face a serious challenge to explain our planet's early habitability—and the implications for other planets and their habitable zones are obvious. Identifying early Earth's precise greenhouse cocktail, probably including water vapor, nitrous oxide, carbon dioxide, and only trace methane, is essential for spectroscopic efforts to assess the habitability of other planets in our galaxy (Olson et al., 2016).

We have explored the potential consequences of low atmospheric pO_2 on the ecological landscape faced by early eukaryotic and metazoan life (Reinhard et al., 2016). Results for Earth system modeling and simple dynamic models of local surface ocean O_2 levels indicate a 'patchy' oxygen environment for much of mid- and late-Proterozoic time, even at pO_2 levels well above those reconstructed with the chromium isotope proxy. These oases—local-to-regional settings dynamic on biologically relevant timescales—may have been inhospitable environments for the origin of animal life but could also have catalyzed evolutionary innovation through their intrinsic insolation and instability once certain ecological conditions were met. Even well-ventilated, shallow-water oases near the coasts, evidenced by iodine proxy (see Composition of the Oceans and Atmosphere: Proxy Development), would have been seasonally choked by anoxia and likely toxic, sulfide-rich waters rising up from the deep. These results are now a centerpiece in the Team's growing body of evidence that low oxygen in the ocean and atmosphere may have challenged the rise of complex life for hundreds of millions of years as well as detectability of that biosphere from remote locations.



METHANE MUTED. The numerical model used in this study, which calculated sulfate concentrations (top), methane oxidation (bottom), and an array of other biogeochemical cycles for nearly 15,000 three-dimensional regions of the ocean, is by far the highest resolution biogeochemical model ever applied to the ancient Earth. Previous models used no more than five regions. Credit: From Olson et al., 2016

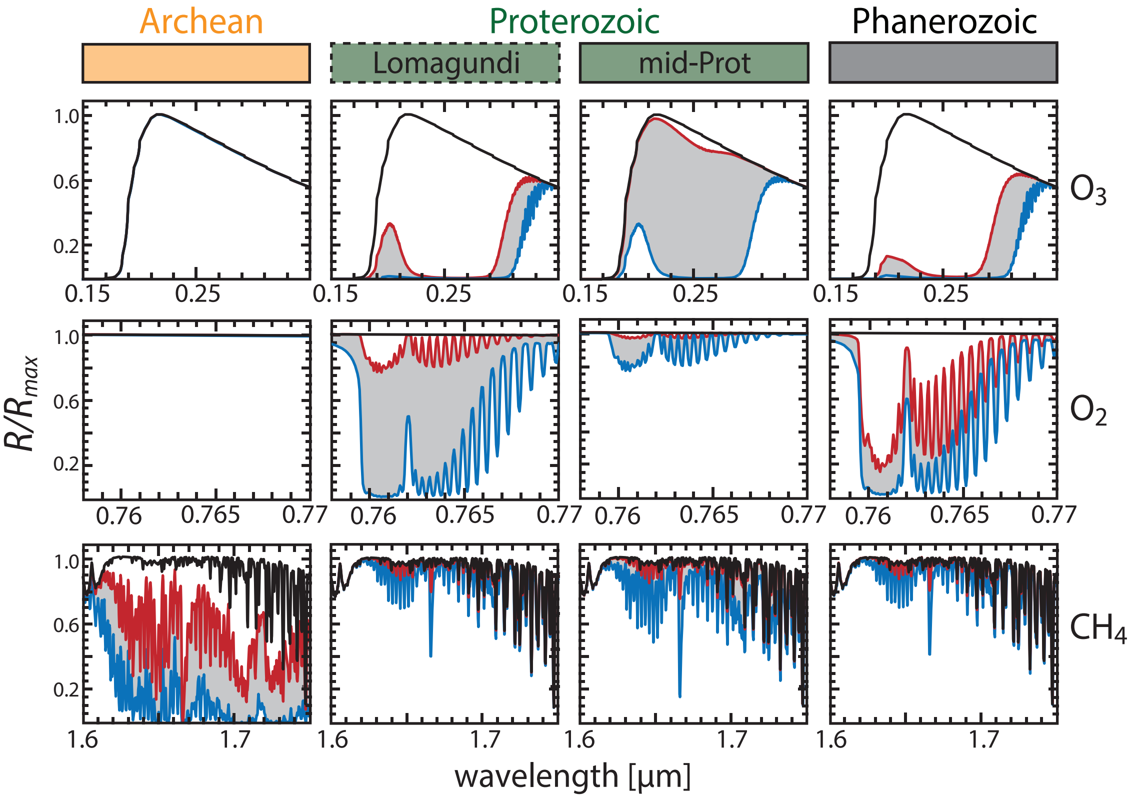
ICY WORLD: Artist's depiction of an ice-covered planet in a distant solar system resembles what early Earth might have looked like if a mysterious mix of greenhouse gases had not warmed the climate. Credit: European Southern Observatory (EsO) via Wikimedia Commons

Stability and Remote Detectability of Biosignature Gases: 1D Photochemical and Radiative Transfer Models

Recent developments from our geochemical proxy records and Earth system models provide insight into the long-term evolution of the most readily detectable potential biosignature gases on Earth—oxygen (O_2), ozone (O_3), and methane (CH_4). In that light, we revisited evolving atmospheric chemistry on Earth in the context of the spectroscopic detectability of Earth's biosphere (Reinhard et al., 2017). We suggest that the O_2-CH_4 disequilibrium biosignature, often touted as the most convincing biosignature for any Earth-like atmosphere, would have been challenging to detect remotely during Earth's ~4.5-billion-year history and, remarkably, that atmospheric O_2/O_3 levels have been a poor proxy for the presence of Earth's biosphere for all but the last ~500 million years. What is more, detecting atmospheric CH_4 would have been problematic for most of the last ~2.5 billion years. Indeed, vast periods of Earth's history would have appeared sterile by these traditional measurers, despite a thriving surface biosphere—representing a series of 'false negative' scenarios for remote life detection.

We stress that internal oceanic recycling of biosignature gases will often render surface biospheres on ocean-bearing silicate worlds cryptic, with the implication that the planets most conducive to the development and maintenance of a pervasive biosphere will often be challenging to characterize via conventional atmospheric biosignatures.

This is our call to arms: future work must seek to identify novel biosignatures that are less prone to being overprinted by exchange with a liquid ocean, and this challenge is motivating our current research. More generally, we have demonstrated Earth's indispensable, quantitative value in guiding the search for life beyond our Solar System.



SYNTHETIC SPECTRA OF 'ALTERNATIVE EARTH' ATMOSPHERES THROUGH TIME. Reflectance spectra of selected O_2, O_3, and CH_4 bands for each geologic eon. Lower abundance limits are given in red, upper limits are given in blue, and the region between these limits is shaded grey. The black line represents the case with no absorption by O_2, O_3, or CH_4. Credit: From Reinhard et al., 2017

Alternative Earths: 2016 Publications

Bindeman, I.N., Bekker, A., and Zakharov, O. (2016). Oxygen isotope perspective on crustal evolution on early Earth: A record of Precambrian shales with emphasis on Paleoproterozoic glaciations and Great Oxygenation Event. *Earth and Planetary Science Letters*. DOI: 10.1016/j.epsl.2015.12.029

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Hood, A.V.S., Planavsky, N.J., Wallace, M.W., Wang, X., Bellefroid, E.J., Gueguen, B., and Cole, D.B. (2016). Integrated geochemical-petrographic insights from component-selective δ238U of Cryogenian marine carbonates. *Geology*. DOI: 10.1130/G38533.1

Korenaga, Jun. (2016). Can mantle convection be self-regulated? *Science Advances*. DOI: 10.1126/sciadv.1601168

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McKenzie, R.N., Horton, B.K., Loomis, S.E., Stockli, D.F., Planavsky, N.J., and Lee, C-T.A. (2016). Continental arc volcanism as the principal driver of icehouse-greenhouse variability. *Science*, 352, 444-447. DOI: 10.1126/science.aad5787

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Sahoo, S.K., Planavsky, N.J., Jiang, G., Kendall, B., Owens, J.D., Wang, X., Shi, X., Anbar, A.D., and Lyons, T.W. (2016). Oceanic oxygenation events in the anoxic Ediacaran ocean. *Geobiology*. DOI: 10.1111/gbi.12182

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