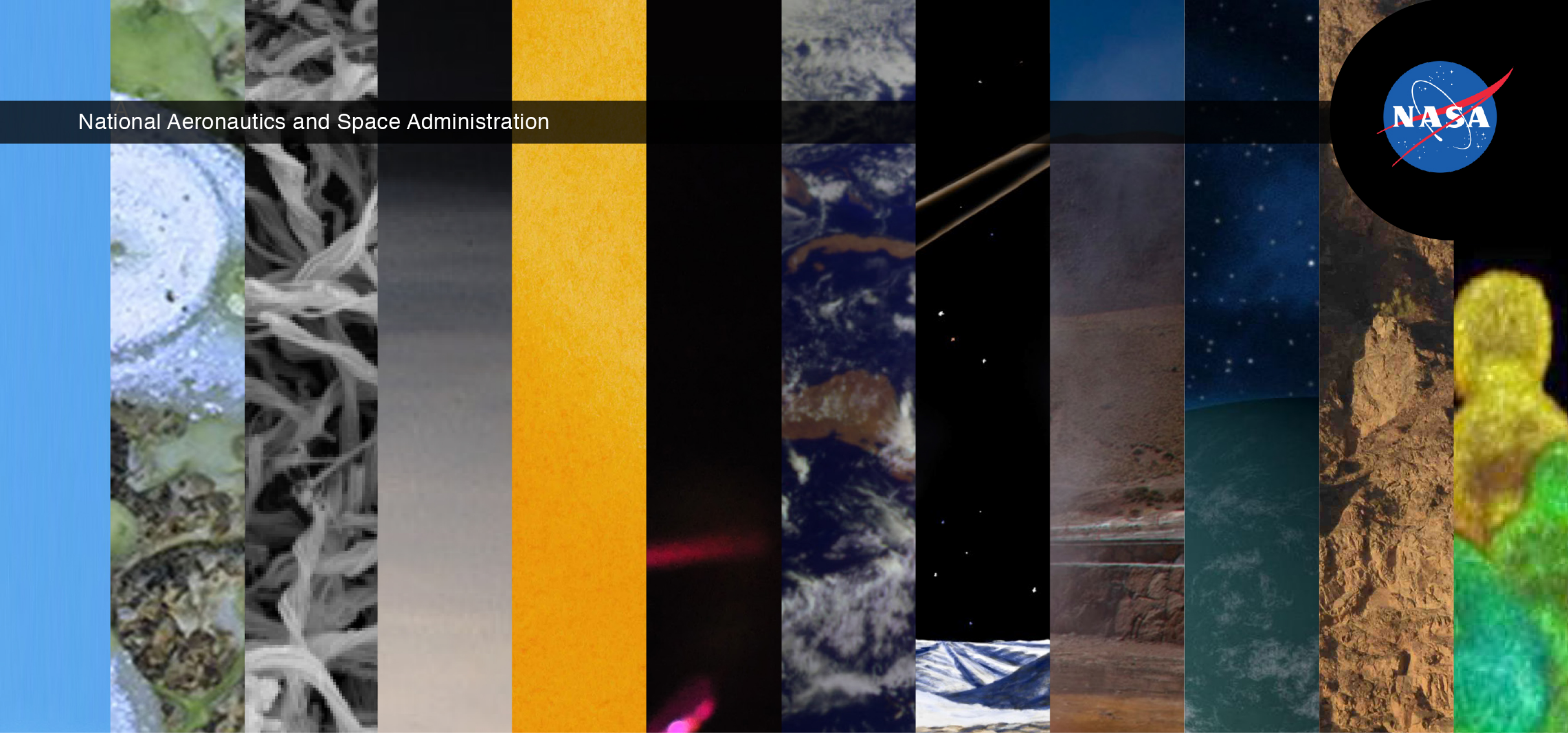
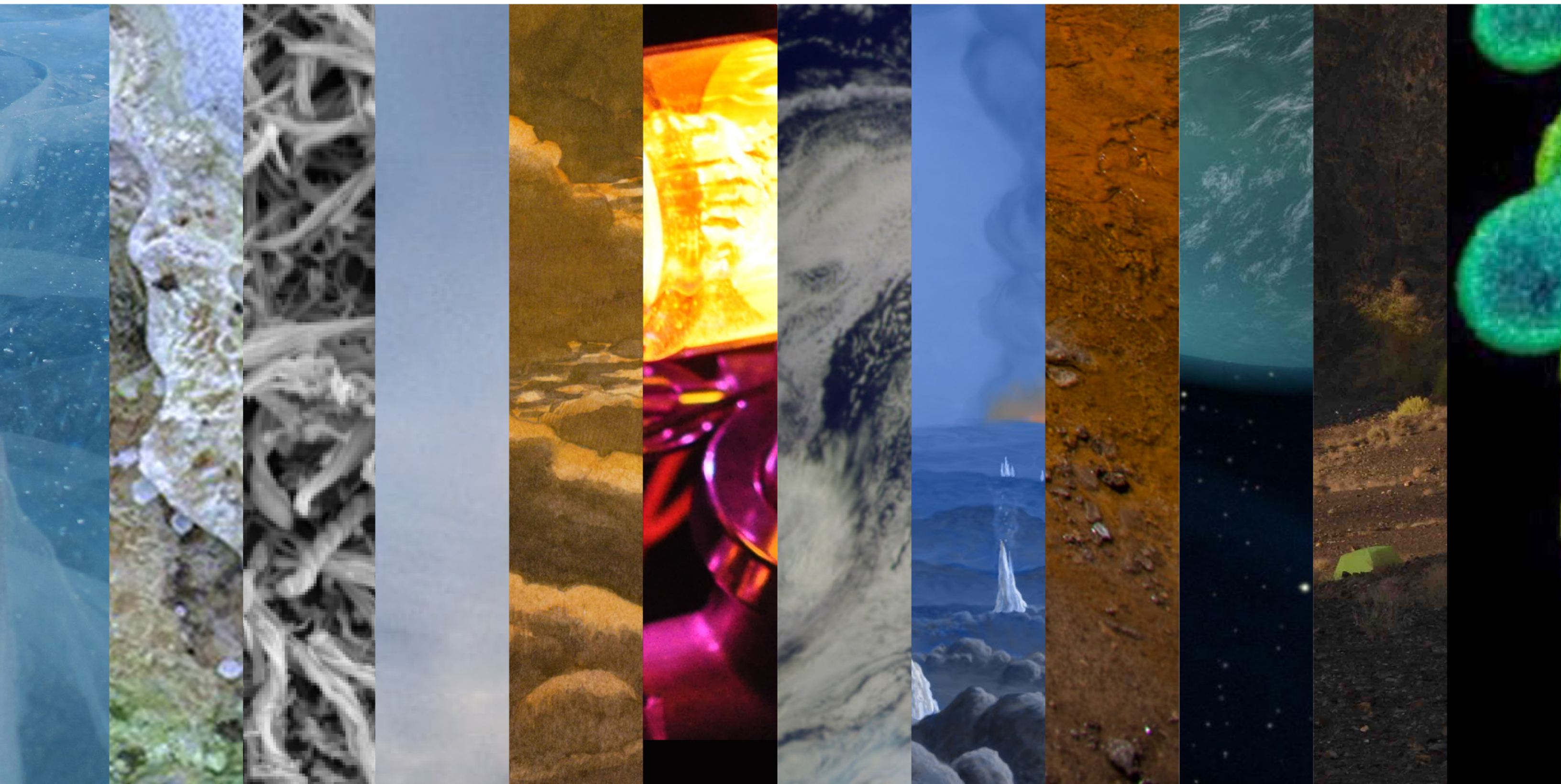


NASA Astrobiology Institute

2017 Annual Science Report

Alternative Earths

University of California, Riverside



ALTERNATIVE EARTHS

Lead Institution:
University of California, Riverside

UCR

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 interdisciplinarity that bridges one perspective to the next:

- Composition of the oceans and atmosphere
- Gas fluxes and ecological impacts
- Stability and remote detectability of biosignature gases

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

2017 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 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 revealed intriguing implications for climate stability and 'false negatives' in remote life detection—despite the earliest emergence of complex life in the oceans below (Reinhard et al, 2017a). That revelation has propelled us to explore seasonality as a biosignature and to develop new biogeochemical models for exploring biospheric evolution and extinction on billion-year timescales. Integrating these models with synthetic atmospheric spectra will make it possible to quantify the detectability of Earth's future biosphere and the 'life spans' of oxygenated biospheres for Earth-like planets more broadly.

We make special efforts to apply our research discoveries to important conversations about future exoplanet observation strategies (Schwieterman et al., 2018a, 2018b). As we look forward, Earth gives us a

Fig. 1. Mary Droser (UCR, red hat band) and her team sample Ediacaran fossil beds at Nilpena Station, South Australia, where her team has worked for more than 20 years.

broadly relevant view of diverse planetary processes, including controls tied to nutrient cycling and the presence, abundance, and interactions among continents. This holisitic perspective will allow us to explore a wider catalog of habitability scenarios—well beyond those represented by early Earth—in theoretical and model space that couples oceans, continents, and the atmosphere in predictable ways.

Fig. 2. Tim Lyons (UCR, far right) and Andrey Bekker (UCR, far left) sample Archean drill core in Minas Gerais, Brazil.

Using Earth's past to guide exoplanet exploration requires a careful 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. Several geochemical systems—chromium, iodine, and thallium in particular—continue to provide new evidence for very low pO_2 during much of the Precambrian. This year we established an increasingly robust framework for the chromium isotope proxy through a variety of experimental and field-based observations (Wu et al., 2017; Saad et al., 2017; Brady et al., 2017). Another primary focus is exploring the ultimate mechanistic underpinnings and ecological consequences of very low pO_2 through sophisticated biogeochemical modeling. Our latest results emphasize the surprising potential importance of certain aspects of the biosphere for buffering climate during times of lower solar luminosity on Earth, with implications for primitive biospheres around dim stars (Zhao et al., 2017; Ozaki et al., 2017).

Significant expansion of our team's expertise is fueling many of our team's most mission-relevant results. The addition of NASA Postdoctoral Program fellows Edward Schwieterman (UCR) and Kazumi Ozaki (GT) brought new arenas of modeling expertise into the mix. A new faculty collaborator, planetary astrophysicist Stephen Kane, joined the team in August as UCR's first-ever astrobiology hire. His exoplanet habitability expertise expands the Alternative Earths team's current strengths and fortifies the official 'university center' status granted in 2016.

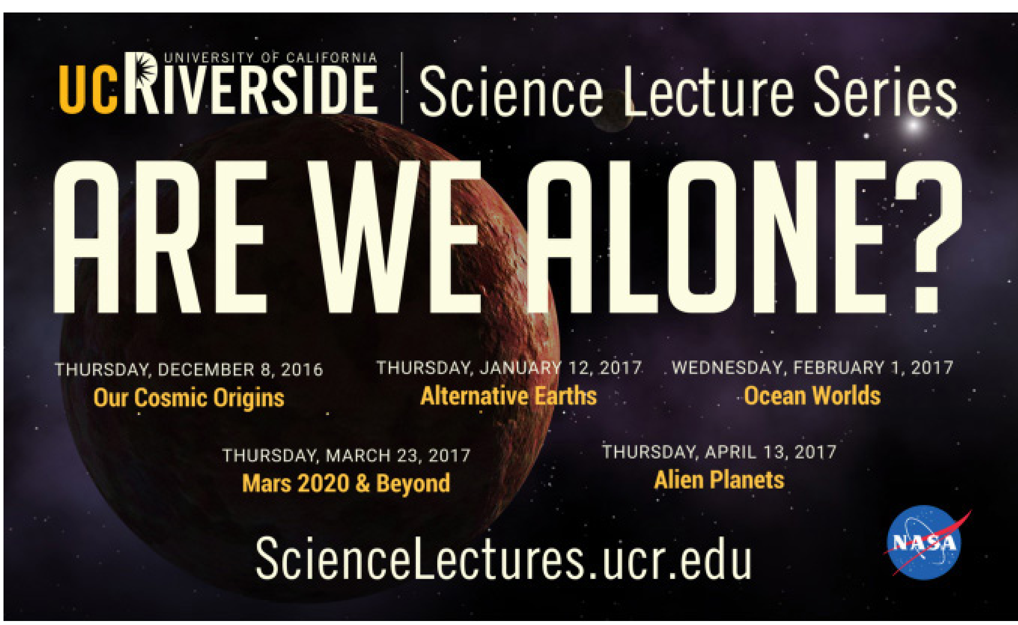


Fig. 3. UCR-sponsored astrobiology lecture series.

Project Reports

Composition of the Oceans and Atmosphere

Our interpretations of the evolution of oxygen in the oceans and atmosphere carry dramatic implications for biological evolution, so we have worked hard this year to establish increasingly robust framework for our key proxies. To constrain oxygen levels in the all-important surface ocean, former UCR graduate student Dalton Hardisty and Tim Lyons (UCR) developed the iodine proxy for reconstructing oxygen levels in the surface ocean. Application of this technique to a large suite of samples spanning Earth's history indicated significant variability of mostly low surface ocean oxygen levels for much of Precambrian time, including frequent upward mixing of anoxic deep waters during the mid-Proterozoic, between 1.8 billion to 800 million years ago (Hardisty et al., 2017).

Similarly, our compilations of chromium isotope data pointed to an extreme paucity of oxygen in the mid-Proterozoic atmosphere. Before 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. To establish an increasingly robust framework for these results, we focused this year on three separate tests of the standard view of the chromium isotope proxy, which is grounded in the idea that oxidative weathering of Cr(III)-containing minerals by manganese oxides, the formation of which requires free oxygen, is required for Cr redox cycling and Cr isotope fractionations.

First, we are designing laboratory experiments to understand factors affecting Cr isotope fractionation during Cr(III) oxidation in modern systems, in work led by postdoctoral researcher Marzia Miletto and Brad Tebo (OSHU), along with postdoctoral researcher Xiangli Wang and Noah Planavsky (Yale) and Tim Lyons (UCR) and his graduate student Chris Tino (Wu et al., 2017). In parallel, graduate student Emily Saad (GT), working with Yuanzhi Tang (GT), Reinhard (GT), and Planavsky (Yale), pioneered experimental approaches resulting in the first well-documented redox-independent Cr isotope effects (Saad et al., 2017).

Finally, postdoctoral researcher Kyle Rybacki (GT) and graduate student Ashley Brady (GT), working with Reinhard, Planavsky, and Tang, tackled the veracity of Cr isotope archives in carbonate rocks (Brady et al., 2017). Taken together, this work suggests we must exercise caution when interpreting Cr isotope records from carbonate rocks—thus justifying our team's usual emphasis on shales and iron formations.

Fig. 4. Chris Reinhard and Yuanzhi Tang are biogeochemists in Georgia Tech's School of Earth and Atmospheric Sciences. Credit: Georgia Tech / Christopher Moore

Gas Fluxes and Ecological Impacts

Understanding the ultimate mechanistic underpinnings and ecological consequences of very low pO_2 during much of the Precambrian remains a research focus for much of our team. For decades scientists invoked high concentrations of greenhouse gases such as carbon dioxide and methane to explain how Earth maintained a largely ice-free climate despite significantly lower solar luminosity in its early history. Our work last year, however, gave rise to a "methane paradox" during the mid-Proterozoic (1.8 to 0.8 billion years ago): biogeochemical models dominated by an ocean biosphere failed to reproduce atmospheric methane abundances high enough to buffer the Proterozoic climate system. This year we found a potential resolution: terrestrial microbial mats.

Postdoctoral researcher Mingyu Zhao (Yale), working with Chris Reinhard (GT) and Noah Planavsky (Yale), developed a biogeochemical model of a terrestrial microbial mat ecosystem to examine how much methane cyanobacteria-rich sediments (mats) on land could have released under the low pO_2 conditions characteristic of most of Precambrian time. Coupling this effort to the same Earth system model developed previously, the team found that terrestrial mats on as little 8% of the exposed land surface during mid-Proterozoic could have maintained a clement climate and detectable levels of atmospheric methane (Zhao et al., 2017)—in contrast to the low levels of methane the oceans would have produced during that time.

To address climate clemency even earlier in Earth history, NASA Postdoctoral Program fellow Kazumi Ozaki (GT), Reinhard (GT), and colleagues in Japan developed a novel model of the atmospheric effects of various forms of primitive photosynthetic biospheres before the Great Oxidation Event. Initial results indicate that interactions among different types of anoxygenic photosynthesizers may amplify biological methane production beyond the capacity of a single metabolic pathway working in isolation (Ozaki et al., 2017). This work widens the window of geochemical conditions that allow for warm climate states and represents a new view on the biogeophysical mechanisms regulating habitability and biosignature production on planets around dim stars.

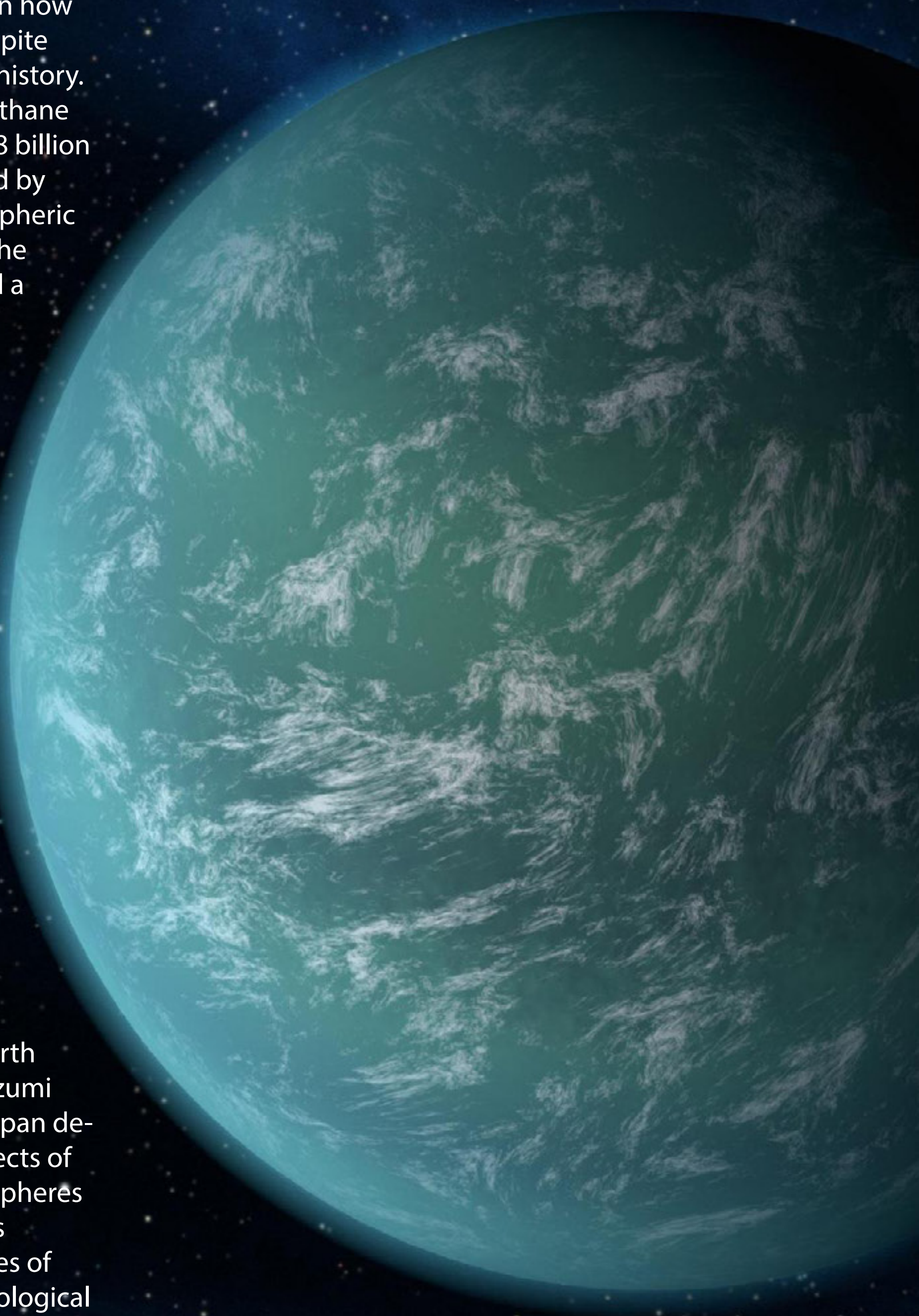


Fig. 5. Artist's depiction of exoplanet Kepler 22b, which receives a similar amount of light and heat from its star as Earth does from the sun. Credit: NASA/Ames/JPL-Caltech

Stability and Remote Detectability of Biosignature Gases

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, Chris Reinhard (GT), graduate student Stephanie Olson (UCR), NASA Postdoctoral Program fellow Edward Schwieterman (UCR), and Tim Lyons (UCR) revisited evolving atmospheric chemistry on Earth in the context of the spectroscopic detectability of Earth's biosphere. They discovered that 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 (Reinhard et al., 2017a).

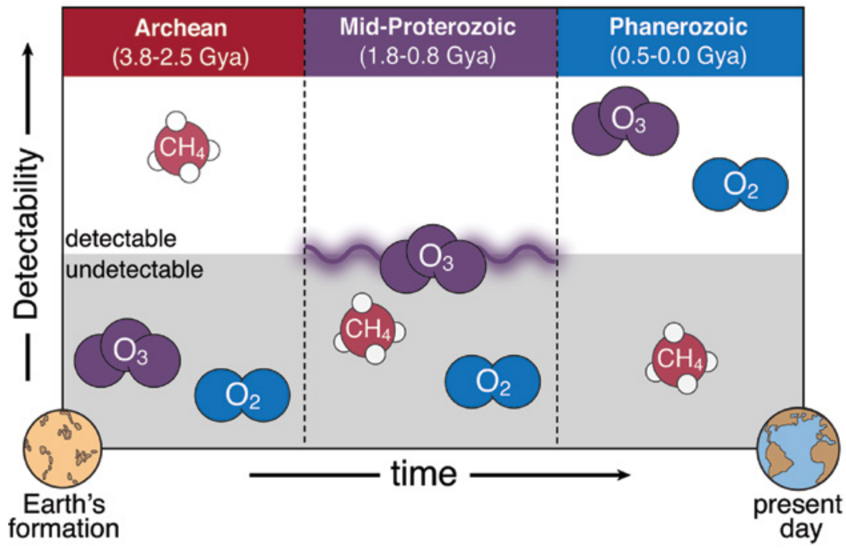


Fig. 6. Remote detectability of commonly referenced biosignature gases for Earth-like exoplanets throughout Earth's own history. Both oxygen (O_2) and methane (CH_4) may have been undetectable during the mid-Proterozoic (Reinhard et al. 2017a), but ozone (O_3) might have been at least intermittently detectable. Credit: Modified from Schwieterman et al. (2018b)

These new insights into the potential for false negatives—together with well-known false positives and the ever-increasing diversity of terrestrial exoplanets—highlight an acute need to develop additional biosignatures. As one strategy, the same four team members have begun an interdisciplinary project to explore the utility of atmospheric seasonality, which has yet to be studied robustly and quantitatively as an exoplanet biosignature. Seasonal oscillation in the composition of Earth's atmosphere is a biologically modulated phenomenon that, by analogy, may fingerprint the activities of a biosphere elsewhere.

Knowing that the telescopes that will define the search for life in the coming decades are being designed now, our team makes a point to apply our research discoveries to important conversations about future strategies. For example, our team participated in the recent solicitation for feedback for the "Astrobiology Science Strategy for the Search for Life in the Universe" by the National Academy of Sciences. In an entirely Alternative Earths–authored submission, Schwieterman, Reinhard, Olson, and Lyons argued for the critical importance of UV capabilities for identifying inhabited exoplanets with next generation space telescopes. The rationale is that 'false positive' O_3 biosignatures can be mitigated through target selection and multi-wavelength planetary characterization (including the UV), while O_2 'false negatives' cannot be eliminated without UV (Schwieterman et al., 2018b).

Likewise, Alternative Earths team members co-authored three out of five white papers resulting from the proceedings for the Nexus for Exoplanet System Science (NExSS) workshop Exoplanet Biosignatures, which will be combined in a special issue of *Astrobiology* (Schwieterman et al., 2018a).

Field Work

Uinta Mountains, northeastern Utah

Institutional PI Noah Planavsky and graduate student Devon Cole (Yale) sampled Neoproterozoic shales in the Uinta Mountains to serve the primary objective of our Alternative Earth 4: Determine the relative roles that biological innovation and environmental change played in reshaping Earth's ecosystems, atmospheric composition, and climate during the early stages of the rise of complex life. Specifically, our goal is to determine whether the diversification of complex life was a major driver of shifts in Earth's oxygenation and of major climate perturbations, including Snowball Earth Events.

Minas Gerais, Brazil

Banded-iron formations and associated carbonates and black shales of the Minas Formation, which span the Great Oxidation Event, provide an opportunity to explore the environmental changes that led to (and resulted from) Earth's initial rise of oxygen and their relationships to life, which serves the primary objective of Alternative Earth 1. UCR graudate student Bridget Lee organized this expedition on behalf of PI Tim Lyons and Co-I Andrey Bekker.

Ries Crater, Nordlingen, Germany

The Ries record of a Mesozoic-age alkaline-crater-fill lake is an intriguing analog for ancient crater-fill lakes on Mars and is the heart of a growing astrobiology collaboration between PI Tim Lyons (UCR) and Eva Stüeken's research group at the University of St. Andrews.

Port-au-Port Peninsula, Newfoundland, Canada

The fossiliferous carbonates of the Cambrian Petit Jardin Formation, in an expedition led by Institutional PI Noah Planavsky (Yale), are making it possible to pursue ongoing research suggesting that the extreme oxygen variability that characterized the end of the Neoproterozoic extended well into the Cambrian.

Nilpena Station (Ediacaran), Flinders Range, South Australia

The state government of South Australia released news in early 2018 that it is investing $1.9 million to protecting and preserving a world-famous Ediacaran fossil field on Nilpena Station in the Flinders Range. Co-I Mary Droser (UCR) has spearheaded fruitful discoveries on this site for the past 20 years, which serve the objectives of our Alternative Earth 4 and dovetail with goals of the CAN6 MIT NAI team.

Ukraine and Moldova

Co-I Andrey Bekker (UCR) led a sampling expedition to Neoproterozoic and Paleoproterozoic successions that address Alternative Earths 2 and 4.

NEW DIRECTIONS: Pyrite as a Potential Biosignature

Identifying the presence of life in the deep past and on other planets cannot necessarily rely on trace or body fossils due to the level of evolution required to form fossils. Leveraging our team's expertise with biogeochemical cycles driven by microbial processes, a UCR-based group—postdoctoral researcher Dan Gregory, graduate student Maria Figueroa, and Tim Lyons—is exploring the biosignature potential of microscopic grains of the iron sulfide mineral pyrite. Pyrite forms regularly within sediments as a result of the bacterial reduction of sulfate, or it can form in hydrothermal fluids in either the presence or absence of biology. Using sophisticated laser analyses and statistical processing of large databases, we can decipher clues to the mineral's origin: telltale suites of trace metals captured in the mineral structure of the pyrite survive weathering and metamorphosis. Indeed, in a preliminary study of ~3,800 trace metal measurements from 84 pyrite samples, a statistical classifier was able to correctly predict the sedimentary pyrite from the other pyrite types 94% of the time. It also correctly identified hydrothermal pyrite that may be related to biology between 84% and 88% of the time. This work refines the team's ability to address life on early Earth—and perhaps on Mars.

Fig. 7. Trace elements in grains of the iron sulfide mineral pyrite, such as those found in the Leicester pyrite member (above), are making it possible to distinguish whether the pyrite formed biologically or abiologically. Credit: Daniel Gregory

Reaching Out for the Stars with Our Feet on the Ground

Our ultimate goal is to model past and future atmospheres on Earth and to extrapolate the lessons learned to exoplanets, but at its core our team relies on traditional fieldwork. It takes 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, to deliver the data that ground-truth our models. Several sampling missions boosted our ongoing research efforts in 2017: Ediacaran fossils of South Australia; alkaline, crater-fill lake sediments in southern Germany; and Precambrian sections in Brazil, Newfoundland, the Ukraine, Moldova, and the Uinta Mountains of Utah—with the help of llamas.

Fig. 8. Noah Planavsky (Yale) with his llama during a 2017 field campaign in the Uinta Mountains. Credit: Devon Cole

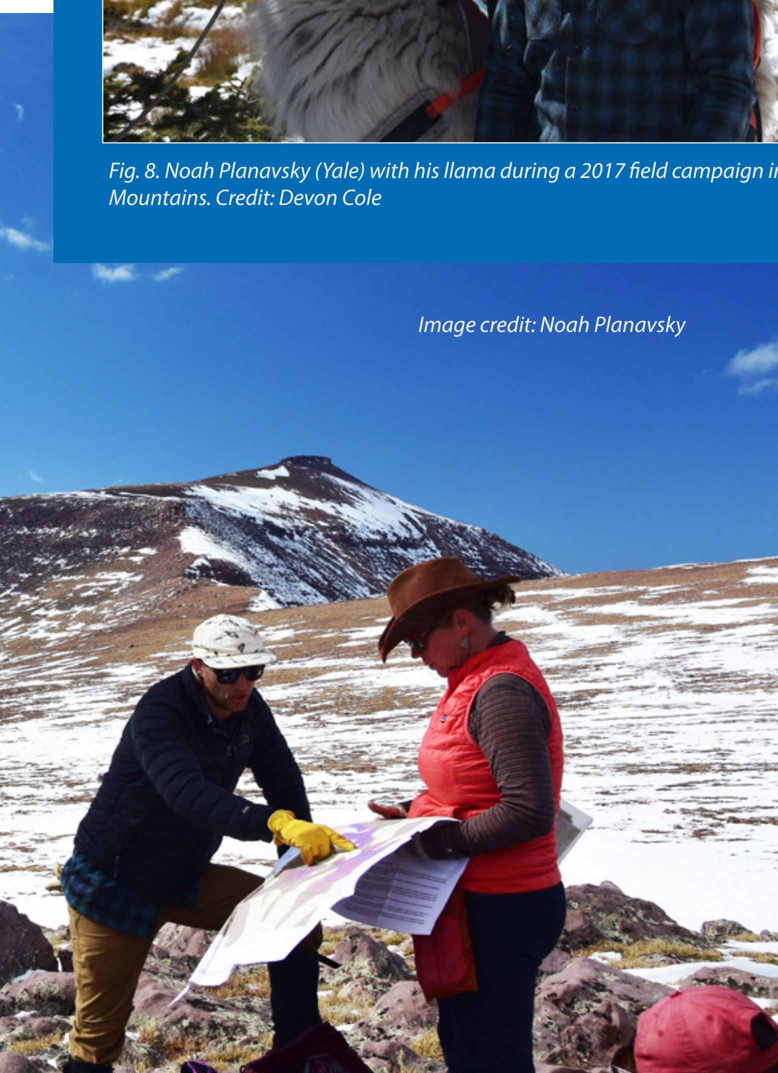


Image credit: Noah Planavsky

Team Members

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Edward Bolton
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Don Canfield
Parker Castleberry
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Chloe Stanton
Dragos Zaharescu
Ashley Brady
Christopher Tino
Eva Stüeken
Marilyn Fogel
Sandra Kirtland Turner
Ming-Yu Zhao

Alternative Earths: 2017 Publications

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