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NAI 2004 SETI Team Annual Science Report

Executive Summary

The NASA Astrobiology Roadmap asks three fundamental questions: (1) How does life begin and evolve? (2) Does life exist elsewhere in the universe? and (3) What is the future of life on Earth and beyond? The SETI Institute NASA Astrobiology Institute (NAI) team is conducting a set of coupled research projects in the co-evolution of life and its planetary environment. These projects begin by examining certain fundamental ancient transitions that ultimately made complex life possible on Earth. They will conclude with a synthesis that will bring many of the team's investigations together into an examination of the suitability of planets orbiting M stars for either single-celled or more complex life.

The astrobiology roadmap calls for a strategy "for recognizing novel biosignatures" that "ultimately should accommodate a diversity of habitable conditions, biota and technologies in the universe that probably exceeds the diversity observed on Earth." Some of our results, especially those concerning abiotic mechanisms for the oxidation of planetary atmospheres, will speak to the interpretation of extrasolar planet atmospheric spectra (and in particular, the role of oxygen as a potential biosignature) in terms of the presence of photosynthesizing life. The team's M-star project addresses the roadmap's observation that "although technology is probably much more rare than life in the universe, its associated biosignatures perhaps enjoy a much higher signal-to-noise ratio. Accordingly, current methods should be further developed and novel methods should be identified for detecting electromagnetic radiation or other diagnostic artifacts that indicate remote technological civilizations." As the roadmap recognizes, there is a continuum of investigations that comprise astrobiology, from prebiotic evolution to the evolution of technology. We believe that we are the only NAI team whose investigations run the gamut of the roadmap's range.

The SETI Institute's NAI team's research emphasizes the elucidation of the co-evolution of life and its planetary environment, investigating global-scale processes that have shaped, and have been shaped by, both. Throughout, the team recognizes the importance of pursuing the planetary evolution aspects of this research in the context of comparative planetology: since laboratory experiments are impossible over many (but not all) of the time and spatial scales relevant to early Earth, we supplement laboratory data with insights gained by exploring extraterrestrial environments that provide partial analogs to the early Earth environment and its processes.

The SETI Institute team is pursuing two investigations into the oxidation of early Earth's environment. While the biological aspects of this "oxygen transition" have been emphasized, our team is exploring non-biological contributions to this transition. Dr. Friedemann Freund and Dr. Lynn Rothschild are investigating oxidation driven by diffusive loss of hydrogen formed within igneous and metamorphic rocks that incorporate water during crystallization. Subsequent weathering of the rocks released hydrogen peroxide into the environment; the previous loss of the hydrogen indicates that this is a net oxidizing mechanism. Experiments are underway (see Fig. 1 for preliminary results) to quantify the importance of this effect for a variety of powdered crystals; new data include the observation of oxygen evolution from finely powdered magnesium oxide crystals grown from melt.
In a second investigation, oxidation driven by atmospheric hydrocarbon (and, more broadly, organic) polymerization is being investigated by Dr. Emma Bakes. Dr. Bakes' research for the early Earth builds on analogies to processes now occurring in the atmosphere of Saturn's moon Titan. With her collaborators, Dr. Bakes is completing a comprehensive theory paper describing the chemical foundations of nitrogenated macromolecules in the Titan haze. This foundation enables the next stage of her research, the theoretical building of prebiotic macromolecules from the haze constituents. This work is complemented by ongoing laboratory work performed by Dr. Bishun Khare and Dr. Hiroshi Imanaka on Titan analog materials, and infrared observations of the Titan haze.

If the oxidation mechanisms being explored were shown to be quantitatively significantï¿½modeling to be done later in the course of this grantï¿½this would suggest that the oxygen transition on an Earth-like world could take place independently of the invention of any particular metabolic pathway (such as photosynthesis or methanogenesis) that have previously been proposed to drive this transition. Since Earth's oxygen transition ultimately set the stage for the oxygen-based metabolism evidently essential for metazoa, understanding this transition is crucial to elucidating both Earth's evolution and the evolution of complex (including intelligent) life. The team's geological investigations are therefore tightly coupled with microbiological experiments, led by Dr. Rothschild, to understand the extent to which the proposed mechanism might have led to the evolutionary invention of oxidant protective strategies and even aerobic metabolism.

Understanding the oxygen balance on early Earth requires attention to sinks as well as sources of oxygen. One major sink for oxygen on early Earth would have been reduced iron. Iron could have simultaneously provided shielding against ultraviolet (UV) light that would have been reaching Earth's surface in the absence of the ozone shield generated by atmospheric oxygen. Nanophase ferric oxide minerals in solution could provide a sunscreen against UV while allowing the transmission of visible light, in turn making the evolution of at least some photosynthetic organisms possible. Dr. Janice Bishop and Dr. Rothschild are testing this hypothesis through coupled mineralogical and microbiological work in both the lab and the field, and examining its implications not only for Earth but for Mars as well, with an emphasis on implications for upcoming spacecraft observations. UV, visible, and infrared spectra have been measured for a collection of iron-oxide-bearing samples, and experiments have been performed on cultures of two photosynthetic microorganisms, Euglena and Chlamydomonas, with and without iron species (see Fig. 2). The spectral data and growth patterns indicate that certain ferric oxide-bearing minerals could indeed have provided protection from UV radiation for early photosynthetic organisms, while still permitting the transmittance of the visible and infrared light required for photosynthesis. These results are consistent with the hypothesis that early photosynthetic organisms may have existed in specific, perhaps small, niches protected by ferric-oxide-bearing material.

The survival of microorganisms in very high UV environments can also be tested empirically through the exploration of Earth's highest altitude lakes and ponds, in Bolivia and Chile. Dr. Nathalie Cabrol and Dr. Edmond Grin (both of whom also this past year served on the Mars Exploration Rover team) have led a series of investigations of these lakes to examine the strategies employed by these microorganisms. The group they lead is currently analyzing samples and data from its 2003 expedition to Licancabur (6,014 m altitude) and lower lakes (Laguna Verde and Laguna Blanca, 4,430 m altitude), on the Bolivia/Chile boundary. Discoveries include an active community of modern stromatolites; the culture and phylogenetic characterization of apparently new bacterial species; and physical and chemical characterization of the lakes.

Just as global-scale changes in oxygen (or iron) were critical for the early biosphere, so too would have been global processes involving other key "biogenic" elements such as carbon (for which Dr. Bakes' work provides insight) or nitrogen. Dr. Rocco Mancinelli, Dr. Amos Banin, Dr. David Summers, and Dr. Khare are pursuing coupled laboratory and field research to understand the partitioning of nitrogen on early Earth and on Mars between different possible reservoirs, and (at least for Earth) the abiotic to biotic transition in this cycling.

Dr. Banin has begun the analysis of soil samples from the Atacama Desert, an extreme terrestrial environment with very low biological activity. In particular, it is as yet unclear what properties of the soil and environment are the limiting factors for biology, and the importance of nitrogen levels in this. Dr. Mancinelli and Dr. Banin have defined new field sites for their work in the Atacama that will begin this fall. Finally, they are experimentally investigating the possibility that binding of nitrogen as NH_4^+ in silicate minerals could account for the ï¿½missingï¿½ N on Mars, examining representative silicate minerals and Mars soil analogs and the biological availability of N when present in this form.

Dr. David Summers and Dr. Khare have begun their experimental work focusing on the demonstration of the abiotic fixation of nitrogen under the CO_2/N_2 atmosphere expected on early Mars. Nitrogen is theoretically predicted to be fixed via the production of NO via shock heating, followed by UV irradiation over liquid water. These experiments should provide a different perspective into the astrobiologically important question of the fate of N on early Mars.

The work described so far examines the evolution of planetary surface habitability. With the recognition that a subsurface ocean likely exists on Jupiter's moon Europa, we know that habitability in possibly entirely subsurface environments must also be explored. Dr. Cynthia Phillips, Dr. Christopher Chyba, and Mr. Kevin Hand (a Stanford PhD student advised by Dr. Chyba) are pursuing spacecraft data analysis and modeling to examine the geology of Europa and its implications for the free energy sources that would be needed to power a Europan biosphere. Dr. Phillips and Dr. Chyba are completing a major project, using Galileo high-resolution imaging of Europa, to quantify the impact cratering "gardening" rate on Europa. This is important in its own right as a fundamental planetary process, but also is important in some astrobiological models because it will allow the quantification of the amount of biologically relevant material, created at Europa's surface through radiogenic processes, that can be mixed down to the gardening depth, and thereby sequestered below the sputtering depth and significant radiolysis depth at the surface.

These results will be coupled with the results of low-temperature laboratory experiments to make predictions about the possible abundance and survivability of any oceanic biomarkers that might reach Europa's surface through active geology, with implications for the astrobiological exploration of Europa from either an orbiter or a surface lander. Mr. Kevin Hand, in collaboration with Dr. Robert Carlson and Dr. Chyba, is pursuing this research in Dr. Carlson's laboratory at the Jet Propulsion Laboratory. Over the past year, Mr. Hand and Dr. Carlson have constructed the irradiation apparatus (including ice deposition chamber and diagnostics) and have preliminary experiments now underway. Dr. Max Bernstein, in his laboratory at NASA Ames, has measured the mid-infrared spectra of several polycyclic aromatic nitrogen heterocycles in both neutral and cationic forms, and finds good agreement between theoretical prediction and experimental observation. Ultimately the behaviorï¿½and detectabilityï¿½of such compounds under Europan conditions will also be determined.

Dr. Peter Backus, Dr. Jill Tarter, Dr. Mancinelli, and Dr. Chyba are beginning their examination of the prospects that planets orbiting dwarf M stars are habitable for either microscopic or complex life. The SETI Institute NAI team's proposal calls for a series of workshops to bring together planetary scientists, biologists, atmospheric modelers, astrophysicists, and SETI scientists to address these issues, to begin in year two of this proposal. Preliminary work so far includes a literature review, identification of workshop participants, and obtaining the full Tycho-2 star catalog and the database software that will be used to produce the list of M stars. The results of this project will ultimately help the next generation scientific Search for Extraterrestrial Intelligence (SETI) choose the million target stars (see the second figure) that it will survey for signs of technical civilizations using the new Allen Telescope Array

(ATA), being built by the SETI Institute in partnership with the University of California, Berkeley.

Finally, education and public outreach are major and integral parts of the work of the SETI Institute's NAI team. They are addressed elsewhere in our first-year summary, so are not presented here.

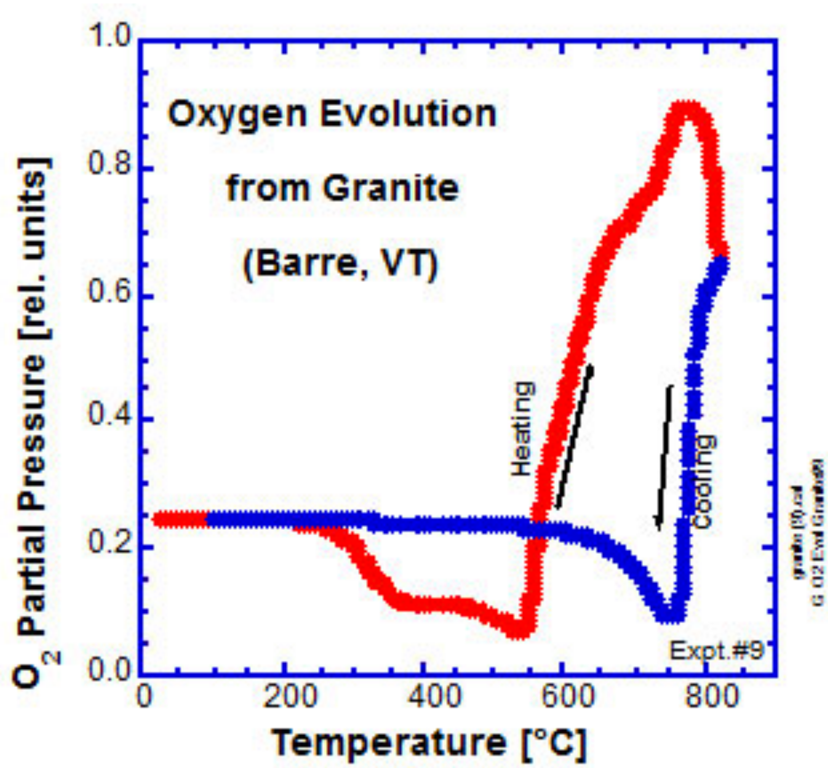

Fig. 1. Preliminary data showing O_2 evolution from crushed granite from the type location Barre , VT , during heating in a stream of N 2 with 100 ppm O_2 . Between 250-550°C O_2 is consumed, but above 550°C excess O_2 is released. The amount of O_2 gives an estimate of the average peroxy content in this rock of at least 500 ppm.

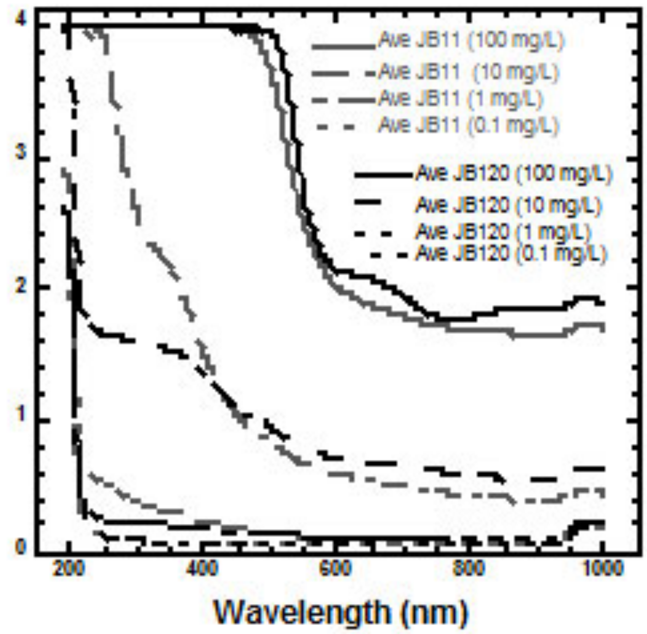

Fig. 2. Absorbance of Euglena and Chlamydonomonas in suspensions. The spectral absorbance due to chlorophyll in these organisms is clearly observed near 450 and 670 nm.

2004 SETI Project Report

Planetary Biology, Evolution and Intelligence

Accomplishments

Friedemann Freund and Lynn Rothschild are investigating oxidation driven by diffusive loss of hydrogen formed within igneous and metamorphic rocks. New data include the observation of oxygen evolution from magnesium oxide crystals. </p> <p>Emma Bakes is completing a paper describing the chemical foundations of nitrogenated macromolecules in Titan's haze. This work is complemented by laboratory work by Bishun Khare and Hiroshi Imanaka.

Janice Bishop and Rothschild have measured ultraviolet (UV), visible, and infrared (IR) spectra for iron-oxide-bearing samples, and experiments have been performed on cultures of two photosynthetic microorganisms. Data indicate that certain ferric-oxide-bearing minerals could have provided protection from UV radiation on early Earth.

Nathalie Cabrol and Edmond Grin have led a series of investigations of high-altitude lakes to examine the strategies employed by their microorganisms. The group they lead is currently analyzing data from its 2003 expedition. Discoveries include an active community of modern stromatolites and the culture and phylogenetic characterization of apparently new bacterial species.

Amos Banin has begun the analysis of soil samples from the Atacama Desert. Rocco Mancinelli and Banin are experimentally investigating whether binding of N as NH₄+ in silicate minerals could account for the "missing" N on Mars.

David Summers and Bishun Khare have begun experimental work on the abiotic fixation of nitrogen under atmosphere expected on early Mars.

Cynthia Phillips and Christopher Chyba are completing a major project, using Galileo imaging of Europa, to quantify the impact cratering "gardening" rate on Europa.

These results will be coupled with the results of low-temperature laboratory experiments. Mr. Kevin Hand, in collaboration with Robert Carlson and Chyba, is pursuing this research at JPL. Over the past year, Hand and Carlson have constructed the irradiation apparatus and have experiments underway.

Max Bernstein, in his lab at NASA Ames, has measured the mid-IR spectra of several polycyclic aromatic nitrogen heterocycles.

Peter Backus, Jill Tarter, Mancinelli, and Chyba have begun their examination of the prospects that planets orbiting dwarf M stars are habitable for either microscopic or complex life.

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Highlights
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- An active community of modern stromatolites producing limestone and developing in the highly saline shallow (50 cm) Laguna Blanca was discovered. From our 2003 reconnaissance, we believe that this community covers the entire floor of the lake (3 km x 1 km).
- The successful culture and phylogenic characterization in laboratory of two isolates from Laguna Blanca are determined to be two new species of the genus *Pseudomonas* and *E. Coli* . (analysis in progress).
- Ongoing characterization of the three lakes microbial communities and ecosystems details can be provided upon request.
- Diatoms (*Haslea*) developing UV shielding strategies (mucilaginous knobs and mesh) have been observed.
- Percentages of malformation and deformities are 10% higher than standard count in other lakes.
- Successful surface, subsurface, and subaqueous sampling (through diving and plankton netting) of water, life, and sediment in the lakes at 6,014 m and 4,430 m was performed.
- An Eldonet UV Dosimeter measuring ultraviolet A (UVA), ultraviolet B (UVB), photosynthetically active radiation (PAR) and Temperature was positioned at the Licancabur summit lake. The dosimeter is now the highest of its kind in the world and will record a yearï¿½s worth of data at 6,014 m. Because of its geographical position, it may also record the advances of the Antarctic ozone hole in this region of the Andes. Another identical dosimeter was positioned on the shore of Laguna Blanca as well as 7 UV

acrylite plate stations. The underplate of these stations (each composed of one UV transmitting and one UV blocking plate) will be sampled in the coming years to study the effects of UV on immobile periphyton.

- Data of water temperature profiles (one year's worth) were collected and chemical analysis of the water for all lakes was performed. Laguna Verde seems to be a very close analog to the Meridiani Planum paleo aqueous environment explored by the rover Opportunity. We report comparable levels of sulfate, bromine and chlorine. Carbonates are present in that lake, but they have not been identified on Mars.
- First Mapping and sonar sounding of Laguna Verde was performed, and sonar mapping of the Licancabur summit lake was initiated.
- Investigation continues to determine if the Atacama Desert soil is a real Mars soil analog.
- The missing nitrogen on Mars may be hidden as fixed ammonium in the Mars soil and regolith.
- There is a suggested possibility that early photosynthetic organisms may have existed in small niches protected by ferric-oxide-bearing material.
- A list of potential workshop participants has been compiled.
- The first star catalog of 2.5 million stars has been obtained.

2004 SETI Members

Rocco Mancinelli
Peter Backus
Emma Bakes
Amos Banin
Max Bernstein
Janice Bishop
Taylor Bucci
Nathalie Cabrol
Chris Chyba
Edna DeVore
Friedemann Freund
Edmund Grin
Bishun Khare
Cynthia Phillips
Lynn Rothschild
Brenda Simmons
David Summers
Jill Tarter

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Bakes, E.L.O. , Bauschlicher, C.W. & Tielens, A. (In Press, 2004). Identifying the UIR feaures in the ISM and Titan's haze. In: A. Witt, G.C. Clayton & B.T. Draine (Eds.). *Astronomical Socity of the Pacific Conferences Series*, Vol. 309. Astrophysics of Dust, Symposium Proceedings, Estes Park, CO.

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If the oxidation mechanisms being explored were shown to be quantitatively significantï¿½modeling to be done later in the course of this grantï¿½this would suggest that the oxygen transition on an Earth-like world could take place independently of the invention of any particular metabolic pathway (such as photosynthesis or methanogenesis) that have previously been proposed to drive this transition. Since Earth's oxygen transition ultimately set the stage for the oxygen-based metabolism evidently essential for metazoa, understanding this transition is crucial to elucidating both Earth's evolution and the evolution of complex (including intelligent) life. The teamï¿½s geological investigations are therefore tightly coupled with microbiological experiments, led by Dr. Rothschild, to understand the extent to which the proposed mechanism might have led to the evolutionary invention of oxidant protective strategies and even aerobic metabolism.

In a second investigation, oxidation driven by atmospheric hydrocarbon (and, more broadly, organic) polymerization is being investigated by Dr. Emma Bakes. Dr. Bakes' research for the early Earth builds on analogies to processes now occurring in the atmosphere of Saturnï¿½s moon Titan. She has begun to map chemical sequences for anions, neutrals and cationic nitrogenated aromatic molecules in Titanï¿½s organic haze layer. She has also begun to extend her study of molecular charging to Martian regolith dust to determine how this affects the UV radiation penetration to the Martian surface. This UV penetration directly affects the survival or destruction of organic molecules and the irradiation of potential life forms. We have also begun a laboratory study of hydrogen molecule synthesis on aromatics and aerosols to see if the suggested theoretical pathway is a plausible mechanism to the accelerated oxidation of Titan and the early Earth. This foundation enables the next stage of her research, the theoretical building of prebiotic macromolecules from the haze constituents. This work is complemented by ongoing laboratory work performed by Dr. Bishun Khare and Dr. Hiroshi Imanaka on Titan analog materials, and infrared observations of the Titan haze.

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They are preparing to evaluate visible/near-infrared (VNIR) spectra of Mars in an effort to characterize deposits of nanophase ferric oxide-bearing minerals that could provide UV protected niches for photosynthetic microbes if they were present on Mars. Concurrent with other projects, we are evaluating the spectral properties of Fe-bearing Mars analog sites on earth and analyzing spectra of Mars for Fe oxide-bearing components. These results are consistent with the hypothesis that early photosynthetic organisms may have existed in specific, perhaps small, niches protected by ferric oxide-bearing material. (See Figures 5, 6 & 7)

The survival of microorganisms in very high UV environments can also be tested empirically through the exploration of Earth's highest altitude lakes and ponds, in Bolivia and Chile. Dr. Nathalie Cabrol and Dr. Edmond Grin (both of whom also this past year served on the Mars Exploration Rover team) have led a series of investigations of these lakes to examine the strategies employed by these microorganisms. This past year they have charcterized the PAR and UV flux, the geology, some microbial mat organisms and the geology and paleobiology of Laguna Blanca and Verde. They have also charcterized the PAR and UV flux of the summit lake of Licancabur as well as developing the first bathymetry map of the lake. The UV flux at those lakes is between 200 and 216% that of sea level and the level of UVB recorded is similar or exceeds that of current UVB on Mars at the equator. (See Figures 1, 2, 3 & 4)

Just as global-scale changes in oxygen (or iron) were critical for the early biosphere, so too would have been global processes involving other key "biogenic" elements such as carbon (for which Dr. Bakesï¿½ work provides insight) or nitrogen. Dr. Rocco Mancinelli, Dr. Amos Banin, Dr. David Summers, and Dr. Khare are pursuing coupled laboratory and field research to understand the partitioning of nitrogen on early Earth and on Mars between different possible reservoirs, and (at least for Earth) the abiotic to biotic transition in this cycling.

Dr. Banin has nearly completed the analysis of soil samples from the Atacama desert, an extreme terrestrial environment with very low biological activity. Although not completely clear what properties of the soil and environment are the limiting factors for biology, these soils are nearly devoid of organic material and contain high levels of perchlorate. They have conducted a series of field experiments, which show that at the driest sites (e.g., Yungay) there is virtually no nitrogen cycling even when the samples are wetted. They have begun a series of experiments in which they are searching for the nitrite reductase gene, a gene critical in denitrification.

Dr. David Summers and Dr. Khare have experimentally verified that the abiotic fixation of NO to nitrite and nitrate would indeed occur, as had been postulated theoretically. It has been shown that two mechanisms exist for this fixation. One proceeds in the presence of liquid was and appears to be consistent with the proposed pathway through HNO. Another proceeds to NO_2 in the absence of liquid water but, in the presence of absorbed water, the NO_2 can be converted to nitric acid. These experiments begin providing a different perspective into the astrobiologically important question of the fate of N on early Mars.

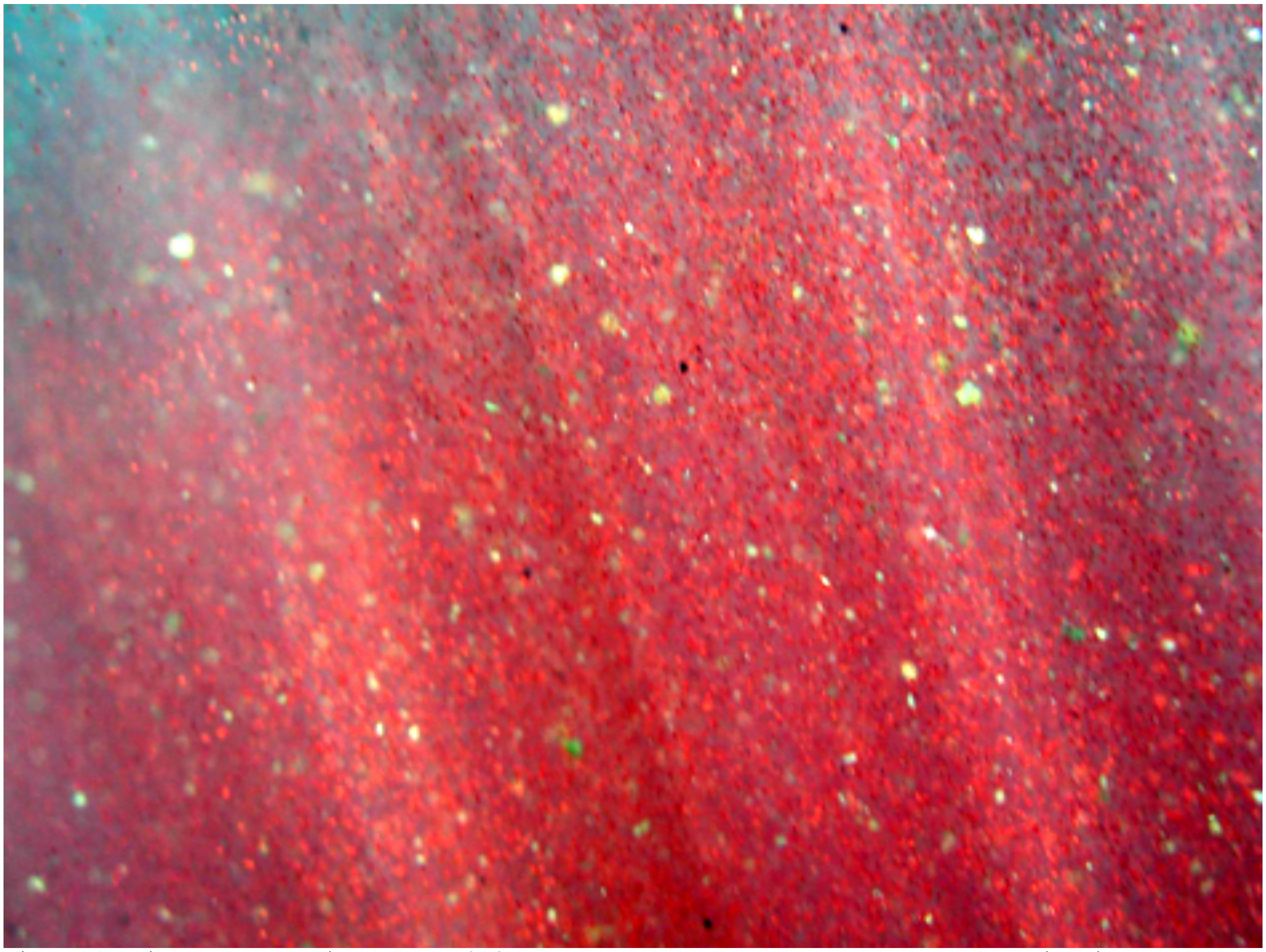
The work described so far examines the evolution of planetary surface habitability. With the recognition that a subsurface ocean likely exists on Jupiter's moon Europa, we know that habitability in possibly entirely subsurface environments must also be explored. Dr. Cynthia Phillips, Dr. Christopher Chyba, and Mr. Kevin Hand (a Stanford PhD student advised by Dr. Chyba) are pursuing spacecraft data analysis and modeling to examine the geology of Europa and its implications for the free energy sources that would be needed to power a europan biosphere. Dr. Phillips and Dr. Chyba are continuing a survey of images of Europa to look for any changes that occurred due to geological activity during the Galileo mission, which if present would indicate active regions of the surface. They are also completing a major project, using Galileo high-resolution imaging of Europa, to quantify the impact cratering 'gardening' rate on Europa. This is important in its own right as a fundamental planetary process, but also is important in some astrobiological models because it will allow the quantification of the amount of biologically relevant material, created at Europa's surface through radiogenic processes, that can be mixed down to the gardening depth, and thereby escape radiolysis.

These results will be coupled with the results of low-temperature laboratory experiments to make predictions about the possible abundance and survivability of any oceanic biomarkers that might reach Europa's surface through active geology, with implications for the astrobiological exploration of Europa from either an orbiter or a surface lander. Mr. Kevin Hand, in collaboration with Dr. Robert Carlson and Dr. Chyba, is pursuing this research in Dr. Carlsonï¿½s laboratory at the Jet Propulsion Laboratory. Over the past year, Mr. Hand and Dr. Carlson have constructed the irradiation apparatus (including ice deposition chamber and diagnostics) and have preliminary experiments now underway. Dr. Max Bernstein, in his laboratory at NASA Ames, is performing lab measurements to enable the detection of signs of life and the discrimination between these and false biomarkers have measured IR spectra of Nitrogen Heterocycles, the class of compounds found in meteorites that include nucleobases. Dr. Bernstein has been concentrating on the kind of conditions found on icy outer Solar System bodies such as Europa and has found good agreement between theoretical prediction and experimental observation. Ultimately the behaviorï¿½and detectabilityï¿½of such compounds under europan conditions will also be determined.

Dr. Peter Backus, Dr. Jill Tarter, and Dr. Mancinelli just completed the first workshop that examines the prospects that planets orbiting dwarf M stars are habitable for either microscopic or complex life. The SETI Institute NAI team's proposal calls for a series of workshops to bring together planetary scientists, biologists, atmospheric modelers, astrophysicists, and SETI scientists to address these issues. They are currently writing up the results of the workshop. In summary nothing about what we currently know about M-dwarfs precludes the possibility of life from originating and evolving on a terrestrial planet orbiting within the habitable zone of an M-dwarf. The results of this project will ultimately help the next generation scientific Search for Extraterrestrial Intelligence (SETI) choose the million target stars that it will survey for signs of technical civilizations using the new Allen Telescope Array (ATA), being built by the SETI Institute in partnership with the University of California, Berkeley.

Finally, during the past year Chyba and Hand completed an invited review article for *Annual Reviews of Astronomy and Astrophysics* titled "Astrobiology: The Study of the Living Universe." The piece makes mention of the NAI both in the acknowledgments and in the first paragraph of the article itself; it surveys current controversial issues across the span of astrobiology and should serve to introduce many astronomers and physicists that are not (yet) astrobiologists to key ideas and controversies in the field.

Education and public outreach are major and integral parts of the work of the SETI Institute’s NAI team.



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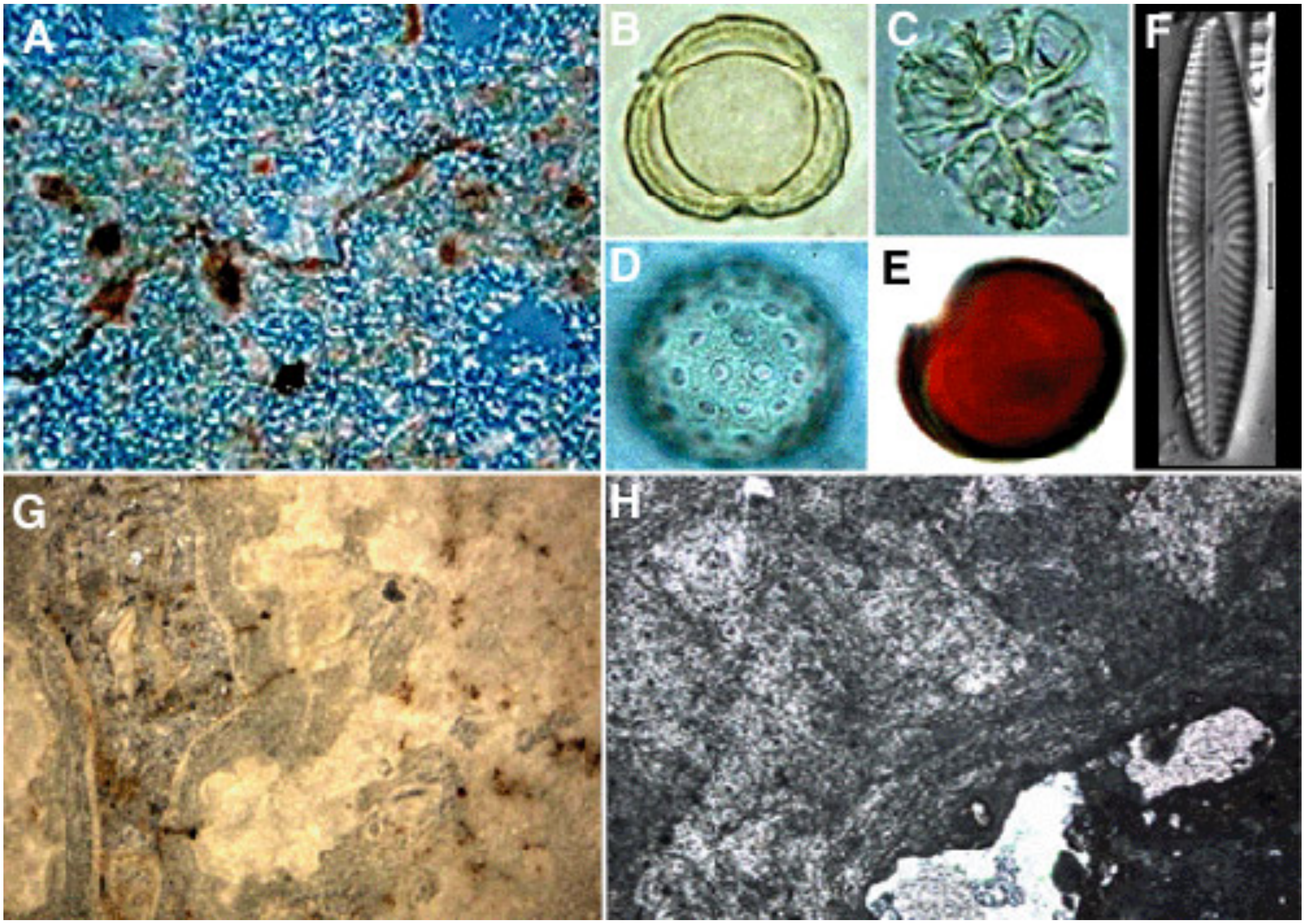

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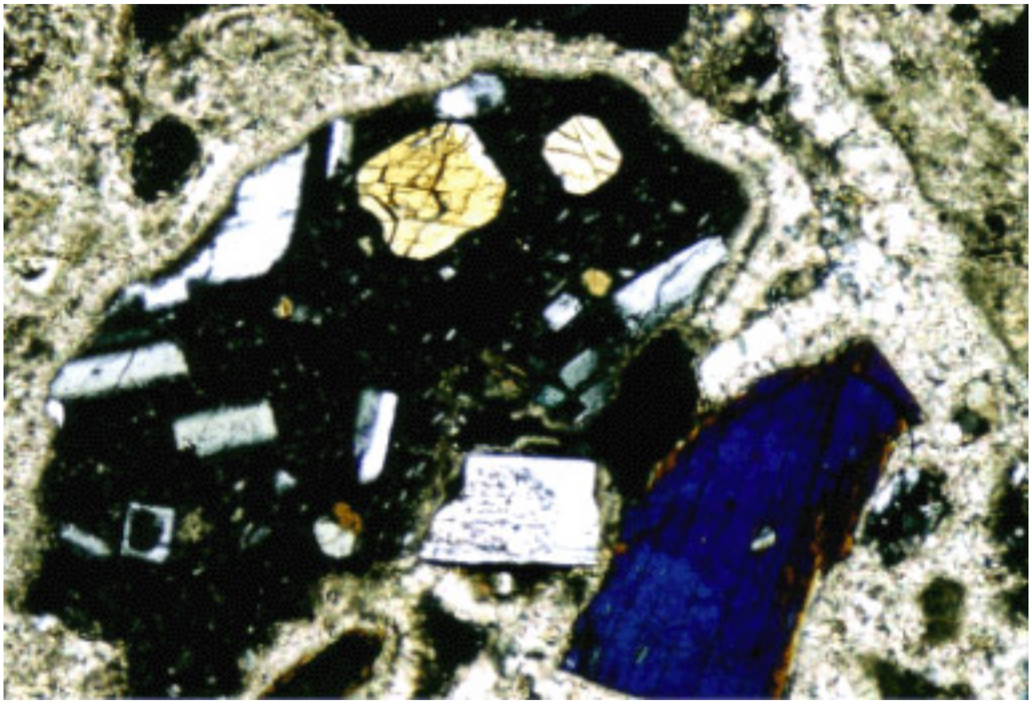

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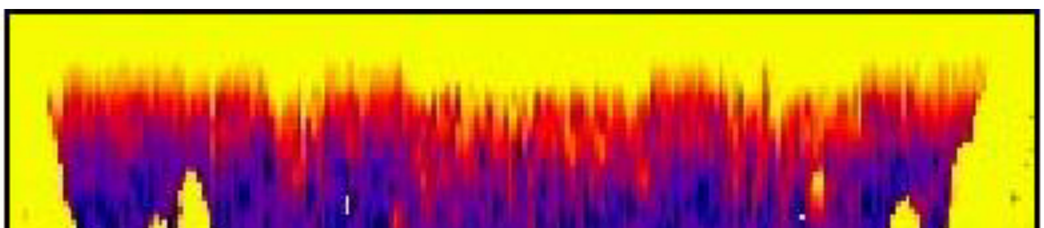

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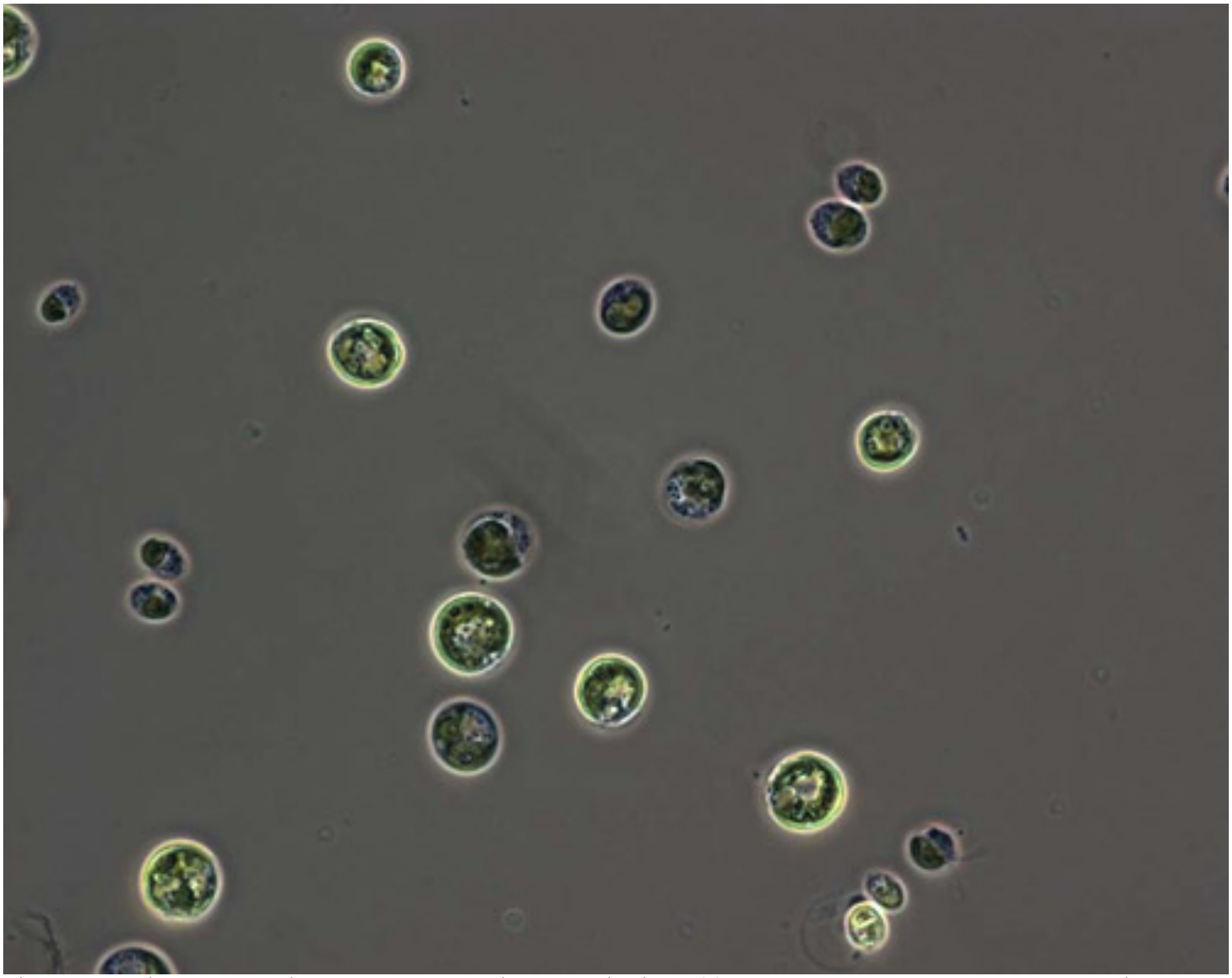

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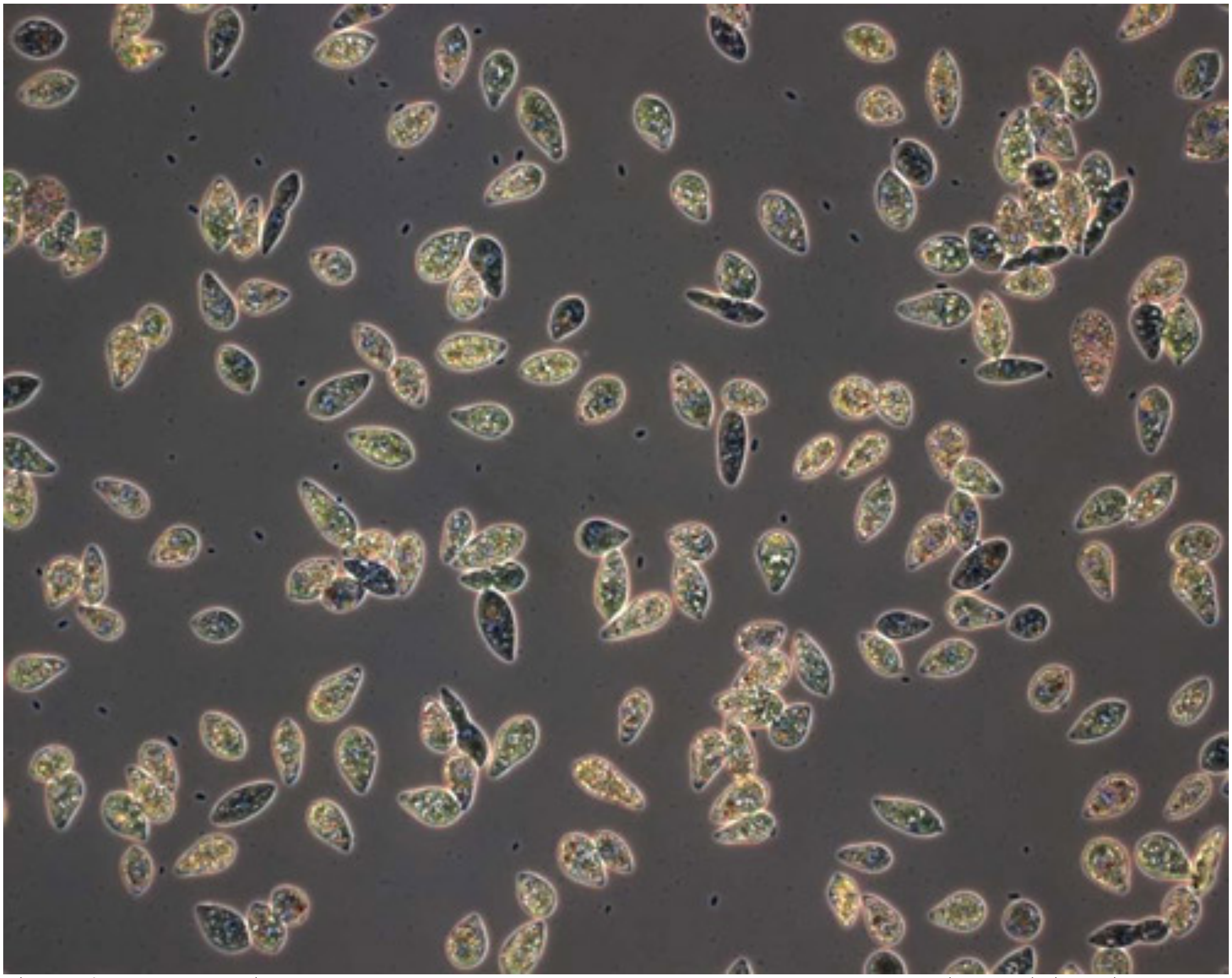
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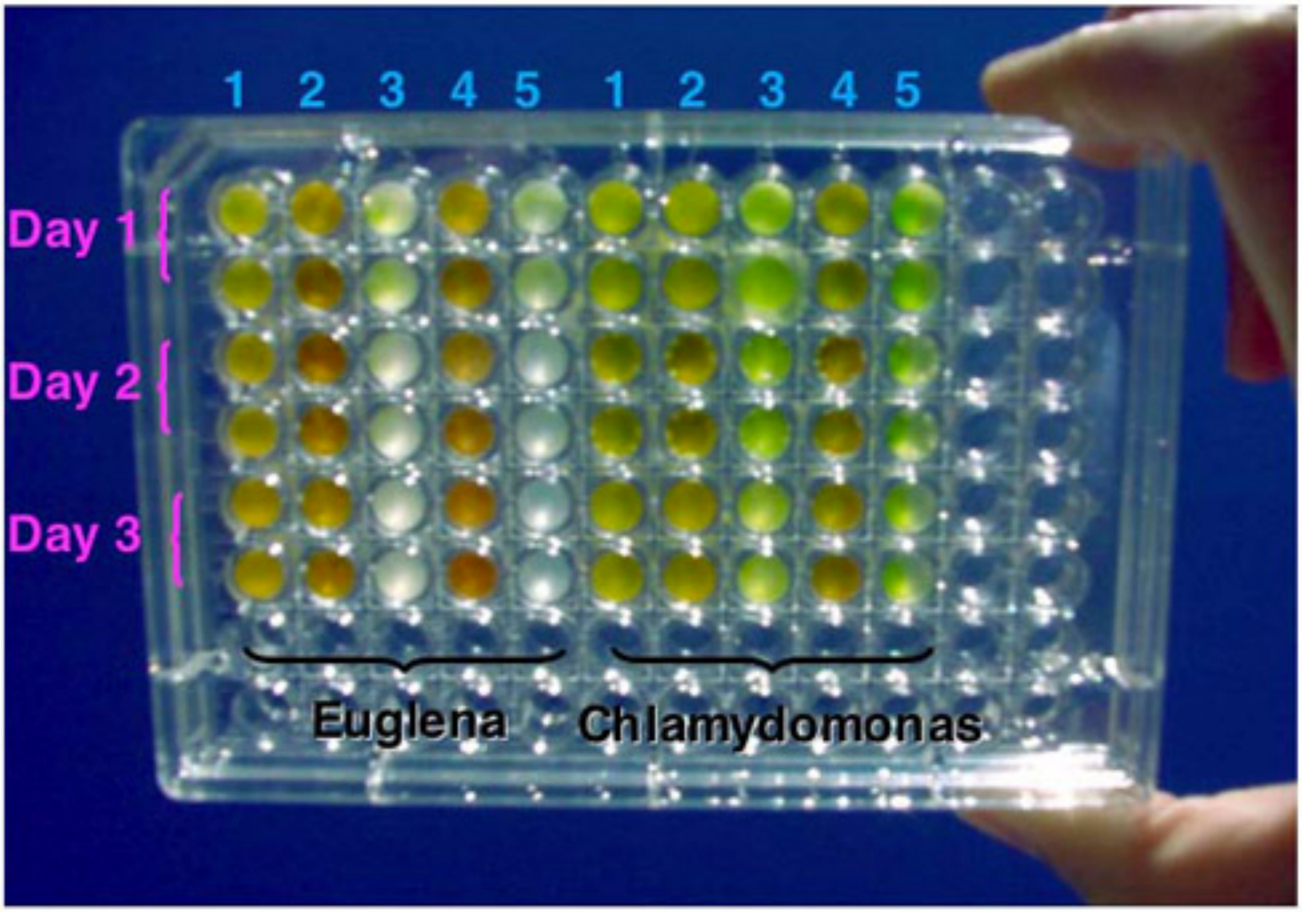


Figure 7. Images of live (clear) and dead (colored) Euglena cells following staining with Trypan blue (magnified 21X).

2005 SETI Project Report

Planetary Biology, Evolution and Intelligence

Accomplishments

Chris Chyba, Cynthia Phillips, Kevin Hand- The project has two components. The first, an overview of the astrobiological potential of various geological features on Europa, is proceeding well -- we are continuing study of various proposed formation mechanisms for different features types such as ridges, bands, and chaotic terrain. The second, a search for current geological activity by comparing Galileo images taken on different orbits, is also in progress. We have performed a first-stage search of the Galileo Europa images to find overlapping images, and are currently working on an automated search method to make sure that we find all possible comparison images. We are also working on automated processing techniques.

Max Bernstein- As part of performing lab measurements to enable the detection of signs of life and the discrimination between these and false biomarkers we have measured IR spectra of Nitrogen Heterocycles, the class of compounds found in meteorites that include nucleobases. We have been concentrating on the kind of conditions found on icy outer Solar System bodies such as Europa.

Rocco Mancinelli- We have collected soil samples from The Yungay region of the Atacama desert and have anayled them for thjier mineralogy and chemical consitiuents, especially salts. Additionally we have condiuced in situ tests in the field for determine potential rates of N-fixation, denitrification, and nitrification. All of these tests were negativeincluding when the soil was wet. This suggests that either there are no organisms capable of N-cyclein in the soil, or the soil contains somethin inhibiting their activity.

Peter Backus, Jill Tarter-We have organized a two and a half day workshop to be held July 18-20, 2005 on the topic of the Habitability of Planets Orbiting M Stars. A total of forty-one scientists from twenty-one institutions in the US and UK will participate. Twenty-two of the participants are from eight NAI Teams. We established a web site <http://mstars.seti.org> to help organize the workshop and provide a focus for post-workshop discussions.

Nathalie Cabrol- All goals set for the 2004 Licancabur expedition were completed, which will allow the team to move on to another high-altitude volcanic lake in 2005 (Poquentica) as planned in our proposal. Achievements include: (1) characterization of Laguna Blanca and Verde geology and paleobiology through sampling (geochemistry, petrography, palynology, diatoms, cyanobacteria, and paleoenvironment); (2) Geochemistry: Sucessful retrieval of 1-year worth of UV data (UVA, UVB, PAR) as well as temperature from our Eldonet UV dosimeters both at the Lagunas and the summit lake of Licancabur. UV at those lakes is between 200 and 216% that of sea level and the level of UVB recorded is similar or exceeds that of current UVB on Mars at the equator. Positioning of two Hobo meterological station (lagunas and summit); (3) Bathymetry of the summit lake (thawed part). This becomes the very first bathymetry of this lake. 4) Biology: Characterization of cyanobacterial colonies building stromatolotic structure; Documentation of life diversity both at the lagunas and summit lake; Discovery of a large colony of ostracods and copepods in the summit lake of Licancabur (sampling and photodocumentation); Successful dives; and (5) Acquisition of physiological data during the expedition.

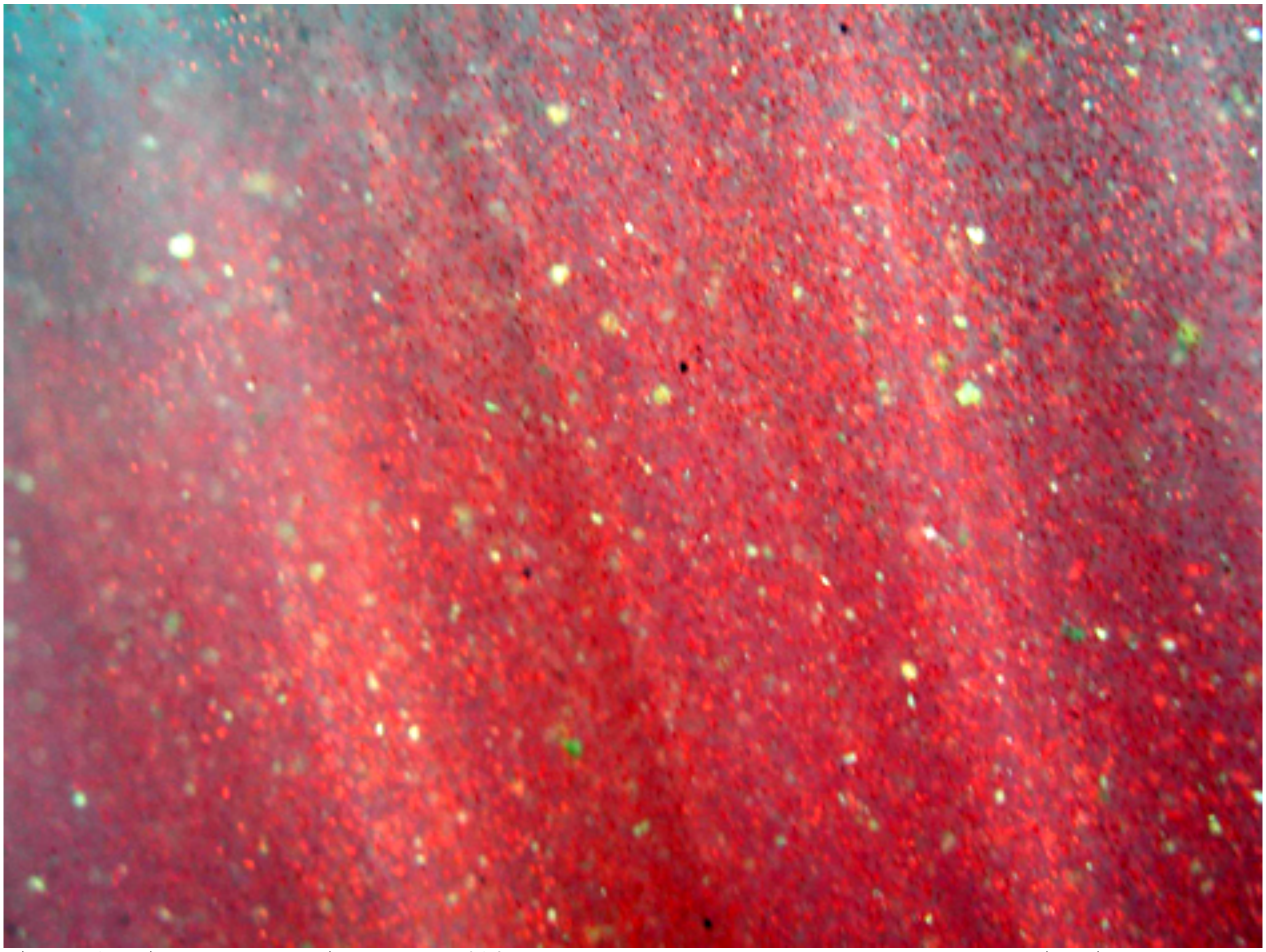
David Summers & Bishun Khare- This work has experimentally verified that the abiotic fixation of NO to nitrite and nitrate would indeed occur, as had been postulate theoretically. It has been show that two mechanisms exist for this fixation. One proceeds in the presence of liquid was and appears to be consistent with the proposed pathway through HNO. Another proceeds to NO₂ in the absence of liquid water but, in presence of absorbed water, the NO₂ can be converted to nitric acid. We are in the process of preparing a communication for submission to Nature.

Emma Bakes- We have begun to map chemical sequences for anions, neutrals and cationic nitrogenated aromatic molecules in Titan's organic haze layer. At this stage, we require the participation of a quantum chemist to map the chemical energetics and the plausibility of each suggested reaction pathway. We have also begun to extend our study of molecular charging to Martian regolith dust to determine how this affects the UV radiation penetration to the Martian surface. This UV penetration directly affects the survival or destruction of organic molecules and the irradiation of potential life forms. We have also begun a laboratory study hydrogen molecule synthesis on aromatics and aerosols to see if the suggested theoretical pathway is a plausible mechanism to the accelerated oxidation of Titan and the early Earth.

Friedmann Freund- The major objective of my project is to study the causes for the slow but inextricable oxidation of the Earth over the first 3 Gyr of its history. During this reporting period our work received a boost from progress achieved by performing new physical measurements on igneous rocks, which lead us towards a quantitative analysis of peroxy oxygen in rocks ranging from ultramafic (peridotite, gabbro) to felsic (andesite, granite).

Janice Bishop & Lynn Rothschild- We have completed a number of lab experiments showing that nanophase iron oxide-bearing minerals facilitate growth of photosynthetic organisms by providing protection from UV radiation. Based on the spectral properties of iron oxides and the results of experiments with photosynthetic organisms, *Euglena* and *Chlamydomonas*, we propose a scenario where photosynthesis, and ultimately the oxygenation of the atmosphere, depended on the protection of early microbes by nanophase ferric oxides/oxyhydroxides. Such niches may have also existed on Mars.

We are preparing to evaluate visible/near-infrared (VNIR) spectra of Mars in an effort to characterize deposits of nanophase ferric oxide-bearing minerals that could provide UV protected niches for photosynthetic microbes if they were present on Mars. Concurrent with other projects, we are evaluating the spectral properties of Fe-bearing Mars analog sites on earth and analyzing spectra of Mars for Fe oxide-bearing components.



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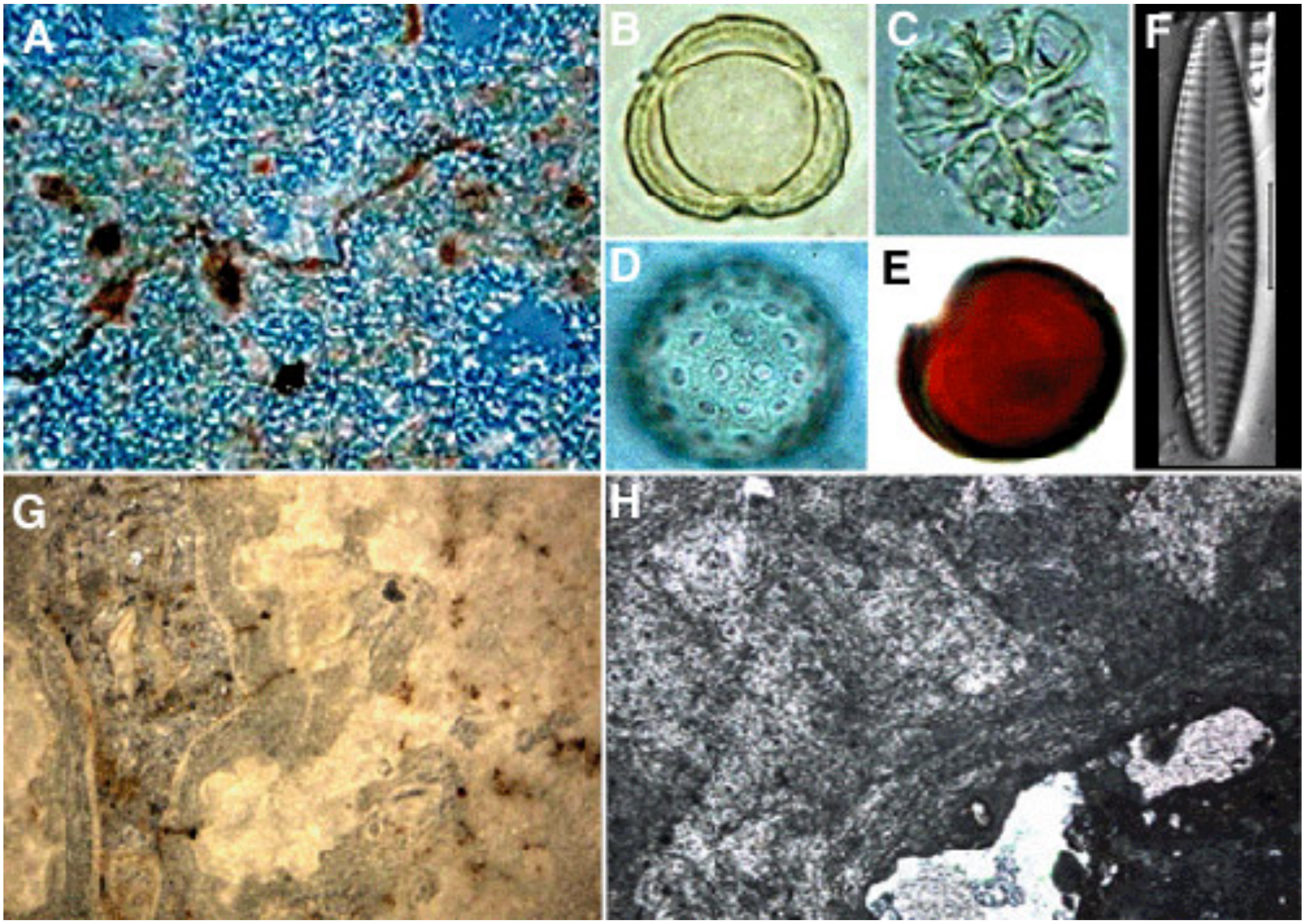

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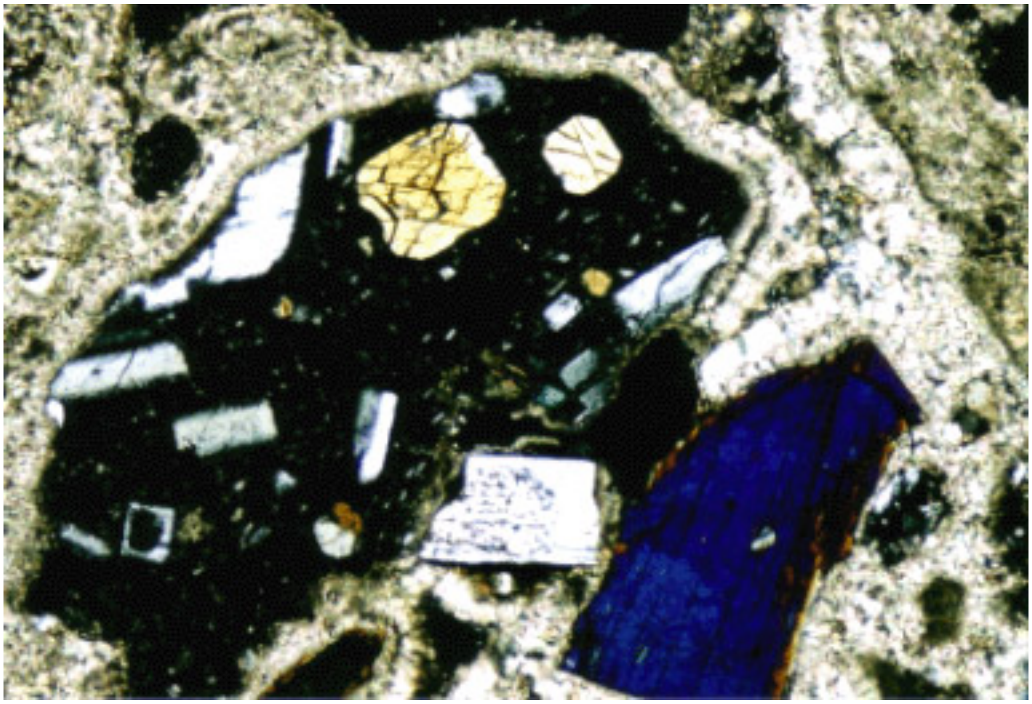
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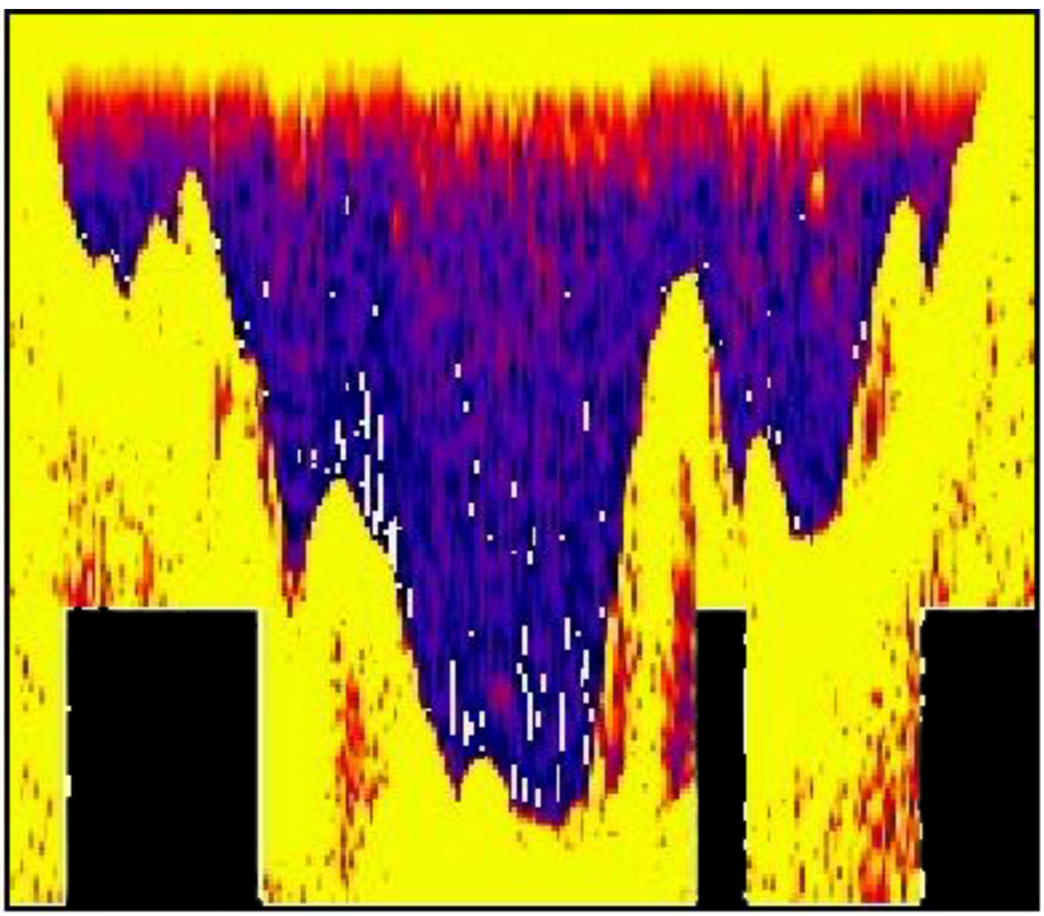

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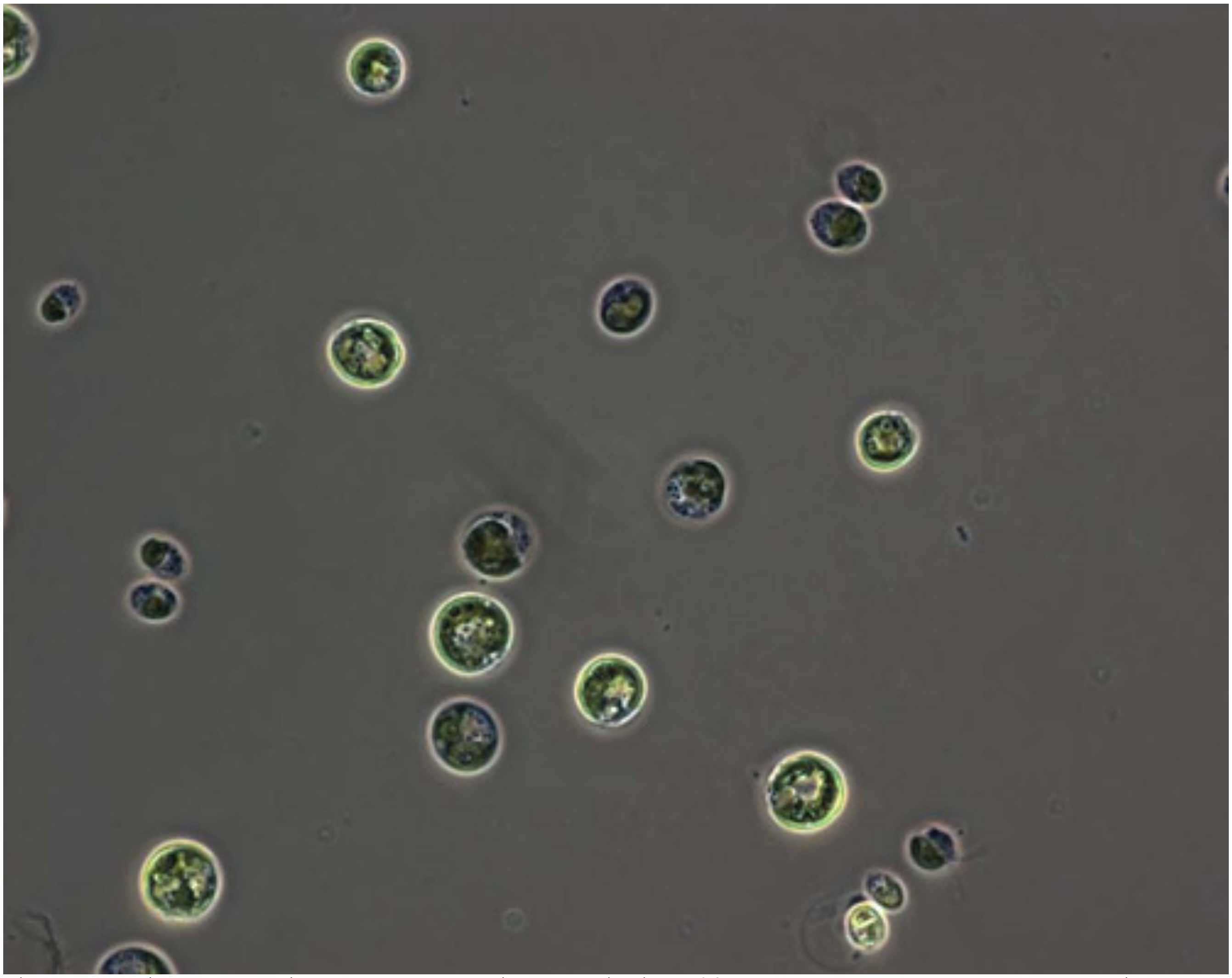

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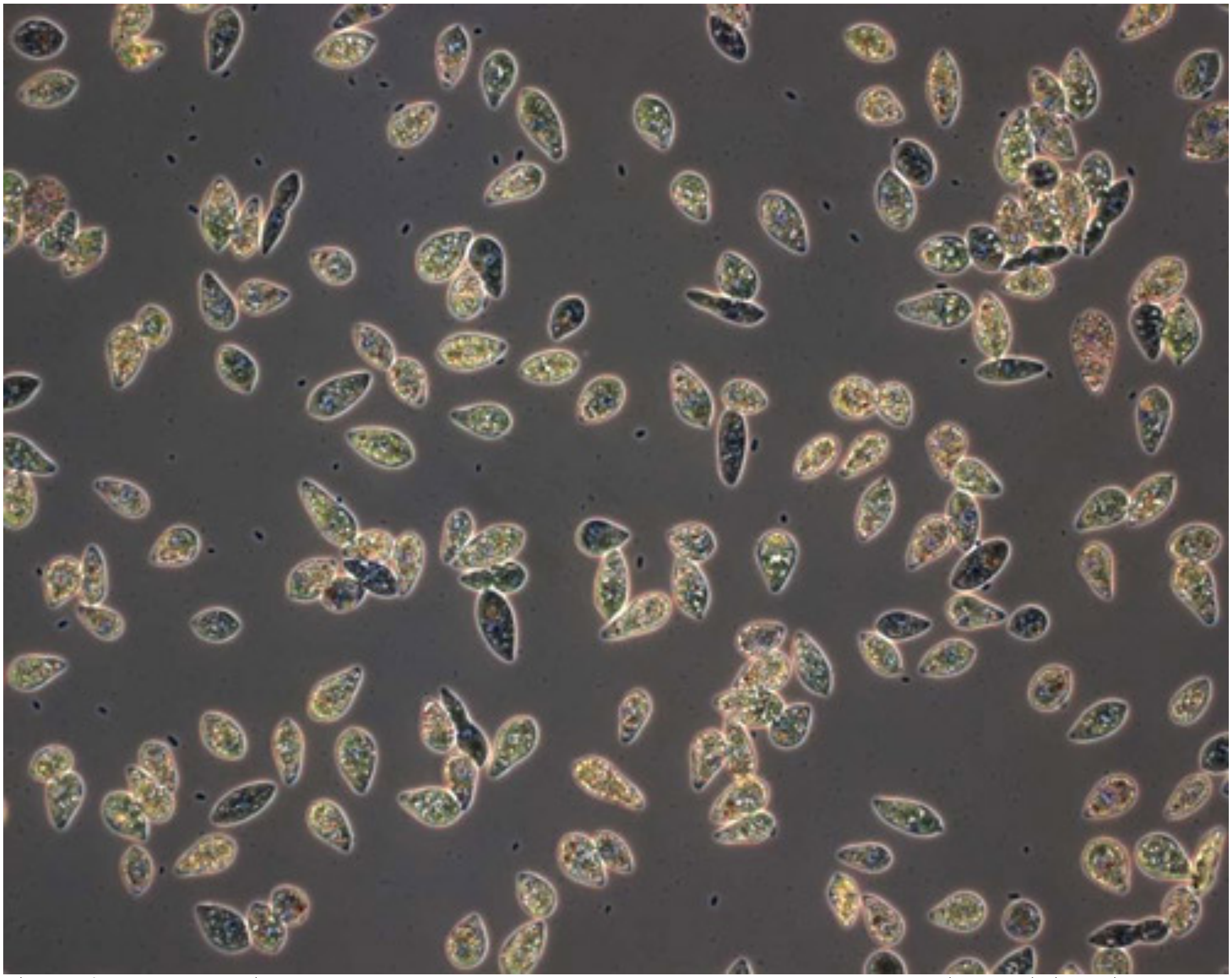
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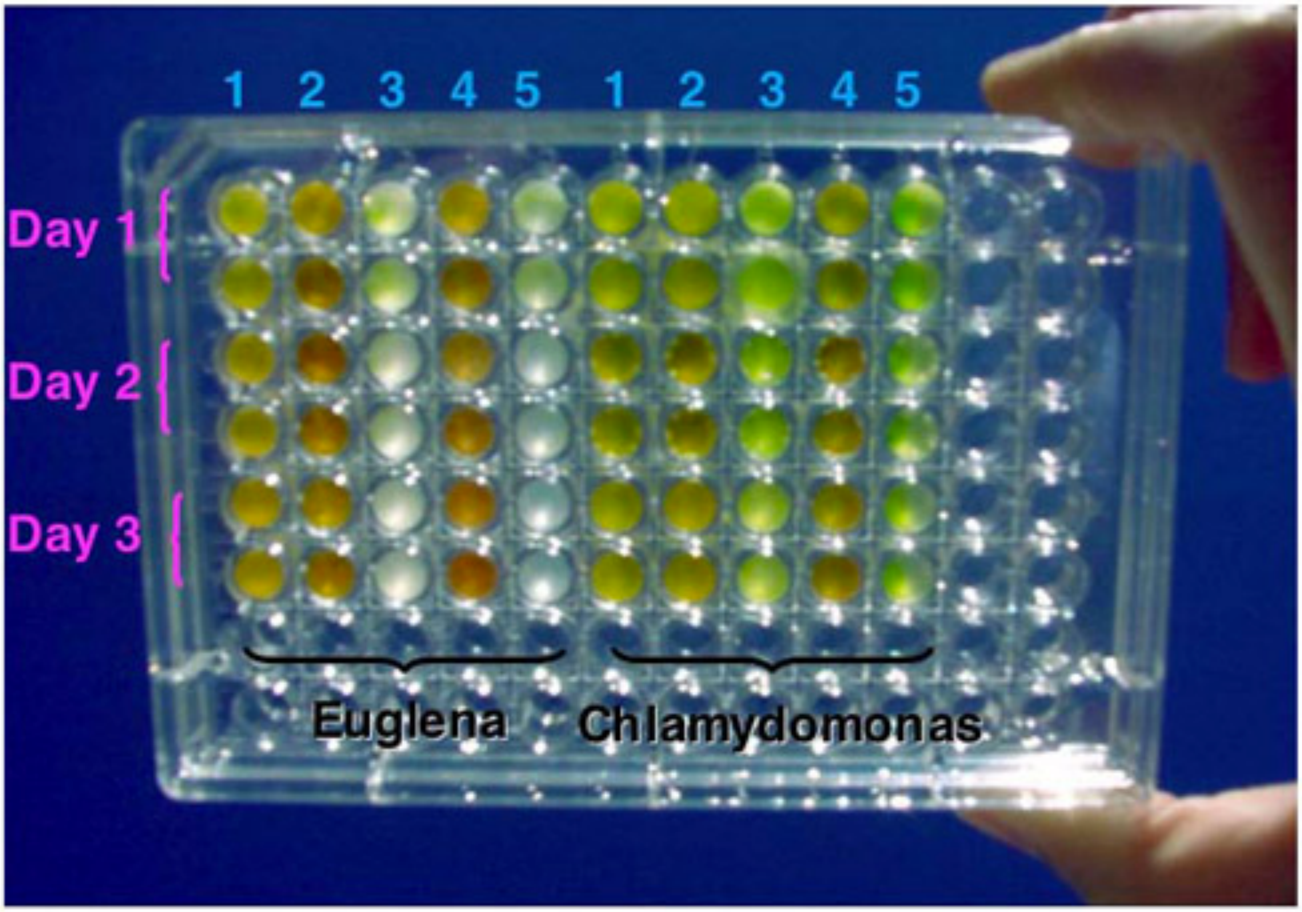

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2005 SETI Members

Rocco Mancinelli
Peter Backus
Emma Bakes
Amos Banin
Max Bernstein
Janice Bishop
Taylor Bucci
Nathalie Cabrol
Guillermo Chong
Chris Chyba
Will Cowell
Edna DeVore
Friedemann Freund
Edmund Grin
Pamela Harman
Andrew Hock
Bishun Khare
Gary Kovacs
Erin Lashnits
Cynthia Phillips
Lee Prufert-Bebout
Dana Rogoff
Lynn Rothschild
Brenda Simmons
David Summers
Jill Tarter
Kimberly Warren-Rhodes

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Cabrol, N.A. (2005). Field and diving exploration of the highest lakes on Earth: Analogy of environment and habitats with early Mars and life adaptation strategies to UV.

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NAI 2006 SETI Team Annual Science Report

Executive Summary

The SETI Institute (SI) NASA Astrobiology Institute (NAI) team is conducting a suite of coupled research projects in the co-evolution of life and its planetary environment. These projects address three of NASAï¿½s Astrobiology Roadmap fundamental questions: (1) how does life begin and evolve; (2) does life exist elsewhere in the universe? and (3) what is the future of life on Earth and beyond? These projects begin by examining specific fundamental ancient transitions that ultimately made complex life possible on Earth. They will conclude with a synthesis that will bring many of the team's investigations together into an examination of the suitability of planets orbiting M dwarfs for either single-celled or more complex life.

The astrobiology roadmap calls for a strategy "for recognizing novel biosignatures" that "ultimately should accommodate a diversity of habitable conditions, biota and technologies in the universe that probably exceeds the diversity observed on Earth." Some of our results, especially those concerning abiotic mechanisms for the oxidation of planetary atmospheres, speak to the interpretation of extrasolar planet atmospheric spectra (and in particular, the role of oxygen as a potential biosignature) in terms of the presence of photosynthesizing life. The team's M-star project addresses the roadmap's observation that "although technology is probably much more rare than life in the universe, its associated biosignatures perhaps enjoy a much higher signal-to-noise ratio. Accordingly, current methods should be further developed and novel methods should be identified for detecting electromagnetic radiation or other diagnostic artifacts that indicate remote technological civilizations." As the roadmap recognizes, there is a continuum of investigations that comprise astrobiology, from prebiotic evolution to the evolution of technology. We believe that we are the only NAI team whose investigations span the gamut of the roadmap's range.

The SETI Institute's NAI teamï¿½s research emphasizes the elucidation of the co-evolution of life and its planetary environment, investigating global-scale processes that have shaped, and been shaped by, both. Throughout, the team recognizes the importance of pursuing the planetary evolution aspects of this research in the context of comparative planetology: since laboratory experiments are impossible over many (but not all) of the time and spatial scales relevant to early Earth, we supplement laboratory data with insights gained by exploring extraterrestrial environments that provide partial analogs to the early Earth environment and its processes.

The SETI Institute team is pursuing two investigations into the oxidation of early Earth's environment. While the biological aspects of this "oxygen transition" have been emphasized, our team is exploring non-biological contributions to this transition. Dr. Friedemann Freund and Dr. Lynn Rothschild are investigating oxidation driven by diffusive loss of hydrogen formed within igneous and metamorphic rocks that incorporate water during crystallization. Subsequent weathering of the rocks released hydrogen peroxide into the environment; the previous loss of the hydrogen indicates that this is a net oxidizing mechanism. During this reporting period we succeeded in completing new physical measurements on igneous rocks, an important step toward the goal of having in hand quantitative analyses of peroxy oxygen in rocks ranging from ultramafic (peridotite, gabbro) to felsic (andesite, granite). In addition, we have shown that the hydrogen peroxide oxidizes reduced transition metal cations, foremost ferrous iron to ferric iron. This leads to the precipitation of ferric oxides in the ocean and, hence, to the deposition of Banded Iron Formations (BIF).

If the oxidation mechanisms being explored were shown to be quantitatively significantï¿½modeling to be done later in the course of this grantï¿½this would suggest that the oxygen transition on an Earth-like world could take place independently of the invention of any particular metabolic pathway (such as photosynthesis or methanogenesis) that have previously been proposed to drive this transition. Since Earth’s oxygen transition ultimately set the stage for the oxygen-based metabolism evidently essential for metazoa, understanding this transition is crucial to elucidating both Earth’s evolution and the evolution of complex (including intelligent) life. The teamï¿½s geological investigations are therefore tightly coupled with microbiological experiments, led by Dr. Rothschild, to understand the extent to which the proposed mechanism might have led to the evolutionary invention of oxidant protective strategies and even aerobic metabolism.

In a second investigation, oxidation driven by atmospheric hydrocarbon (and, more broadly, organic) polymerization is being investigated by Dr. Emma Bakes. Dr. Bakes’ research for the early Earth builds on analogies to processes now occurring in the atmosphere of Saturn’s moon Titan. Her mapping of the chemical sequences for anions, neutrals and cationic nitrogenated aromatic molecules in Titan’s organic haze layer is well underway, utilizing the participation of quantum chemist Alessandra Ricca. We are mapping the chemical energetics and the plausibility of each suggested reaction pathway for bicyclic nitrogenated aromatics suggestive of purine and pyrimidine bases of RNA and DNA molecules to probe the plausibility of their photochemical formation in an atmsosphere. UV penetration directly affects the survival or destruction of organic molecules and the irradiation of potential life forms and we have completed and published our investigation of how the UV radiation interacts with large molecules, tholins and the gas phase and to what degree it penetrates to the surface of Titan. Our laboratory study of hydrogen molecule synthesis on aromatics and aerosols to seek a physically plausible pathway to the accelerated oxidation of Titan and the early Earth is complete and published. She has also begun to extend her study of molecular charging to Martian regolith dust to determine how this affects the UV radiation penetration to the Martian surface. This UV penetration directly affects the survival or destruction of organic molecules and the irradiation of potential life forms.

Understanding the oxygen balance on early Earth requires attention to sinks as well as sources of oxygen. One major sink for oxygen on early Earth would have been reduced iron. Iron could have simultaneously provided shielding against ultraviolet (UV%) light that would have been reaching Earth’s surface in the absence of the ozone shield generated by atmospheric oxygen. Nanophase ferric oxide minerals in solution could provide a sunscreen against UV while allowing the transmission of visible light, in turn making the evolution of at least some photosynthesic organisms possible. Dr. Janice Bishop and Dr. Rothschild are testing this hypothesis through coupled mineralogical and microbiological work in both the lab and the field, and examining its implications not only for Earth but for Mars as well, with an emphasis on implications for upcoming spacecraft observations. They have completed a number of lab experiments showing that nanophase iron oxide-bearing minerals facilitate growth of photosynthetic organisms by providing protection from UV radiation. This year they have completed analyzing the data from previous years lab experiments and summarized our results in a paper that is in press in the International Journal of Astrobiology. This work showed that nanophase iron oxide-bearing minerals can facilitate growth of photosynthetic organisms by providing protection from UV radiation. Based on the spectral properties of iron oxides and the results of experiments with two photosynthetic organisms, they propose a scenario where photosynthesis, and ultimately the oxygenation of the atmosphere, depended on the protection of early microbes by nanophase ferric oxides/oxyhydroxides. They have also begun evaluating the OMEGA hyperspectral visible/near-infrared (VNIR) spectra of Mars in an effort to characterize deposits of nanophase ferric oxide-bearing minerals that could provide UV protected niches for photosynthetic microbes if they were present on Mars. This part of the project will be expanded in the coming year as the CRISM hyperspectral VNIR images become available. Concurrent with other projects, they are evaluating the spectral properties of Fe-bearing Mars analog sites on earth and analyzing spectra of Mars for Fe oxide-bearing components.

Environmental conditions for life in terrestrial lakes located at extreme high altitudes in Bolivia and Chile provide a good analogy to Martian paleolakes dating back 3.5 Ga. Through the exploration of these lakes the survival strategies of microorganisms in very high UV environments can be elucidated. A team led by Dr. Nathalie Cabrol and Dr. Edmond Grin conducted a series of investigations of these lakes examining the geology, paleobiology and extant biology of these lakes. This past year the team sampled new sites (evaporating lakes, salars, and geothermal centers), as well as laying down a new stratigraphical transect in the geological record of Laguna Verde to study the evolution of paleohabitats and life during fast changing climate conditions. The UV flux at these high altitude lakes was examined in more detail. Samples from Laguna Blanca were analyzed by Raman Spectroscopy in an attempt to develop a database for characterizing the structure and stability of biogenic carbonaceous material in such samples.

Just as global-scale changes in oxygen (or iron) were critical for the early biosphere, so too would have been global processes involving other key "biogenic" elements such as carbon (for which Dr. Bakesï¿½ work provides insight) or nitrogen. Dr. Rocco Mancinelli, Dr. Amos Banin, Dr. David Summers, and Dr. Khare are pursuing coupled laboratory and field research to understand the partitioning of nitrogen on early Earth and on Mars between different possible reservoirs, and (at least for Earth) the abiotic to biotic transition in this cycling.

Dr. Banin has completed the analysis of soil samples from the Atacama desert, an extreme terrestrial environment with very low biological activity. Although not completely clear what properties of the soil and environment are the limiting factors for biology, these soils are nearly devoid of organic material and contain high levels of perchlorate. They have conducted a series of field experiments, which show that at the driest sites (e.g., Yungay) there is virtually no nitrogen cycling even when the samples are wetted. In a series of experiments in which they have searched for the nitrite reductase gene, a gene critical in denitrification, they have found none. They are currently planning a series of experiments to test the potential toxicity of the soil for nitrogen cycling microbes.

Dr. David Summers and Dr. Khare have experimentally verified that the abiotic fixation of NO to nitrite and nitrate would indeed occur, as had been postulated theoretically. It has been shown that two mechanisms exist for this fixation. One proceeds in the presence of liquid was and appears to be consistent with the proposed pathway through HNO. Another proceeds to NO_2 in the absence of liquid water but, in the presence of absorbed water, the NO_2 can be converted to nitric acid. Their study has expanded to include the study of the stable isotope fractionation and the effects of water layers on mineral surfaces. Specifically, analysis of the isotope fractionation in the reduction of nitrite to ammonia, which shows an average fractionation of -4 per mil. These experiments begin providing a different perspective into the astrobiologically important question of the fate of N on early Mars.

The work described so far examines the evolution of planetary surface habitability. With the recognition that a subsurface ocean likely exists on Jupiter's moon Europa, we know that habitability in possibly entirely subsurface environments must also be explored. Dr. Cynthia Phillips, Dr. Christopher Chyba, and Mr. Kevin Hand (a Stanford PhD student advised by Dr. Chyba) are pursuing spacecraft data analysis and modeling to examine the geology of Europa and its implications for the free energy sources that would be needed to power a europan biosphere. Dr. Phillips and Dr. Chyba are continuing a survey of images of Europa to look for any changes that occurred due to geological activity during the Galileo mission, which if present would indicate active regions of the surface. We have completed a first-stage search of the Galileo Europa images to find overlapping images, and are continuing to work on improving our automated search method to make sure that we find all possible comparison images. We have processed a number of comparison pairs, and are currently working on automated techniques for speeding up the comparison process.

These results will be coupled with the results of low-temperature laboratory experiments to make predictions about the possible abundance and survivability of any oceanic biomarkers that might reach Europa's surface through active geology, with implications for the astrobiological exploration of Europa from either an orbiter or a surface lander. Mr. Kevin Hand, in collaboration with Dr. Robert Carlson and Dr. Chyba, is pursuing this research in Dr. Carlsonï¿½s laboratory at the Jet Propulsion Laboratory. Dr. Max Bernstein, in his laboratory at NASA Ames, is performing lab measurements to enable the detection of signs of life and the discrimination between these and false biomarkers have measured IR spectra of Nitrogen Heterocycles, the class of compounds found in meteorites that include nucleobases. Dr. Bernstein has been concentrating on the kind of conditions found on icy outer Solar System bodies such as Europa and has found good agreement between theoretical prediction and experimental observation. Ultimately the behaviorï¿½and detectabilityï¿½of such compounds under europan conditions will also be determined.

Dr. Peter Backus, Dr. Jill Tarter, and Dr. Mancinelli just completed the first workshop that examines the prospects that planets orbiting dwarf M stars are habitable for either microscopic or complex life. Thirty scientists from nineteen institutions in the US and UK participated. Thirteen of the participants were from six other NAI Teams. Results of the workshop are reported in a paper submitted to the journal Astrobiology. The results of the first of two workshops suggest that from the data we have there is no reson to preclude that life cannot evolve on a planet orbiting a dwarf M-star.

Education and public outreach are major and integral parts of the work of the SETI Institute’s NAI team

2006 SETI Project Report

Planetary Biology, Evolution, and Intelligence

Accomplishments

Chris Chyba, Cynthia Phillips, Kevin Hand- The project has two components. The first, an overview of the astrobiological potential of various geological features on Europa, is proceeding well -- we are continuing the study of various proposed formation mechanisms for different feature types such as ridges, bands, and chaotic terrain. The second, a search for current geological activity by comparing Galileo images taken on different orbits, is also in progress. We have completed a first-stage search of the Galileo Europa images to find overlapping images, and are continuing to work on improving our automated search method to make sure that we find all possible comparison images. We have processed a number of comparison pairs, and are currently working on automated techniques for speeding up the comparison process.

Max Bernstein- As part of performing lab measurements to enable the detection of signs of life and the discrimination between these and false biomarkers we have measured IR spectra of Nitrogen Heterocycles, the class of compounds found in meteorites that include nucleobases. We have been concentrating on the kind of conditions found on icy outer Solar System bodies such as Europa.

Rocco Mancinelli and Amos Banin- In a set of soil samples from the Yungay region of the Atacama desert we have conducted detailed analyses of organic and inorganic C and N concentrations. Organic carbon (OC) and organic nitrogen (ON) were low, especially in the soils from the most extreme arid region. OC/ON ratio was in the range typical for biotically synthesized organic matter. Comparison to estimates of C content in the Mars soil analyzed by the Viking Landers show that the Atacama soils, even in the hard-core extreme desert sites, have very low biological activity as terrestrial soils are concerned, but still have higher concentrations of total organic carbon compared to the Mars soils analyzed by the Viking Pyrolytic experiment.

When soil samples collected from the Yungay region of Atacama desert were analyzed for DNA encoding the genes for the nitrite reductase S gene the gene encoding for the key denitrification enzyme, it was not found. These data combinded with last years data where no trace of nitrogen cycling was detected in the field, even under wet conditions suggests that that either there are no organisms capable of N-cyclein in the soil, or the soil contains somethin inhibiting their activity.

Peter Backus, Jill Tarter, Rocco Mancinelli - We held a two and a half day workshop on July 18-20, 2005 on the topic of the Habitability of Planets Orbiting M Stars. Thirty scientists from nineteen institutions in the US and UK participated. Thirteen of the participants were from six other NAI Teams. Results of the workshop are reported in a paper submitted to the journal Astrobiology. The paper was written over many months through the use of email lists and a secure private web site. Another web site http://mstars.seti.org provided information for the general public.

Nathalie Cabrol- Despite harsh weather conditions in the altiplano this year, both planned ascents were completed successfully, one on the Licancabur volcano to continue our work from previous years, and the other one on our new site (Poquentica), another volcano hosting a lake located 800 km north of Licancabur. During our one-month, 800 km, trek through the Bolivian altiplano, the team also sampled about a half-a-dozen new sites (evaporating lakes, salars, and geothermal centers) Achievements include: (1) a new stratigraphical transect in the geological record of Laguna Verde to study the evolution of paleohabitats and life during fast changing climate conditions; (2) Biological sampling and water chemistry of the summit and lower lakes; (3) Retrieval of data from the meteorological station at the summit of Licancabur which logged for one year; (4) Geophysics: Measurements of UVA, UVB, PAR and UVC were performed; (5) Sampling of frozen soil (or permafrost) on the shore of the Licancabur and Poquentica lakes and sampling of ice from those lakes which were both frozen to depth this year preventing diving. Bin Chen has analyzed salt samples from the 2005 trip. She has identified organic composition in the Laguna Blanca samples. She is using the database to characterize the concentration and structure stability of biogenic carbonaceous contents, especially biomarkers such as hopane and the derivatives, which likely existed in the prokaryotic and eukaryotic membranes; study the chemical structures of the organic species and their interactions with the host environment (as in rock, salt and soil mixtures) to understand the preservation and evolution of the life in local conditions that include extremes of UV radiation, desiccation, cold temperature and salinity. She investigates abiogenic organics and components such as carbonate, oxyanionic mineral groups, sulfides and hydroxides produced from the biological activities. The next step will be to study the chemical stability and relative abundance of the biomarkers in the samples obtained from the geological transects in conjunction with the geochemistry, temperatures, pH (current lakes), salinity, UV radiation level, elevation in the transect and paleoenvironment. The correlation will help us understand how both extant and extinct life adapt to changes.

Figure 1. The weather was exceptionally cold and windy in 2005. Left: Licancabur summit lake, November 4, 2005. The lake was frozen over 80 cm; Right: Poquentica summit lake, frozen as well. Samples of ice at both lakes are being analyzed currently for airborne deposits as well as trapped microbial organisms (copepods) for Licancabur.

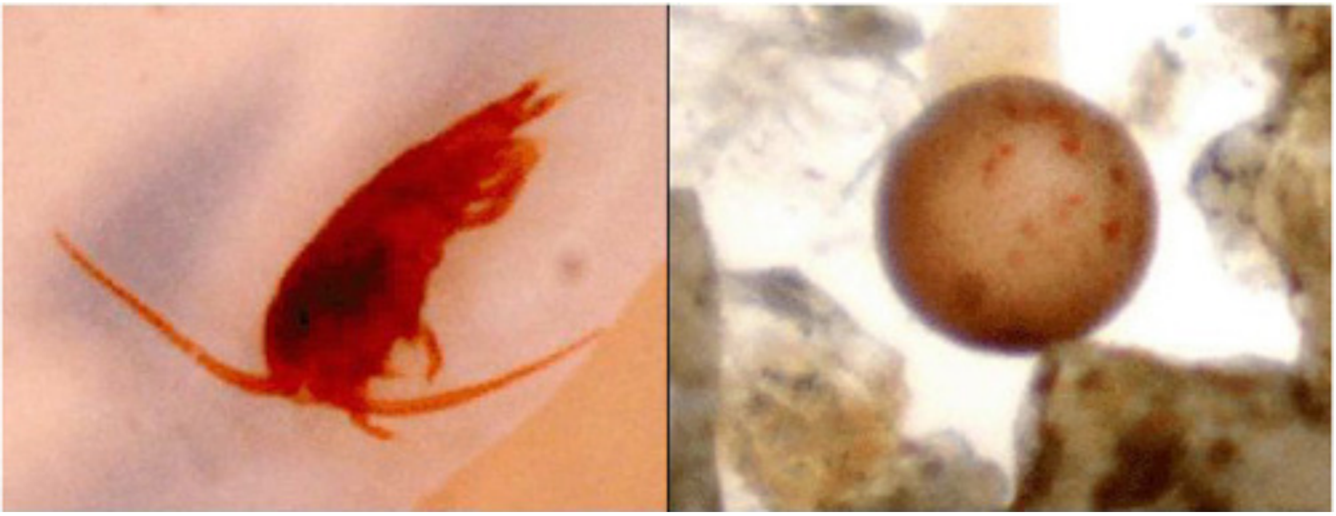
Figure 2. Left: Copepod from the Licancabur summit lake (x 50). The copepod remained trapped in the ice 6 months in the field and 3 more in the lab. Once the ice thawed, the copepod resumed swimming immediately. The red pigment shows protection against UV; Right: Ostracod egg (x 200) in quartz grains from the summit soil.

David Summers & Bishun Khare- A paper is currently under review in the journal Astrobiology. Effort has partially turned to study of the stable isotope fractionation and the effects of water layers on mineral surfaces. (This data could then be combined with future isotopic composition work from the Atacama where nitrates may be of abiotic origin.) This included designing and constructing a new irradiation apparatus (now finished). Work also contributed to the study of the isotope fractionation in next step in the reaction sequence, reduction of nitrite to ammonia $FeS + NO_2^-$ at pH ~5, shows an average fractionation of +6 per mil; $FeCl_2 + NO_2^-$ at pH 8.2 shows an average fractionation of -4 per mil). This work will also contributes to experiments to include the action of Fe(II) in the aqueous phase on the fixation processes.

Emma Bakes- Our mapping of the chemical sequences for anions, neutrals and cationic nitrogenated aromatic molecules in Titan's organic haze layer is well underway, utilizing the participation of quantum chemist Alessandra Ricca. We are mapping the chemical energetics and the plausibility of each suggested reaction pathway for bicyclic nitrogenated aromatics suggestive of purine and pyrimidine bases of RNA and DNA molecules to probe the plausibility of their photochemical formation in an atmsosphere. UV penetration directly affects the survival or destruction of organic molecules and the irradiation of potential life forms and we have completed and published our investigation of how the UV radiation interacts with large molecules, tholins and the gas phase and to what degree it penetrates to the surface of Titan. Our laboratory study of hydrogen molecule synthesis on aromatics and aerosols to seek a physically plausible pathway to the accelerated oxidation of Titan and the early Earth is complete and published.

Friedemann Freund & Lynn Rothschild - The major objective of this task is to study the causes for the slow but inextricable oxidation of the Earth over the first 3 Gyr of its history. Contrary to the widely held belief that planet Earth became oxidized due to the activity of early photosynthetic microorganisms (akin to present-day blue-green algae and cyanobacteria), we have convincingly shown that there is an alternative and entirely abiogenic pathway toward global oxidation: the presence of oxygen anions in the minerals of common igneous rocks that have converted from a valence of 2-- to a valence of 1-- (peroxy). Upon weathering this peroxy fraction hydrolyzes to hydrogen peroxide, which in turn oxidizes reduced transition metal cations, foremost ferrous iron to ferric iron. This leads to the precipitation of ferric oxides in the ocean and, hence, to the deposition of Banded Iron Formations (BIF). After this process has gone on for sufficiently long time, 1-2 billion years, the rocks on the continents will evolve toward andesitic-granitic compositions and free oxygen will begin to be injected into the atmosphere.

Janice Bishop & Lynn Rothschild- This year we completed analyzing the data from our initial lab experiments and summarized our results in a paper that is in press in the International Journal of Astrobiology. This work showed that nanophase iron oxide-bearing minerals can facilitate growth of photosynthetic organisms by providing protection from UV radiation. Based on the spectral properties of iron oxides and the results of experiments with two photosynthetic organisms, we propose a scenario where photosynthesis, and ultimately the oxygenation of the atmosphere, depended on the protection of early microbes by nanophase ferric oxides/oxyhydroxides. Such niches may have also existed on Mars.

We have begun evaluating the OMEGA hyperspectral visible/near-infrared (VNIR) spectra of Mars in an effort to characterize deposits of nanophase ferric oxide-bearing minerals that could provide UV protected niches for photosynthetic microbes if they were present on Mars. This part of the project will be expanded this year as the CRISM hyperspectral VNIR images become available. Concurrent with other projects, we are evaluating the spectral properties of Fe-bearing Mars analog sites on earth and analyzing spectra of Mars for Fe oxide-bearing components. We have collected some material containing nanophase ferric oxides/oxyhydroxides from Yellowstone that we have begun analyzing. From the chemical and spectral data this sample appears interesting and we are hoping to perform some in situ field measurements during the next year.

2006 SETI Members

Rocco Mancinelli
Peter Backus
Emma Bakes
Amos Banin
Max Bernstein
Janice Bishop
Taylor Bucci
Nathalie Cabrol
Guillermo Chong
Chris Chyba
Will Cowell
Edna DeVore
Friedemann Freund
Edmund Grin
Pamela Harman
Andrew Hock
Bishun Khare
Gary Kovacs
Erin Lashnits
Cynthia Phillips
Lee Prufert-Bebout
Melissa Rice
Dana Rogoff
Lynn Rothschild
Brenda Simmons
David Summers
Jill Tarter
Kimberly Warren-Rhodes

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NAI 2007 SETI Team Annual Science Report

Executive Summary

The SETI Institute (SI) NASA Astrobiology Institute (NAI) team is conducting a suite of coupled research projects in the co-evolution of life and its planetary environment. These projects address three of NASA's Astrobiology Roadmap fundamental questions: (1) how does life begin and evolve; (2) does life exist elsewhere in the universe? and (3) what is the future of life on Earth and beyond? These projects begin by examining specific fundamental ancient transitions that ultimately made complex life possible on Earth. They conclude with a synthesis that brings many of the team's investigations together into an examination of the suitability of planets orbiting M dwarfs for either single-celled or more complex life.

The astrobiology roadmap calls for a strategy "for recognizing novel biosignatures" that "ultimately should accommodate a diversity of habitable conditions, biota and technologies in the universe that probably exceeds the diversity observed on Earth." Some of our results, especially those concerning abiotic mechanisms for the oxidation of planetary atmospheres, speak to the interpretation of extrasolar planet atmospheric spectra (and in particular, the role of oxygen as a potential biosignature) in terms of the presence of photosynthesizing life. The team's M-star project addresses the roadmap's observation that "although technology is probably much more rare than life in the universe, its associated biosignatures perhaps enjoy a much higher signal-to-noise ratio. Accordingly, current methods should be further developed and novel methods should be identified for detecting electromagnetic radiation or other diagnostic artifacts that indicate remote technological civilizations." As the roadmap recognizes, there is a continuum of investigations that comprise astrobiology, from prebiotic evolution to the evolution of technology.

The SETI Institute's NAI team's research emphasizes the elucidation of the co-evolution of life and its planetary environment, investigating global-scale processes that have shaped, and been shaped by both. Throughout, the team recognizes the importance of pursuing the planetary evolution aspects of this research in the context of comparative planetology: since laboratory experiments are impossible over many (but not all) of the time and spatial scales relevant to early Earth, we supplement laboratory data with insights gained by exploring extraterrestrial environments that provide partial analogs to the early Earth environment and its processes.

The SETI Institute team is pursuing two investigations into the oxidation of early Earth's environment. While the biological aspects of this "oxygen transition" have been emphasized, our team is exploring non-biological contributions to this transition. Dr. Friedemann Freund and Dr. Lynn Rothschild are investigating oxidation driven by diffusive loss of hydrogen formed within igneous and metamorphic rocks that incorporate water during crystallization. The major objective of this task is to study the causes for the slow but inextricable oxidation of the Earth over the first 3 Gyr of its history. Contrary to the widely held belief that planet Earth became oxidized due to the activity of early photosynthetic microorganisms, they have shown that there is

an alternative, entirely abiogenic pathway toward global oxidation: the presence of oxygen anions in the minerals of common igneous rocks that have converted from a valence of 2– to a valence of 1– (peroxy). Upon stressing the rocks, the peroxy bonds break up and generate mobile electronic charge carriers, defect electrons, also known as positive holes or pholes for short. The pholes have the unusual capacity that they can flow out of the stressed rock volume, generating electric currents that can reach or exceed 100,000 amperes, if the stressed rock volume is a cubic kilometer in size. They have shown that this electric current flowing through rocks converts quantitatively into hydrogen peroxide, H_2O_2 , at the rock-water interface. This discovery opens the door to re-assess the conditions that primitive microorganisms, which lived in contact with rock surfaces, must have encountered on the early Earth.

In a second investigation, oxidation driven by atmospheric hydrocarbon (and, more broadly, organic) polymerization is being investigated by Dr. Allesandra Ricca. Dr. Ricca is investigating the chemical energetics and plausibility of reaction pathways leading to the formation of nitrogenated aromatics suggestive of purine and pyrimidine bases of RNA and DNA molecules using quantum chemistry. She has focused on the reactivity of pyridine radical cation with acetylene and shown that it is a viable reaction pathway leading to the formation of a bicyclic nitrogenated aromatic molecule. Very recent experiments performed at Virginia Commonwealth University have confirmed her results. In addition, we are investigating the reactivity of N+ with various unsaturated hydrocarbons, such as 1,3-butadiene, to form small nitrogenated heterocycles.

Understanding the oxygen balance on early Earth requires attention to sinks as well as sources of oxygen. One major sink for oxygen on early Earth would have been reduced iron. Iron could have simultaneously provided shielding against ultraviolet (UV%) light that would have been reaching Earth’s surface in the absence of the ozone shield generated by atmospheric oxygen. Nanophase ferric oxide minerals in solution could provide a sunscreen against UV while allowing the transmission of visible light, in turn making the evolution of at least some photosynthesic organisms possible. Dr. Janice Bishop and Dr. Lynn Rothschild are testing this hypothesis through coupled mineralogical and microbiological work in both the lab and the field, and examining its implications not only for Earth but for Mars as well, with an emphasis on implications for upcoming spacecraft observations. They performed experiments testing minerals as potential sunscreens. For example, nanophase-FeOx mixed with clay enabled *C. reinhardtii* and *Euglena* to survive exposure to UV radiation longer than controls not mixed with clay. In addition, absorbance spectra show a strong 674 nm absorption chlorophyll band associated with organism growth: that is, live cells exhibit a strong 674 nm absorption band whereas dead cells do not. The 674 nm band weakens with increasing UV exposure, then returns for nanophase-FeOx containing clay samples following rehabilitation in a visible light incubator. They have shown that the 674 nm band disappears and cells die in experiments without nanophase-FeOx containing clay. Current experiments involve mineralogical characterization of Fe-rich environments where photosynthetic organisms are thriving below the surface.

Environmental conditions for life in terrestrial lakes located at extreme high altitudes in Bolivia and Chile provide a good analogy to martian paleolakes dating back 3.5 Ga. Through the exploration of these lakes the survival strategies of microorganisms in very high UV environments can be elucidated. A team led by Dr. Nathalie Cabrol and Dr. Edmond Grin conducted a series of investigations examining the geology, paleobiology and extant biology of these lakes. This past year the team sampled new sites (evaporating lakes, salars, and geothermal centers), as well as laying down a new stratigraphical transect in the geological record of Laguna Verde to study the evolution of paleohabitats and life during fast changing climate conditions. The UV flux at these high altitude lakes was examined in more detail. Samples from Laguna Blanca were analyzed by Raman Spectroscopy in an attempt to develop a database for characterizing the structure and stability of biogenic carbonaceous material in such samples.

Just as global-scale changes in oxygen (or iron) were critical for the early biosphere, so too would have been global processes involving other key "biogenic" elements such as carbon (for which Dr. Allesandra Ricca's work provides insight) or nitrogen. Dr. Rocco Mancinelli, Dr. Amos Banin, Dr. David Summers, and Dr. Bishun Khare are pursuing coupled laboratory and field research to understand the partitioning of nitrogen on early Earth and on Mars between different possible reservoirs, and (at least for Earth) the abiotic to biotic transition in this cycling.

Dr. Banin has completed the analysis of soil samples from the Atacama desert , an extreme terrestrial environment with very low biological activity. Although not completely clear what properties of the soil and environment are the limiting factors for biology, these soils are nearly devoid of organic material and contain high levels of perchlorate. They have conducted a series of field experiments, which show that at the driest sites (e.g., Yungay) there is virtually no nitrogen cycling even when the samples are wetted. They have shown that the soil is not toxic and capable of allowing a variety of microbes to flourish if organic material is added. These results are being pursued to better understand the relationship between the soil redox potential and the denitrification pathway.

Dr. Summers and Dr. Khare have completed the first experiments to demonstrate abiotic nitrogen fixation. Results show that both the theoretically predicted pathway and an alternate pathway can occur and that the observed chemistry is dependent on the amount of water and the state (liquid or gas) in which water is present. They have also discovered that NO can alternately be directly reduced to ammonia by FeS minerals in aqueous solution. Currently, they are studying pH and other variables for this reaction and are in the process of identifying a gaseous by-product. They are also conducting experiments to determine the most effective method for measuring isotope fractionation. The resulting method will be used as a benchmark for biogenic determination and for identifying the isotopic composition of samples from the Atacama, where nitrates may be of abiotic origin. These experiments begin providing a different perspective into the astrobiologically important question of the fate of N on early Mars.

The work described so far examines the evolution of planetary surface habitability. With the recognition that a subsurface ocean likely exists on Jupiter's moon Europa, we know that habitability in possibly entirely subsurface environments must also be explored. Dr. Cynthia Phillips, Dr. Christopher Chyba, and Dr. Kevin Hand (who just received his Ph.D. from Stanford under the mentorship of Dr. Chyba) are pursuing spacecraft data analysis and modeling to examine the geology of Europa and its implications for the free energy sources that would be needed to power a europan biosphere. Dr. Phillips and Dr. Chyba are continuing a survey of images of Europa to look for any changes that occurred due to geological activity during the Galileo mission, which if present would indicate active regions of the surface. We have completed a search of the Galileo Europa images to find overlapping images, and are continuing to work on improving their automated search method to ensure that they find all possible comparison images.

These results will be coupled with the results of low-temperature laboratory experiments to make predictions about the possible abundance and survivability of any oceanic biomarkers that might reach Europa's surface through active geology, with implications for the astrobiological exploration of Europa from either an orbiter or a surface lander. Dr. Hand, in collaboration with Dr. Robert Carlson and Dr. Chyba, is pursuing this research in Dr. Carlson's laboratory at the Jet Propulsion Laboratory. Dr. Max Bernstein, in his laboratory at NASA Ames, is performing measurements to detect biomarkers. He is discriminating between true and false biomarkers. Dr. Bernstein has been concentrating on the kind of conditions found on icy outer Solar System bodies such as Europa and has found good agreement between theoretical prediction and experimental observation. One of his significant findings indicate that radiation can cause changes that may make it more difficult to distinguish a biomolecule from abiotic organics.

Dr. Peter Backus, Dr. Jill Tarter, and Dr. Rocco Mancinelli published results from the first workshop that examined the prospects that planets orbiting dwarf M stars are habitable for either microscopic or complex life in the Journal Astrobiology (see reference section of the report). The results suggest that there is no reson to preclude that life cannot evolve on a planet orbiting a dwarf M-star.

Education and public outreach are major and integral parts of the work of the SETI Institute's NAI team.

2007 SETI Project Report

Planetary Biology, Evolution, and Intelligence

Accomplishments

Peter Backus, Jill Tarter, Rocco Mancinelli- The results of a two and a half day workshop on the topic of the Habitability of Planets Orbiting M Stars was published recently. Thirty scientists from nineteen institutions in the US and UK participated. Thirteen of the participants were from six other NAI Teams. Results of the workshop are reported in a paper published in a special issue of the journal Astrobiology earlier this year. The paper was written over many months through the use of email lists and a secure private web site. Another web site, http://mstars.seti.org provided information for the general public. The paper concluded that M dwarf stars might indeed host habitable planets and identified research topics that would help clarify the issues. Since the workshop, participants have published more than a dozen relevant papers. We had planned to have a second workshop this year to review and discuss progress, but it was canceled due to funding cuts. We are, however, reviewing the literature and will write a final paper as an update to the published paper next year based on our literature review.

Max Bernstein- We have been performing lab measurements to enable the detection of molecular signs of life and discriminate between true and false biomarkers. We have measured IR spectra and photochemistry of aromatic nitrogen heterocycles, the class of compounds that include nucleobases, under conditions found on icy outer Solar System bodies such as Europa. These compounds are good test molecules since they bridge the biotic and planetary domains; they are both fundamental to, and ubiquitous in biochemistry, yet also are present in meteorites, and asteroidal and cometary dust. We found that radiation can cause changes that may make it more difficult to distinguish a biomolecule from abiotic organics.

Janice Bishop & Lynn Rothschild- This year we published a paper in the International Journal of Astrobiology that describes the results of our lab experiments with nanophase iron oxide-bearing minerals as potential sunscreening agents for photosynthetic organisms. Transmittance spectra are shown in Figure 4 of *Euglena* grown in a suspension of ferrihydrite-schwertmannite-montmorillonite. The chlorophyll absorption at 674 nm decreases with exposure in days and then greatly increases again after resuscitating the *Euglena* in a visible-light incubator. The normalized chlorophyll band is plotted in Figure 5 for three mineral suspensions and water, and shows an increase in chlorophyll for the ferrihydrite-montmorillonite suspensions indicating that the *Euglena* grown in the presence of these nanophase Fe minerals are more resistant to solar UV damage. Concurrent with other projects, we are evaluating the spectral properties of Fe-bearing Mars analog sites on Earth and analyzing spectra of Mars for Fe oxide-bearing components. We have collected some material from Yellowstone National Park (YNP) and Bolivia that are currently under study. Spectra of materials from many of these sites (Figure 6) show the presence of nanophase iron oxides/oxyhydroxides that may be facilitating growth of photosynthetic organisms in these natural environments by providing protection from UV radiation. An image of the YNP Chocolate Pots site is shown in Figure 7. Based on the spectral properties of iron oxides and the results of experiments with two photosynthetic organisms, we propose a scenario where photosynthesis, and ultimately the oxygenation of the atmosphere, depended on the protection of early microbes by nanophase ferric oxides/oxyhydroxides. Such niches may have also existed on Mars.

We have been evaluating the Pancam multispectral visible/near-infrared (VNIR) images of Mars from Gusev crater, Mars Express/OMEGA hyperspectral VNIR images and MRO/CRISM hyperspectral VNIR images of Mars in an effort to characterize deposits of nanophase ferric oxide-bearing minerals that could provide UV protected niches for photosynthetic microbes if they were present on Mars. There are a few sites that have been revealed in Gusev crater that show elevated S levels and are brighter than surrounding areas. It appears that this bright salty material is in a layer below the surface dust in a few regions near the Columbia Hills. Spectral analyses of this material indicate the presence of ferric sulfate minerals (Lane et al., 2006,2007; Parente et al., 2007). These unique bright salty patches exposed by the rover wheels in a few locations could represent locations where ferric minerals have provided a UV protected niche for photosynthetic organisms. Analyses of the OMEGA data showed the presence of sulfate minerals in association with hydrated minerals (Bishop et al., 2006). We are investigating these sites further with CRISM data in order to characterize the phyllosilicate and sulfate minerals present and identify ferric oxide/oxyhydroxide minerals accompanying them (Bishop et al., 2007a,b,c). Mapping ferric oxide/oxyhydroxide/sulfate minerals and phyllosilicates on Mars leads us to sites where water was present at one time. Understanding where ferric-bearing components were present in these aqueous environments further helps identify potential UV protected niches.

Nathalie Cabrol- The High-Lakes Project (HLP) completed successfully all ascents and scientific activities planned for the 2006 expedition, which took place October 28--November 26, 2006. The general public could follow the expedition daily on http://highlakes.seti.org. The samples of zooplankton from Licancabur and Laguna Blanca are currently being analyzed (e.g., taxonomy, molecular analyses) by experts in the US, Canada, Australia, Russia, Brazil, and Belgium. Several species are still unidentified as of now. Microbial organisms are being analyzed in the US and Chile and preliminary results suggest a high percentage of unknown organisms at the genus or phylum level. One article was published this year as a chapter of a book at the Cambridge University Press; a second is under review; and a third one has been submitted to the same editor. Two abstracts were selected as oral presentation in professional conferences. We are currently preparing a special issue with the Journal of Geophysical Research. The special issue will consist of 12 articles focused on the results of HLP, and 6 invited papers from other studies by experts on high-altitude lakes.</p>

Chris Chyba, **Cynthia Phillips**, **Kevin Hand**- The project has two components. The first, an overview of the astrobiological potential of various geological features on Europa, is proceeding well -- we are continuing the study of various proposed formation mechanisms for different feature types such as ridges, bands, and chaotic terrain. The second, a search for current geological activity by comparing Galileo images taken on different orbits, is also in progress. We have completed a first-stage search of the Galileo Europa images to find overlapping images, and are continuing to work on improving our automated search method to make sure that we find all possible comparison images. We have processed a number of comparison pairs, and are currently working on automated techniques for speeding up the comparison process.

We also received funding from the NAI DDF to include 4 extra students in our NSF-funded REU summer program that brings undergraduate students from around the country to the SETI Institute to do research in astrobiology (Figure 8). The four students received a stipend, travel, and housing for the summer. The students were selected in a competitive process from a pool of over 100 applicants. The selected students were: 1) Elizabeth Frank, from RPI, who worked with Jean Chiar at the SETI Institute on a project relating to chemistry of interstellar materials that might be important in the origin of life, 2) Amanda Smith, from University of Virginia, worked with Hector D'Antoni and Jay Skiles of the Ames NAI team, on a project related to paleoclimatology and early Earth conditions relevant to the origin of life, 3) Andrew Honma, from University of Hawaii, worked with Janice Bishop at the SETI Institute on a project relating to spectroscopy of materials on the surface of Mars with potential for aqueous alteration, 4) Teresa Cadarette, of Scripps, worked with Scott Sandford and Rachel Mastrapa of the Ames NAI team, on a project doing laboratory experiments with interstellar ice materials important for prebiotic organic chemistry. The students all will present a talk at the end of the summer summarizing their research, to which members of the SETI Institute and Ames NAI teams, and NAI Central, will be invited. The DDF funding also helped support Cynthia Phillips who ran the program.

Friedemann Freund & Lynn Rothschild- The major objective of this task is to study the causes for the slow but inextricable oxidation of the Earth over the first 3 Gyr of its history. Contrary to the widely held belief that planet Earth became oxidized due to the activity of early photosynthetic microorganisms, we have shown that there is an alternative, entirely abiogenic pathway toward global oxidation: the presence of oxygen anions in the minerals of common igneous rocks that have converted from a valence of 2-- to a valence of 1-- (peroxy). Upon weathering this peroxy fraction hydrolyzes to hydrogen peroxide, which in turn oxidizes reduced transition metal cations, foremost ferrous iron to ferric iron. This is expected to lead to the precipitation of ferric oxides and, hence, to the deposition of Banded Iron Formations (BIF) in the ocean. After a sufficiently long time, 1-2 billion years, the continental rocks will evolve toward andesitic-granitic compositions, releasing less ferrous iron during weathering, and free oxygen will begin to be injected into the atmosphere. The presence of oxygen in the valence 1--, in the form of peroxy, has yet another important consequence: Upon stressing the rocks, the peroxy bonds break up and generate mobile electronic charge carriers, defect electrons, also known as positive holes or pholes for short. The pholes have the unusual capacity that they can flow out of the stressed rock volume, generating electric currents that can reach or exceed 100,000 amperes, if the stressed rock volume is a cubic kilometer in size. We have shown that this electric current flowing through rocks converts quantitatively into hydrogen peroxide, H2O2, at the rock-water interface. This discovery opens the door to re-assess the conditions that primitive microorganisms, which lived in contact with rock surfaces, must have encountered on the early Earth.

Rocco Mancinelli & Amos Banin- We tested soil samples, from the Yungay region of Atacama desert, for toxicity against a variety of microbes ranging from pure cultures obtained from the ATCC to isolates obtained from soil just outside the laboratory. The results indicate that the Atacama soil is not toxic. We also tested Atacama soil for its ability to reduce nitrate to nitrite, the first step in denitrification. These tests were negative. Additionally, we mixed Atacama soil with pure and mixed cultures of denitrifiers to determine if the soil inhibited denitrification in known denitrifiers. These tests have not yet been concluded. These data combined with past data indicate no detection of nitrogen cycling in the field, even under wet conditions. The nitrite reductase gene analyzed for DNA encoding for the key denitrification enzyme suggests that either there are no organisms capable of N-cycling in in the soil, or the soil contains something inhibiting their activity. In a set of soil samples from the Yungay region of the Atacama desert we have conducted detailed analyses of organic and inorganic C and N concentrations. Organic carbon (OC) and organic nitrogen (ON) were low, especially in the soils from the most extreme arid region. The OC/ON ratio was in the range typical for biotically synthesized organic matter. Comparison to estimates of C content in the Mars soil analyzed by the Viking Landers show that the Atacama soils, even in the hard-core extreme desert sites, have very low biological activity as far as terrestrial soils are concerned, but still have higher concentrations of total organic carbon compared to the Mars soils analyzed by the Viking Pyrolytic experiment.

Alessandra Ricca- We are investigating the chemical energetics and plausibility of reaction pathways leading to the formation of nitrogenated aromatics suggestive of purine and pyrimidine bases of RNA and DNA molecules using quantum chemistry. We have focused on the reactivity of pyridine radical cation with acetylene and shown that it is a viable reaction pathway leading to the formation of a bicyclic nitrogenated aromatic molecule. Very recent experiments performed at Virginia Commonwealth University have confirmed our results. In addition, we are investigating the reactivity of N⁺ with various unsaturated hydrocarbons, such as 1,3-butadiene, to form small nitrogenated heterocycles.

Seth Shostak & Molly Bentley- "Are We Alone?" radio show. We have expanded content and improved technical quality of a weekly, one-hour radio program devoted to the topics of astrobiology, SETI, space exploration, and related areas. Whereas most programs of a year ago would have one or two guests, it is now typical to have four, resulting in a greater range of subjects, and snappier interviews. Other show elements, including humorous skits and wider use of music, have been incorporated. In addition, we have invested in hardware and software that has improved both the audio quality and speed and flexibility of production.

Once a month we do a special show on skepticism, taking on such controversial topics as intelligent design and the boundary between religion and science. These are among our most popular shows.

A highly abbreviated listing of guests of the past six months include:

Lee Gutkind	Author	“Making Robots Think”
John Marshall	Planetary Geologist	The Phoenix Mission
awrence Krauss	Physicist, Case Western Reserve	Cosmology in an accelerating universe
Tori Hoehler	NASA Ames	Food of the future

David Morrison	NASA Ames	Missions to asteroids
Victor Stenger	Univ. of Hawaii and Univ. of Colorado	“God: The Failed Hypothesis”
Frank Tipler	Tulane University	“The Physics of Christianity”
Carolyn Porco	Planetary scientist	Rings of Saturn
Natalie Angier	Science writer, *New York Times*	“The Canon”
John Rummel	Senior Scientist, NASA	Planetary protection
Vikki Meadows	Jet Propulsion Lab and Caltech	Alien vegetation
Max Bernstein	NASA Ames	Chemical precursors to life

In February, a reorganization at Discovery Communications eliminated their science channel on Sirius Satellite Radio, which broadcast "Are We Alone?" four times a week. We have since begun an effort to secure on-the-air replacement distribution, and are currently uploading shows to the National Public Radio satellite, making the programs available for distribution to the NPR network. However, irrespective of broadcast, the show is clearly enjoying a growing popularity. Internet downloads in the week previous to this report were approximately 50 thousand. Indeed, in 2007, we are expecting that the total number of one-hour shows downloaded will be between one and two million. The show is hosted by P.I. Seth Shostak (SETI Institute) and produced by Molly Bentley, whose efforts are supported by this NAI grant (Figure 9).

David Summers & Bishun Khare- We completed the first experiments to demonstrate abiotic nitrogen fixation this year. Results show that both the theoretically predicted pathway and an alternate pathway can occur and that the observed chemistry is dependent on the amount of water and the state (liquid or gas) in which water is present. We have also discovered this year that NO can alternately be directly reduced to ammonia by FeS minerals in aqueous solution, with good product yield (15-20%). Currently, we are studying pH and other variables for this reaction and are in the process of identifying a gaseous by-product. We are also conducting experiments to determine the most effective method for measuring isotope fractionation. The resulting method will be used as a benchmark for biogenic determination and for identifying the isotopic composition of samples from the Atacama, where nitrates may be of abiotic origin. The results of this work were published in the Journal of Astrobiology.

Figure 1. One of the (frozen) summit ponds at Escalante. Photo Credit: Victor Gaete, HLP/NAI/SETI/NASA ARC.


Figure 2. Red copepods and green algae in the north shallow end of Licancabur (< 1.2 m). Photo Credit: Clayton Woosley, HLP/NAI/SETI/NASA ARC.

Figure 3. Summit lake of Aguas Calientes. The lake is mostly circular and about 120 m x 115 m. Depth could not be estimated this year. Photo Credit: Cristian Tambley, HLP/NAI/SETI/NASA ARC.

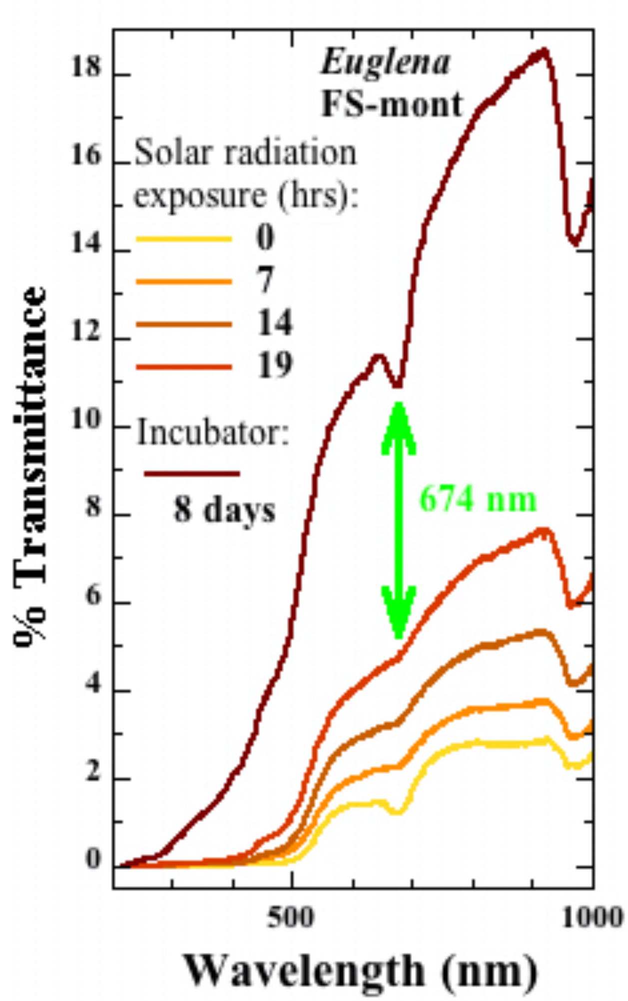

Figure 4. Transmittance spectra of Euglena suspensions in a ferrihydrite-schwertmannite-montmorillonite (FS-mont) assemblage exposed to natural solar radiation over several days. Decreases in the chlorophyll bands are observed with increasing solar radiation as the Euglena are stressed from the UVR. An additional spectrum was measured after growing the stressed organisms in the laboratory incubator for 8 days. This final spectrum showed a return of the chlorophyll band at 674 nm.

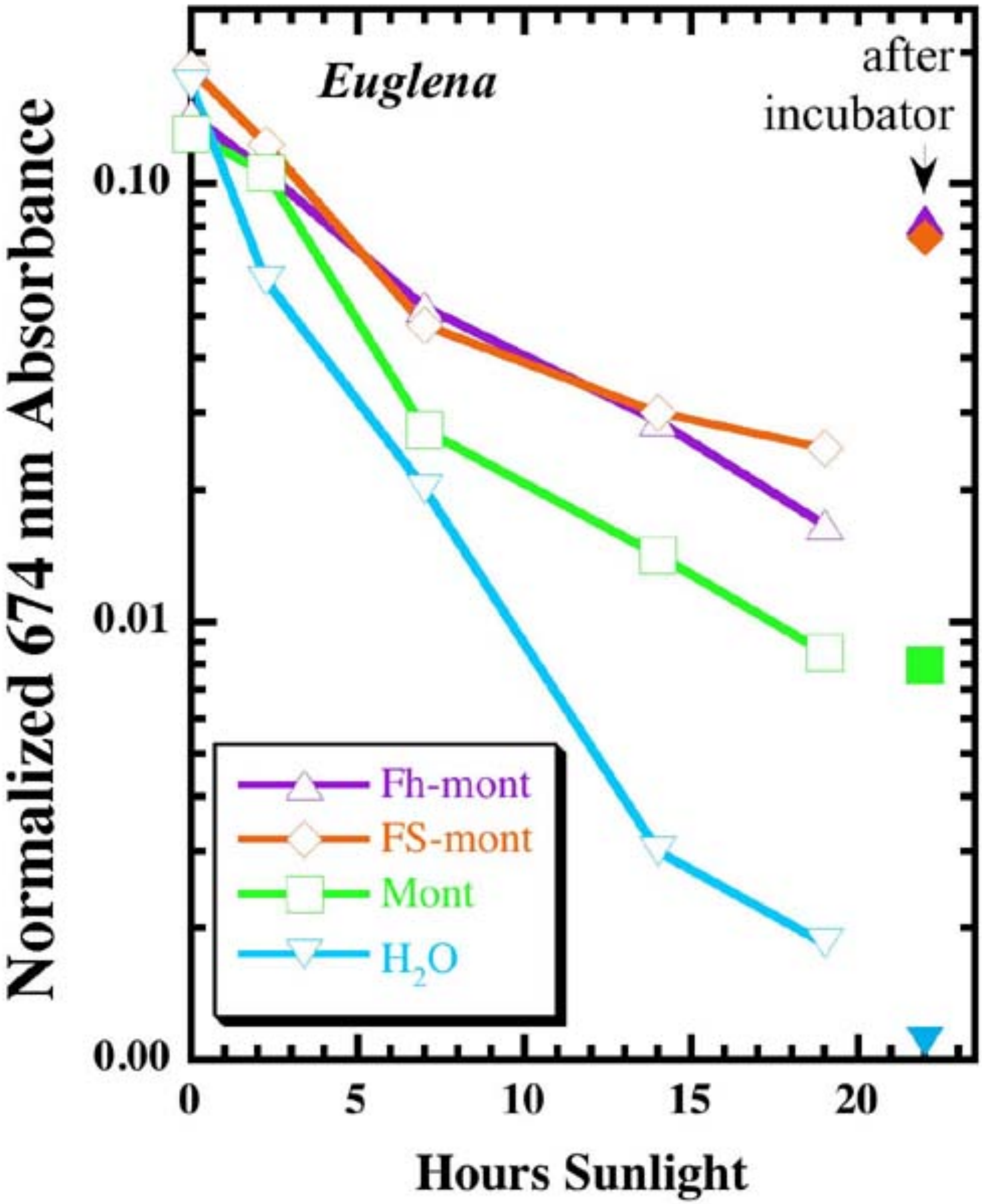

Figure 5. Normalized absorbance of chlorophyll a at 674 nm in spectra of Euglena suspensions a) H2O control, b) Montmorillonite, c) Ferrihydrite-montmorillonite assemblage, and d) Ferrihydrite-schwertmannite-montmorillonite assemblage. These were exposed to natural solar radiation in small doses

over several days. An additional spectrum was measured after growing the stressed organisms in the laboratory incubator for 8 days.

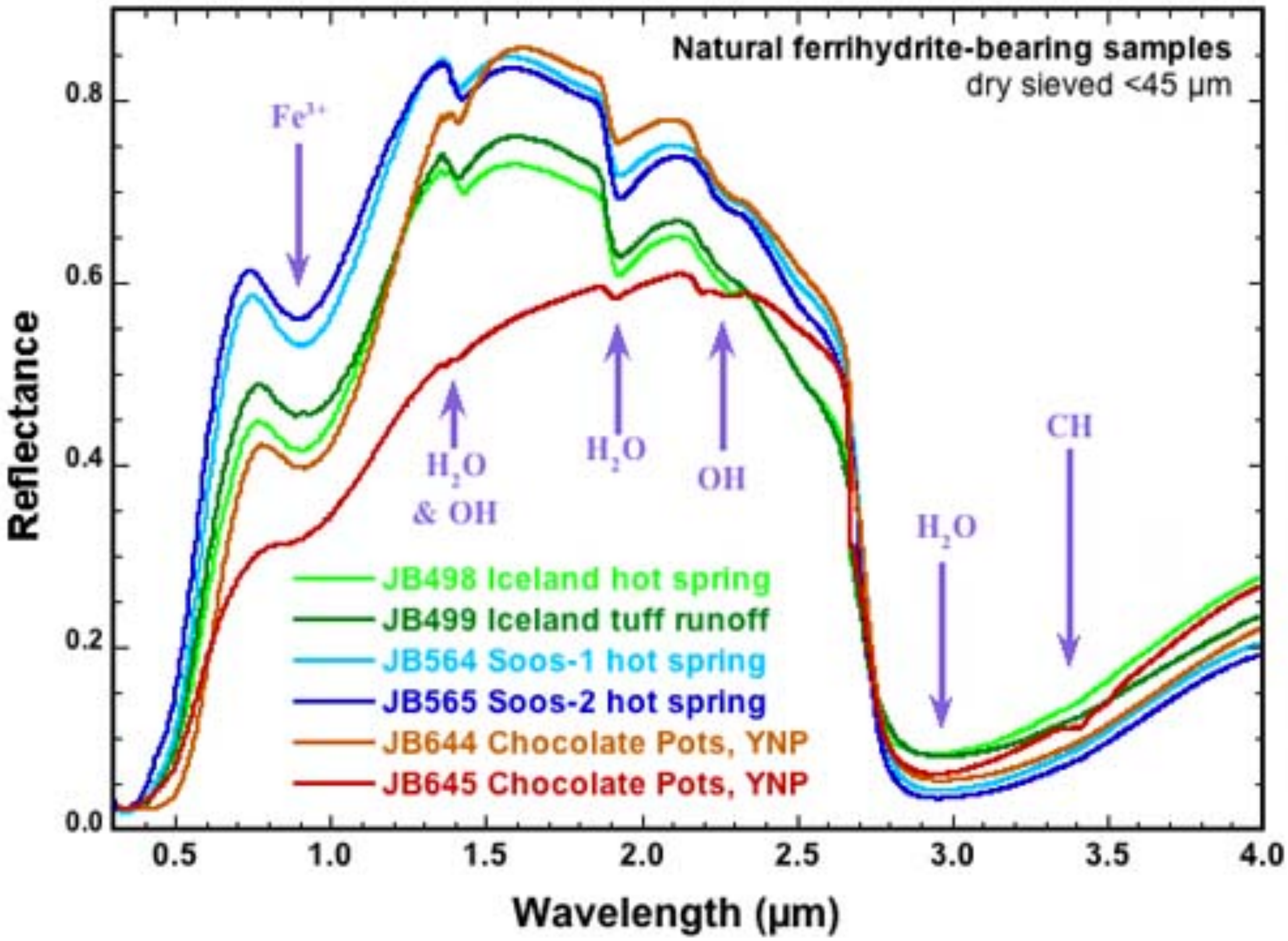

Figure 6. Visible/near-infrared reflectance spectra of natural ferrihydrite-bearing samples from chocolate pots and other locations.

Figure 7. Image of Chocolate Pots research site at Yellowstone National Park. Portions of the bright orange-red material are currently under study.


Figure 8. 2007 REU students at Lassen Volcanic National Park, funded in part by the NAI DDF.


Figure 9. "Are We Alone" radio show staff. From the left, Barbara Vance, Seth Shostak, and Molly Bentley.

2007 SETI Members

Rocco Mancinelli
Peter Backus
Melike Balk
Amos Banin
Molly Bentley
Max Bernstein
Janice Bishop
Milton Bose
Nathalie Cabrol
Teresa Cadarette
Bin Chen
Guillermo Chong
Edna DeVore
Cecilia Demergasso
G√∂zen Ertem
Elizabeth Frank
Friedemann Freund
Matthieu Galvez
John Gibson
Edmund Grin
Lisa Grossman
Andrew Hock
Andrew Honma
Gloria Hovde
Antonia Hubbard
Linda Jahnke
Bishun Khare
Darlene Lim
David McKay
Edwin Minkley
Robert Morris
Mairo Parente
Cynthia Phillips
Lee Prufert-Bebout
Alessandra Ricca
Dana Rogoff
Lynn Rothschild
Seth Shostak
Amanda Smith
Eric Smith
David Summers
Jill Tarter
Kimberly Warren-Rhodes
Clayton Woosley

Publications

No publications were reported.

NAI 2008 SETI Team Annual Science Report

Executive Summary

The SETI Institute (SI) NASA Astrobiology Institute (NAI) team is conducting a suite of coupled research projects in the co-evolution of life and its planetary environment. These projects address most of the Roadmap Objectives that are organized under the seven broader Roadmap Goals; Goal 1: Habitable Planets; Goal 2: Life in our Solar System; Goal 3: Origins of Life; Goal 4: Earth's Early Biosphere and its Environment ; Goal 5: Evolution, Environment, and Limits of Life ; Goal 6: Life's Future on Earth and Beyond; Goal 7: Signatures of Life. These projects begin by examining specific fundamental ancient transitions that ultimately made complex life possible on Earth. They conclude with a synthesis that brings many of the team's investigations together into an examination of the suitability of planets orbiting M dwarfs for either single-celled or more complex life.

The astrobiology roadmap calls for a strategy "for recognizing novel biosignatures" that "ultimately should accommodate a diversity of habitable conditions, biota and technologies in the universe that probably exceeds the diversity observed on Earth." Some of our results, especially those concerning abiotic mechanisms for the oxidation of planetary atmospheres, speak to the interpretation of extrasolar planet atmospheric spectra (and in particular, the role of oxygen as a potential biosignature) in terms of the presence of photosynthesizing life. The team's M-star project addresses the roadmap's observation that "although technology is probably much more rare than life in the universe, its associated biosignatures perhaps enjoy a much higher signal-to-noise ratio. Accordingly, current methods should be further developed and novel methods should be identified for detecting electromagnetic radiation or other diagnostic artifacts that indicate remote technological civilizations." As the roadmap recognizes, there is a continuum of investigations that comprise astrobiology, from prebiotic evolution to the evolution of technology.

The SETI Institute's NAI team's research emphasizes the elucidation of the co-evolution of life and its planetary environment, investigating global-scale processes that have shaped, and been shaped by both. Throughout, the team recognizes the importance of pursuing the planetary evolution aspects of this research in the context of comparative planetology: since laboratory experiments are impossible over many (but not all) of the time and spatial scales relevant to early Earth, we supplement laboratory data with insights gained by exploring extraterrestrial environments that provide partial analogs to the early Earth environment and its processes.

The SETI Institute team is pursuing two investigations into the oxidation of early Earth's environment. While the biological aspects of this "oxygen transition" have been emphasized, our team is exploring non-biological contributions to this transition. Dr. Friedemann Freund and Dr. Lynn Rothschild are investigating oxidation driven by diffusive loss of hydrogen formed within igneous and metamorphic rocks that incorporate water during crystallization. The major objective of this task is to study the causes for the slow but inextricable oxidation of the Earth over the first 3 Gyr of its history.

Contrary to the widely held belief that planet Earth became oxidized due to the activity of early photosynthetic microorganisms, they have shown that there is an alternative, entirely abiogenic pathway toward global oxidation: the presence of oxygen anions in the minerals of common igneous rocks that have converted from a valence of 2- to a valence of 1- (peroxy). Upon stressing the rocks, the peroxy bonds break up and generate mobile electronic charge carriers, defect electrons, also known as positive holes or pholes for short. The pholes have the unusual capacity that they can flow out of the stressed rock volume, generating electric currents that can reach or exceed 100,000 amperes, if the stressed rock volume is a cubic kilometer in size. They have shown that this electric current flowing through rocks converts quantitatively into hydrogen peroxide, H_2O_2, at the rock-water interface. This discovery opens the door to re-assess the conditions that primitive microorganisms, which lived in contact with rock surfaces, must have encountered on the early Earth. Through 2007 they continued to measure the electric currents flowing out of stressed rocks in order to gain a handle on the total amount of peroxy oxygen in a given rock. So far they have confirmed that the concentrations of peroxy oxygen in igneous rocks, in particular in gabbro and anorthosite, are higher than previously thought, but quantitative data are not yet available. In early 2008, they procured a dissolved oxygen (DO) meter and a pH meter to continuously measure the formation of hydrogen peroxide at the rock-water interface. They have set up the two meters and began operation, however they encountered a problem because the DO meter consumes dissolved oxygen during measurements. To correct for it, they are currently trying to find a way to independently determine the consumption rate.

In a second investigation, oxidation driven by atmospheric hydrocarbon (and, more broadly, organic) polymerization is being investigated by Dr. Alessandra Ricca. Dr. Ricca is investigating the chemical energetics and plausibility of reaction pathways leading to the formation of nitrogenated aromatics suggestive of purine and pyrimidine bases of RNA and DNA molecules using quantum chemistry. She has focused on the reactivity of pyridine radical cation with acetylene and shown that it is a viable reaction pathway leading to the formation of a bicyclic nitrogenated aromatic molecule. In collaboration with Prof. M. Samy El-Shall at Virginia Commonwealth University, she has demonstrated that acetylene undergoes sequential additions onto the benzene radical cation with two different mechanisms operating at low and high temperature. These findings illustrate that complex organics can form under a wide range of conditions that can be found in outer space environments.

Understanding the oxygen balance on early Earth requires attention to sinks as well as sources of oxygen. One major sink for oxygen on early Earth would have been reduced iron. Iron could have simultaneously provided shielding against ultraviolet (UV%) light that would have been reaching Earth's surface in the absence of the ozone shield generated by atmospheric oxygen. Nanophase ferric oxide minerals in solution could provide a sunscreen against UV while allowing the transmission of visible light, in turn making the evolution of at least some photosynthesic organisms possible. Dr. Janice Bishop and Dr. Lynn Rothschild are testing this hypothesis through coupled mineralogical and microbiological work in both the lab and the field, and examining its implications not only for Earth but for Mars as well, with an emphasis on implications for upcoming spacecraft observations. They performed experiments testing minerals as potential sunscreens. For example, nanophase-FeOx mixed with clay enabled *C. reinhardtii* and *Euglena* to survive exposure to UV radiation longer than controls not mixed with clay. Recently the bright salty soils found at Paso Robles and other sites in Gusev crater on Mars showed that this material is composed of the ferric minerals ferricopiapite, fibroferrite and/or ferristrunzite. Although these sulfates may imply the presence of brines too salty for many microbes, the UV-VIS properties of these ferric minerals could have provided solar protection for microbes able to withstand the salty conditions. In addition, analysis of MRO/CRISM hyperspectral VNIR images of Mars showed the presence of a large phyllosilicate outcrop at Mawrth Vallis, one of the potential landing sites for future missions. The most abundant clay phase found here is an Fe/Mg-smectite. The depth and breadth of this clay deposit suggests long-standing water on Mars. The iron-bearing clay also absorbs some of the UV-VISsolar radiation and could have provided solar protection to any microbes present.

Environmental conditions for life in terrestrial lakes located at extreme high altitudes in Bolivia and Chile provide a good analogy to martian paleolakes dating back 3.5 Ga. Through the exploration of these lakes the survival strategies of microorganisms in very high UV environments can be elucidated. A team led by Dr. Nathalie Cabrol and Dr. Edmond Grin conducted a series of investigations examining the geology, paleobiology and extant biology of these lakes. This past year the team retrieved data from the Eldonet UV station and positioned a new short UV wavelength dosimeter at the summit of the Simba (volcano). The team also explored new investigation sites, including Laguna Lejia and Laguna Aguas Calientes.

Just as global-scale changes in oxygen (or iron) were critical for the early biosphere, so too would have been global processes involving other key "biogenic" elements such as carbon (for which Dr. Alessandra Ricca's work provides insight) or nitrogen. Dr. Rocco Mancinelli, Dr. Amos Banin, Dr. David Summers, and Dr. Bishun Khare are pursuing coupled laboratory and field research to understand the partitioning of nitrogen on early Earth and on Mars between different possible reservoirs, and (at least for Earth) the abiotic to biotic transition in this cycling.

Dr. Banin has completed the analysis of soil samples from the Atacama desert, an extreme terrestrial environment with very low biological activity. Although not completely clear what properties of the soil and environment are the limiting factors for biology, these soils are nearly devoid of organic material and contain high levels of perchlorate. They have conducted a series of field experiments, which show that at the driest sites (e.g., Yungay) there is virtually no nitrogen cycling even when the samples are wetted. They have shown that the soil is not toxic and capable of allowing a variety of microbes to flourish if organic material is added. Denitrification tests were negative, including those from the wet test, suggesting that low water activity alone cannot account for the lack of denitrification in this system. However, when organic matter was mixed with the soil and incubated nitrite was produced. This suggests that denitrifiers are present in the soil, but the lack of organics (a potential electron donor) may account for the lack of denitrication in the system. Additionally, it is known that O2 inhibits denitrification and raises the cell's redox level. Following from this we hypothesize that the high soil redox potential is also responsible for the lack of denitrification.

Dr. Summers and Dr. Khare have completed the first experiments to demonstrate abiotic nitrogen fixation. Work this year focused on the reduction of NO to ammonia by FeS minerals in aqueous solution. This represents a third nitrogen fixation pathway in addition to the ones identified in previous work. Product yields of ~50% for ammonia were measured. The yield of ammonia formation appears to peak at pH 7 and falls of into acidic or basic conditions. Currently, we are using isotope labeling to identify a gaseous product observed with peaks at 2235, 2100, 1300, and 1270 cm-1 in the IR. We have conducted isotope labeling experiments with 2D2O, H218O, and N18O. The gaseous compound(s) appear to be CNO, (NCO)2, or some related species (a cyanato or isocyanato species). HCNO, HNCO, HOCN, and HONC have been ruled out. The gaseous product is formed in yields that are unaffected by the pH, but which increase as the amount of FeS is increased. We are currently conducting 13C isotope labeling experiments and looking to the 14N isotope fractions of all the reactions we have been studying. These experiments begin providing a different perspective into the astrobiologically important question of the fate of N on early Mars.

The work described so far examines the evolution of planetary surface habitability. With the recognition that a subsurface ocean likely exists on Jupiter's moon Europa, we know that habitability in possibly entirely subsurface environments must also be explored. Dr. Cynthia Phillips, Dr. Christopher Chyba, and Dr. Kevin Hand are pursuing spacecraft data analysis and modeling to examine the geology of Europa and its implications for the free energy sources that would be needed to power a europan biosphere. They have completed a first-stage search of the Galileo Europa images to find overlapping images, and are continuing to work on improving our automated search method to make sure that they find all possible comparison images. We have processed a number of comparison pairs, and are currently working on automated techniques for speeding up the comparison process. In addition, a related project to study impact gardening on Europa and its potential for surface – subsurface transport of potential biogenic materials has reached some interesting conclusions. The gardening depth on Europa is thinner than we thought, probably only about a centimeter. This means that sputtering will tend to win out over gardening, and that less material can be mixed down to Europa's subsurface beneath the radiation processing layer to be preserved.

These results will be coupled with the results of low-temperature laboratory experiments to make predictions about the possible abundance and survivability of any oceanic biomarkers that might reach Europa's surface through active geology, with implications for the astrobiological exploration of Europa from either an orbiter or a surface lander. Dr. Hand, in collaboration with Dr. Robert Carlson and Dr. Chyba, is pursuing this research in Dr. Carlson's laboratory at the Jet Propulsion Laboratory.

Dr. Peter Backus, Dr. Jill Tarter, and Dr. Rocco Mancinelli published results from the first workshop that examined the prospects that planets orbiting dwarf M stars are habitable for either microscopic or complex life. They are applying the results of the workshop as they compile a list of "target" stars for SETI on the Allen Telescope Array. Under their supervision, a student in the Research Experience for Undergraduates program (sponsored by the NAF and the NAI) is sifting through a catalogue of more than a billion stars. They will continue this work and refine the derived target list based on research published subsequent to the workshop. We will publish this new catalog of roughly a million "Habstars", stars suitable to host habitable planets, extending current work.

Education and public outreach are major and integral parts of the work of the SETI Institute's NAI team. Among the several accomplishments are those from the "Are We Alone?" weekly science radio show. The improvement in show quality, both technical and in terms of presentation and content, continues apace. Some of the important changes in the past year include hiring a part-time assistant producer. Another recent improvement has been to broaden the scope of the show by having an expanded web presence, as well as a blog dedicated to the program. The show is also represented on Facebook, My Space, Digg and other social networking sites. Participants in Second Life can also listen to the show in a specially constructed setting.

2008 Project Reports

Abiotic Nitrogen Cycling

Summary

This work considers how the chemistry in the atmosphere of Mars (and other "Earth-like" planets) may have affected life, including how prebiotic nitrogen species may have been formed for the origin of life, and how these atmospheres may have been changed. When too much nitrogen is removed from the atmosphere, this can result in a planet with too little atmospheric pressure to support liquid water and life on the surface.

Accomplishments

David Summers & Bishun Khare- Work this year focused on the reduction of NO to ammonia by FeS minerals in aqueous solution. This represents a third nitrogen fixation pathway in addition to the ones identified in previous work. Product yields of ~50% for ammonia were measured. The yield of ammonia formation appears to peak at pH 7 and falls of into acidic or basic conditions. Currently, we are using isotope labeling to identify a gaseous product observed with peaks at 2235, 2100, 1300, and 1270 cm⁻¹ in the IR. We have conducted isotope labeling experiments with 2D2O, $H2^{18}O$, and $N^{18}O$. The gaseous compound(s) appear to be CNO, (NCO)2, or some related species (a cyanato or isocyanato species). HCNO, HNCO, HOCN, and HONC have been ruled out.   The gaseous product is formed in yields that are unaffected by the pH, but which increase as the amount of FeS is increased. We are currently conducting 13C isotope labeling experiments and looking to the 14N isotope fractions of all the reactions we have been studying. These results were presented in an invited paper at the 2008 COSPAR (Committee on Space Research) and at the 2008 Astrobiology Science Conference.

"Are We Alone?" Weekly Science Radio Show

Summary
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Production and distribution of a weekly, one-hour radio program whose subject matter is rooted in the discipline of astrobiology. The show consists of interviews with practicing scientists, reporters, and engineers, as well as other elements designed to make the program appealing to a wide range of the public, both domestic and international. Once monthly, a special edition of the show is devoted to skepticism: taking on pseudo-science and contrasting it with the workings of research.

Accomplishments
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Seth Shostak & Molly Bentley -"Are We Alone?" weekly science radio show. The improvement in show quality, both technical and in terms of presentation and content, continues apace. A typical, one-hour program features interviews with three or four researchers, writers, or reporters, a skit, music, and banter between Shostak and Bentley commenting on the subject matter.

Some of the important changes in the past year include hiring a part-time assistant producer, Gary Niederhoff (this hire was made possible by a NASA grant). Niederhoff brings to the show not only a high level of expertise, but also considerable "on-mic" talent.

Another recent improvement has been to broaden the scope of the show by having an expanded web presence, ably constructed and maintained by Barbara Vance, as well as a blog dedicated to the program. The show is also represented on Facebook, My Space, Digg and other social networking sites. Participants in Second Life can also listen to the show in a specially constructed setting.

Some of the recent guests include:

Paul Davies	Neil de Grasse Tyson	Aubrey de Grey
David Quammen	Alex Filippenko	Craig Venter
Owen Gingrich	Sam Harris	Vernor Vinge
Patricia Churchland	Richard Dawkins	Ray Kurzweil
Phil Plait	Neil Shubin	Marvin Minsky
Steve Aquyres	Max Tegmark	Susan Clancy
Mary Roach	Hans Moravec	Susan Jacoby
Nina Jablonski	Timothy Ferris	Janice Bishop

Distribution on the internet has changed in the past year, as the weekly download traffic was substantially slowing the SETI Institute servers. Consequently, the show files are now hosted on the servers of Sun Microsystems, thanks to a no-cost arrangement with that company. Additionally, approximately six PBS stations nationwide are now broadcasting the show. This number is expected to grow in the next six months, thanks to active marketing of the program.

A special NASA grant via Harvard University will sponsor thematic programs on "Are We Alone?" for the 2009International Year of Astronomy.

The show is hosted by P.I. Seth Shostak (SETI Institute) and co-hosted and produced by Molly Bentley.

Link to S. Shostak radio shows made with NAI funding:

http://radio.seti.org/past-shows.php

Link to 50+ articles written by S. Shostak for SPACE.com since January 2005:

http://www.space.com - enter search word Shostak

Expanding the List of Target Stars for Next Generation SETI Searches

Summary

For decades the conventional wisdom considered M dwarf stars unsuitable hosts for habitable planets. We convened an interdisciplinary workshop of thirty scientists to reconsider the issue. They concluded that life could evolve on planets orbiting higher mass M dwarfs. This improves the prospects for finding extraterrestrial life since M dwarfs account for about 75% of all stars. Based on these results, we are preparing a list of more than a million "target" stars for a search for extraterrestrial intelligence (SETI) project.

Accomplishments

Peter Backus, Jill Tarter, Rocco Mancinelli- We are applying the results of our NAI workshop on the Habitability of Planets Orbiting M Stars as we compile a list of "target" stars for SETI on the Allen Telescope Array. Under our supervision, a student in the Research Experience for Undergraduates program is sifting through a catalogue of more than a billion stars. We will continue this work and refine the derived target list based on research published subsequent to the workshop. We will publish this new catalog of roughly a million "Habstars", stars suitable to host habitable planets, extending the work of Turnbull and Tarter (2003a,b). This paper will include an update of the published conclusions of the workshop (Tarter, et al., 2007).

Formation of Nitrogenated Aromatics in the Interstellar Medium

Summary

We are investigating the chemical energetics and plausibility of reaction pathways leading to the formation of nitrogenated aromatics suggestive of purine and pyrimidine bases of RNA and DNA molecules using quantum chemistry.

Accomplishments

Alessandra Ricca- We are investigating the chemical energetics and plausibility of reaction pathways leading to the formation of nitrogenated aromatics suggestive of purine and pyrimidine bases of RNA and DNA molecules using quantum chemistry. We have worked in collaboration with Prof. M. Samy El-Shall at Virginia Commonwealth University who has studied the reactions of benzene ion and pyridine radical cation with acetylene over a wide temperature range, from 120 to 650 K, using the mass-selected ion mobility (drift cell) technique. Experiments shows that acetylene undergoes sequential additions onto the benzene radical cation with two different mechanisms operating at low and high temperature. Our calculations simulated the low temperature regime and agree with the experimental results. A manuscript entitled "Formation of Complex organics from Acetylene Catalyzed by Ionized Benzene" by P. O. Momoh, A. Soliman, M. S. El-Shall and A. Ricca has been submitted to J. Amer. Chem. Soc. A manuscript on the reactions of pyridine radical cation with acetylene is in preparation. These findings show that complex organics can form even under a wide range of conditions that can be found in outer space environments. In addition, we are investigating the reactivity of N⁺ with various unsaturated hydrocarbons, such as 1,3-butadiene, to form small nitrogenated heterocycles.

Iron, the Oxygen Transition, UV Shielding, and Photosynthesis

Summary

Our combined field and lab work has shown that iron oxide bearing minerals could be important in protecting photosynthetic organisms from UV radiation and that nanophase ferric oxyhydroxides in a clay matrix are particularly effective. We have collected several iron-rich samples from hot springs where microbes thrive and are completing characterizing the minerals present and their spectral properties. We are also identifying iron oxides and clay minerals on Mars in order to determine possible environments where microbes could have been protected from solar radiation.

Accomplishments

Janice Bishop & Lynn Rothschild- We continued analysis of the spectral properties of Fe-bearing Mars analog sites on Earth and analyzing spectra of Mars for Fe oxide-bearing components. We are preparing the data on samples from Yellowstone National Park (YNP) and Bolivia for publication. Spectra of materials from the YNP Chocolate Pots site (Figure 1) show the presence of nanophase iron oxides/oxyhydroxides that may be facilitating growth of photosynthetic organisms in these natural environments by providing protection from UV radiation. An image of the YNP Chocolate Pots site is shown in Figure 2. Based on the spectral properties of iron oxides and the results of experiments with two photosynthetic organisms, we propose a scenario where photosynthesis, and ultimately the oxygenation of the atmosphere, depended on the protection of early microbes by nanophase ferric oxides/oxyhydroxides. Such niches may have also existed on Mars.

Work this year on the bright salty soils found at Paso Robles and other sites in Gusev crater showed that this material is composed of the ferric minerals ferricopiapite, fibroferrite and/or ferristrunzite (Lane et al., 2008, Parente et al., 2008). Pancam multispectral visible/near-infrared (VNIR) images of Mars from Gusev crater are shown in Figures 2 and 3. Analysis of these Pancam data together with the mini-TES and MÖssbauer data collected by MER enabled characterization of the minerals in the bright salty soils. Although these sulfates may imply the presence of brines too salty for many microbes, the UV-VIS properties of these ferric minerals could have provided solar protection for microbes able to withstand the salty conditions.

Analysis of MRO/CRISM hyperspectral VNIR images of Mars showed the presence of a large phyllosilicate outcrop at Mawrth Vallis, one of the potential landing sites for future missions. The most abundant clay phase found here is an Fe/Mg-smectite. The depth and breadth of this clay deposit suggests long-standing water on Mars (Bishop et al., 2008). The iron-bearing clay also absorbs some of the UV-VIS solar radiation and could have provided solar protection to microbes if present. A border of Fe²⁺ material in between the Fe³⁺ and Al clays suggests a change in chemistry typically associated with microbial activity on Earth. This shows an active early chemistry in these ancient martian rocks.

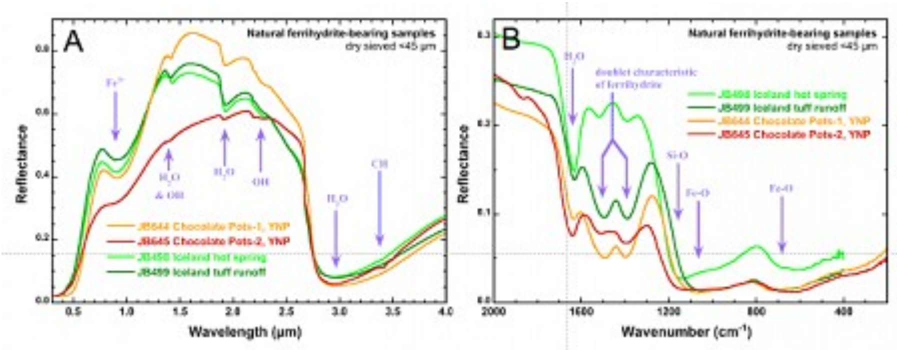

Figure 1 Reflectance spectra of two chocolate pots samples show that these are dominated by ferrihydrite: A) VNIR region and B) mid-IR region. Chocolate Pots-1 (orange) exhibits spectral features consistent with pure ferrihydrite, while the spectrum of Chocolate Pots-2 (red) contains less clear ferrihydrite bands and additional features due to other phases. These are compared with spectra of natural ferrihydrite-bearing precipitates from Iceland. The dark green spectrum exhibits the features due to pure ferrihydrite, while the light green spectrum indicates the presence of some impurity phases.

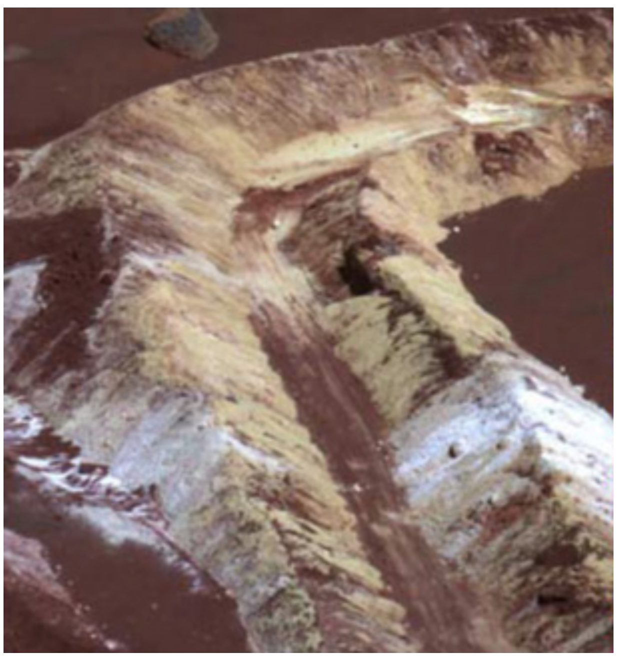

Figure 2 Approximate true color Pancam Image of bright yellow and white soils exposed by rover wheel tracks at Paso Robles in Gusev crater, Mars.

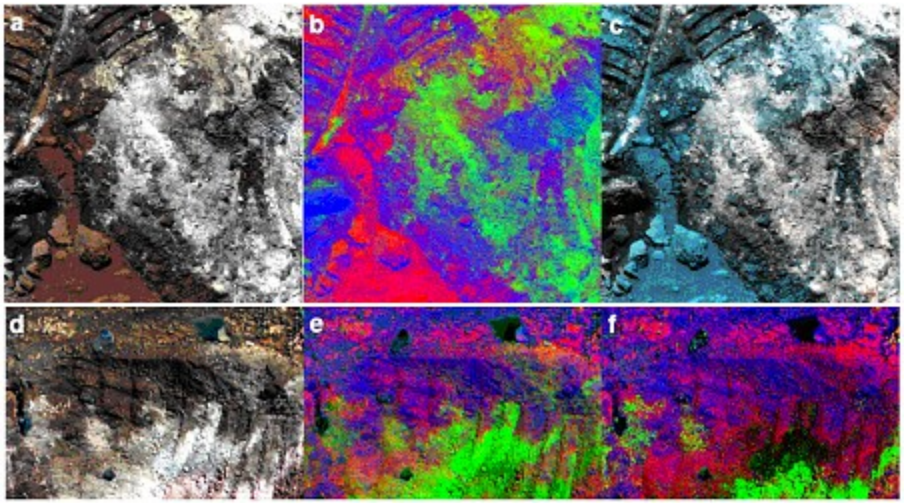

Figure 3 Pancam images of bright salty material at Paso Robles in Gusev crater, Mars. a & d) show R=673 G=535 B=436 nm (dust as dark red and sulfate-rich phases as white and yellow). c) shows R=482 G=753 B=864 nm (shows sulfate unit similar at these channels). b,e & f) map end-member components with R=dust, G=bright white, yellow and pink material from a & f), B=shade.

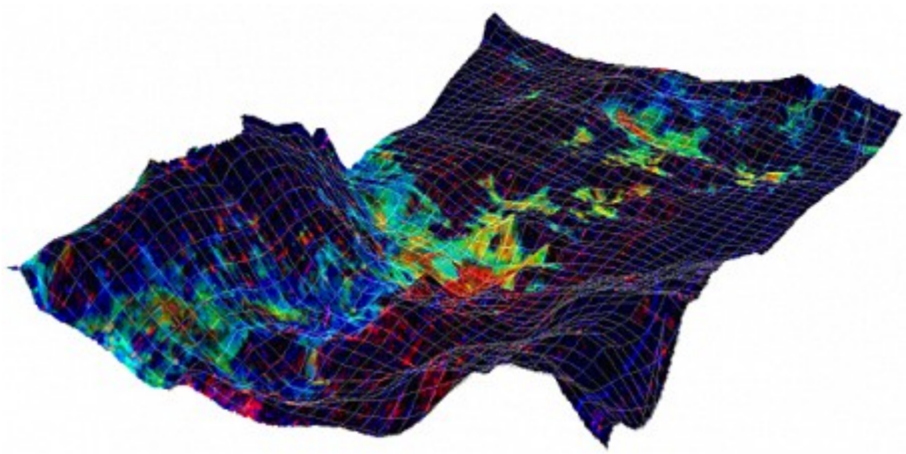

Figure 4 Map of clays in Mawrth Vallis, Mars, made from CRISM image draped over MOLA terrain. Fe/Mg-phyllosilicate is shown in red, Al-phyllosilicate is shown in blue, hydrated silica and an Fe2+ phase is shown in yellow/green.

Planetary-Scale Transition From Abiotic to Biotic Nitrogen Cycle

Summary

Nitrogen is an essential element for life. Understanding the planetary nitrogen cycle is critical to understanding the origin and evolution of life. The earth's atmosphere is full of nitrogen gas (N_2). However, this large pool of nitrogen is unavailable to most of the life on earth except a few microbes capable of "fixing" nitrogen into a form that can be used by other organisms (e.g., NH_3, NH_4^+, NO_x, organic-N). Without fixed nitrogen life would not have originated on earth and would most likely not occur on any other planet. The Atacama Desert in Chile is an enigma in that it contains vast nitrate (a type of fixed nitrogen) deposits. Elsewhere on earth, nitrate is either denitrified (transformed into N_2 and released back into the atmosphere) through the activity of microorganisms, or is dissolved and leached from the system. Although the Atacama is the driest desert in the world we have shown that lack of water alone cannot account for the lack of nitrogen cycling in this desert. Preliminary data suggest that it may be due to the high oxidation level of the soil in combination with a lack of organic material in the soil.

Accomplishments

Rocco Mancinelli & Amos Banin- Nitrogen is an essential element for life. Understanding the planetary nitrogen cycle is critical to understanding the origin and evolution of life. Of particular significance to prebiotic and biotic chemistry is "fixed N" (NH₃, NH₄+, NOx, organic-N). Without fixed nitrogen life would not have originated on earth and would most likely not occur on any other planet.

The Atacama Desert in Chile is an enigma in that it contains vast nitrate deposits. Elsewhere on earth, nitrate is either denitrified through the activity of microorganisms, or is dissolved and leached from the system. The low water supply (1-2 mm rainfall yr^{-1}) in the Atacama limits biological activity, including denitrification, and leaching of salts from the soil, and is hypothesized as the primary reason for the observed stability of nitrate. In some parts of the Atacama, such as Yungay (24°S, 69°W), the soil parent material is volcanic in origin. As a result, these soils contain high concentrations of oxidized transition metal minerals, particularly chromium and manganese, as well as perchlorate. The presence of these oxidized metals stabilizes the soil redox potential at high values, which may inhibit denitrification and also contribute to nitrate stability.

Data from measurements of salinity in the Atacama soils and other extreme deserts were compiled and analyzed as a possible close model for Mars soils. The aforementioned presence of perchlorate (ClO_4^-), a highly oxidized soluble salt of chloride is well established, but its ratio to the ion Cl^- has not been fully studied and is not well understood. The recent detection of perchlorate in the Polar Plains of Mars by the Phoenix Lander, if corroborated, is intriguing and its astrobiological ramifications may be assessed using results of previous chemical and biological tests conducted on the Atacama soils.

Denitrifiers in most soil environments are ubiquitous and should be in the atmosphere and falling to the desert surface. The results of experiments to isolate and culture denitrifying organisms from Yungay soils were negative. However, fragments of the nir-s gene could be amplified from the soil at a low level, suggesting that denitrifiers occur in the soil. It has been shown that very low concentrations of organic-C and organic-N exist in the surface soil, i.e. stable soil organic matter, which indicates very limited biological soil activity.

Rates of denitrification were determined using acetylene to block the reduction of N₂O to N₂. The soil samples were placed into vials fitted with syringe septa, and incubated for at least 10 hours, dry, wet, anaerobic, and aerobic. Controls were run with no acetylene. Periodically, gas samples were collected and analyzed via gas chromatography. Rates of nitrogen fixation were determined using the acetylene reduction method. No nitrogen fixation was detected, which is not unexpected due to the abundance of NO₃. Denitrification tests were negative, including those from the wet test, suggesting that low water activity alone cannot account for the lack of denitrification in this system. However, when an organic matter was mixed with the soil and incubated nitrite was produced. This suggests that denitrifiers are present in the soil, but the lack of organics (a potential electron donor) may account for the lack of denitrication in the system. Additionally, it is known that O₂ inhibits denitrification and raises the cell's redox level. Following from this we hypothesize that the high soil redox potential is also responsible for the lack of denitrification. To date, the Yungay region represents the only place in the world where anaerobic denitrification cannot be detected in the presence of nitrate.

Surface Processes and Surface-Subsurface Transport on Europa

Summary

This project looks at Jupiter's moon, which has a subsurface ocean under its icy surface. We have three main components -- we are studying images taken by the Galileo spacecraft, we are looking at different geological features to determine their potential to be involved in the vertical transport of material to and from the surface ,and we are studying one process, impact gardening by small micrometeorites that churn the surface, in detail.

Accomplishments

Chris Chyba, Cynthia Phillips, Kevin Hand- The project has two components. The first, an overview of the astrobiological potential of various geological features on Europa, is proceeding well -- we are continuing the study of various proposed formation mechanisms for different feature types such as ridges, bands, and chaotic terrain. The second, a search for current geological activity by comparing Galileo images taken on different orbits, is also in progress. We have completed a first-stage search of the Galileo Europa images to find overlapping images, and are continuing to work on improving our automated search method to make sure that we find all possible comparison images. We have processed a number of comparison pairs, and are currently working on automated techniques for speeding up the comparison process. In addition, a related project to study impact gardening on Europa and its potential for surface -- subsurface transport of potential biogenic materials has reached some interesting conclusions thanks to the input of undergraduate student Lisa Grossman from Cornell University who worked with Phillips at an REU student in 2007. The gardening depth on Europa is thinner than we thought, probably only about a centimeter. This means that sputtering will tend to win out over gardening, and that less material can be mixed down to Europa's subsurface beneath the radiation processing layer to be preserved. The project resulted in a number of conference presentations, and a publication is currently in preparation.

We also received funding from the NAI DDF to include 4 extra students in our NSF-funded REU summer program that brings undergraduate students from around the country to the SETI Institute to do research in astrobiology (Figures 1, 2). The four students received a stipend, travel, and housing for the summer. The students were selected in a competitive process from a pool of over 100 applicants. The selected students were: 1) Matthew Levit, from La Salle University, who worked with Scott Sandford and Stefanie Milam of the NASA Ames NAI team on a project doing laboratory experiments with interstellar ice materials important for prebiotic organic chemistry, 2) Alicia Muirhead, from UC Santa Cruz, who worked with Janice Bishop on a project related to the surface composition of Mars using laboratory data and data from the CRISM instrument on Mars Reconnaissance Orbiter, 3) William Swearson, from University of North Dakota, worked with Hector D'Antoni and Jay Skiles of the Ames NAI team, on a project related to paleoclimatology and early Earth conditions relevant to the origin of life, and 4) Shicong Xie, from UC Berkeley, who worked with Friedemann Freund on a project related to the physics and chemistry of rock alteration.

The students all will present a talk at the end of the summer summarizing their research, to which members of the SETI Institute and Ames NAI teams, and NAI Central, will be invited. The DDF funding also helped support Cynthia Phillips who ran the program.

Figure 1. The 2008 SETI Institute REU students on a field trip to Lassen Volcanic National Park to study extreme environments for life.

Figure 2. REU student Efrosini Proios, from the College of San Mateo, worked on a microbiology project studying halophiles with SETI NAI Team PI, Rocco Mancinelli.

The High Lakes Project (HLP)

Summary
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The High Lakes Project is a multi-disciplinary astrobiological investigation studying high-altitude lakes between 4,200 m and 5,916 m elevation in the Central Andes of Bolivia and Chile. Its primary objective is to understand the impact of increased environmental stress on lake habitats and their evolution during rapid climate change as an analogy to early Mars. Their unique geophysical environment and mostly uncharted ecosystems have added new objectives to the project, including the assessment of the impact of low ozone/high solar irradiance in non-polar aquatic environments, the documentation of poorly known ecosystems, and the quantification of the impact of climate change on lake environment and ecosystem.
Data from 2003 to 2007 show that solar irradiance is 165% that of sea level with instantaneous UV-B flux reaching 17W/m2. Short UV wavelengths (260-270 nm) were recorded and peaked at 14.6 mW/m2. High solar irradiance occurs in an atmosphere permanently depleted in ozone falling below ozone hole definition for 33-36 days and between 30-35% depletion the rest of the year. The impact of strong UV-B and UV erythemally-weighted daily dose on life is compounded by broad daily temperature variations with sudden and sharp fluctuations. Lake habitat chemistry is highly dynamical with notable changes in yearly ion concentrations and pH resulting from low and variable yearly precipitation. The year-round combination of environmental variables define these lakes as end-members. In such an environment, they host surprisingly abundant and diverse ecosystems including a significant fraction of previously undescribed species of zooplankton, cyanobacterial, and bacterial populations.

Accomplishments
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Nathalie Cabrol- In 2007, HLP focused on lakes located in the Chilean altiplano. Activities : (1) the retrieval of data from our Eldonet UV station, the retrieval of the station, and the positioning of a short UV wavelength dosimeter at the summit of the Simba (volcano); (2) the exploration of new investigation sites, including Laguna Lejia and Laguna Aguas Calientes; (3) Data analysis and interpretation; (4) Presentation of results at the NASA Astrobiology conference in Santa Clara, and the preparation of a special issue on HLP for the Journal of Geophysical Research-Biogeosciences.


Figure 1. Ostracod (3.2 mm across) from the Licancabur lake. Previously undescribed species of the genus Amphycitris. Identification and taxonomy performed by Ricardo Lourenco Pinto, Universidade de São Paulo, Brazil.

Training for Oxygen: Peroxy in Rocks, Early Life and the Evolution of the Atmosphere
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Summary

We try to find answers to a range of deep questions about the early Earth and about the origin and early evolution of life. How did the surface of planet Earth become slowly but inextricably oxidized during the first 2 billion years? We present evidence that it was not through the early introduction of oxygenic photosynthesis but through a purely abiotic process, driven by the tectonic forces of the early Earth and the weathering cycle. Only much later in Earth's history, about 2.4 billion years ago, did photosynthesis kick in, boosting the oxygen level in the atmosphere to the levels that we enjoy now. If this is so, other Earth-like planets around other stars can be expected to undergo the same evolution from an early reduced state to an oxidized state.

Accomplishments

Friedemann Freund & Lynn Rothschild– The major objective of this task is to study the causes for the slow but inextricable oxidation of the Earth over the first 3 Gyr of its history. Contrary to the widely held belief that planet Earth became oxidized due to the activity of early photosynthetic microorganisms, we have shown that there is an alternative, entirely abiogenic pathway toward global oxidation: the presence of oxygen anions in the minerals of common igneous rocks that have converted from a valence of 2-- to a valence of 1-- (peroxy). Upon weathering this peroxy fraction hydrolyzes to hydrogen peroxide, which in turn oxidizes reduced transition metal cations, foremost ferrous iron to ferric iron. This is expected to lead to the precipitation of ferric oxides and, hence, to the deposition of Banded Iron Formations (BIF) in the ocean. After a sufficiently long time, 1-2 billion years, the continental rocks will evolve toward andesitic-granitic compositions, releasing less ferrous iron during weathering, and free oxygen will begin to be injected into the atmosphere. The presence of oxygen in the valence 1--, in the form of peroxy, has yet another important consequence: Upon stressing the rocks, the peroxy bonds break up and generate mobile electronic charge carriers, defect electrons, also known as positive holes. The positive holes have the unusual capacity that they can flow out of the stressed rock volume. They generate electric currents that can reach or exceed 100,000 amperes, if the stressed rock volume is a cubic kilometer in size. The major discovery of early 2007 was that this electric current converts quantitatively into hydrogen peroxide, H_2O_2, at the rock-water interface. This finding opens the door to re-assess the conditions that primitive microorganisms, living in contact with rock surfaces, must have encountered on the early Earth. Through 2007 we continued to measure the electric currents flowing out of stressed rocks in order to gain a handle on the total amount of peroxy oxygen in a given rock. So far we have confirmed that the concentrations of peroxy oxygen in igneous rocks, in particular in gabbro and anorthosite, are higher than previously thought, but quantitative data are not yet available. In early 2008, we procured a dissolved oxygen (DO) meter and a pH meter to continuously measure the formation of hydrogen peroxide at the rock-water interface. We have set up the two meters and began operation. We encountered a problem because the DO meter consumes dissolved oxygen during measurements. To correct for it we have to find a way to independently determine the consumption rate. This work is in progress.

2008 SETI Members
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Rocco Mancinelli
Peter Backus
Amos Banin
Ranor Basa
Molly Bentley
Janice Bishop
Milton Bose
Nathalie Cabrol
Guillermo Chong
Cecilia Demergasso
Cristina Dorador
Darby Dyar
Samy El-Shall
G√∂zen Ertem
Erich Fleming
Friedemann Freund
Victor Gaete
John Gibson
Edmund Grin
Lisa Grossman
Katherine Harris
Gloria Hovde
Antonia Hubbard
Donat-P H√§der
Bishun Khare
Patrick Kociolek
Ipek Kulahci
Ragnhild Landheim
Melissa Lane
Darlene Lim
Edwin Minkley
Gary Niederhoff
Mairo Parente
Cynthia Phillips
Lee Prufert-Bebout
Alessandra Ricca
Dana Rogoff
Lynn Rothschild
Carlos Salazar
Seth Shostak
David Summers
Cristian Tambley
Jill Tarter
Ingrid Ukstins Peate
Barbara Vance
Kimberly Warren-Rhodes
Clayton Woosley
Huifang Xu

2008 SETI Publications
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