Astrobiology at Arizona State University: An Overview of Accomplishments

Final Report for Grant NCC2-1051
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Background and Introduction

During our five years as an NAI charter member, Arizona State University sponsored a broadly-based program of research and training in Astrobiology to address the origin, evolution and distribution of life in the Solar System. With such a large, diverse and active team, it is not possible in a reasonable space, to cover all details of progress made over the entire five years. The following paragraphs provide an overview update of the specific research areas pursued by the Arizona State University (ASU) Astrobiology team at the end of Year 5 and at the end of the 4 month and subsequent no cost month extensions. For a more detailed review, the reader is referred to the individual annual reports (and Executive Summaries) submitted to the NAI at the end of each of our five years of membership. Appended in electronic form is our complete publication record for all five years, plus a tabulation of undergraduates, graduate students and post-docs supported by our program during this time.

The overarching theme of ASU's Astrobiology program was "Exploring the Living Universe: Studies of the Origin, Evolution and Distribution of Life in the Solar System". The NAI-funded research effort was organized under three basic sub-themes: 1. Origins of the Basic Building Blocks of Life, 2. Early Biosphere Evolution and 3. Exploring for Life in the Solar System. These sub-theme areas were in turn, subdivided into Co-lead research modules. In the paragraphs that follow, accomplishments for individual research modules are briefly outlined, and the key participants presented in tabular form. As noted, publications for each module are appended in hard copy and digital formats, under the name(s) of lead Co-Is.

Theme 1: Origins of the Basic Building Blocks of Life

At ASU, the origins of living systems focused primarily on understanding 1) exogenous sources of carbon compounds (through studies of the cosmoschemistry of carbonaceous meteorites) and 2) by experiments to examine endogenous processes for the abiotic synthesis of organics (specifically, deep sea hydrothermal vent environments).

A. Cosmochemistry of carbonaceous meteorites.

Co-I Laurie Leshin and her group lead studies of the chemistry of carbonaceous meteorites. During Year 5, the group coupled models of accretionary processes in the early Solar System, with D/H estimates obtained from meteorites, to produce consistent water delivery scenarios for the Earth and Mars (Lunine et al., 2003). In addition, Astrobiology Postdoctoral fellow, Michele Minitti showed that the high D/H values of Martian rocks probably did not result from shock (Minitti et al. 2004). Research into nature of hydrous alteration environments on carbonaceous meteorite parent bodies was also published by NAI Astrobiology Postdoc Gretchen Benedix in Geochemica et Cosmochemica Acta (Benedix et al. 2003). Using a combination of oxygen isotopic, electron microprobe and petrographic methods, this study established the nature and timing of aqueous alteration processes on the meteorite parent body. In addition, C isotope data provided new constraints on magmatic and surficial carbon reservoirs in the Martian carbon cycle (Goreva et al., 2003, Niles et al., in prep.)

Laurie Leshin	ASU	Lead Co-I
Sandra Pizzarello	ASU	Co-I
Michelle Minitti	ASU	Post-doc
Paul Niles	ASU	PhD student
Julia Goreva	ASU	Post-doc
Yunbin Guan	ASU	Research Staff
Amy McAdam	ASU	PhD Student
Jonathan Lunine	UA	Collaborator
Thomas Ahrens	Caltech	Collaborator
Sabine Airieau	UCSD	PhD Student
Mark Thiemens	UCSD	Collaborator
James Farquhar	Maryland	Collaborator

B. Abiotic synthesis of organic compounds in hydrothermal environments. Co-I's John Holloway and Peggy O'Day lead an effort to understand the endogenous (terrestrially-based) synthesis of prebiotic organic compounds at high temperatures, specifically, seafloor black smoker hydrothermal systems. During Year 5, the group advanced a corollary to their previously published hypothesis that the degassing of seafloor basaltic magmas can provide hydrogen and carbon dioxide for abiotic organic syntheses (Holloway & O'Day, 2000). This study also showed that the same processes can operate in conjunction with silicic magmas (Holloway, 2003). The team also continued to explore the synthesis of organic compounds from hydrogen and carbon dioxide in the presence of mineral catalysts under seafloor hydrothermal conditions. In this work they showed that smectite clay minerals, common in seafloor hydrothermal deposits, provide reactive sites for synthesis of complex organic compounds, such as hexamethylbenzene and long-chain methyl esters from aqueous methanol solutions (Williams, et al., 2002; Canfield, et al., 2003).

The Holloway-O'Day group also applied synchrotron computed microtomography to characterize hydrothermal microhabitats by imaging the physical structure of young hydrothermal chimneys from 9°N East Pacific Rise. This analysis showed that the internal structure of sulfide chimneys consists of a loosely connected network of euhedral mineral grains (predominantly sulfide by bulk X-ray diffraction analysis) and is dominated by diffuse (i.e., unchannelized) flow. Imaging established that the physical structure of sulfide chimneys can indeed serve as an effective molecular sieve for the adsorption of organic compounds and bacteria from vent fluids and seawater. This work provided the basis for formulating a model to explain how organic compounds could accumulate on catalytic mineral surfaces under pre-biotic conditions.

John Holloway	Arizona State Univ	Lead Co-I
Peggy O'Day	Arizona State Univ	Co-I
Ken Voglesonger	Arizona State Univ	PhD student
Dawn Ashbridge	Arizona State Univ	PhD student
Eileen Dunn	Arizona State Univ	Research Staff
S. Craig Cary	Univ. of Delaware	Collaborator

Theme II: Early Biosphere Evolution

The early evolutionary history of living systems on Earth was addressed in a variety of ways at ASU, including ecological and molecular studies aimed at understanding the origins of photosynthesis, studies of microbial fossilization in modern terrestrial environments (with applications for interpreting the biosignatures preserved in ancient terrestrial (and extraterrestrial) geological materials), by novel approaches to the reconstruction of paleoenvironmental conditions on the Archean Earth (with implications for early Mars) and by understanding the role of impacts in shaping the early biosphere.

The appearance of oxygenic photosynthesis is regarded as one of the pivotal evolutionary events in the development of Earth's biosphere because the accumulation of photosynthetic oxygen at the Earth's surface and in the atmosphere ultimately paved the way for the origin of advanced multicellular life and human intelligence. Continuing controversies over the paleoenvironmental context and biogenicity of the oldest known terrestrial fossils, as well as the origin of putative fossil biosignatures in Martian meteorite ALH 84001, have emphasized the need to develop more robust chemical and morphological criteria for the recognition of ancient environments and fossil biosignatures in ancient rocks. At ASU, an interdisciplinary effort has been underway to address important aspects of the nature of Precambrian paleoenvironments and to define new approaches to approaches to fossil biosignature capture, preservation and detection in ancient terrestrial and extraterrestrial materials.

A. Origins of oxygenic photosynthesis.

During Year 5, Co-I Robert Blankenship lead a group to study the origin and evolution of photosynthetic systems. This effort involved a broadly-based interdisciplinary collaboration between a half-dozen partnering universities. The Blankenship team continued their search for novel phototrophs by exploring aphotic environments of hydrothermal vents. It has been discovered that deep-sea hydrothermal vents emit a small amount of fluorescent light from both thermal and non-thermal sources. This emitted light has been suggested to be a potential energy source for primitive photoautotrophic organisms. Organisms collected during a 2001 field expedition to hydrothermal vents of the Nine North vent system of the East Pacific Rise, were successfully cultured in the laboratory and are being evaluated for their phylogenetic affinities and metabolic capabilities. Additional light measurements taken at vents along the Mid-Atlantic Ridge and yielded results similar to vents in the Pacific (White et al. 2003). This work on alternative energy sources holds important implications for the exploration for habitable environments elsewhere in the Solar System (e.g. deep ocean floor environments of Europa).

Field and laboratory studies of photosynthetic organisms in iron-rich environments also showed that some photosynthetic organisms utilize reduced iron as an electron donor. This has important implications for understanding the origin of banded iron formations on the Precambrian Earth and for interpreting the history of atmospheric oxygen. The Blankenship team isolated and analyzed mutant proteins that are potential candidates for Fe-oxidizing complexes that may have been important on the early Earth.

B. Origins and preservation of fossil microbial biosignatures in hydrothermal and saline, alkaline lake environments.

The interpretation of biosignatures in ancient terrestrial and extraterrestrial materials depends critically upon an understanding of the processes of microbial fossilization, the nature of inherent biases in biosignature capture and preservation and the effects of diagenesis (post-burial alteration) on long-term biosignature retention. The most relevant systems for study are those extreme environments, which provide good analogs for the ancient Earth, or other planetary settings, like Mars. During Year 5 of NAI membership, a group lead by Co-I Jack Farmer completed a study of the fossilization processes associated with carbonate oncoids (spherical stromatolites) forming in the Rio Mesquites, Cuatro Cienegas Basin, Central Mexico. Results were reported at the NAI general meeting and a manuscript is in preparation. This work was done in close collaboration James Elser and group (see subsequent module description for Cuatro Cienegas) who have been studying the ecological aspects of the same system (see below). The paleontological study established that surface biofilms have a bi-layered community structure, with the upper zone being dominated by several groups of larger, mostly erect-growing filamentous cyanobacteria and many species of diatoms. Microelectrode studies showed that these surface species effectively control precipitation of calcium carbonate through photosynthesis. However, most mineralization occurred at a depth of 1-2 mm below the biofilm surface in association with a subsurface community that was dominated by smaller filamentous species. Pervasive carbonate precipitation at this depth entombed the deeper community, preserving numerous cellular remains. Interestingly, species of the surface community were rarely preserved, creating a strong taphonomic bias toward preservation of the subsurface community.

Farmer's group also began a study to characterize bioflims and microbial fossil assemblages associated with low temperature, carbonate-precipitating springs on the floor of Mono Lake, an alkaline-saline lake located in eastern California. (This comprises the topic of a PhD dissertation by Mike Thomas). The goal of the study was to trace the fate of biosignatures from their initial capture during carbonate precipitation, through early diagenetic mineral transformations of unstable phases. The results of the work in Mono Lake will be compared with ancient carbonate spring deposits elsewhere in the Mono Basin that were formed during the last glacial period when the lake was much deeper and colder. The work in the Mono Basin involved a collaboration with the Woods Hole team who are focusing on the eukaryotic biodiversity of Mono.

Hydrothermal systems are regarded as widespread environments on the early Earth and provide a window into early biosphere evolution. Studies of subsurface hydrothermal and contiguous surface travertine spring deposits in the Furnace Creek area of Death Valley, provided a basis for 1) evaluating the utility of microfabric associations for establishing a paleoenvironmental context and 2) examining the persistence of microbial biosignatures in deposits that had undergone significant diagenesis. Conclusions of the study, which formed the basis of a Masters Thesis for Tomoko Adachi, were that microfabric-specific oxygen isotope signature preserve important paleotemperature information of the original system (despite substantial diagenetic alteration) and that microbial biosignature preservation consists primarily of meso- and micro-scale biofabrics. A noteable exception was the discovery of an indigenous thermophilic ostracode fauna, comparable to thermophilic ostracodes observed in some modern hot springs of the western US.

Jack Farmer	Arizona State Univ	Lead Co-I
Ferran Garcia-Pichel	Arizona State Univ	Collaborator
Brian Wade	Arizona State Univ	MS student
Valeria Routt	Arizona State Univ	MS Student
Mike Thomas	Arizona State Univ	PhD student
Tomoko Adachi	Arizona State Univ	MS student

C. Modes of microbial fossil preservation in Precambrian cherts.
Evaluating the nature of organic biosignature preservation at the cellular scale is an important line of inquiry that could eventually lead to robust criteria for the recognition of biogenic signatures in ancient terrestrial (and extraterrestrial) materials. During Year 5, Co-I Tom Sharp's group continued to apply methods of Analytical Transmission Electron Microscopy (ATEM) to characterize the nanometer scale microstructures and compositions of kerogenous microbial biosignatures preserved in the 2.0 Ga Gunflint Iron Formation (Moreau and Sharp 2004). Electron Energy-Loss spectroscopy (EELS) confirmed that microfossils are comprised of amorphous kerogen concentrated along grain boundaries of micro-quartz. Kerogen is amorphous, with little evidence for graphitization. In coccoidal microfossils, kerogen formed cell-wall like features

around cores of granular microquartz, whereas in filamentous forms, the kerogen was disseminated along needle-shaped grain boundaries that separated submicron-sized fibers of chalcedonic quartz. Sharp's team also applyied similar methods to the study of putative biosignatures in the controversial 3.5 Ga Apex Chert from Western Australia. The goal is to characterize the composition, crystallinity and distribution of the kerogen to determine whether this material is of biogenic or inorganic (hydrothermal) origin. This work is ongoing, but formed the basis an MS thesis by John Moreau and a PhD dissertation by Brad DeGregorio.

D. Origin of magnetite in Martian meteorite, ALH84001.

The hypothesis of a biogenic origin for magnetite grains preserved in carbonates of Martian meteorite ALH84001 has been touted as the most compelling line of evidence for Martian life by McKay et al (1996). During Year 5, Co-I Peter Buseck and colleagues continued their work with electron tomography and holography to evaluate the biogenicity of putative magnetite biosignatures in Martian meteorite ALH845001 (Buseck et al. 2002). The ultimate goal of the research was to determine whether the characteristics of crystal size distributions (CSDs) and shape factor distributions (SFDs) of magnetite obtained from magnetotactic bacteria can be used as mineral biosignatures. The group found that CSDs of magnetite obtained from 16 uncultured strains of bacteria showed both similarities and differences among crystals from bacteria from distinct localities and environments. Using a numerical method, the group sorted magnetite crystal populations based on features of the SFD of all particles and found that the numerical methods are useful for identifying bacterial magnetite in rocks. Basic conclusions may be summarized as follows: 1) Using electron tomography, there was too much uncertainty in TEM results to confirm a biogenic origin for the magnetite in meteorite ALH84001; 2) Magnetite crystals in bacterial strain MV-1, the standard for comparison for ALH84001 magnetites, showed variations in chain length and rounding of faces, which are not as well developed, or crisp as suggested in current published interpretations; and 3) Progress was made toward developing automated procedures for electron tomographic data acquisition, reconstruction, and visualization.

Peter R. Buseck	Arizona State University	Lead Co-I
Martha R. McCartney	Arizona State University	Co-I
Richard Frankel	California Polytechnic State University	Collaborator
Dennis Bazylinski	Iowa State University	Collaborator
Mihály Pósfai	University of Veszprém, Hungary	Co-author
Rafal Dunin-Borkowski	University of Cambridge, UK	Co-author
Matthew Weyland	University of Cambridge, UK	Co-author
Paul Midgley	University of Cambridge, UK	Co-author
Heiner Friedrich	Arizona State University	Research Professional
Kelli Donnelly	Arizona State University	Summer Intern

E. Inferring paleoenvironmental conditions on the early Earth (and Mars): The initial colonization of the land surface marked an important event in the evolution of the biosphere. This opened a whole new habitat dimension for biological occupation and dramatically expanded microbial involvement in global biogeochemical cycles.

During Year 5, Co-I Paul Knauth (Dept. of Geological Sciences) submitted a manuscript that described the geologic context of the world's oldest land-based microbial fossil assemblage, dated at 1.2 Ga (Apache Group paleokarst, north-central Arizona). A second study described cave deposits associated with the Apache Group paleokarst and putative microfossils entombed within these deposits. This latter study formed the basis for a PhD dissertation by Steve Skotniki and a mansuscript is in preparation. In addition, Knauth also completed a paleontological study of terrestrial caliche deposits developed through arid weathering of basalt lava flows (Knauth 2003). This particular study demonstrated the potential of caliche as a host medium for capturing and preserving microfossils on Mars and form preserving an isotopic signature of life. Caliche is a predicted weathering product on Mars, provided the planet once had a warm, wet climate, now proven by the MER mission.

L.P. Knauth	Arizona State University	Lead Co-I
S. Skotnicki	Arizona State University	Post-doc
Donald Lowe	Stanford University	Collaborator
Thomas Foltz	Arizona State University	MS student
Kathleen McFadden	Arizona State University	MS student
Donald Burt	Arizona State University	Collaborator

F. Role of Impacts in Early Biosphere Evolution.
Asteroid and cometary impacts have been identified as an important environmental and evolutionary agent throughout the history of Earth's biosphere. During Year 5, Co-I David Kring's group determined the distribution of impact-generated wildfires for the Chicxulub (end Cretaceous) impact event (~65 Ma) and illustrated how impact parameters (e.g., trajectory) can influence the distribution of wildfires (Kring and Durda, 2002). An invited review paper outlined the environmental and biologic effects of large impact events, like Chicxulub, throughout Earth history (Kring, 2003). The Kring group also continued their analysis of lunar impact melts, to determine the flux of impact cratering events in the Earth-Moon system, particularly during the first billion years of Earth's history (Daubar et al. 2002; Cohen et al. submitted). In an invited review paper, the group also explored the impact delivery of Earth's water, a key ingredient for life's origin (Campins et al., 2003) and initiated new directions in the study of impact-generated hydrothermal systems, habitats that may have been a particularly widespread and important during the early evolution of life on Earth.

David Kring	Univ. Arizona	Lead Co-I
Oleg Abramov	Univ. Arizona	PhD student

G. Microbially-based Ecosystems, Cuatro Cienegas Mexico: Windows for Lower Cambrian Ecosystem Structure and Function.

The sudden appearance of complex, well-skeletonized invertebrates at the base of the Cambrian marks a singular event in the history of our biosphere. In an incredibly short interval of geologic time (<10 million years), representatives of all of the modern animal phyla appeared. With the addition of large herbivores and predators, a new global ecology emerged, replacing the microbial mat-dominated benthic ecosystems that had previously been the norm. The rise of large, multicellular bottom dwellers is broadly correlated with the decline of stromatolites, the fossilized biosedimentary structures produced by microbial mats. The disappearance of stromatolites has been attributed to competitive exclusion by algae and/or disturbance by invertebrate grazers. Whatever the cause, the nature of simple microbe-based/grazer ecosystems, the role of environmental and genomic factors in the evolution of such ecosystems and the nature of nutrients and energy flows, provide an important context for evaluating the ecological and evolutionary context of the Cambrian explosion.

To better understand the ecological interactions that may have prevailed during the Cambrian transition, an interdisciplinary team of ASU and Mexican scientists, lead by Co-I James Elser (Dept. of Biology) studied the ecology of simple, microbially-based (fish-snail-microbial mat) ecosystems found in modern desert spring environments in the Cuatro Cienegas Basin, Central Mexico. Goals of the study included an improved understanding the energy flow within such simple ecosystems, an improved understanding of the ecological factors that contributed to explosive evolution within highly endemic clades, the nature of ecological interactions between grazers and stromatolite-producing microbial mat communities and mechanisms of microbial fossilization. Ultimately this highly interdisciplinary study (still ongoing) aims to test specific hypotheses about the ecological mechanisms that contributed to the Proterozoic decline of stromatolite-producing microbial ecosystems, as well as the ecological and evolutionary factors (particularly stoichiometric constraints on evolution, arising from disparities in C:N:P, that could have contributed to the Cambrian explosion that followed (Elser et al. in press).

During the last year the team tested the hypothesis that the metazoan grazers of stromatolitic microbes face a stoichiometric constraint that results from consuming microbial biomass with elevated C:P ratio (Elser et al. 2004; Elser et al. in press). This should lead to microbes having a high biomass C:P ratio due to extreme PO4 limitation under the well-illuminated, but highly oligotrophic spring fed environments that typify the study area. The study confirmed that environmental levels of PO4 at Cuatro Cienegas are indeed extremely low (<3 μg/L usually; levels of inorganic N are high) while organic matter in the surficial layers of various mats and oncoid stromatolites exhibits an extremely high C:P ratio, greatly exceeding values seen for other autotrophic communities in aquatic ecosystems and resembling the extremely nutrient-poor autotroph biomass observed in terrestrial ecosystems. The group also determined that PO4 added to Cuatro Cienegas waters containing algal mats or stromatolites is removed extremely rapidly and results in a significant lowering of biomass C:P in the mat. Does such P-enrichment of microbial biomass improve the performance of metazoan grazers, as we have hypothesized?

The first experiment to answer this question was performed during summer 2001, when a 2-week P-enrichment treatment lowered mat biomass from >3000 (by atoms) to ~900. Snails (*Mexithauma* sp.) grazing on P-enriched mats had higher RNA:DNA ratios than those feeding on unenriched control stromatolites (generally RNA:DNA ratio is considered a good indicator of growth rate). The encouraging results from 2001 inspired a larger, longer-term (2-month) experiment performed during summer 2002 when a factorial experiment was performed in which both PO4 and the presence / absence of snails were manipulated. Data indicated that PO4 enrichment lowered microbial C:P from ~1000 to ~100. However, in contrast to the 2001 experiment, snails on P-enriched stromatolites had lower RNA:DNA ratios and experienced high rates of mortality and significantly lower rates of tissue and shell growth. Thus, P enrichment in 2002 appears to have "poisoned" the snails. This outcome was perplexing but is comprehensible in light of recent findings related to another herbivore known to be often P-limited, *Daphnia*, which grows slowly when food C:P ratios are reduced to unnaturally low levels. It was hypothesized that *Mexithauma* has evolved in the presence of consistently low P availability and experiences routine P-limitation in nature; however, when exposed to unnaturally P-rich food, it suffers a growth penalty. Thus, the simple food webs at CC may be poised on a stoichiometric “knife's edge” with regard to phosphorus. Could the same have held true for the simple microbially-based ecosystems of the lower Cambrian. A summary of these results is in press in the Proc. Royal Society of London (Elser et al. in press)

The team also conducted a series of studies using microelectrode profiling and bulk incubations to quantify calcification rates of stromatolites. This appears to be the first time this type of experiment has been accomplished on modern stromatolites. Areal rates of calcification were determined to be very high (~150 mg CaCO3 cm-2 yr-1), similar in magnitude to those measured in tropical coral reefs. However, rates of bioerosion by invertebrates that grazed the same oncolites (based on an analysis of fecal pellet production) are only slightly lower (~106 mg CaCO3 cm-2 yr-1). This indicates that the system is in a precarious balance between net carbonate accumulation and destruction by consumers. This delicate balance could explain why stromatolites are so rare in grazer-dominated ecosystems. It also provides support for the grazer hypothesis as an explanation for the late Proterozoic decline of stromatolites. The results of this work were recently published in Geobiology (Garcia-Pichel et al. 2004).

Another goal of the Cuatro Cienegas study is to characterize the genetic and morphological diversity of its understudied biota (esp. microbes, cyanobacteria, and snails) in order to advance our understanding of the evolutionary forces that have affected species, especially the desert pupfish and snail species, which exemplify extraordinarily rapid diversification under environmental extremes of temperature and salinity.

With regard to microbial diversity, Garcia-Pichel (et al., 2002) described novel associations of cyanobacteria that exhibit exceptionally novel adaptations for buoyancy involving calcite as ballast. In addition, a new form of extremely rare fresh-water red alga is in the process of being formally described.

Collaborator Valeria Souza (UNAM) isolated nearly 3500 separate strains of eubacteria and archaea from various habitats (benign to extreme) at Cuatro Cienegas and characterized the DNA for 350 strains using RFLP with sequencing of the 16S rDNA in selected cases. Sequenced strains from cultivable bacteria include Gram-positive taxa (*Bacillus* and *Staphylococcus*) and an ample suite of Gram-negative forms (*Pseudomonas, Aeromonas, Aquaspirilum, Vibrio* and *Halomonas* predominate, while clones of uncultivable DNA show marine Archaea and taxa previously isolated at hydrothermal vents). Preliminary analysis of TRFLP patterns of CC microbes shows a moderate alpha diversity, with few species dominating the community (within a site) and a very large beta diversity (between sites) where each site has its own species. The observed dominance of marine species suggests the possibility that Jurassic limestones in the region (which have been subjected to extensive karstification), may have contributed to the microbial biodiversity of the system. This result has been submitted to the Proc. of the National Academy of Sciences (Souza et al. in press).

High levels of morphological diversity were also demonstrated for the hydrobiid snail *Mexipyrgus* by Co-Is Carol Tang and Peter Roopnarine. Morphometric analysis of samples of *Mexipyrgus* populations revealed an extremely high level of morphological diversification and differentiation among even closely adjacent habitats. A goal of future work will be to examine the ecogenomic basis of this diversification and to determine if the high degree of morphometric variation documented is controlled by dominantly environmental or genetic factors.

Jim Elser	ASU	Lead Co-I
Jack Farmer	ASU	Co-I
Tom Dowling	ASU	Co-I
Ferran Garcia-Pichel	ASU	Co-I
Carol Tang	Cal Academy of Science	Co-I
Valeria Souza	UNAM	Co-I
Luis Eguiarte	UNAM	Co-I
Peter Roopnarine	Cal Academy of Science	Collaborator

Evan Carson	ASU	PhD student
James Watts	ASU	PhD student
Brian Wade	ASU	M.S. student
Jen Harden	ASU	PhD student
John Schampel	ASU	Research staff
Anne Kelsen	ASU	Research staff
Ana Escalante	UNAM	PhD student
Rene Cerritos	UNAM	PhD student
John Gable	ASU	Undergraduate student
Karla Lopez,	UNAM	Undergraduate student
Pablo Castillo	UNAM	Undergraduate student
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Erika Aguirre	UNAM	Research staff
Ricardo Colin	UNAM	Research staff
Andrea Campusano	UNAM	Research staff
Zita Maliga	SFSU	M.S. student
Evan Saint-Pierre	UCSC	Undergraduate student
Michael Rothrock	ASU	Research staff
Valeria Routt	ASU	Undergraduate student

Theme III. Exploring for Life in the Solar System.

The active involvement of ASU astrobiologists in NASA missions to Mars and Europa has provided ongoing opportunities for research and training in the exploration for life elsewhere in the Solar System. Data from the MGS and Odyssey orbiters continued to provide the ASU team with new mineralogical and geomorphic information needed to explore the past water and habitable environments on Mars and for identifying high priority landing sites for future Mars missions for Astrobiology. Orbital data from the Galileo spacecraft has allowed critical testing of the hypothesis of liquid water environments on Europa, Ganymede and Callisto and provided a basis for the selection of high priority landing sites for Astrobiology. Involvement of ASU astrobiologists in various Mars Program missions, such as the Mars Exploration Rovers (Co-Is Christensen, Farmer and Greeley) and mission planning efforts during Year 5, all strengthened the NAI's contribution to NASA's missions.

Co-I Philip Christensen is Principal Investigator for four instruments on current missions to Mars, including the Thermal Emission Spectrometer (TES) instrument (onboard the Mars Global Surveyor (MGS) orbiter), the THEMIS instrument (onboard the Odyssey orbiter) and two mini-TES instruments (Mars Exploration Rover (MER) mission). Co-Is Greeley (2001-2002) and Farmer (2003) were Chairs of the Mars Exploration Payload Assessment Group (MEPAG), the primary community-based science strategy group for the Mars Program. Co-I Farmer also lead MEPAG's Astrobiology Science Steering Group and was Chair of the NAI Mars Focus Group. In 2003, Greeley and Farmer were members of the Mars Exploration Review Team (MERT) and MAST (Mars Ad Hoc Science Team), each an external oversight committee for the Mars Exploration Program. Greeley and Farmer are also participating scientists on the Mars Exploration Rover Mission and Phil Christensen is PI for the mini-TES instrument on MER. Co-I Laurie Leshin was PI for a Mars Scout mission proposal (SCIM). These diverse mission related activities provided excellent opportunities for NAI participtation in NASA missions and mission planning.

A. Astrobiological Exploration of Mars.
The Mars Global Surveyor Thermal Emission Spectrometer (TES) data continued to provide new information about the role of aqueous processes in shaping the history of Mars. Although no large-scale carbonate deposits have yet been detected on Mars, spectral evidence was obtained for the presence of H2O-bearing minerals and carbonates within Martian dust. Based upon spectral details of the dust, it appears that aqueously-formed zeolites are a possible candidate for an unbiquitous silicate mineral component of dust. The observation of carbonates in Martian dust was also confirmed during the MER mission in 2004.

TES data were also used to refine selection criteria for landing sites for the 2003 MER mission. Newly acquired images from the Thermal Imaging System (THEMIS) on the Odyssey orbiter were used to characterize the candidate landing sites at Merdiaini Planum and Gusev Crater in much greater detail than was previously possible. Many new geologic features at these sites were revealed with stunning clarity using THEMIS data, helping to further refine the geologic context of the MER landing sites.

Along with Gusev Crater, the specular hematite deposit at Meridiani Planum, discovered with TES data in 2001, was a designated as a primary landing site for one of two Mars Exploration Rovers launched in 2003. On Earth, coarse-grained (specular) hematite deposits only form in the presence of large amounts of water and most are hydrothermal in origin. Results of the Opportunity investigations at Meridiani Planum in 2004 showed that an evaporative paleolake once occupied that site.

Masters student Alice Baldridge, under Co-I Farmer's direction, developed detailed mineralogical ground truth for remotely sensed analog sites for Mars located in the Badwater Basin of Death Valley (Baldridge et al. 2004). MASTER (mid-infrared spectral) data were used to identify the locations of mineralogically-pure, end-member pixels (carbonate, sulfate and silicates) within the basin. To establish ground truth, end member pixels were located on the ground and sampled for detailed laboratory analysis of mineralogy. Laboratory methods included X-ray Diffraction, electron microprobe, electron microscopy, thin section petrography and point counting, lab and ground-based spectral analysis (using TES analog spectrometers). To aid spectroscopic identifications, a mid-IR spectral library was developed for evaporate minerals and added to ASU's spectral data base for use by the THEMIS project team who are still mapping at Mars. These spectra are also being used by the MER project team. Results of this study were used to establish abundance thresholds (for natural mixtures in the Badwater Basin) necessary for the detection of discrete evaporite deposits on Mars (especially carbonates, sulfates and silicates, including zeolites). Results suggested that at the coarse spatial of the TES instrument (3 km/pixel), the detection of carbonates and sulfates is unlikely. However, at the enhanced spatial resolution of THEMIS (100 m/pixel), both carbonates and sulfates should be easily detected, provided they are present at abundances exceeding ~15%. This work was published in the Journal of Geophysical Research-Planets last year (Baldridge et al. 2004)

A second Masters study was also completed during Year 5, which explored the margins of the north polar remnant ice cap of Mars, to search for sites of possible magma-cryosphere (volcano-ice) interactions. This work comprised a Masters thesis by Meredith Payne who has since entered the PhD program at Oregon State University. The study commenced with broad photo-geological reconnaissance of the north polar region of Mars, using Viking data to identify potential water-formed geomorphic features. This was followed by detailed studies at four sites, selected to cover a range of potential aqueous processes. Hypotheses posed for the origin of geomorphic features were tested using Mars Orbiter Laser Altimeter (MOLA) data and GIS tools (e.g. Digital Elevation Models) and comparisons to terrestrial analogs. In the course of this work, it was discovered that MOLA data is sensitive to sub-glacial topography in areas that have been recently deglaciated, but are still covered by snow. The ability to "see through the ice" broadens our access to polar geological history based on MOLA topography (Payne and Farmer, submitted, Icarus). In addition, the hypothesis of a pseudocrater origin for a small field of cinder cone-like features was tested using MOLA data. It was determined that they are more likely be of a subglacial origin, but still formed by a process involving liquid water (Payne and Farmer, submitted, JGR-Planets).

A highlight of Year 5 was the publication of a paper by Co-I Christensen in Science which provided an alternative hypothesis for the origin of the numerous seep sites identified previously by Malin and Edgett (2001) based on Mars Orbiter Camera (MOC) data (Christensen 2003). The Christensen paper was based on THEMIS visible imaging, which suggested that the seeps could have formed beneath snow-pack accumulated during a recent period of low obliquity, and not by outflows of subsurface water (e.g. hydrothermal brines), as previously suggested.

Reconnaissance studies of Astrobiology Martian landing sites for the Mars Exploration Rover mission, as well as detailed studies of the Gusev Crater landing site, provided another major focus for the project during Year 5. Gusev was selected as the site for the first MER (Spirit rover) landing, which occurred in

January 2004, while the hematite site at Meridiani Planum was chosen for the second MER (Opportunity rover) landing a few weeks later. Results of these landing site studies were presented at several community workshops, to the Mars Exploration Payload Analysis Group (MEPAG) and to the MER project team. Co-I Farmer was also a member of the MER Landing Site Selection Committee.

In addition to planning for NASA missions, Ronald Greeley also participated extensively in planning for the Mars Express mission, which was successfully launched by the European Space Agency in 2003 and has been mapping from Mars orbit the past year. Greeley is a Co-Investigator on the High Resolution Stereo Camera System (HRSC) imaging team and provided a list of high priority imaging targets for Astrobiology to the imaging team for use with that instrument. Similarly, Co-I Farmer provided a similar list of high priority Astrobiology targets to the CRISM instrument team (CRISM is a hyperspectral near-IR spectrometer which will be launched to Mars later this year).

Jack Farmer	Arizona State Univ	Co-I
Phil Christensen	Arizona State Univ	Co-I
Ronald Greeley	Arizona State Univ	Co-I
Vicky Hamilton	Univ of Hawaii	Post-doc
Jeffrey Moersch	Univ. of Tennessee	Collaborator
Steve Ruff	Arizona State Univ	Post-doc
Meredith Payne	Arizona State Univ	M.S. Student
Doug Grant	Arizona State Univ	M.S. student
Alice Baldridge	Arizona State Univ	M.S. Student
Ruslan Kuzmin	Verndansky Institute	Collaborator
David Nelson	Arizona State Univ.	Research Staff
Lynn Neakrase	Arizona State Univ.	PhD Student

B. Astrobiological Exploration of Europa

Co-I Ron Greeley's group completed a study of the "mitten" feature on Europa, which represents the extrusion of ice onto the surface from a subsurface source (Figueredo et al. 2002). As such, the mitten structure comprises a high priority target for the future exploration of Europa to search for past or present life. Pole-to-pole geological mapping of Europa was also completed for strips representing the leading and the trailing hemispheres of Europa. This mapping was to explore for potential latitudinal or hemispheric asymmetries in ice fracture patterns. Studies of ice deformation in another region of Europa provided evidence for crustal fore-shortening, important for understanding deformation processes in Europa's crust. Each of the above activities helped to further characterize the nature and evolution of surface-near-surface environments on Europa needed to further assess the potential for habitable zones of subsurface liquid water. It was concluded from an analysis of domes and other features on Europa that they are geologically young and appear to have brought material to the surface from beneath the ice crust. Additional global geological mapping of Europa was also initiated during Year 5 as a first step toward identifying key sites for future surface exploration of Europa. Current data for Europa obtained by the Galileo project are also being analyzed to further understand the potential for europan environments conducive for life (Figueredo et al. 2004).

Ronald Greeley	Arizona State Univ.	Lead Co-I
Patricio Figueredo	Arizona State Univ.	Post-Doc
Max Coon	NorthWest Res. Assoc.	Collaborator

Mars Focus Group

The Mars Focus Group was established to provide a forum within the NAI to identify important scientific goals, objectives and investigations for the astrobiological exploration of Mars and to help define mission priorities, measurement requirements and new technology developments needed to support Mars Astrobiology. Following its inception in 2001, membership of the NAI Mars Focus Group grew to >100 participants, with representatives from a broad array of scientific disciplines within Astrobiology. To enrich our discussions, scientists outside of the NAI were also encouraged to attend our meetings to help the group identify crucial programmatic recommendations for the astrobiological exploration of Mars. The Mars Focus Group helped to meet a critical need within NASA and the broader Mars science community by providing regular scientific input and recommendations to Mars program planners to ensure proper implementation of astrobiologically-relevant Mars missions. Results of previous site reviews and discussion summaries were archived on an NAI Mars Focus Group node of Arizona State University's Astrobiology Program website (http://astrobiology.asu.edu). The NAI Mars Focus Group also supported site selection related web archiving activities by the Center for Mars Exploration (CMEX), based at NASA Ames. NAI MFG annual activity reports for previous years are on file at NAI Central, NASA Ames. A few highlights follow:

In 2001 the Mars Focus Group responded to the programmatic crisis that ensued with losses of the Mars Climate Orbiter and Mars Polar Lander missions by preparing a white paper recommendation that defined program priorities for Astrobiology for the present decade of Mars exploration. This white paper was presented to a NASA Mars Architecture Team headed by Charles Elachi (now Director of JPL) and subsequently published and distributed to a broad spectrum of scientists in the Mars planning community.

In 2002, Mars Focus Group activities focused primarily on identifying high priority astrobiological targets on Mars for orbital remote sensing observations by MGS and Odyssey and for *in situ* exploration by landed missions (e.g. MER). Reviews of key landing sites were conducted by videoconference, with follow-up discussions to define landing site options and recommendations for the 2003 Mars Exploration Rover (MER) mission. To ensure that astrobiologically-significant sites were considered during the landing site selection process for MER, specific site recommendations were presented by NAI Mars Focus Group members at a series of four community-lead workshops and also conveyed to NASA's MER Landing Site Selection Steering Committee through Co-I Farmer.

Two of the Focus Group's top candidate sites, Meridiani Planum (the so-called "hematite site") and Gusev Crater were ultimately selected as the primary landing site choices for the twin MER rovers.

During the Summer and Fall of 2002, the NAI Mars Focus Group participated in joint videoconference presentations and discussions with the Mars Exploration Payload Assessment Group (MEPAG), the primary community-based forum for providing scientific recommendations NASA for planning future Mars missions. Discussions focused on a variety of topics, including a programmatic overview, the 2009 Mars Smart Lander mission and payload, the role of Mars sample return(s), and planning for post-'09 Mars Program science investigations (i.e., "science investigation pathways"). Recommendations from these joint discussions were presented in draft form to the MEPAG in September 2002 with many of those recommendations being carried forward into subsequent planning activities for the Mars Science Laboratory (2009) lander mission and investigation options for the decade of Mars exploration that will follow 2009.

In February of 2003, the Mars Focus Group met briefly during the NAI General meeting to review recent progress with then yet to be launched MER mission and to begin to outline potential future directions for the group. The initial three-year charter for the group ended in December. However, given the programmatic importance to the NAI and the past effectiveness of the MFG in representing the broader Astrobiology community, the NAI recently renewed the group's charter indefinitely, making it a standing committee. With ASU's failure to be renewed under CAN 3, the Mars Focus Group charter was not renewed under Co-I Farmer's leadership, but leadership responsibilities returned to the NAI.

In years past, several NAI astrobiologists were active members of MEPAG. But the fact is, Astrobiology has historically been under-represented in MEPAG meetings. Given the prominence of life-oriented themes in NASA's mission and vision statements, it is also worth noting that participation of astrobiologists on other NASA Mars Program advisory groups (e.g. SSES, SScAC, etc.) has also been quite limited. To facilitate participation by Mars Focus Group members in future NASA mission strategic planning activities, the NAI should consider: 1) providing travel funding to ensure attendance at future MEPAG meetings and 2) seeking to expand participation of astrobiologists on standing NASA committees. With regard to meeting crucial needs in the area of astrobiology instrumentation, the NAI MFG should work cooperatively with the newly proposed Astrobiology Instrumentation Focus Group to increase the involvement of biologists in technology development programs and to promote Astrobiology instrumentation developments for the next decade of Mars exploration. The Mars Focus Group should also work to encourage basic research activities in critical areas of Mars astrobiology that can directly contribute to future missions.

Jack Farmer (Chair)	Arizona State University
C. Alexander	Carnegie Inst.
Ricardo Amils	CAB
Sushil K. Atreya	Univ. of Michigan
Alice Baldridge	ASU
Olga Prieto Ballesteros	CAB
Brian Beard	U of Wisconsin
Steve Benner	U of Florida/Scripps
Robert Blankenship	ASU
B. Blumberg	NAI
Samuel Bowring	MIT
Adrian Brown	Australian Astrobiology Center
Carmen Cordoba-Jabonero	CAB
Gary Coulter	Colorado St. Univ.
Andrew D Czaja	UCLA
Wanda Lorraine Davis	SETI/NASA Ames
Rebecca Davis	ASU
David DesMarais	NASA Ames
Eileen Dunn	ASU
Doug Erwin	Smithsonian
David Fernandez-Remolor	CAB
Tom Foltz	ASU
Victor Parro Garcia	CAB
A. Gimenez	CAB
Matthew Golumbek	Jet Propusion Lab
Julia Goreva	ASU
F. Doug Grant	ASU
Ronald Greeley	ASU
Victoria E. Hamilton	U. of Hawaii
Andrew Hock	UCLA
John Holloway	ASU
Clark Johnson	U of Wisconsin
Tom Kieft	NMTech/JSC
A.H. Knoll	Harvard
Dana Kovaric	UCLA
Timothy J. Lee	Ames Research Center
Robin Lloyd	Space.com
Isela Maldonado	ASU
Jesús Martínez-Frías	Centro de Astrobiología (CSIC-INTA)
David McKay	JSC
Mark Messerli	MBL
Michelle Minitti	ASU
Michael Mischna	UCLA
David Morrison	Ames Research Ctr.

Paul Niles	ASU
Nora Noffke	Old Dominion University
Doug Grant	ASU
Meredith Payne	ASU
Juan Perez-Mercader	CAB
Sandra Pizzarello	ASU
Jeff Plescia	USGS
Margaret Race	SETI
Jim Rice	ASU
Valeria Routt	ASU
Steve Ruff	ASU
Bruce Runnegar	UCLA
Tom Sharp	ASU
David Smith	MIT
Leigh Anne Smith	UCLA
Mitchell Sogin	MBL
Sean Solomon	Carnegie Inst.
Valeria Souza	UNAM Ecology
Christopher Staples	ASU
Mike Tice	Stanford
Allan Treiman	LPI
Luis Vazquez Martinez	CAB
Brian Wade	ASU
Veronia Ann Zabala	ASU
Maria-Paz Zorzano	CAB

Europa Focus Group

The Europa Focus Group (EFG) was organized to foster research dealing with Jupiter's moon, Europa, and its potential as a habitat for past or present life. In addition, the EFG considered the principal science objectives for future exploration of Europa by spacecraft, including the critical measurements needed to understand its astrobiological importance.

Membership in the EFG included planetary scientists, biologists, terrestrial sea-ice experts, oceanographers, and space science technologists. The EFG was open to all interested members of the scientific community and functions primarily through workshops. The workshops provided a venue where participants could share relevant research results and establish collaborations which might not otherwise occur. During the workshops the participants also addressed specific scientific issues important for the exploration of Europa, such as defining instruments that should fly on future missions.

Two workshops were held during the five year period of the grant. At the September 2002 workshop, the scientific strategy for the exploration of Europa was discussed and objectives for a landed mission were formulated. Specific investigations and measurements were identified and prioritized. The results were then presented to the National Academy of Sciences (National Research Council) study team responsible for formulating the exploration strategy for the outer planet satellites in the coming decade. The results from the EFG were incorporated into the NRC final report.

The Arctic Ice Field Conference, held in Barrow, Alaska in April 2003, was organized to provide participants with the opportunity to observe sea-ice first-hand, in order to have a better understanding of the differences and similarities of a terrestrial ice province compared with the icy crust of Europa. Through an aerial reconnaissance and ground excursions, participants gained a better appreciation of the physics, chemistry, and biology of sea ice.

Ronald Greeley	Chairperson, ASU
David Agresti	Univ. of Alabama at Birmingham
Lou Allamandola	NASA Ames
Jeffrey Bada	Univer. California at San Diego
Amy Barr	Univ. of Colorado
Deborah Bass	JPL
Max Bernstein	NASA Ames
David Blake	NASA Ames
Diana Blaney	JPL
Henry Bortman	NAI website
Baruch Blumberg	NAI
Jerome Borucki	NASA Ames
Karen Bradford	NASA Ames
Karen Brinton	JPL
Bob Carlson	JPL
Christian Caron	Springer-Verlag, Germany
David A. Caron	Univ of Southern California
Frank Carsey	JPL
Ara Chutjian	JPL
Chris Chyba	SETI
Ben Clark	Lockheed-Martin Aeronautics
Simon Clemett	Johnson Space Center
David Cole	USA CRREL
Eric Collins	Univ. of Washington
Max Coon	NorthWest Res. Assoc.
John Cooper	GSFC/Raytheon
Dale Cruikshank	NASA Ames
Andy Czaja	UCLA
Brad Dalton	NRC/NASA Ames
Leonard David	Space.com
Wanda Davis	SETI/NASA Ames
Jody Deming	Univ. Washington

Steven D'Hondt	Univ. Rhode Island
Thomas Dowiak	Univ. of Alabama at Birmingham
Jason Dworkin	NASA Ames
Hajo Eicken	Univ. Alaska
Lisa Faithorn	NASA Ames
Jack Farmer	ASU
Larry Feinberg	ASU - microbiology
David Fernandez-Remolar	INTA
Michael Flynn	NASA Ames
Marilyn Fogel	Carnegie Instit. of Washington
Christian Fritsen	DRI
Rebecca Gast	Woods Hole Oceanographic Institution
Perry Gerakines	Univ. of Alabama at Birmingham
Zann Gill	NASA Ames
Nicolas Glansdorff	Vrije University, Brussels, Belgium
James Granahan	BAE SYSTEMS
Ronald Greeley	ASU
Will Grundy	Lowell Observatory
James Head	Brown
Tracey Herrera	UCLA
Paul Holland	Thorleaf Research Inc.
Chris House	Penn State
Louis Irwin	Univ. of Texas at El Paso
Robert Johnson	Univ. Vigrinia / Charlottesville
Torrence Johnson	JPL
Jeffrey Kargel	USGS
Jozef Kazmierczak	Polish Acad. Sciences
Stephan Kempe	TU-Darmstadt
Bishun Khare	NASA Ames
Krishan Khurana	UCLA
R.M. Killen	SWRI
Jim Klemaszewski	Arizona State University
Jennifer Kwong	NASA Ames
A. Lonne Lane	JPL
Matt Levy	Univ. of Texas
Jere H. Lipps	Univ. of California @ Berkeley
Robin Lloyd	Space.com
James Lyons	UCLA
Adam Maloof	Harvard
Ram Manvi	JPL
Nicholas Makris	MIT
Giles Marion	DRI
Tom McCollom	Univ. of Colorado
Tom McCord	Univ. Hawaii

Miles McPhee	McPhee Research Co.
Chris McKay	NASA Ames
Gary McMurtry	Univ. of Hawaii
Stanley Miller	Univ. of California at San Diego
L. Montoya	UNAM
Jeff Moore	NASA Ames
William Moore	UCLA
David Morrison	NASA Ames
Rafael Navarro-Gonzalez	UNAM
Susanne Neuer	ASU
Gian Gabriele Ori	In'tl Res. School of Planetary Sciences
Robert Pappalardo	University of Colorado
Victor Parro	Centro de Astrobiologia
Gerald Patterson	Univ. Colorado
Meredith Payne	ASU
Cynthia Phillips	SETI
Carl Pilcher	NASA
David Portree	Lowell Observatory
Olga Prieto Ballesteros	Centro de Estudios Universitarios
Daniel Prieur	Univ. de Bretagne Occidentale
Louise Prockter	JHU/APL
Matt Pruis	NorthWest Res. Assoc., Inc.
Guillermo Rodriguez	JPL
Valeria Timoteo Routt	ASU
Bruce Runnegar	UCLA
Scott Sandford	NASA Ames
Paul Schenk	LPI
Greg Schmidt	NASA Ames
Erland Schulson	Dartmouth College
Dirk Schulze-Makuch	Univ. Texas at El Paso
Miles Smith	University of Washington
Steven J Smith	JPL
Nicole Spaun	Ames Research Center
John Spencer	Lowell Observatory
Timothy Swindle	Univ. of Ariz.
Leslie Tamppari	JPL
Aaron Thode	MIT
Steve Vance	University of Washington
Luis Vazquez Martinez	Univ. Complutense de Madrid
Keith von der Heydt	Woods Whole Oceanographic Institution
Brian Wade	ASU
Kim Warren-Rhodes	NRC/NASA Ames
Chuck Weisbin	JPL
Llyd E. Wells	Univ. Washington

Ying Xu	Vrije Universiteit Brussel
Kevin Zahnle	NASA Ames
Daniel Zeigler	Ohio State Univ.
Wayne Zimmerman	JPL

Activities Under Four-Month Extension
A four-month extension of NAI funding enabled the continuation of project activities over the summer and into the Fall of 2003. Personnel affected by this extension included a four person office staff, under the direction of Principle Investigator Farmer, 12 Lead Co-I's, 35 additional Co-I's and collaborators, and 40 students and post-docs.

The following paragraphs highlight the research that was carried forward under the four-month extension. The research program affected by the extension consisted of ten modules that focused on the following areas: (1), Cosmochemistry of carbonaceous meteorites (Lead-Co-I Laurie Leshin); (2) Organosynthesis in hydrothermal environments (Lead Co-I's, John Holloway and Peggy O'Day), (3) Origins and early evolution of photosynthesis (Lead Co-I, Robert Blankenship), (4) Nature and preservation of the microbial biosignatures in extreme environments (Lead Co-I, Jack Farmer), (5) Nature and evolution of Archean Earth environments (Lead Co-I, Paul Knauth), (6) Ultrastructure and composition of Precambrian cellular microfossils (Lead Co-I, Tom Sharp), (7) EM tomography of ALH84001 and terrestrial magnetites (Lead Co-I: Peter Buseck) (8) Ecology and evolution of a microbially-based desert spring ecosystems (Lead Co-I, James Elser), (9) Astrobiological exploration of Mars (Lead Co-I's Phil Christensen, Jack Farmer and Ronald Greeley) and (10) Astrobiological exploration of Europa (Lead Co-I, Ronald Greeley), (11) Role of meteorite and cometary impacts on the history of life (Lead Co-I: David Kring, Univ. of Arizona).

(1) <u>The Cosmic Water and Carbon Cycles: Constraints from Studies of Primitive and Martian Meteorites</u>. Lead- Co-I: Laurie Leshin (Geological Sciences, ASU). *Goal:* Gain a better understanding of the origin, distribution and history in our Solar System of the essential ingredients for life, carbon and water. The extension enabled a continuation of research into the isotopic chemistry of Martian meteorites.

(2) <u>Synthesis of Organic compounds under simulated deep sea floor hydrothermal conditions.</u> Lead Co-I's John Holloway and Peggy O'Day (Departments of Geology and Chemistry, Arizona State University). *Goal:* Understand the potential for organic synthesis under hydrothermal conditions. Experiments were conducted to synthesize complex organic compounds under experimental hydrothermal conditions by simulating deep-sea vent (black smoker) environments. The extension enabled a continuation of the work on alcohol synthesis.

(3) <u>The Change from Anoxygenic to Oxygenic Photosynthesis and the Transition to an Aerobic World.</u> Lead Co-I: Robert Blankenship (Department of Chemistry and Biochemistry, ASU). *Goal:* Understand how and when oxygenic photosynthesis first arose on Earth. The four-month extension enabled continuation of the recently-published work on the molecular phylogeny of photosynthetic microbial groups and the culturing and characterization of novel, pigmented, deep-sea vent microbes, suspected of having photosynthetic

capabilities that take advantage of thermoluminescent light emitted by deep-sea vents.

(4) Microbial fossilization processes in extreme environments. Lead Co-I Jack Farmer (Dept. of Geology, Arizona State University). Goal: Understand the processes of biosignature capture and preservation in mineralizing hydrothermal spring and alkaline lake environments and the effects of diagenesis on biosignature retention. The extension enabled the completion of graduate student work on modern and ancient carbonate spring deposits in Mono Lake and Cuatro Cienegas and ancient hydrothermal deposits in Death Valley.

(5) Salinity and temperature environments of the Precambrian Earth. Lead Co-I: Paul Knauth (Dept. of Geological Sciences, ASU). *Goal:* Using tools of isotopic geochemistry, understand the nature of Precambrian environments as a context for early biosphere evolution on Earth. Examine implications for Martian environments as a context for exploring for extraterrestrial life. The extension allowed completion of work on Apache Group cherts (north central Arizona) to better understand their paleoenvironmental significance and to complete characterization of suspect microbial fossils found therein. This work formed the basis for a doctoral dissertation by Steve Skotniki.

(6) The structure and preservation of Precambrian cellular microfossils (Lead Co-I Thomas Sharp, Arizona State University). *Goal:* Understand the nature of cellular microfossil preservation in Precambrian cherts. The extension enabled progress to examine the biogenicity of carbonaceous materials in the Apex Chert. This work formed the basis for a masters thesis by John Moreau (Moreau and Sharp 2004) and a PhD dissertation by Brad DeGregorio (in progress).

(7) ALH84001 Magnetites: EM tomography on experimental and natural samples. Lead Co-I: Peter Buseck (Depts. of Geological Sciences and Chemistry/Biochemistry, ASU). *Goal:* Resolve current controversies over claims of biogenic magnetite in Martian meteorite ALH84001. The extension enabled comparisons of magnetite nanocrystals from the ALH84001 meteorite, with magnetites from natural, magnetotactic bacteria, in order to assess criteria for recognizing biogenicity.

(8) Ecosystem heterogeneity and the evolution of ecological structure: Observational and experimental studies in stromatolite-based food webs. Lead Co-I: James Elser (School of Life Sciences, Arizona State University) *Goal:* Understand the ecology, evolution and fossilization potential of microbially-based ecosystems living in extreme fluvial-lacustrine environments of the Cuatro Cienegas basin, Coahuila, Mexico. The four-month extension allowed completion of phosphate limitation experiments on cyanobacterial oncoids and their gastropod grazers at study sites along the Rio Mesquites, which were the focus of two graduate student thesis projects (one Masters, one Ph.D.).

(9) Exploring for Past Habitable Environments on Mars. Lead Co-I's, Phil Christensen, Jack Farmer and Ronald Greeley, Dept. of Geological Sciences, Arizona State University). *Goal:* Explore for evidence of recently active habitable zones of liquid water within ice-dominated surface environments of Mars, from mid- to polar latitudes. The extension allowed completion of two Masters theses and site selection studies to support the 2009 Mars Science laboratory mission.

(10) Evaluating the Astrobiological Potential of Europa.. Lead Co-I: Ronald Greeley (Dept. of Geological Sciences, Arizona State University). *Goal*: Develop plausible models for the origin and nature of a europan ocean. The extension allowed a continuation of geological mapping of Europa and a synthesis of data into general models, to predict the depth and longevity of a subsurface ocean.

(11) Impacts and the Origin, Evolution, and Distribution of Life. Lead Co-I: David A. Kring, (Lunar and Planetary Laboratory, University of Arizona). *Goal:* Define the role of impact cratering in the origin, evolution, and distribution of life on Earth, with an emphasis on improving our understanding of the biological and preservational potentials of impact-generated hydrothermal systems. The extension allowed a continuation of hydrocode modeling to understand how impact-generated hydrothermal systems evolve over time.

Project Management- The collaborative research activities outlined above were managed by the Institutional P.I. and Director of ASU's Astrobiology Program, Prof. Jack Farmer (Dept. of Geological Sciences, ASU) using the same principles of engagement followed during the first five years of the program: 1) Monthly meetings of Co-Is, 2) Regular email exchanges and 3) Monthly Astrobiology forums.

Institutional Commitments- Under a no-cost extension, ASU continued to provide furnished office space to maintain the Astrobiology Program at ASU and contributed the P.I.'s time to direct the program (20% FTE).

Training- The no-cost extension also enabled a continuation of the research and training of graduate students as outlined under each of the above modules from the summer of 2003, to the Fall of 2004. A list of students supported is included in the Appendices.

E&PO- ASU participated extensively in Education and Public outreach activities related to the launch of the Mars Exploration Rover mission, through regular interactions with the Public by ASU-NAI members Christensen, Farmer and Greeley.

Implementation of Collaborative and Networking Activities of the NAI- The ASU program remained active during the extension period through the the use of video- and desk-top conferencing. This included advertised videocons of the Mars Focus Group.