Yellowstone Resources and Issues Guide

Astrobiology

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ASTROBIOLOGY: LIFE THROUGH SPACE AND TIME

Why is NASA interested in the Natural History of Yellowstone? Part of NASA's mission is to understand the origin and evolution of life in a planetary context. To accomplish this mission NASA has created the Astrobiology program. Astrobiology seeks to understand the origin, evolution, distribution and future of life in the Universe. It involves the study of life on earth (the only place so far known to harbor life), as well as the exploration for habitable environments and life on other bodies in our Solar System and beyond. To understand how life began on Earth, it is necessary to study the origin of the chemical compounds that make up simple living systems as well as the physical factors needed to create an environment capable of supporting life. The pristine thermal springs of Yellowstone Park are especially important in this regard. They provide access to a wide variety of environmental extremes resembling those that were widespread on the early earth when life originated and that are also found today on other bodies in our Solar System, and possibly early Mars.

Current interpretations of the early history of Mars suggest many similarities with the early Earth and therefore raise the possibility that the early history of life on Earth could have a counterpart on Mars. Terrestrial experience suggests that, with techniques that can be employed remotely, ancient springs, including thermal springs, could yield important information. By delivering water and various dissolved species to the sunlit surface of Mars, springs possibly created an environment suitable for life, which could have been difficult, if not impossible, to attain elsewhere on the surface of Mars. The chemical and temperature gradients associated with thermal springs sort organisms into sharply delineated, distinctive and different communities, and so diverse organisms are concentrated into relatively small areas in a predictable and informative fashion (see section 3.7). A wide range of metabolic strategies (e.g., photosynthsizers as well as organisms that use chemical sources of energy) are concentrated into small areas, thus furnishing a useful and representative sampling of the existing biota. Mineral-charged spring waters frequently deposit chemical precipitates of silica, carbonate or iron that entomb microorganisms and preserve them as fossils.

The juxtaposition of stream valley headwaters with volcanoes and impact craters on Mars suggests that subsurface heating of groundwater may have once produced thermal springs there. On Earth, thermal springs create distinctive geomorphic features and chemical signatures that can be detected by remote sensing. Spring deposits can be quite different chemically from surrounding country rocks. Individual springs can be hundreds of meters wide, and complexes of springs occupy areas up to several kilometers. Benthic microbial mats and the resultant microbial sediments occupy a large fraction of the available area. The relatively high densities of fossils and microbial fabrics within these deposits make them highly prospective in any search for morphological evidence of life, and there are examples of microbial fossils in thermal spring deposits as old as 3.5 billion years.

1. How did we get here? The origin and evolution of life

Life on Earth requires liquid water, a source of nutrients (basic chemical building blocks) and a source of energy. The most prolific energy source is sunlight, which many surface-dwelling organisms exploit for the biosynthesis of organic matter. This process is referred to as photosynthesis and is discussed in more detail in section 1.2, below. However, prior to the advent of photosynthesis, early life forms may have exploited simpler, less abundant forms of chemical energy, such as those provided by hot springs and their subsurface counterparts. During the prolonged history of our biosphere, chemical energy sources have remained a mainstay for organisms that live in subsurface hydrothermal environments, or around hot vents on the deep sea floor where sunlight is unavailable. Recently scientists have become aware of a vast subsurface biosphere on the Earth, fueled by chemical energy. This subsurface habitat may account for as much as half of the Earth's total biomass. Such environments are very important to astrobiology because they provide the most likely energy sources for extraterrestrial life on more distant planets like Mars, or on some icy satellites in the outer solar system (e.g. the Galilean moons of Jupiter: Europa, Callisto and Ganymede) where surface energy from sunlight is inadequate to support photosynthetic life but where chemical energy sources, along with extensive groundwater systems (e.g., Mars), or subcrustal oceans (e.g., Galilean satellites) could provide habitable zones for life.

Chemical elements that are required for living organisms are referred to as the biogenic elements. The most important include carbon, hydrogen, nitrogen, oxygen, phosphorus and sulfur, as well as a number of trace metals like iron, molybdenum, nickel, and chromium. We know that all of these elements were forged within the hot interiors of ancient stars and later widely distributed throughout the Galaxy during end stages in the evolution of massive stars (supernova explosions). Given the widespread abundance of the biogenetic elements and amino acids (the most basic building blocks for life), both within our Solar System and beyond, the primary limiting factors for extraterrestrial life are liquid water and energy sources to drive the production of more complex biomolecules.

Much remains to be learned about the environment and composition of the early Earth. Because of this, scientists are studying and searching for the conditions that they believe were present when life began. If we know these conditions then perhaps we can discover the molecular building blocks from which life arose. Yellowstone National Park is one place where such studies are taking place. There is debate over the way the organic compounds of living organisms formed from simple inorganic compounds on early earth. Some believe that these compounds originated as an early anaerobic atmosphere containing methane, ammonia and hydrogen was "sparked" by lightning. It is now more commonly thought that organic compounds originated outside the earth and were brought here on comets or meteorites. Third hypothesis has recently shown that thermal springs on the deep sea floor can synthesize important prebiotic compounds.

An important goal of Astrobiology is to explore for habitable environments within our Solar System and beyond where liquid water exists in conjunction with exploitable energy sources (see Section 2, below). The steps in this exploration effort are many. But as a basis for formulating meaningful exploration strategies we naturally look to the earth to better understand the conditions necessary for life and how those conditions have varied over the roughly 4.6 billion year history of our planet, regulating biodiversity (see section 1.5, below) through geological and environmental change.

1.1 Environments for the origin and early evolution of life: The Yellowstone Connection Yellowstone hot springs provide a glimpse into the nature of the early biosphere. Understanding how life began on earth (the only place we know, for certain, that life has developed) is a natural starting point for astrobiology. Comparisons of the DNA sequences of many different microorganisms, along with their biochemical and structural differences, suggest that the last common ancestor of all living organisms today may have lived in a high-temperature environment, not unlike a Yellowstone hot spring. One idea is that the early biosphere was threatened by one or more giant meteor impacts that would have volatilized the oceans and created widespread hydrothermal conditions over the Earth. If this happened, it would have forced the earth's biosphere through a kind of hydrothermal bottleneck, wiping out all but the high temperature organisms. In this context, the thermal features of Yellowstone Park provide a kind of portal to the early Earth through which we might glimpse the nature of the primitive biosphere.

Research conducted on the microbial communities of Yellowstone hot springs has also extended scientific knowledge regarding the physical and chemical limits of life. This new area of biology is commonly referred to as extremophile research, that is, the study of life over its environmental extremes. For example, until recently, it was thought that life could not survive at any temperature near the boiling point of water because high temperatures denature proteins and nucleic acids, and disintegrate lipid membranes; all of which are essential building blocks of cells. However, studies of microbes in deep sea hydrothermal vent systems and terrestrial hot springs have shown that microbial communities can thrive at temperatures at or near the boiling point of water by creating special proteins and enzymes that maintain **or** assist in the repair of these important biomolecules. Similarly, low-pH (acidic) environments (below a pH of 4-5) are considered extreme and harsh to humans. Yet, it has been discovered that many microorganisms such as algae, archaea, bacteria and fungi can thrive under these conditions.

1.2 Why did photosynthesis emerge on earth?

Yellowstone microbial communities are studied to understand the origin and evolution of photosynthesis. Life began very early in earth's history, perhaps before 3800 Ma, and it achieved remarkable levels of metabolic sophistication before the close of the Archaean Eon, some 2500 My ago. This great antiquity of our biosphere indeed illustrates the rapidity with which life can arise on a habitable planet.

In order for life to exist, organisms must transform common inorganic compounds such as carbon dioxide and water into biochemical building blocks such as proteins and nucleic acids, which form functional biomolecules such as enzymes and genes. To achieve this, some organisms have the ability to transfer energy from other sources, such as solar energy or geochemical energy, into chemical energy that can be used to build the organic materials necessary for life. Not all energy sources are equal. Sunlight, for example, is much more abundant and energetic than geochemical energy, so use of solar energy would be more efficient. However, early organisms did not have the ability to transform solar energy. Such organisms are found at the highest temperatures of Yellowstone's hot springs. They are not visible to the naked eye. At slightly lower temperatures, white, gray, and pink filamentous organisms use dissolved chemicals such as hydrogen, sulfur or arsenic compounds as a source of energy (see section 3.7). These organisms resemble what is thought to be the last common ancestor, a chemosynthetic hyperthermophile (chemical-using, heat-tolerant organism). However, the quantity and efficiency of these chemicals as a source of energy is much less than that of highly energetic solar energy that hits the Earth. To harness this solar energy, organisms developed pigments. Pigments are colored substances that absorb light at certain wavelengths and reflect light at different wave-lengths. The absorbed light changes the electronic structure of the pigment slightly. In order to return the pigment to its original structure, the pigment molecule reacts with other compounds and, in so doing, converts those compounds to more energy-rich forms. It is in this way that organisms convert solar energy to a useful chemical energy, that is, the organisms photosynthesize. Organisms have different photosynthetic pathways. All pathways result in the oxidation of some biogenic compounds and the simultaneous reduction of compounds to form formation of organic matter. If the process produces oxygen, it is called oxygenic photosynthesis. If it does not, then it is called anoxygenic photosynthesis. The development of oxygenic photosynthesis was a significant evolutionary step. So also was the ability to tolerate, and eventually use, oxygen as a means for releasing energy during metabolism.

Yellowstone hot springs and their effluent channels harbor microbial mats constructed by the full range of photosynthetic microorganisms, including purple and green bacteria, cyanobacteria, and algae. (Cross reference relevant section 3:7 subsections) This is significant from an evolutionary perspective, because the different kinds of photosynthetic microorganisms appear to have different evolutionary histories (cross reference 3:7 section RE SSU rRNA trees) For example, the earliest type to evolve may have been a green nonsulfur bacterium. There is evidence that the more advanced cyanobacteria, which produce oxygen in photosynthesis, may have evolved from some combination amalgam of green and purple bacteria. It is clear that algae evolved through the development of symbiotic associations between single-celled eukarya and cyanobacteria, which eventually became chloroplasts that algae use for photosynthesis. Algae later gave rise to plants. Because there are microbial mats constructed by different types of photosynthetic microorganisms in Yellowstone, scientists have studied them to discover whether they have unique biogeochemical signatures that might be used to tell what kind of photosynthesis was conducted by their ancient fossilized counterparts. Such chemical signatures might also be used to generate unequivocal evidence on life elsewhere in the universe.

The earliest sedimentary rock record typically has been extensively altered by metamorphism. Thee term "Metamorphism" refers to all of the chemical and physical changes that occur in the rock after deep burial in the Earth's crust. This process typically takes a serious toll on microfossils. While rare, a microbial fossil record has been discovered in ancient rocks, and it dates back to the earliest periods of Earth history. In addition, the biological molecules and chemical pathways used during metabolism also provide a record of organism relationships. These dual records are highly complementary. The geologic record offers both the absolute timing of evolutionary innovations as well as their environmental context. The living biochemical record can reveal the sequence of development of key pathways and biomolecules. Recent molecular biological research has tapped this molecular record both by obtaining new sequence information for certain genes involved in photosynthesis and also by performing phylogenetic analyses upon the major groups of photosynthetic bacteria. Such work better defines the molecular origins of these groups, and it clarifies the great antiquity off anoxygenic photosynthesis.

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Organisms require biogenetic elements in specific forms for their metabolism and for biosynthesis of their organic cellular components. For instance, nitrogen is required to make proteins, which comprise about 50% of a cell. Although nitrogen commonly occurs in many forms (e.g., nitrate, nitrite N2 gas, and ammonia), in organisms it occurs in the form of ammonia in amino acids, the building blocks of proteins. Similarly, sulfur is required in the form of sulfide, even though it also occurs as elemental sulfur and sulfate. The cycling of elements among these various forms, which is thus essential to the survival of life on Earth, goes on behind the scenes, catalyzed by the diverse metabolisms of microorganisms. Although we cannot see the microorganisms or the chemical changes they catalyze, their collective actions can keep these cycles running to the benefit of all on Earth. In Yellowstone there is a dramatic example of one part of the sulfur cycle. At Roaring Mountain (see section 3.7), the hydrogen sulfide that is emitted in the steam vents and makes the place smell like rotten eggs, is the food for some unusual archaea and bacteria. They convert the sulfide to sulfuric acid, and the acid accelerates erosion of the mountainside. It also makes the environment at Roaring Mountain unfavorable for plant life. The sulfuric acid flows off to other places where microbes participating in the sulfur cycle convert it to sulfide, closing the loop

1.3 What makes Yellowstone microbial communities modern analogs of ancient systems?
Astrobiologists use inhabitants of modern analog environments in Yellowstone National Park to study ancient organisms, scientists also use the environments themselves to simulate ancient conditions to learn how past communities may have functioned. Because of the prevalence of "biologically-mediated sediments in the fossil record from 3.5 to 0.6 billion years ago, microbial mats, which are modern analogs of such communities, are studied with particular intensity. These studies allow astrobiologists to utilize modern techniques such as molecular biology and geochemistry to reconstruct how life functioned in the past, from the molecular level of genes all the way to the level of ecosystem function. The microbial mat communities in the hot springs are studied as analogs of ancient microbial communities (see section 3.7). These communities sometimes form “stromatolites”, defined as biolaminated sediments formed by the trapping and binding and/or precipitation of minerals by microorganisms (chiefly cyanobacteria.) Biolaminated, “stramatolitic” sedimentary rock structures have been found in very ancient rocks and they represent perhaps our most abundant and widespread evidence of early microbial ecosystems. However, many microbial communities, in Yellowstone, do not form sedimentary laminations. These nonlaminated communities represent additional examples of fossilized evidence of early life.

1.4 What signatures of past microbial life are found in Yellowstone? Through various metabolic and behavioral activities, living systems modify their environment and produce structures and organo-chemical products that comprise unique signatures for life. Some of these signatures for life can be fossilized and preserved. Fossil information comes in a variety of forms, ranging from the skeletal hard parts formed by large multicellular animals, to the woody materials produced by plants. The fossils produced by microbial life, although less familiar, are nonetheless very important, particularly for the fossil record prior to about 600 million years ago, when our biosphere consisted entirely of microbial life forms. The fossil biosignatures of microbial life range from megascopic sedimentary structures called biologically mediated sediments, to intermediate scale biofabrics, to microscopic cellular structures (microfossils) and biominerals, to chemical biomarkers (derived from descriptive cell components, as if “chemical fossils”). Micro paleontologists studying Yellowstone hot springs are interested in understanding all of these types of fossil biosignatures as a basis for interpreting the older records of life found on our planet. We have already mentioned the possibility that life originated at high temperatures. But after life appeared, hydrothermal environments are also likely to have been prevalent during the early history of our planet, providing widespread habitats for the early evolution of the biosphere.

Fossilization in thermal spring environments involves the complex interaction of physical, chemical and biological processes. Obviously, not all organisms or organic by-products they produce are preserved. Typically, >98% of the organic materials produced by organisms is completely degraded and recycled. However, under the right conditions, organic structures can be fossilized and preserved. For example, there are many examples of beautifully preserved fossil microbial cells found in ancient rock sequences on Earth. Such fossilized remains provide important insights into the early history of life on our planet, prior to the advent of multicelled animals and plants. Yellowstone hot springs provide a wonderful natural laboratory for studies of microbial fossilization because microbial life completely dominates at higher temperatures. The varied environments and microbial community types found along temperature gradients in Yellowstone hot springs allows access to an astounding array of conditions for studying the processes of fossilization. A key factor controlling fossilization process in Yellowstone Hot Springs is the typically rapid rate of mineralization that occurs when mineral-laden, subsurface water reaches the surface. Rapid mineral deposition occurs as spring waters surface begin to cool and de-gas. This lowers the solubility of minerals in solution, causing them to precipitate out as deposits broadly referred to as sinter, or geyserite. Understanding the basic processes that control fossilization and defining the nature of biases that favor the preservation of one group of organisms over another, are important research objectives that are helping scientists better interpret the ancient records of life on Earth.

The rapid precipitation of minerals around hot springs typically entombs numerous microorganisms and communities, preserving them as fossils. In most cases, microorganisms and entire mat surfaces become encrusted by precipitating minerals, and the organic materials eventually decayed away leaving molds of the original cells. But in some instances, particularly at lower temperatures, cells and related structures can be infused with minerals and preserved, in much the same way that wood is petrified.

The major challenge faced by microbes living in many hot springs is not the high temperature, or other environmental extremes, but rather entombment by precipitating minerals. Evidence for this process can be seen around many Yellowstone hot-springs where beautiful and complexly structured microbial mats are being actively encrusted by minerals and turned into hardened sinter. The details of the process are of great interest to paleontologists because they record a transitional state as organisms enter the fossil record. By comparing modern and ancient sinter deposits, paleontologists are also able to track changes in different types of microbial biosignatures as sinter deposits are buried and hardened into dense rock. One of the most informative paleontological studies to date involves the comparison of Yellowstone hot-springs and ancient sinter deposits found in Australia which have been dated at >350 million years. These ancient deposits are very similar in character to the siliceous spring deposits found in the Lower, Midway and Upper Geyser Basins of Yellowstone Park and reveal a lot about the changes that affect biosignature preservation during deep burial.

One goal of the work in Yellowstone is to prepare scientists to be able to recognize unequivocal signatures for life not only in ancient rocks from Earth, but also in samples from other planets, like Mars. For example, studies of fossilization processes in Yellowstone have contributed directly to the ongoing debate over putative signatures for life discovered in a Martian meteorite, ALH84001, found in the Alan Hills region of Antarctica in 1984. This meteorite contains globules of iron-rich hydrothermal carbonate minerals, which, in turn, contain a number of chemical and structural features interpreted by some to be fossil biosignatures. Although the biological interpretation for this meteorite remains highly controversial, the work points to the value of paleontological studies in hot-spring settings like Yellowstone in laying groundwork for the study of rocks returned from Mars. The first samples from Mars are expected to be returned during the next decade of exploration.

1.5 Evolution of diversity

The study of biodiversity in Yellowstone National Park extends from the microbiota to the macrobiota, The astrobiologists in Yellowstone are concentrating on the microbiota and are investigating hot springs to learn about the diversity, ecology and evolution of microorganisms inhabiting microbial communities. Evolutionary studies are of particular interest since thermophilic microorganisms appear to have evolved early in life's history on earth and because microbial mats are considered analogs of Earth's earliest fossilized communities.

Microbiologists have studied Yellowstone microbial communities intensively as model systems for understanding the composition, structure and function of microbial communities. Traditional methods of analysis such as microscopy and laboratory cultivation are not suited to the task. For example, many different microorganisms may share the same appearance. Additionally, collecting samples from the field and attempting to grow and isolate the microbes from them in the laboratory is difficult. The organisms that grow in the laboratory do not always represent those found most abundant in nature, because the laboratory environment does not mimic the variety of natural microenvironments that support the growth of microbes in nature. Hence, microbiologists have turned to using tools of molecular biology to discover the diversity that really occurs in hot spring microbial communities. Essentially, a gene found in the DNA of all organisms is recovered from the environment. Variation in the DNA sequence of this gene has been found to represent distinct microorganisms found under different microenvironmental conditions in nature. For instance, microbes adapted to different temperature and light conditions exist along temperature and light gradients. Microbiologists are discovering an incredible, heretofore unknown, collection of microbial species. In the process they are discovering the process by which microbial species form. As with plant and animal diversity, microbial biodiversity appears to have arisen through adaptive evolutionary radiation and geographic isolation.

2. Are we alone? The Search for Life Elsewhere in the Universe

In 1958, the United States Congress created the National Aeronautics and Space Administration, or NASA. Its purpose was to coordinate and conduct all aeronautical and space activities for the United States of America, except those of the military. Among the many current NASA programs the search for life outside our home planet is an important one. To assist this goal, NASA established the Astrobiology Institute, which consists of 15 partnering research and academic institutions around the country, which conduct interdisciplinary research, related to the exploration for extraterrestrial life.

While astrobiology is not synonymous with the search for life in the universe, it is a vital part of the enterprise. This search includes determining the limits of life, the factors that make a planet habitable, and how to recognize signs of current and past life within our solar system. (Particularly on Mars and the icy satellites of Jupiter, including Europa, Ganymede and Callisto). In searching for extraterrestrial life both within and eventually outside of our Solar System, scientists are following a three-pronged strategy to 1) search for microscopic life forms on other bodies in our Solar System (Mars and Europa) using robotic and eventually human means of exploration, 2) explore for life outside the solar system with powerful telescopes that search for habitable planets around other stars in the nearby galaxy, and, 3) by scanning the skies for radio signals from advanced civilizations through a project called SETI (Search for Extraterrestrial Intelligence).

Future Exploration?

Future destinations for scientific exploration will include Mars, Europa, and various comets and asteroids. Back on Earth, Yellowstone National Park will continue to be an important field area for studies of life at the physical and chemical limits for survival Studies which provide scientists with a better understanding of "possible" conditions for life. The tools of molecular biology will also continue to advance at a tremendous pace, allowing rapid DNA sequencing, determinations of gene regulation, and analyses of protein function. Computational astrobiology has been created to handle the flood of data, and it exploits recent advances in computer technology. Improved access to space and the opportunity to perform biological experiments there will increase through both robotic and human missions using NASA's space and the International Space Station. In this rapidly advancing discipline, unanticipated breakthroughs will become increasingly common and will continue to revise and expand our view of life.

Examples of other sites where Earth-based astrobiological
Studies are presently underway:

- Polar Sites
  - Antarctic Dry Valleys
  - Arctic Haughton Impact Crater
  - Arctic cold springs
- Salterns
  - Guerrero Negro, Mexico
  - San Francisco Bay
- Deep Sub-surface
  - South African gold mines
  - Deep drilling projects World wide
  - Lecheguia Caves