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Mars Exopaleontology

Liquid water, regarded as essential for life, is unstable at the surface of Mars due to the low atmospheric density (−7.5 mb) and temperature (−93”C to +13° C). The Viking missions (1975–82) revealed the Martian surface to be not only dry, but highly oxidizing, with a UV flux that is fatal to terrestrial organisms. It is perhaps not surprising that Viking GCMS failed to detect a single organic molecule in the Martian regolith (even at ppb concentrations). The Viking biology experiments have since been effectively modeled by inorganic processes, and the present consensus assumes the Martian surface to be lifeless. It should be noted, however, that the Viking missions provided a very limited sample of potential Martian habitats, and life could exist within ephemeral liquid water environments or "oases" not yet discovered. In that regard, prime candidates are subsurface environments where liquid water should be stable because of the higher temperatures and pressures. On Earth, subsurface hydrothermal systems and deep aquifers are known to harbor diverse associations of heterotrophic microorganisms. Unfortunately, the deep subsurface of Mars is not likely to be explored prior to manned missions, perhaps decades hence. Of the other planets in the solar system, Mars still holds the greatest promise for having developed life. NASA has identified the search for extraterrestrial life as a primary goal for future space exploration. *So* where does this leave us with regard to a strategy for Mars Exobiology?

The Viking orbital missions provided compelling geological evidence that the climate of early Mars was more like the Earth, with a denser atmosphere and abundant surface water. Complex channel networks similar to those formed on Earth by running water are common features, particularly within the heavily cratered southern highland terranes of Mars. In some cases, the channel networks debouch onto flat-floored basins where water may have once ponded to form lakes. The duration of these hydrological systems on Mars is uncertain, but crater count ages, calibrated to lunar chronologies, suggest that liquid water was most abundant 3.0–4.0 Ga, when life first emerged on Earth.

The earliest fossil microbiotas on Earth are found in ancient volcanic sequences in Australia and South Africa dated about 3.5 Ga. These early assemblages are morphologically diverse, and suggest that by that time microbial life had diverged into several major groups. A magma "ocean" is thought to have existed on the Earth as late as −4.2 Ga, and life would not have been possible prior to that time. Furthermore, during late accretion the development of a terrestrial biosphere may have been frustrated by large, frequent impacts. Life may have been extinguished several times, or forced through high temperature "bottlenecks." Such processes could explain the present structure of the RNA tree which suggests thermophylly to be primitive among the Archaea. The last sterilizing impact could have occurred as late as 3.7 Ga, further shrinking the time available for originating the last common ancestor of terrestrial life. Taken together, these observations indicate that terrestrial life evolved rapidly, perhaps within 700 Ma, and possibly in as little as 200 Ma. Such constraints lend credibility to suggestions that life could have also developed on an Archean-aged Mars during the time that liquid water was abundant at the surface. A Martian biosphere may have subsequently retreated, first to ice-covered lakes and streams, and then into the deep subsurface, as the planet lost its atmosphere and began to refrigerate.

If life did develop on Mars, could it have left behind a fossil record? The fact that >99% of the carbon fixed by living organisms is destroyed through respiration, attests to the effectiveness of microbial recycling. What are the keys to preservation that could allow organic signatures to survive in crustal rocks for billions of years? The answer to this question is key in defining a strategy to search for ancient life on Mars, and for that matter, on the early Earth as well.

Jack Farmer examining the wall of Excelsior geyser crater in the Midway Geyser Basin of Yellowstone National Park. Farmer has a Ph.D. in paleobiology from the University of California, Davis and is currently a member of the Exobiology Branch at NASA's Ames Research Center. Current research interests include microbial mat systems as analogs for the Precambrian benthos, microbial taphonomy and morphogenesis in stromatolites, microbial mat-grazer interactions, biosedimentology in extreme environments, and mission planning for Mars Exopaleontology.

Since Viking, the goals of Mars Exobiology have been expanded to include the search for a fossil record. In fact, given present conditions on Mars, it may be much easier to discover fossils than extant organisms. But until quite recently we have lacked a coherent strategy for exploration. Over the last year, with colleague David Des Marais (NASA Ames), I have been defining a conceptual framework and strategy, to guide upcoming efforts to explore for an ancient biosphere on Mars. The strategy has grown from ongoing studies of microbial biosedimentology, and taphonomy in modern terrestrial environments that are commonly regarded as analogs for the early Earth and Mars. In addition to analog studies, principles have also been gleaned from microbial paleontology and biogeochemistry. These observations have been catalytic in identifying exopaleontological goals for the decade long Mars Global Surveyor Program that will begin in 1996.

It is important to realize that exploring for an ancient biosphere on Mars requires a fundamentally different approach than the search for extant life. A focus on ancient Martian life creates a unique interface with planetary science I call "Exopaleontology," a name that serves to distinguish the activity from its sister discipline, Exobiology. In a broad sense, Exopaleontology can be viewed as that subdiscipline of paleontology that deals with the study of ancient extraterrestrial biospheres and their evolution. It presently consists of little more than a strategy for Mars exploration, but also embodies a preliminary, but necessary step in NASA's quest to answer the question, " Are we alone in the Universe?" Exopaleontology is clearly an interdisciplinary effort that must integrate observations over fields as diverse as paleontology, sedimentology, biogeochemistry, planetary geology, remote sensing and robotics. The exploration methods are not only sophisticated, but costly, and involve a significant investment in technology. Obviously, exopaleontological investigations require substantial "front end" strategy development, which provides a basic rationale for my present research activities. Much of the work in the coming decade will be carried out using virtual reality applied to telepresence robotics. An important set of questions, which are just now being addressed, concern how to efficiently extract relevant information from rocks using remote sensing techniques, both from orbit and on the ground. A fundamental part of the activity is the targeting of sites for high resolution orbital imaging and spectroscopy, and for landed missions that will lead to sample return.

Clearly the geological and historical differences between the Earth and Mars are many, and Martian life could have evolved in ways we can not anticipate. But we must begin with what we understand about living systems based on the one example available for study. From our studies of modern and ancient analogs, a taphonomic theme has emerged that may transcend such planetary differences. Paleontological evidence indicates that the most important factor in microbial fossilization, for rocks of any age, is the rapid entombment of organisms by an impermeable aqueous mineral phase. For long term preservation, the entombing mineral should be chemically stable and resistant to dissolution and diagenesis. This simple concept lies at the heart of our strategy for Mars Exopaleontology and underpins our current approaches to mission planning.

Modern terrestrial environments, where aqueous minerals commonly incorporate and preserve microorganisms, include subaerial and subaqueous thermal springs within volcanic terranes, subaqueous springs and evaporites associated with terminal, alkaline lake basins, subsoil "hardpans" (calcretes, silcretes) formed within arid soils, and high latitude ground ice and permafrost. To refine our present exploration model, we are carrying out Earth-based paleontological research in these environments to better understand the patterns and processes of microbial fossilization. Recent studies of thermal spring environments with collaborators Malcolm Walter (Macquarie University, Sydney), Dave Des Marais and Sherry Cady (both of NASA Ames) have provided important insights into how biological information is preserved in modern and ancient spring sinters. Studies of subaqueous spring deposits, evaporites and mineralized soils are just beginning.

The concepts of relative mineral stability and crustal residence time are also an important part of the strategy. Favored mineralogies are those that 1) are fine-grained and therefore impermeable, thus creating a closed chemical system, 2) are relatively stable and resist chemical weathering and dissolution, and 3) retain primary microstructural and biogeochemical signatures through diagenesis. Precambrian terrestrial examples include microbial lagerstatten such as the Belcher Island, Gunflint and Bitter Springs microbiotas, which were all apparently preserved by rapid entombment and/or replacement by silica. Phosphate minerals provide another excellent host for microbial fossils, as do clay-rich shales. Some clays bind organic molecules as interlayer cations and can even absorb small organisms (microphages), thereby enhancing their preservation.

Although Viking provided data on elemental abundance, we know very little about the mineralogy of the Martian surface. Carbonates are common on Earth and theoretical models predict that they should also be widespread on Mars. However, carbonates tend to be prone to recrystallization, and retain biological signatures with less fidelity than either silica or phosphate. Similarly, evaporites tend to be unstable in the presence of an active hydrological cycle and are rare in older rocks on Earth, except where replaced by stable minerals, such as barite. However, the global hydrological cycle died early on Mars, and evaporites may yet survive there. The floors of some terminal basins on Mars exhibit high albedo deposits that could well prove to be evaporites, inclusive of carbonates. On the other hand, ice, another potential host mineral, has a very short crustal residence time and given the chaotic obliquity postulated for Mars, has probably been gained and lost from the crust many times during Mars' history. Therefore ice holds the most interest for capturing evidence of a recent Martian biosphere, especially where it is spatially related to channels formed by subsurface outflows. Martian ground ice is believed to be stable at latitudes exceeding 40° and the search for this type of target is being focused within subpolar and polar regions.

What if life never developed on Mars? Aqueous mineral deposits are still regarded as important targets for sampling the prebiotic organic compounds that preceded the origin of life **on** Earth. This early organic record has been lost from our planet by extensive processing of the crust. Mars, on the other hand, shows no sign of resurfacing after late accretion, and may provide our best opportunity to sample the primitive crust of an inner planet. Finally, aqueous minerals may also preserve a record of the volatile and climatic history of Mars as fluid inclusions incorporated during crystallization. The first step in all of this is to identify and locate aqueous mineral deposits on the Martian surface, a task we hope to accomplish during the '96 and '98 Global Surveyor missions.

In collaboration with Ronald Greeley (Arizona State) we have now identified more than 50 sites on Mars that have priority for Exopaleontology. Site selection got off to a start this past year with publication of a landing site catalog for Mars (NASA Reference Publication 1238), that includes detailed descriptions of 25 sites of exopaleontological interest. It is essential that these sites and others be imaged at high resolution during upcoming orbital missions. The Mars Global Surveyor orbital mission in 1996 will obtain visible imaging at a few pre-selected sites with spatial resolutions as good as ~2 m/pixel. In addition, infrared spectroscopy will be acquired from orbit, providing mineralogical information at – 3km/pixel resolution. Such data will lay groundwork for detailed geological and compositional mapping needed to refine site priorities for landed missions early next century.

George Gaylord Simpson described Exobiology as a science that has yet to discover what it purports to study. The same can be said of Exopaleontology. But from a practical standpoint, there is a legitimate need for a logical conceptual framework and systematic approach to guide our exploration efforts. It is also prudent to distinguish present goals and methods from those of Viking. The important discoveries still lie ahead. But in the interim, we will continue to refine our strategy for Mars Exopaleontology, while seeking to apply any scientific and technological 'spin-offs'to paleontological studies here on the home planet.

--JACK D. FARMER