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INSIDE

Hydrothermal Systems: Doorways to Early Biosphere Evolution

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ABSTRACT

Hydrothermal systems may have provided favorable environments for the prebiotic synthesis of organic compounds necessary for life and may also have been a site for life's origin. They could also have provided a refuge for thermophilic (heat-loving) microorganisms during late, giant-impact events. Phylogenetic information encoded in the genomes of extant thermophiles provides important clues about this early period of biosphere development that are broadly consistent with geological evidence for Archean environments. Hydrothermal environments often exhibit high rates of mineralization, which favors microbial fossilization. Thus, hydrothermal deposits are often rich storehouses of paleobiologic information. This is illustrated by studies of the microbial biosedimentology of hot springs in Yellowstone National Park that provide important constraints for interpreting the fossil record of thermophilic ecosystems. Hydrothermal processes appear to be inextricably linked to planetary formation and evolution and are likely to have existed on other bodies in the solar system. Such environments may have sustained an independent, extraterrestrial origin of life. Thus, hydrothermal systems and their deposits are considered primary targets in the search for fossil evidence of life elsewhere in the solar system.

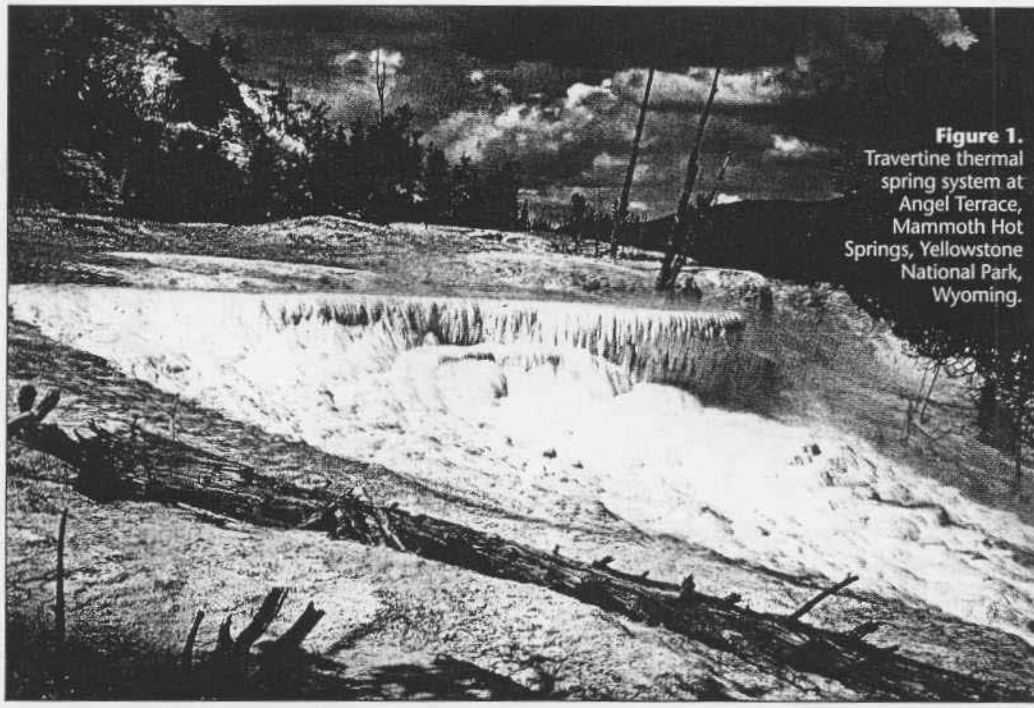

Figure 1. Travertine thermal spring system at Angel Terrace, Mammoth Hot Springs, Yellowstone National Park, Wyoming.

INTRODUCTION

Hydrothermal systems develop anywhere in the crust where water coexists with a heat source. Hydrothermal systems were important in the differentiation and early evolution of Earth because they linked the global lithospheric, hydrologic, and atmospheric cycles of the elements (Des Marais, 1996). Over geologic time, volatile chemicals released by hydrothermal systems have contributed significantly to the evolution of the oceans and the atmosphere.

Most terrestrial hydrothermal systems are sustained by magmatic heat sources. Variations in the temperature (and density) of fluids drive convective circulation in the crust, producing large-scale transfers of energy and materials. As hot fluids move through the crust, they interact chemically with their host rocks, leaving behind distinctive geochemical, mineralogical, and biological signatures. The chemical precipitates of hydrothermal systems, called sinters, typically consist of simple mineral assemblages dominated by silica, carbonate, metallic sulfides and oxides, and clays. The mineralogy of hydrothermal deposits depends both on host rock composition and on the temperature, pH, and Eh of hydrothermal fluids.

This paper covers: (1) the importance of hydrothermal systems in the history of the biosphere, (2) the nature of biogeological information contained in hydrothermal deposits (e.g., travertine spring systems at Mammoth Hot Springs, Yellowstone National Park, Wyoming [Fig. 1]), and (3) hydrothermal systems as potential environments for prebiotic synthesis and biological evolution on other bodies in our solar system.

HYDROTHERMAL SYSTEMS AND EARLY BIOSPHERE EVOLUTION

Molecular phylogenies derived from comparisons of genetic sequences of living species have radically altered our view of the biosphere and of the contribution of microbial life to planetary

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IN THIS ISSUE

CORRECTION: The fax numbers for registering for the 2000 GSA Annual Meeting in Reno are 303-443-1510 or 303-447-0648. An incorrect number was published on page 50 of the June issue of *GSA Today.*

In Memoriam

Leroy E. Becker
Princeton, Illinois
July 15, 1999

Carlos Walter M. Campos
Rio de Janeiro, Brazil
February 18, 2000

Rollin Eckis
La Jolla, California
November 1999

John A. Forman
Goleta, California

Bernold M. Hanson
Midland, Texas
April 13, 2000

Harold L. James
Bellingham, Washington
April 2, 2000

William J. Morris
Battle Ground, Washington
January 2000

Kim R. Robeson
Logan, Utah

I. Gregory Sohn
Washington, D.C.

Rolfe S. Stanley
Fairfield, Virginia
February 15, 2000

Charles J. Vitaliano
Bloomington, Indiana
April 6, 2000

Robert A. Zimmermann
Englewood, Colorado
March 2000

Please contact the GSA Foundation for information on contributing to the Memorial Fund.

Hydrothermal Systems

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biodiversity. By comparing genetic sequences in highly conserved molecules like ribosomal RNA, living species have been shown to cluster into three domains—the Archaea, the Bacteria, and the Eukarya (Fig. 2). When we look at the distribution of organisms within this "universal tree," exciting patterns emerge. The deepest branches (those nearest the common ancestor of all life) and the shortest branches (i.e., the most slowly evolving) of the domains Bacteria and Archaea are all populated by heat-loving species (hyperthermophiles) that only grow at temperatures >80 °C (Figure 2, red branches; see Woese, 1987; Stetter, 1996). The distribution of thermophiles suggests that hydrothermal systems may have been a "cradle" for early biosphere evolution. The most deeply branching thermophiles (i.e., most primitive) are all chemosynthetic organisms that use hydrogen and sulfur in their metabolism. Thus, both chemotrophy and thermophily are generally regarded as the most likely characteristics of the common ancestor of all life on our planet.

To date, only a small fraction (perhaps 1%–2%) of the total biodiversity on Earth has been sampled (Pace, 1997). However, the sampling of environments covered by the RNA tree is very broad and the three-domain structure of the RNA tree has only been strengthened with the addition of new taxa. The thermophilic

Dialogue

Sara Foland, CEO

© Paul Abdoo

> "A sound economy is a sound understanding brought into action: it is calculation realized; it is the doctrine of proportion reduced to practice; it is foreseeing consequences, and guarding against them; it is expecting contingencies and being prepared for them."
>
> —*Hannah More*

Stewardship of GSA Resources

Over the past several months, we've been examining GSA's core value of stewardship. So far we've looked at three different facets: GSA's stewardship of earth science information; the role of geoscientists as stewards of Earth itself; and stewardship as practiced by applied geologists. I'd like to wrap up by sharing with you a few thoughts on my role as steward of GSA's resources.

So Is This What the "CEO" Title Is All About?

When I arrived at GSA in May 1999, considerable buzz took place regarding my title. I think some feared GSA would turn into a corporate bureaucracy, insensitive to the needs and desires of its members and inappropriately obsessed with the bottom line. In fact, the title change from "Executive Director" to "Chief Executive Officer" was about taking more responsibility and maintaining a proactive relationship with GSA's Council. As GSA Treasurer David Dunn once noted, "I look forward to the day when Council can spend most of its time on policy issues, knowing that staff is, and will remain, fiscally prudent."

So as CEO, I was given full responsibility for operations, freeing the Council to spend more time on strategic thinking and planning for the organization. It's also my role to make sure that resources are available to implement the plans Council funds on members' behalf.

Balancing the Budget

My first, most urgent task was to pull GSA out of a deficit spending pattern that had existed since the early 1980s. Annual deficits ran, on average, from $500,000 to $600,000. This was due largely to a proliferation of programs in an environment with no strategic planning framework, no regular assessment of member needs and priorities, and no comprehensive budgeting process.

When I arrived at GSA, its projected year-end deficit was $1.5 million. At the end of the year, our actual deficit was $62,000 when adjusted for one-time inventory valuation and reorganization expenses. As of the end of first quarter 2000, GSA is operating in the black.

Stewardship of GSA's Endowment

An equally high priority was (and still is) ensuring the protection and growth of GSA's endowment, currently valued at $39.6 million. Under the leadership of Carel Ott and George Davis, GSA's Investment Committee made significant changes to our investment management practices. These improvements, coupled with a strong market, resulted in a 21.7 percent return on combined GSA and GSA Foundation assets. In fact, by year-end 1999, we had outperformed the Custom Index of not-for-profit organizations by 5.5 percent.

A Model That's Working

The next step was to balance portfolio growth with investment in GSA's core competencies, such as publications and meetings, and to ensure availability of funds for new programs. Now, we reinvest in the portfolio before any funds are spent, and we have three budgets that work together to ensure our resource needs are met and appropriately managed:

Operating. Within the authority of the CEO, with oversight by the Budget Committee, this encompasses all projects that are part of GSA's core business.

Capital. Within the authority of the CEO, with oversight by the Budget Committee, this encompasses non-routine maintenance, facility improvements, and new equipment for GSA's headquarters building in Boulder.

Strategic. Within the authority of the Programmatic Overview Committee and Council, this encompasses new projects funded from return on investments or from revenues from the GSA Foundation.

Nine outstanding business plans are currently under consideration for the 2001 Strategic Budget. Included among them are new Science, Education, and Outreach initiatives, online publications, electronic and online business capabilities, and globalization of GSA.

I'm confident these changes will prove to be beneficial for GSA over the long haul. That's what stewardship is all about. ■

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character of the deep branches has also been widely embraced, although it has become clear that precise branching orders have been complicated by the transfer of genetic information between domains (Doolittle, 1998). Therefore, the properties of the common ancestor may undergo some revision as additional sequences are obtained from a broader range of environments.

Despite the uncertainties, the high-temperature nature and other properties of the common ancestor implied by the RNA tree are consistent with a wide variety of independent geological evidence, which indicates that hydrothermal, reducing environments were widespread on early Archean Earth. Theoretical calculations (Turcotte, 1980) indicate that crustal heat flows were much higher during the Archean and volcanism was more widespread. The restriction of komatiitic lavas (surface eruptions of high-temperature peridotite magmas) to primarily Archean terranes indicates that average crustal temperatures must have been much higher at that time. This view is also supported by trends in oxygen isotope abundances for well-preserved siliceous sediments (cherts) that suggest a steady decline in average surface (climatic) temperature from early Archean highs of 50–70 °C, to present values (Knauth and Lowe, 1978).

On early Earth, hydrothermal systems could also have been created by large asteroid or comet impacts. The lunar cratering record suggests that following an initial period of heavy bombardment, which lasted from ~4.6 to 3.8 Ga, both impactor size and flux declined dramatically (Maher and Stevenson, 1988). Theoretical considerations suggest that the stable atmosphere and oceans necessary for life's origin would have been possible only after ~4.4 Ga and that life could have been established on Earth by ~4.2 Ga (Chang, 1994; Zahnle et al., 1988).

Hydrothermal systems may also have been a primary site for life's origin. Thermodynamic calculations for hydrothermal environments suggest that a variety of complex organic compounds (potential precursor molecules for living systems) are synthesized at high temperatures (Shulte

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and Shock, 1995). Recent experimental work (Voglesonger et al., 1999) has demonstrated the synthesis of alcohols under simulated black smoker conditions, lending support to thermodynamic arguments for the role of hydrothermal systems in prebiotic organic synthesis.

As mentioned above, the origin of life appears to have overlapped with the end of heavy bombardment. Early biosphere development could have been frustrated by one or more late, giant impacts which would have disrupted early habitats, possibly extinguishing all surface life. For example, models indicate that a giant impact of ~500 km diameter would create a transient atmosphere of molten rock vapor that would evaporate the oceans over a period of months (see Chang, 1994). This would produce a steam atmosphere that would rain out over a period of a few thousand years, eventually restoring the oceans (Zahnle et al., 1988). Such high-temperature events could eliminate most, if not all, surface life, allowing only hyperthermophilic (primarily subsurface chemotrophic) species to persist.

If this scenario is true, then the thermophilic nature implied for the common ancestor of life could be simply a legacy of one or more late giant impacts that occurred during late bombardment (Gogarten-Boekel et al., 1995). Impact flux models suggest the last such events could have occurred as late as ~3.9 Ga, the age of the Imbrium Basin on the Moon and the approximate age of the oldest preserved metasedimentary sequences on Earth (Isua Supergroup, Akilia Island, Greenland), dated at >3.85 Ga (Nutman et al., 1997). These same sequences are purported to contain the oldest fossil biosignatures on Earth, chemofossils characterized by light (biologically fractionated?) carbon isotope signatures preserved in iron-rich metasedimentary rocks (Mojzsis et al., 1996; Mojzsis and Harrison, 2000). The geological events outlined above are broadly consistent with basic branching patterns observed in the RNA tree.

The root of the RNA tree is generally placed at the midpoint of the long branch that separates the Bacteria from the Archaea (Fig. 2). As noted previously, the deep basal branches are occupied by hyperthermophilic species that exhibit chemotrophic strategies based on hydrogen and sulfur. In contrast, photosynthesis, the surface metabolic strategy that supports most of the productivity on Earth today, apparently originated within the sulfur bacteria (anoxygenic photoautotrophs; Fig. 2). Oxygenic photosynthesis, an event of singular importance in the history of the biosphere, first appeared in the cyanobacteria and was later transferred to plants (domain Eukarya) through the development of endosymbiotic associations with that group (Fig. 2; Margulis and Chapman, 1998). Deposition of the banded iron formations, a proxy for the buildup of oxygen in the oceans, peaked around 2.5 Ga, at which time Earth's surface environment began to undergo a dramatic changeover to the highly oxidizing conditions that prevail today (Des Marais, 1997).

PALEOBIOLOGY OF THERMAL SPRINGS

Studies of ancient hydrothermal systems can provide important constraints for reconstructing the evolutionary history of thermophilic ecosystems on Earth (Walter, 1996). Comparative studies of the geochemistry, microbial biosedimentology, and fossilization processes in modern thermal spring systems (see Cady and Farmer, 1996) have provided a basis for constructing facies frameworks (e.g., Farmer and Des Marais, 1992), which have utility for interpreting the paleobiology of ancient deposits (e.g., Walter et al., 1996, 1998). Such studies also hold importance for refining our strategies to explore for signatures of life or prebiotic chemistry on other bodies in the solar system, as well as providing more robust criteria for recognizing biogenic features in ancient terrestrial and extraterrestrial materials (Farmer, 1995).

We have studied active travertine (carbonate-precipitating) thermal springs located at Angel Terrace, Mammoth Hot Springs, Yellowstone National Park, Wyoming (Bargar and Muffler, 1975; Farmer and Des Marais, 1994; Fouke et al., 2000). The following highlights three microfacies within this system that represent major differences in mineralogy, in community composition and style of microbial mat development, in stromatolite morphogenesis, and in sedimentary fabrics. Trends in the composition of microbiotas along thermal gradients (from high to low temperature), broadly mirror the inferred sequence of evolutionary events implied by the RNA tree for the global biosphere (cf. Figs. 2 and 4).

VENT MICROFACIES

Angel Terrace is a sulfide spring system (Castenholz, 1977) with vent temperatures and pH values of ~74 °C and ~6.7, respectively (Farmer and Des Marais, 1994). On Angel Terrace, vents exhibit both a high rate of discharge (~75–100 cm/s) and a rapid rate of carbonate (aragonite) precipitation (~35 cm/yr; Farmer and Des Marais, 1994). Vents and proximal channels (Figs. 3A and 3B) are dominated by filamentous sulfide and hydrogen-oxidizing species (Fig. 3B) that comprise the group Aquificales (Anna Louise Reysenbach, 1999, personal commun.). The Aquificales group (represented by *Aquifex* in Fig. 2) presently represents the deepest branch in the RNA tree. In shallow channels where flow rates are high, *Aquifex* mats form bacterial "streamers" (Fig. 3B) that become encrusted, forming characteristic sinter fabrics that preserve original

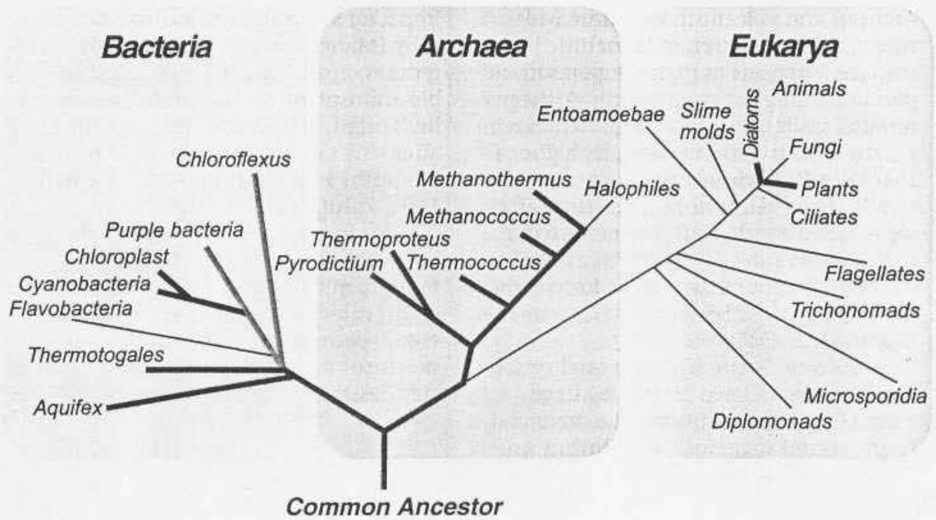

Figure 2. Universal phylogenetic tree based on comparative sequence data from 16S or 18S ribosomal RNA (modified from Madigan et al., 1997). Colors highlight three domains of life (Archaea, Bacteria, and Eukarya). Evolutionary distances between groups are proportional to branch length (from tip to branch node). Hyperthermophilic species (those that only grow at >80 °C) are represented by red. Anoxygenic photosynthetic species are lavender. Oxygenic photosynthetic species are green. Note that chloroplasts group with cyanobacteria, indicating that genes for oxygenic photosynthesis were transferred to Eukarya through development of endosymbioses with cyanobacteria.

flow orientations. These fabrics are retained during the recystallization of aragonite to calcite. Remarkably similar bacterial streamers have been described from ancient siliceous thermal spring sinters in the Carboniferous Drummond Basin of northeast Queensland, Australia (Walter et al., 1996, 1998).

MID-TEMPERATURE POOLS

The floors of mid-temperature (45–60 °C) ponds on Angel Terrace (Fig. 3C), are covered by centimeter-thick photosynthetic mats (Fig. 3D). These mats are dominated by a number of cyanobacterial form taxa (Farmer and Des Marais, 1994), including species of *Spirulina, Oscillatoria, Synechococcus,* and the green sulfur bacterium *Chloroflexus,* an anoxygenic photoautotroph (see Fig. 2). In this part of the system, flow rates are much lower (~10 cm/s), as are rates of aragonite precipitation (~5 cm/yr). Light-induced gliding of the filamentous cyanobacteria produces a variety of tufted (coniform) and ridged mat structures (Fig. 3D). Collectively, mat species produce a dense, gelatinous slime (exopolymer) matrix that entraps bubbles of photosynthetic oxygen and other gases, forming "lift-off" structures (Fig. 3D). These features eventually become mineralized to form distinctive associations of fabrics and microtextures that survive recrystallization to calcite. Much of the aragonite precipitation at mid-temperatures occurs just beneath the mat surface where pH is elevated during photosynthesis, favoring carbonate precipitation (Farmer and Des Marais, 1994).

DISTAL SLOPE ENVIRONMENTS

On the distal slopes of Angel Terrace (Fig. 3E), lying below the mid-terrace ponds discussed above are shallow (centimeter deep) terracette ponds (Fig. 3F) that are characterized by slow flow rates (<50 cm/s) and low rates of carbonate precipitation (<2 cm/yr). Temperatures are also low, falling in the range, ~40–15 °C. The microbial communities of these distal slope environments comprise a diverse association of microorganisms, including many species of diatoms and other representatives of the Eukarya, as well as grazing insects and protozoans. At the lowest temperatures, small enclaves of higher plants also survive on distal slopes (Fig. 3E). The filamentous cyanobacteria present include species of *Spirulina* and *Calothrix,* the latter characterized by heavy exopolymer sheaths that are relatively resistant to degradation. The primary precipitate in this part of the system is calcite, which tends to nucleate on organic surfaces, eventually forming small spherulites of calcite that accrete as they are rolled downslope along the floors of shallow channels (Fig. 3F). As the spherulites grow, they entomb cyanobacterial sheaths, epiphytic diatoms, and other attached organisms, which are often seen in thin sections of spherulites.

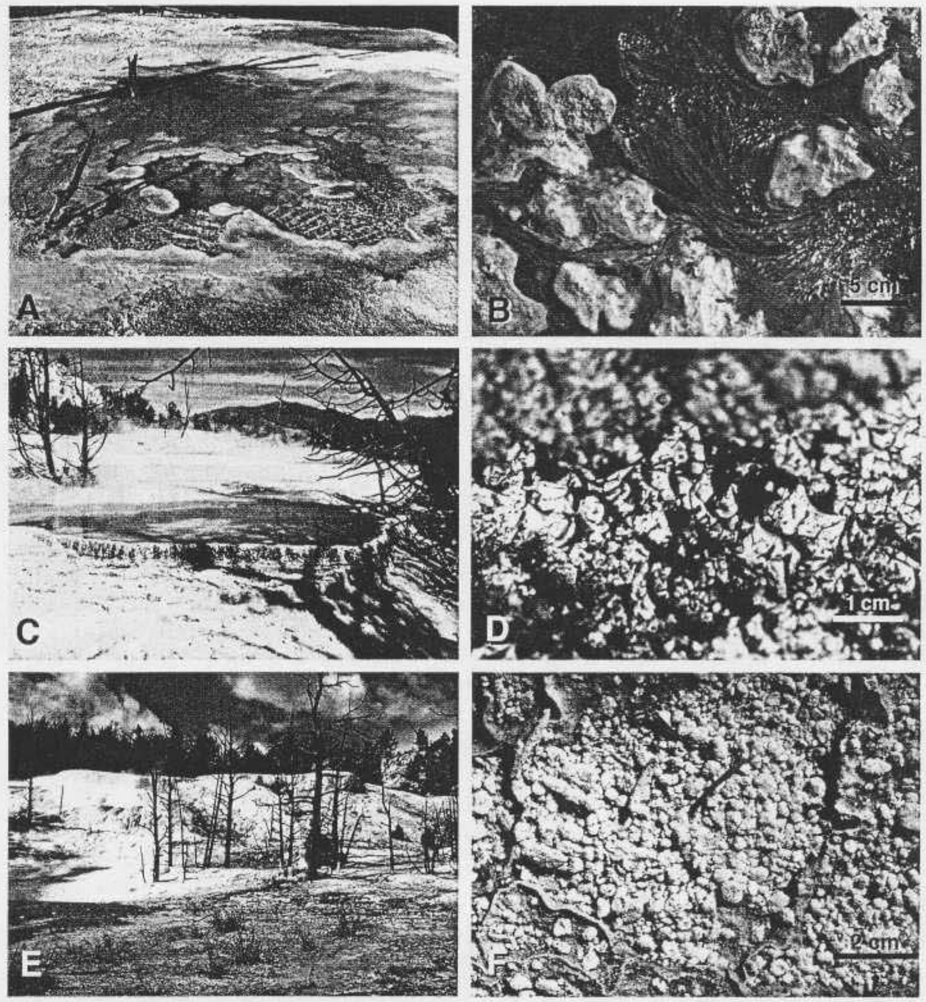

Figure 3. Microbial mats and microenvironments found at Angel Terrace. **A.** Sulfide vent that formed on south end of Angel Terrace in 1993. Vent temperature was ~73 °C and pH ~6.4. Orange colors along edges of vent are cyanobacterial communities living on and within drying sinter. **B.** Dominant mat-forming microorganism covering vent walls and channel floors is filamentous form that is genetically related to *Aquifex* (Anna Louise Reysenbach, 1999, personal commun.). *Aquifex* forms streamers in channels that become oriented by the flow. Bacterial streamers are eventually encrusted by aragonite, preserving original flow directions in sinter fabric. **C.** Large mid-temperature pond formed on Angel Terrace in 1996. Near upstream end of pond, temperature was ~65 °C (pH ~7). Floor of pool was covered by cm-scale aragonite shrubs (not shown). At temperatures up to and including 73 °C, thin biofilms of unicellular cyanobacteria *(Synechococcus)* covered surfaces of shrubs, tinting them yellow-orange. At downstream edge of pond, pool temperature was ~45 °C (pH ~8) and floor was covered by centimeter-thick coniform cyanobacterial mats (Fig. 3D). **D.** Coniform photosynthetic mats dominated by cyanobacterial taxa, including *Spirulina, Phormidium, Synechococcus,* and several unidentified oscillatoriceans. Also present is *Chloroflexus,* an anoxygenic photosynthesizer. Basic mat structure consists of cone-shaped peaks and networks of ridges formed by phototactic (light-induced) gliding of cyanobacteria. Some cones have bulbous enlargements at their tops where mat had entrapped gases (primarily photosynthetic oxygen). Tufted mat structure is faithfully replicated in microtexture of associated sinters. **E.** Distal slope environment at base of Angel Terrace, Mammoth Hot Springs, Yellowstone National Park, Wyoming (view looking west) (Fouke et al, 2000). Persistent thermal activity had killed most of the trees in this area. **F.** View of floor of shallow (<cm deep) terracette pond covered by spherulites of calcite. Spherulites typically form by nucleation of carbonate on organic material and continue to accrete as they are transported (rolled) downslope.

FACIES MODEL FOR TRAVERTINE THERMAL SPRINGS

Observations of modern springs at Angel Terrace were used to construct the integrated biofacies and lithofacies model shown in Figure 4. The model is organized around systematic variations in temperature, pH, and flow rates typically observed along spring outflows in the Mammoth Hot Springs area. Such facies frameworks are useful tools for reconstructing the paleobiology of ancient sinter deposits. We have recently extended this model to include important aspects of aqueous and

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solid-phase geochemistry, documenting systematic trends in oxygen and carbon isotopes, and elemental abundances along spring outflows (Fouke et al., 2000). Systematic variations in carbon and oxygen isotope abundances with declining temperature were entirely accounted for by CO_2 outgassing and evaporation, with no evidence of significant biological fractionation, even where mats were well developed (Fouke et al., 2000). This result emphasizes the importance of textural information in reconstructing the paleobiology of ancient subaerial sinters.

HYDROTHERMAL PROSPECTING ELSEWHERE IN THE SOLAR SYSTEM

Because subsurface fluids and crustal heat sources could have also coexisted on other planetary bodies in the solar system, hydrothermal deposits are also important targets for planetary exploration and the search for extraterrestrial life. Potential targets for hydrothermal systems include active vents on the floor of a putative subsurface ocean on Europa (Reynolds et al., 1983) and possibly other icy satellites in the outer solar system (Pendleton and Farmer, 1997). Results from the Galileo mission have significantly advanced our understanding of Europa, providing support for a substantial subcrustal ocean maintained by tidal frictional heating of the Moon's interior. Given the potential for abundant water, a sustained heat source, and reduced compounds, hydrothermal systems on Europa could provide long-term habitats for chemotrophic microbial ecosystems similar to those found in deep-sea vent environments on Earth (Pappalardo et al., 1999).

Hydrothermal systems may also have been important during the early history of the dark asteroids (Cronin et al., 1988), which are considered the most likely parent bodies for carbonaceous (C-1) chondrites. These meteorites show evidence of extensive aqueous alteration of minerals over a temperature range of 50–100 °C. The Murchison meteorite, perhaps our best studied carbonaceous meteorite, contains a diverse assemblage of biologically important amino acids (Cronin, 1989) that were apparently synthesized on the meteorite parent body during an early, transient hydrothermal phase (Oro and Mills, 1989). Along with comets, carbonaceous meteorites are believed to have contributed significantly to the early inventory of prebiotic organic compounds needed for the origin of life (Chyba and Sagan, 1992).

Hydrothermal environments also appear to have been widespread on Mars early in the planet's history (Farmer, 1996, 1998). Siliceous thermal spring deposits have been cited as important targets in the search for evidence of an ancient biosphere on Mars (Walter and Des Marais, 1993; Cady and Farmer, 1996). Based on our studies of terrestrial analogs, the discovery of ancient hydrothermal systems on Mars would provide access to: (1) localized environments capable of sustaining high rates of microbial productivity, and (2) high rates of mineralization (chemical precipitation), favorable for capturing and preserving microbial biosignatures. Thus, hydrothermal deposits are considered high-priority targets in the exploration for a Martian fossil record (Farmer and Des Marais, 1999).

Although active surface hydrological systems appear to have largely disappeared on Mars after ~3.5 Ga, models suggest that a global groundwater system could still be present on Mars today (Clifford, 1993; Carr, 1996). This view is supported by the

Engaging "My Neighbor" in the Issue of Sustainability Part VII: Spaceship Earth: There Is No Place Else to Go

A.R. Palmer, Institute for Cambrian Studies, Boulder, Colorado

Space travel has stirred our imaginations for more than a century and inspired not only writers of science fiction and "trekkies," but also the scientists and engineers of space agencies worldwide. At frequent intervals, presentations in various media speculate about human travel far beyond the international space station to other planets in our solar system in the not-too-distant future. To some people, this could solve Earth's population problem because they believe we will be able to emigrate to other worlds when push comes to shove. Space travel may be the special privilege of a few adventurous astronauts, but as a solution to our earthly problems, there is need for a reality check.

Let's start with a trip to the Moon and a look back to our blue planet—a spectacular view now common on many advertising pages. But look elsewhere in the universe. Nothing else that we see looks any bigger than it did from Earth. Planets are still points of light, as are the stars and galaxies. We are a long way from even our nearest planetary neighbor!

And then there's simple math. Earth's current population (about six billion) is increasing by about 1% annually. The U.S. Census Bureau projects that by 2050 there will be a somewhat smaller rate of increase of 0.46%, and a probable median population of nearly nine billion people. The ANNUAL population increase in 2050 (9 billion × .0046) will be an estimated 41.5 million persons, down from the present annual increase of about 60 million. On a DAILY basis (41.5 million ÷ 365), population increase in 2050 will be about 115,000 persons, down from the present DAILY increase of about 170,000 persons. Daily permanent emigration of that many people, even given possible technological advances in space vehicles and propulsion by 2050, might be a bit optimistic.

For all practical purposes, we must internalize and make plans for "Spaceship Earth" as the only realistic habitation for humans. Bringing human occupancy of this planet into balance with available ecological areas and terrestrial and oceanic resources must be one of our highest priorities if we wish a sustainable future for our descendants.

Note: This series of essays, with some enhancements for teachers, is now available through a link on GSA's Web site, www.geosociety.org. From either Public Interest or the "Related Links" area of Geoscience Initiatives, click "Sustainability" then "Toward a Stewardship of the Global Commons." ■

presence of large outflow channels in some younger Martian terranes formed during catastrophic releases of groundwater (Baker, 1982). Many Martian outflow channels originate within chaos terranes, collapse features thought to have formed by melting of the shallow cryosphere. Some chaos features show clear associations with potential magmatic heat sources (e.g., chaos at the base of Apollonaris Patera in Figure 5) that could have sustained hydrothermal systems for prolonged periods (Farmer, 1996).

The thermal emission spectrometer is a mid-infrared mapping spectrometer presently in orbit around Mars. The spectrometer recently detected a large deposit of coarse-grained (specular) hematite at Sinus Meridiani (Christensen et al., 2000). On Earth such deposits normally form by aqueous precipitation at elevated temperatures. This discovery lends credibility to the idea that hydrothermal systems were once active in shallow crustal environments on Mars.

CONCLUSIONS

Hydrothermal systems appear to have played a fundamental role in the early evolution of Earth and in the endogenous synthesis of prebiotic organic compounds that were the basic building blocks for life. The phylogenetic information encoded in the genomes of extant thermophilic species appears to provide important clues about early biosphere evolution and the processes that shaped its history. In addition to providing a potential site for life's origin, hydrothermal environments may also have been a refuge for thermophilic organisms during the late, giant-impact events that overlapped with early biosphere evolution. Hydrothermal environments typically sustain high rates of inorganic mineral precipitation favorable for capturing and preserving a microbial fossil record and integrated studies of the microbial biosedimentology, paleontology, and geochemistry of modern and ancient hydrothermal deposits provide important constraints for interpreting the fossils of thermophilic ecosystems. Hydrothermal systems are considered primary targets in the exploration for prebiotic chemistry and life on other bodies in the solar system (e.g., Mars, Europa, and dark asteroids) and could have provided cradles for the emergence of life in other planetary systems within our galaxy, and beyond.

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REFERENCES CITED

Baker, V.R., 1982, The channels of Mars: Austin, Texas, University of Texas Press, 198 p.

Bargar, K.E., and Muffler, L.P.J., 1975, Geologic map of the travertine deposits, Mammoth Hot Springs, Yellowstone National Park, Wyoming: U.S. Geological Survey, Miscellaneous Field Studies Map MF-659, 1:62,500 and 1:4,800 scales (sheet 1), 1:2,400 scale (sheet 2).

Cady, S.L., and Farmer, J.D., 1996, Fossilization processes in siliceous thermal springs: Trends in preservation along thermal gradients, *in* Bock, G., and Goode,

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J., eds., Evolution of hydrothermal ecosystems on Earth (and Mars?): New York, John Wiley & Sons, p. 150–173.

Carr, M.H., 1996, Water on Mars: London, Oxford University Press.

Castenholz, R.W., 1977, The effect of sulfide on blue-green algae of hot-springs II: Yellowstone National Park: Microbial Ecology, v. 3, p. 79–105.

Chang, S., 1994, The planetary setting of prebiotic evolution, *in* Bengston, S., ed., Early life on Earth, Nobel Symposium No. 84: New York, Columbia University Press, p. 10–23.

Christensen, P.R., Clark, R.L., Kieffer, H.H., Malin, M.C., Pearl, J.C., Banfield, J.L., Edgett, K.S., Hamilton, V.E., Hoefen, T., Lane, M.D., Morris, R.V., Pearson, R., Rousch, T., Ruff, S.W., and Smith, M.D., 2000, Detection of crystalline hematite mineralization on Mars by the thermal emission spectrometer: Evidence for near-surface water: Journal of Geophysical Research, v. 105, p. 9623–9642.

Chyba, C.F., and Sagan, C., 1992, Endogenous production, exogenous delivery and impact-shock synthesis of organic molecules: An inventory for the origins of life: Nature, v. 355, p. 125–131.

Clifford, S.M., 1993, A model for the hydrologic and climatic behavior of water on Mars: Journal of Geophysical Research, v. 88, p. 2456–2474.

Cronin, J.R., 1989, Origin of organic compounds in carbonaceous chondrites: Advances in Space Research, v. 9, p. 54–64.

Cronin, J.R., Pizzarello, S., and Cruikshank, D.P., 1988, Organic matter in carbonaceous chondrites, planetary satellites, asteroids and comets, *in* Kerridge, J.F., and Matthews, M.S., eds., Meteorites and the early solar system: Tucson, University of Arizona Press, p. 819–857.

Des Marais, D.J., 1997, Long-term evolution of the biogeochemical carbon cycle, *in* Bandfield, J.F., and Nealson, K.H., eds., Geomicrobiology: Interactions between microbes and minerals: Reviews in Minerology, v. 35, p. 429–448.

Des Marais, D.J., 1996, Stable light isotope biogeochemistry of hydrothermal systems, *in* Bock, G., and Goode, J., eds., Evolution of hydrothermal ecosystems

Facies Model for Angel Terrace Travertines

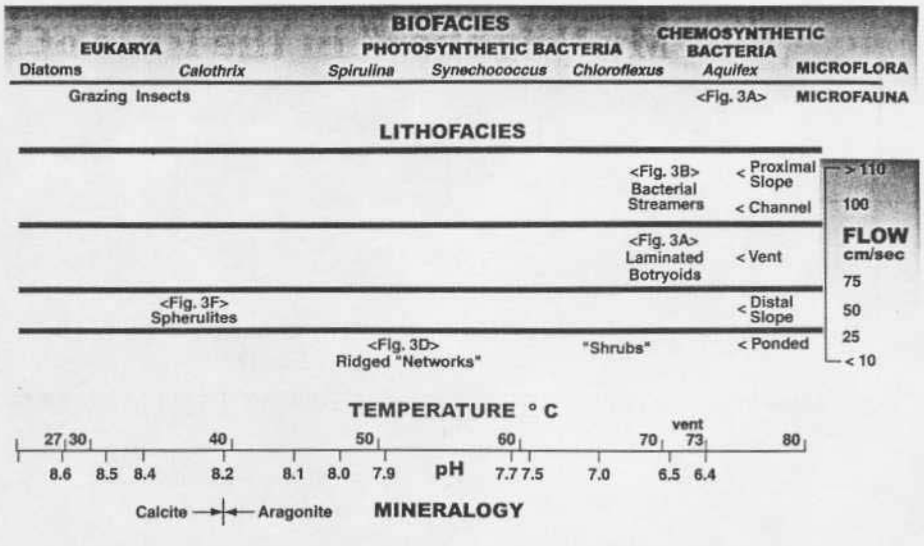

Figure 4. Simplified facies model for travertine thermal springs based on comparative study of springs in Mammoth Hot Springs system. Model integrates biological and lithological observations relative to changes in temperature and pH measured along outflows. In diagram, dominant groups of microorganisms and grazing metazoans are positioned relative to their average temperature and/or pH distribution and associated sinter microstructures.

on Earth (and Mars?): New York, John Wiley & Sons, p. 83–93, 273–299.

Doolittle, R.F., 1998, Microbial genomes opened up: Nature, v. 392, p. 339–342.

Farmer, J.D., 1998, Thermophiles, early biosphere evolution and the origin of life on Earth: Implications for the exobiological exploration of Mars: Journal of Geophysical Research, v. 103, p. 28,457–28,461.

Farmer, J.D., 1996, Hydrothermal processes on Mars: An assessment of present evidence, *in* Bock, G., and Goode, J., eds., Evolution of hydrothermal ecosystems on Earth (and Mars?): New York, John Wiley & Sons, p. 273–299.

Farmer, J.D., 1995, Mars exopaleontology: Palaios, v. 10, p. 197–198.

Farmer, J.D., and Des Marais, D.J., 1999, Exploring for a record of ancient Martian life: Journal of Geophysical Research, v. 104, p. 26,977–26,995.

Farmer, J.D., and Des Marais, D.J., 1994, Biological versus inorganic processes in stromatolite morphogenesis: Observations from mineralizing systems, *in* Stal, L.J., and Caumette, P., eds., Microbial mats: Structure, development and environmental significance: Berlin, Springer-Verlag, p. 61–68.

Farmer, J.D., and Des Marais, D.J., 1992, Comparative biosedimentology of some terraced travertine deposits: Geological Society of America Abstracts with Programs, v. 24, no. 7, p. 53–54.

Fouke, B.W., Farmer, J.D., Des Marais, D.J., Pratt, L., Sturcio, N.C., Burns, P.C., and Discipulo, M.K., 2000, Depositional facies and aqueous-solid geochemistry of travertine-depositing hot-springs (Angel Terrace, Mammoth Hot Springs, Yellowstone National Park, U.S.A.): Journal of Sedimentary Research, v. 70, p. 565–585.

Gogarten-Boekel, M., Hilario, H., and Gogarten, J.P., 1995, The effects of heavy meteorite bombardment on early evolution—The emergence of the three domains of life: Origins of Life and Evolution of the Biosphere, v. 25, p. 251–264.

Knauth, L.P., and Lowe, D.R., 1978, Oxygen isotope geochemistry of cherts from the Onverwacht Group (3.4 billion years), Transvaal, South Africa with implications for secular variations in the isotopic compositions of cherts: Earth and Planetary Science Letters, v. 41, p. 209–222.

Madigan, M.T., Martinko, J.M., and Parker, J., 1997, Brock biology of microorganisms, 8th edition: New Jersey, Prentice-Hall.

Maher, K.A., and Stevenson, D.J., 1988, Impact frustration of the origin of life: Nature, v. 331, p. 612–614.

Margulis, L., and Chapman, M.J., 1998, Endosymbioses: Cyclical and permanent in evolution: Trends in Microbiology, v. 6, p. 342–345.

Mojzsis, S.J., and Harrison, T.M., 2000, Vestiges of a beginning: Clues to the emergent biosphere recorded in the oldest known sedimentary rocks: GSA Today, v. 10, no. 4, p. 1–6.

Mojzsis, S.J., Arrhenius, G., McKeegan, K.D., Harrison, T.M., Nutman, A.P., and Friend, C.R.L., 1996, Evidence for life on Earth before 3,800 million years ago: Nature, v. 384, p. 55–59.

Nutman, A.P., Mojzsis, S.J., and Friend, C.R.L., 1997, Recognition of >3,850 Ma water-lain sediments and their significance for the early Archean Earth: Geochimica et Cosmochimica Acta, v. 61, p. 2475–2484.

Oro, J., and Mills, T.V., 1989, Chemical evolution of primitive solar system bodies: Advances in Space Research, v. 9, p. 105–120.

Pace, N.R., 1997, A molecular view of microbial diversity and the biosphere: Science, v. 276, p. 734–740.

Pappalardo, R.T., Head, J.W., and Greeley, R., 1999, The hidden ocean of Europa: Scientific American, v. 281, no. 10, p. 34–43.

Pendleton, Y., and Farmer, J.D., 1997, Life: A cosmic imperative?: Sky and Telescope, v. 94, p. 42–47.

Reynolds, R.T., Squyres, S.W., Colburn, D.S., and McKay, C.P., 1983, On the habitability of Europa: Icarus, v. 56, p. 246–254.

Figure 5. Mars Orbiter Camera image (false color) of Apollonaris Patera, an ancient Martian caldera (~70 km diameter) located in Elysium Basin–Terra Cimmeria region of Mars. Note chaos features and associated outflow channels especially abundant near base of volcano (lower left), which could have formed by melting of subsurface cryosphere. Proximity of chaos to volcano suggests possibility of prolonged hydrothermal activity (courtesy of NASA).

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