Hydrothermal Systems: Doorways to Early Biosphere Evolution

Jack D. Farmer, Department of Geology, Arizona State University, P.O. Box 871404, Tempe, AZ 85287, USA, jfarmer@asu.edu.

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.

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
IN THIS ISSUE

Hydrothermal Systems: Doorways to Early Biosphere Evolution ........................................... 1
In Memoriam .......................................................................................................................... 2
Dialogue .............................................................................................................................. 3
Toward a Stewardship of the Global Commons, Part VII ................................................ 4
Call for Geological Papers for 2001 GSA Section Meetings ........................................... 7
GSA on the Web ................................................................................................................ 9
Penrose Conference Report: The Marine Eocene-Oligocene Transition ............................ 10
Sedimentary Systems in Space and Time—High Priority National Science Foundation Research Initiatives in Sedimentary Geology ......................................................... 12
GSA-GSL 2001 Meeting .................................................................................................... 14
GSA Election Goes Electronic ........................................................................................... 16
GSA Employment Service ................................................................................................. 17
Shop for the GreaterGood of IEE ..................................................................................... 17
Application for Employment Matching Service .................................................................... 18
Employer’s Request for Earth Science Applicants ............................................................. 19
GSA Foundation Update ................................................................................................... 20
Summit 2000—Short Courses ............................................................................................ 22
Monitoring Rapid Geological Change in Eastern Europe ................................................. 25
Geology in the Parks and Forests: Summer Internship Programs ................................. 26
Summer 2000 Intern Update .............................................................................................. 26
Shlemen Workshops: A Success at 2000 Section Meetings ........................................... 27
2000 GeoVentures ............................................................................................................. 28
Earth Science Week Is October 8–14 ................................................................................. 29
2001 GSA Annual Meeting ............................................................................................... 29
July Bulletin and Geology Highlights .............................................................................. 29
Calendar .............................................................................................................................. 30
Classifieds ........................................................................................................................... 30

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

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

Hydrothermal Systems continued from p. 1

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...
**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 incomparably 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.

---

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 (Shulite et al., 1972).

---

Hydrothermal Systems

continued on p. 4
Hydrothermal Systems
continued from p. 3

and Shock, 1995). Recent experimental work (Vogelsonger 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 (Mojsis et al., 1996; Mojsis 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 (anoxogenic phototrophs; 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 Cadiz 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, 1973; 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 microorganisms 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 comm.). 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 entrained, forming characteristic sinter fabrics that preserve original
flow orientations. These fabrics are retained during the recrystallization 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 photosynthetic organism (Farmer and Des Marais, 1994). Light-induced gliding of the filamentous cyanobacteria produces a variety of tufted (conform) 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.

**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 hydrothermal systems continued on p. 6.
Hydrothermal Systems

continued from p. 5

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 CO₂ 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 taxonomic information in reconstructing the paleobiology of ancient subaerial sizers.

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 (Coffin, 1993; Carr, 1996). This view is supported by the
Toward a Stewardship of the Global Commons

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.”

ACKNOWLEDGMENTS

Work on hydrothermal systems was supported by grants from the NASA Astrobiology Institute and the NASA Exobiology Program. I thank Dave Des Marais (NASA Ames), Malcolm Walter (Macquarie University, Sydney), Bruce Fouke (University of Illinois), Laurie Lesher (Arizona State University), and Norman Pace (University of Colorado) for informative discussions, and Steve Mojsis (University of California, Los Angeles) and Horton Newcomb (University of New Mexico) for valuable reviews of the manuscript. I also thank Sue Selkirk and Maria Farmer (both from Arizona State University) for technical assistance in preparing the figures.

REFERENCES CITED


Hydrothermal Systems continued on p. 8
Hydrothermal Systems
continued on p. 7


Hydrothermal Systems
continued on p. 9