GEOBIOLOGY:

EXPLORING THE INTERFACE BETWEEN THE BIOSPHERE AND THE GEOSPHERE

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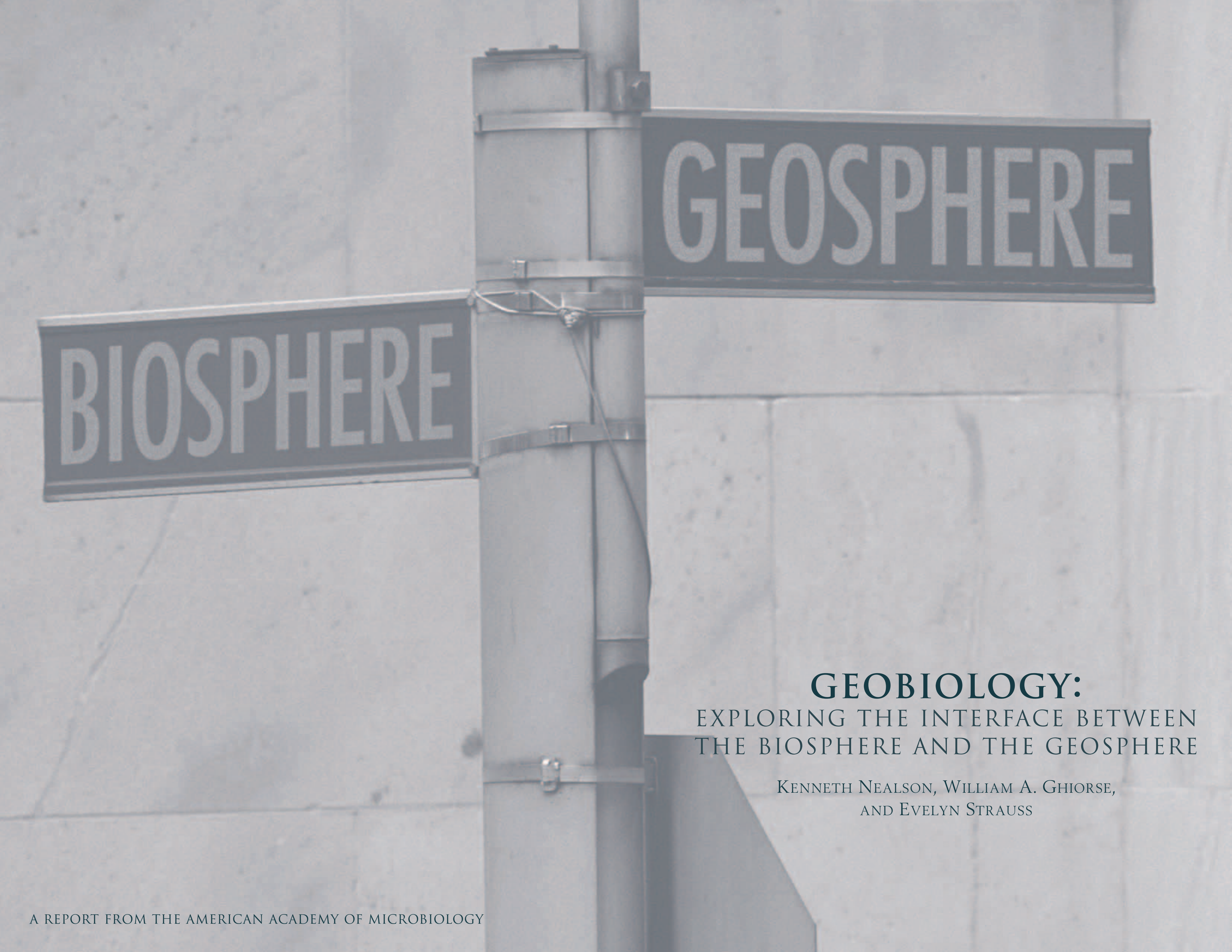

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A REPORT FROM THE AMERICAN ACADEMY OF MICROBIOLOGY

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EXECUTIVE SUMMARY

A colloquium was convened by the American Academy of Microbiology to deliberate issues relating to the intersecting fields of biological and geological sciences. The colloquium was held in Tucson, Arizona, December 1–3, 2000. The principal findings of the colloquium are summarized below.

A wide chasm may seem to divide the living from the non-living. On closer inspection, however, these two realms do not perch on separate ridges, but knit together to form a single lush domain. Geological and biological activities are integrated, and they influence each other in profound ways. This interplay has shaped the Earth and all creatures on it. Studies of geobiology—the present and past interactions between life and inanimate matter—promise to reveal the secrets of life, its origins and evolution, and its present functions on our planet. Such studies hold enormous practical potential as well.

Long ago, life arose from chemicals. As new creatures evolved, their activities changed the environment. The altered surroundings in turn invited different types of organisms, which again altered the world around them. Geobiological interactions have created the gases we breathe and the soil in our forests. They contribute to global warming and some forms of pollution, yet knowledge of geobiological processes offers strategies for remedying some of these problems and for enhancing the quality of life on our planet in other ways as well.

The new discipline of geobiology will provide a plethora of exciting intellectual and practical rewards. Geobiologists hope, for example, to discern how life began and how it evolved. Furthermore, they aim to identify how environmental conditions influenced these processes and, in turn, were altered by life. Understanding the past will equip us to predict the future. The Earth has already conducted many experiments over the course of its evolution, but, because of the complexity of geobiological interactions, we are unable at present to decipher our planet's lab notebook. Current and future investigations will improve our ability to read the relevant records, interpret them, and make predictions based on past results.

Many geobiological processes affect environmental quality and impact human health, which in turn influence the economy and work force. As a result, critical public and science policy issues require input from this field. The study of geobiology offers significant payoffs that touch society in many ways. To exploit the possibilities, we need to focus diverse resources on this rapidly growing and tremendously promising new field.

INTRODUCTION

Living creatures and the inanimate worlds they inhabit dance an intimate tango. As each partner steps to Nature's tune, the other responds in harmony. Organisms alter their surroundings as part of their normal activities, and in turn, the changed surroundings nurture different types of life and altered modes of living. This interplay of Life with Earth has shaped our present environment. Indeed, Life and Earth, through this "Geobiological Tango," continue to choreograph the co-evolution of the biosphere and the geosphere. Understanding the detailed history and workings of these interactions will provide insight into the origins and evolution of the geobiological world. Learning the choreographic design of the tango will help us to better manage environmental affairs and shed light along the path to their future.

The environment has been spawning innovations in biology ever since it sparked life itself. Early on our planet, the line between life and non-life was much thinner than it seems today. At some point, inanimate chemicals and physical forces interacted in new ways to provide compounds and reactions that made life possible. As biology stirred, its activities sent ripples through the inanimate world. Bacteria, algae, and, eventually, plants pumped oxygen into the air, for instance, profoundly changing the composition of the atmosphere and supporting the development of creatures that breathe this gas. Microbes in the soil captured critical nitrogen minerals from rocks and packaged them into forms that other creatures could use to make essential molecules such as proteins. Such activities changed the environment, rendering habitats more comfortable for some organisms and harsher for others. The resulting fluxes of species and their specialized biochemical activities in turn registered effects on the surroundings. In such ways, the interactive cycle between living things and their geological surroundings never ceases. For example, geological materials have served as energy sources (electron donors) for lithotrophic metabolism and as electron acceptors for anaerobic respiration of many types. This often results in inadvertent dissolution and/or formation of minerals. Organisms—especially the more complex eukaryotic organisms—have developed exquisite abilities to create structural materials, such as calcite, silicates, cellulose, and chitin. These "biominerals" have served to allow organisms to become large three-dimensional structures, e.g., to thwart gravity, to increase predatory efficiency, and to be used as protective structures from other predators. Perhaps of equal importance, they have supplied us with a fossil record detailing much of the recent history of life on our planet.

Studies of geobiology will reveal these events and elucidate their details. Increased knowledge in this area will enhance our comprehension of how the planet Earth has evolved and continues to evolve. In addition to uncovering the underlying designs of natural processes that have shaped Earth, we will learn the details and environmental consequences of current human activity. Such insights will allow us to modify certain activities in ways that will heal and maintain our environment.

Furthermore, we may devise ways to apply geobiological phenomena in our search for solutions to some of our environmental problems. Some interactions between living creatures and matter are enhancing the quality of life for other creatures, for example, and point toward further inventions that might build upon these natural success stories. Many microbes transform poisons, such as heavy metals, into harmless compounds, or repackage them so they are physiologically unavailable. Others degrade organic pollutants, restore key nutrients to depleted soil, or act as a sink for greenhouse gases, such as carbon dioxide, from the atmosphere. Understanding both biology and geology is critical to solutions aimed at many major societal issues, including groundwater quality, environmental contamination, the loss of productive agricultural lands, and global warming.

Geobiological studies may produce other benefits as well. Many microbes produce chemicals of practical use, such as ethanol, which directly affects the price of gasoline, more cheaply or leanly than do industrial processes. Some produce unique complex compounds that cannot, as yet, be synthesized by industry, and others make compounds with special properties that lend themselves to particular engineering demands. Greater understanding of geomicrobiological processes could easily lead to new products.

While scientists can cite many isolated examples of biology influencing the environment and vice versa, they do not fully grasp how these interactions have changed over time or how they all fit together. Furthermore, large gaps riddle our understanding of critical past events, and gargantuan holes confound our ability to explain what forces drove particular occurrences or why certain organisms and communities responded to their circumstances in the ways they did. In order to interpret Earth's past history or to predict its future, scientists must expose the story of how the geosphere and the biosphere co-evolved. By studying present day geobiology, scientists hope to fill in its history and better predict Earth's trajectory into the future.

This colloquium was organized to devise plans that will outline the challenges faced by the nascent field of geobiology, to devise plans that will address the challenges, and to propose some solutions. Although the dominions of geology and biology have independently matured, the intersection of these two areas remains relatively immature and underdeveloped. Under the influence of heightened interest in life in remote and extreme environments, the boundaries of geobiology are expanding rapidly. The breadth and scope of this expanding discipline need to be more clearly defined and directed. Intellectual, economic, social, and educational issues associated with advances in the field must be anticipated, identified, and analyzed to create a plan of action. A list of urgent scientific questions needs to be compiled and evaluated to direct and adequately fund scientific inquiry. Critical intervention at this time by experts in the intersecting and allied fields should help to guide the development of the field and usher it to its full promise.

Interactions between the microbial and geological worlds represent a large swath from the cloth of interactions between living organisms and the geosphere they inhabit. Thus, most of the examples in this document focus on geomicrobiology. While it was well recognized that animals and plants interact in significant ways with the geosphere, colloquium participants concentrated on geomicrobiology two reasons: (i) it reflected their expertise, and (ii) the time period over which the geosphere and biosphere have co-evolved is known to be overwhelmingly dominated by microbes. The more complex eukaryotic organisms have evolved relatively recently. Colloquium participants recognize that the activities of animals, plants, and other complex organisms have and will continue to exert an enormous impact on the geobiosphere. They project and hope that future geobiological research will encompass increasing contributions from the scientific disciplines that deal with more complex organisms. In the meantime, examples from the realm of geomicrobiology handily illustrate the power and potential of geobiology as a whole.

THE PAST, THE PRESENT, THE FUTURE, AND THE POSSIBILITY OF EXTRATERRESTRIAL LIFE

The field of geobiology offers clues to a wide range of practical and philosophical enigmas. It has the potential to profoundly change both the quality and our understanding of life. Findings in this area will influence the health of all life on Earth and the planet itself. The field promises tremendous ecological, economic, and intellectual rewards.

While microbes have historically exerted the largest effect on the Earth, humans are now making a huge impact. Society today faces challenging questions about how to counteract some of the damage that we are inflicting. Humans are encroaching on natural habitats and rapidly polluting and depleting the environment through activities such as mineral mining, oil and gas production, large-scale farming, logging, and industrial production of toxic waste. This damage encompasses the Earth's continents, as indicated by, for example, the increasing evidence of global atmospheric and oceanic warming. But we also have the opportunity to counteract some of the destructive by-products of an urbanized civilization. Humanity can aim its technology in more constructive directions. In addition, we have many valuable natural resources derived from geobiological processes. Microbes, for example, perform a multitude of biogeochemical feats that can be put to good use, from cycling carbon, nitrogen, and sulfur to transforming toxic chemicals, including heavy metals. In the future, we must devise more schemes that responsibly exploit the opportunities that present themselves in the complex natural world.

Scientists must tease apart the complexity of contributions from different organisms and reactions and use this information to predict how the environment is changing. To meet this challenge, we must learn all that we can about how geology and biology interact. For example, how do temperature fluctuations impact living things? How do microbes respond to long- and short-term environmental perturbations? How do the biological changes caused by environmental perturbations affect the regional geochemistry? And how will these answers change over time?

The study of geobiology allows us to look backward as well as forward. In its infancy, conditions on Earth did not welcome life. In order to understand the planet's continued evolution, we must understand its past. A clear picture of how life arose and prospered will undoubtedly lead us toward answers about how to successfully maintain life on this planet.

Since the beginning of scientific inquiry, people have wondered how life began and how the zoo of complex creatures on our planet arose from our simple predecessors. Pondering these issues while surveying the night sky evokes the question of whether life has arisen elsewhere in the universe. The study of geobiology will undoubtedly provide insights into this question as well.

GEOBIOLOGY'S POTENTIAL

Interactions between living creatures and inanimate matter have shaped Earth and its inhabitants since life arose from our comparatively simple ancestors. Yet, we have just begun to appreciate the extent of its influence. A vast repertoire of diverse microbial talent has eluded scientists until recently. Researchers have found microbes in remote places, such as deep-sea thermal vents, which at first were considered too hostile to support life. Organisms that survive and even thrive in these extremes of temperature, pressure, or unusual chemical environment, also perform unusual and, in many cases, unanticipated biochemical feats. Many of these involve geochemical reactions—making or breaking minerals, transforming elements from one form into another, producing compounds that dramatically alter the immediate surroundings, and, thus, affect the entire local community of organisms, or that build up in the atmosphere and impact the entire planet.

The discovery of such microbes and the study of their activities have forced scientists to broaden their ideas about life's capabilities, limits, and effects. While the list of unusual microbiological activities grows longer with every discovery, each "surprising" finding hints at a lengthening list of unknown ones. We have only begun to dig into the wealth of this information and to gain tantalizing glimpses of its significance.

Microbes influence the geosphere in myriad ways, especially through influences on the cycling of elements, which affect the quality of all life on this planet; yet critical features controlling the elemental cycles remain elusive. Keys to global warming, for example, are likely to lie inside microbial cells, because multitudes of these tiny creatures emit and deplete enormous amounts of gases, such as carbon dioxide and methane, that trap heat around the Earth. Despite the importance of such physiological processes, huge holes in our knowledge foil attempts to assemble the relevant pieces. Microbes and plants transform carbon dioxide, the most abundant greenhouse gas, from the air into sugars and other organic molecules, or solid carbonate structural elements. Other organisms consume organic chemicals, and in the process of breaking them down for energy, spit out the carbon in the form of carbon dioxide. While these events provide a satisfying qualitative view of the carbon cycle, they don't explain all aspects quantitatively. For example, it has been impossible so far to balance the carbon cycle on the global scale. Somewhere on the planet is a substantial sink for carbon dioxide that is not yet discovered and, therefore, not understood. Understanding the sources and sinks of carbon, and the fluxes into and out of these boxes, is key to understanding and intelligently dealing with the issues of global climate. Similar information for the cycling of other elements with key geological and biological roles is also missing and of great interest.

The geological and biological worlds interact in many other ways as well. Recent studies have established that some microbes obtain energy for growth by transferring electrons to a wide range of toxic or environmentally harmful metals, such as uranium, chromium, selenium, arsenic, technetium, and plutonium. In some cases—for uranium, chromium, and technetium—these activities produce reduced metals that are insoluble, effectively removing them from exposure to the food chain. In others, undesirable effects occur. For example, iron and manganese oxides are scavengers of toxic transition (copper, nickel, cobalt, zinc), radioactive (uranium, platinum, technetium), and heavy (lead, mercury) metals. When microbial reduction of iron or manganese occurs, the dire consequences might mean that these toxic metals are set free, effectively concentrated in the environment due to metal oxide scavenging. Knowing what can—and will—happen will require extensive knowledge of the iron and manganese oxides, the extent of toxic load they are carrying, and the abilities of the microbes in the environment (or of those that might be added to a polluted system).

In addition to repackaging or dissolving minerals, microbes can produce them. Magnetotactic bacteria, for example, manufacture tiny magnetite crystals forming microbial compasses. These tiny crystals display properties that may render them particularly useful in electronics or microchip construction. Other bacteria construct extractable crystalline surfaces (S-layers) that are amenable to forming nanoscale electrical circuits once "doped" with metal atoms. Some bacteria even produce a compound, crystalline cellulose, which has unusual acoustic characteristics. Engineers have already incorporated this material into stereo speakers. These examples underscore not only the ability of microbes to produce substances of great practical use, but also illustrate their ability to leave distinct geobiological signatures. The magnetotactic bacteria, for example, produce ultrafine-grain magnetite particles with unique shapes and magnetic properties that have been invoked as evidence for past life on Mars.

Tiny microbial cells can affect large—even global—environments, as well as local ones. For example, microbes in organic-rich sediments under the ocean floor produce enormous amounts of methane gas. Scientists estimate that this methane store amounts to about twice that of the recoverable gas, oil, and coal deposits on the entire planet. As such, it represents a tremendous potential energy resource. Furthermore, the trapped gas, which exists in crystalline form combined with water in the form of "methane hydrates," holds other importance. Formation and decomposition of methane hydrates can alter the sediment's stability, with potentially devastating effects. Many scientists think that methane hydrates have played a role in generating some of the huge landslides that occur under the ocean next to continents.

Some scientists, therefore, suggest that building oil platforms on top of methane hydrate pockets is risky. Pumping hydrocarbons generates heat, and raising the temperature melts methane hydrates, which weakens sediments and may trigger submarine landslides. In addition to dramatic effects on the ocean (and underwater oil rigs), such bursts might release huge amounts of methane into the ocean and perhaps the atmosphere as well. Indeed, scientists propose that increases in temperature might provoke a cascade of global warming. Indeed, even more methane is trapped, frozen, in huge peat deposits of the Canadian and Russian Arctic. As the Earth heats up, methane—itself a potent greenhouse gas—vaporizes, escapes, and pushes temperatures further upward. Events such as these may have exerted strong effects on global climate over the Earth's development. Despite the tremendous potential impact of microbially produced methane hydrates on human welfare and the environment, many important questions remain about its generation and dissipation, as well as its possible use as an energy source and its hazardous potential.

While many geobiological phenomena result from natural processes, others are by-products of industrialized civilization. For example, mining operations release toxic heavy metals, such as chromium, copper, zinc, arsenic, lead, and mercury, into local and regional environments. Such operations bring ore to the Earth's surface and vastly increase the surface area of these minerals through crushing and milling. These processes expose them to air and make them react more quickly with water, thus increasing the acidity of the environment and releasing toxic heavy metals into natural bodies of water, soil, and the atmosphere.

These examples hint at the wide extent of interactive effects that occur at the intersection of the biosphere and the geosphere. If we uncover and understand the full range of these possibilities, we will stand in a position to use these natural processes to benefit humankind and, possibly, to rejuvenate the planet.

There are many potential practical and intellectual benefits that might arise from the study of geobiology, including:

- Cleaning up oil spills and other environmental hazards with microbes.
- Producing useful substances in easier and cleaner ways, as compared with conventional engineering approaches.
- Providing information about why water supplies in many areas are dwindling. It would be useful to know what roles microbes are playing in such events, and to discern whether they can be used as indicators of water sources and quality.
- Understanding the conditions that result in the dissolution and precipitation of economically important minerals.
- Protecting from various sorts of corrosion in a cost-effective manner by modifying or exploiting microbial communities. Both biological and non-biological phenomena erode and otherwise damage buildings, roads, sewer systems, ships, and even sculptures.
- Harnessing microbes to detoxify industrially produced poisons, such as PCBs, that contaminate water, soil, and other parts of the environment. Scientists already know that some microorganisms are capable of converting the offending chemical groups in these compounds into harmless products. However, we don't yet know how best to harness these capabilities.
- The ability to recycle, which is a fundamental activity of microbes, should be utilized to increase the efficiency and specificity of recycling human-generated waste materials.
- Understanding how particular geobiological processes may create environments that support or suppress the growth of emerging, and potentially dangerous, microbes.
- Cleaning up toxic mine tailing leachates. While daunting, such situations might offer a positive side. For example, the right methodologies—perhaps ones that include special talents of particular microbes—might recover valuable metals from such cleanups. We need to develop methodologies to turn environmental disasters into economic prosperity.
- Understanding better how microbes are involved in energy production.
- Understanding Earth's history, including the origin of life and the evolution of global biogeochemical cycles.
- A greater appreciation for how life survives at nutritional, chemical, and physical extremes.
- Improving our knowledge of how cell-to-cell communications and microbial community interactions can control global biogeochemical processes.

Finally, we look beyond Earth. The finding of life on another planet would represent the greatest scientific and ultimately societal event of this century, and perhaps of all time. The discoveries of microbes that thrive in extreme environments has expanded notions about how life began on Earth and strengthened the possibility that similar microbes may live on other planets.

SEIZING THE MOMENT

Many scientists from a broad range of disciplines are thinking expansively about geobiology and its potential. Geochemistry, geohydrology, oceanography, astrobiology, microbiology, environmental studies, ecology, molecular biology, genomics, paleobiology, and mineralogy represent only some of the specialties falling under the broad canopy of geobiology. This tremendous span begins to provide a glimpse at the vast field and implications of geobiology. Certainly this discipline is greater than the sum of its parts.

Fruitful new endeavors and groundbreaking research will likely lead and challenge those from these overlapping disciplines. Much research in the basic sciences is moving toward interdisciplinary research, and the field of geobiology is poised to lead this movement and set precedents for the future of collaborative research that bridges diverse specialties. Compelling questions are already launching researchers in fruitful directions, with enthusiasm fueling the progress. The appropriate recognition and support for this growing field promise to provide a model for other emerging, interdisciplinary scientific disciplines at the same time that it addresses key environmental and basic science topics that have huge impacts on social and economic issues.

CURRENT STATUS

Microorganisms have lived at the Earth's surface for most (about 85%) of Earth's age, and the importance of microbial activity in shaping the Earth's oceans and atmospheres has long been accepted. Only recently, however, have geologists, geohydrologists, and geochemists recognized the broad consequences of microbial activity. Microbes impact and are impacted by virtually all geochemical processes that occur at the Earth's surface, as well as deep within its subsurface.

Our ignorance represents possible hazards and lost opportunities. The economic potential of understanding how microorganisms function in the geosphere is tremendous. Although this area is receiving increased attention, it remains largely untapped. Currently hidden metabolic processes might present us with new options for transforming one substance into another or for utilizing other useful activities. In order to harness the potential of microbes, we must better understand their natural capabilities. Furthermore, major unknown metabolic activities could be exerting huge effects on the geochemistry of the planet. If these unknown phenomena touch upon geobiological systems that humans are trying to cope with, our lack of understanding might foil our efforts; perhaps we are not incorporating all of the relevant considerations and components into our plans.

Technological and scientific advances in the last decade have fostered interdisciplinary alliances between the earth and life sciences and have allowed scientists to probe geobiological interactions in ways that previously were not possible. For example, now scientists can detect trace elements that previously would have gone unnoticed and observe microbes that cannot be grown in the lab in their natural habitats. Progress in light and electron microscopy is permitting quantitative studies of microbial interactions at the community level in biofilms and with mineral surfaces at the atomic scale. Breakthroughs in molecular biology and, in particular, revelations about the genomic content of many different organisms have spurred an explosion of information about the capabilities of living things. For the most part, high-temperature geology explains what we know about the cycling of rocks and minerals, because, at high temperatures, the rocks melt. At low temperatures characteristic of the surface and near subsurface, where geological processes are slow, life intervenes and speeds up the reactions to its own benefit.

As such techniques improve, the complexity and richness of the geobiological world are coming into focus on the canvas of the globe. Fuzzy ideas are sharpening as scientists exploit better tools and develop new hypotheses. These insights are revealing ever deeper ties between the biological and geological worlds. The methodological improvements have allowed scientists to more accurately assess the geochemical and ecological consequences of perturbations to the environment sparked by both natural biological processes and the technological activities of human beings.

This progress represents some of the first steps toward understanding how living things and their environments influence each other and promises to help rectify many environmental problems. However, many challenges remain.

Although analysis of genetic sequences has revealed the existence of microorganisms that have not previously been grown in the laboratory, this information doesn't establish what biochemical tricks these microbes can perform or what environmental conditions trigger these feats. Furthermore, although we now know that scientists grossly underestimated the extent of microbial diversity, most microbes and their functions still have not been identified. For example, while decades of intense study have provided information about how living things—especially microorganisms—interact with organic compounds in the environment, a view into interactions with inorganic compounds is only now beginning to crack open.

Other tasks loom large as well. For example, scientists need tools and research programs that more precisely document geobiological processes as they occur. Improvements in detection methods and monitoring tools are needed. In this area, particular problems arise: how to study extremely slow-growing or dormant life, for example, and how to recognize and understand the meaning of subtle microbial signatures in rocks.

Countless other examples exist of questions that can only be answered by knowledge and technology currently unavailable. In order to exploit the great potential of geobiology, new methodologies and intellectual frameworks that address all such issues must be developed. To achieve this goal, scientists and engineers might need to exploit and adapt technologies from other disciplines than their own.

Scientists from different disciplines are forging research alliances to delve into the growing field of geobiology, but education in this area is insufficient. Geologists are not generally trained in biology and vice versa. In isolation, these fields can be expected to mature in their own directions, but they will not merge on their own. Now is the time to bring them together. The discipline of geobiology needs the concerted efforts of the scientific and informed lay communities to identify the important problems and knowledge gaps and then to devise novel approaches to resolve them. Results from geobiological studies will positively impact global change, illuminate the deep biosphere, demystify astrobiology, unravel the complexities of extreme environments, and elucidate the processes of evolution. This will be reflected in new job opportunities at all levels. Thus, the field needs to recruit and prepare students to meet this demand.

With a growing appreciation for the magnitude of geobiological effects and improved technology, scientists in a wide variety of disciplines are poised to achieve tremendous gains in this area. Available funds, however, currently are too limited to support the kinds of interdisciplinary research programs that need to be launched and sustained. Future investigations should not only delve deeper into questions that have already been explored, but should expand into areas that have experienced relatively less examination. Our biases have directed us more strongly in some directions than others. For example, we have interrogated outer space more diligently than the sea floor or deep beneath the Earth's surface.

We stand at a unique time in history. Humans are impacting the environment in significant negative ways, but our technological and cognitive capabilities allow us to alter conditions for the future. At the moment, a huge scientific chasm separates us from a full understanding of our planet and its deep reservoirs of biochemical and geobiological reactions, which may affect Earth in ways that we don't currently comprehend and can't predict. This wide zone of ignorance compels exploration to the next frontier of knowledge.

The field of geobiology faces many challenges and opportunities as it attempts to address key fundamental questions. Of course, these challenges represent research opportunities that will help to set the research agenda for this new field. Some of the questions discussed at the colloquium are:

- What role do living things play in the cycling of "geological" substances? There is increasing recognition that microorganisms are important agents in planetary scale processes such as carbon cycling (which relates to a number of phenomena that include climate change and food production), oxygen levels in the atmosphere, and weathering and precipitation of rocks and minerals. Yet we know relatively little about the microbial mechanisms involved, the rates and extents of these processes on a global scale, and how humankind may be irreversibly altering them.

- How do reactions on surfaces and at interfaces contribute to geobiological events? Interfaces occur on both small and large scales. Cell surfaces, for example, are very reactive and can spur minerals to precipitate and dissolve. Some microbial communities exist as structured "biofilms," which are highly organized communities with different physical, chemical, and biological characteristics in different regions of their matrices. Transition zones on larger scales include, for example, the areas between freshwater and saltwater. These regions typically nurture a wide array of life forms. This abundance of life reflects a healthy ecosystem and can serve as a source of novel biological products and capabilities. Details of events at all of these (and other) natural boundaries remain largely unknown and untapped, both practically and conceptually.

There were also questions about the origins and evolution of life on Earth. Many of these questions may be asked about the origins and evolution of life on other planets and the conditions that could support life elsewhere in the universe.

- What were the physical conditions on Earth before life arose? (Was there water? How hot was it?)

- How deeply entwined were the bio- and geospheres on the primitive Earth and has this dependence altered over time?

- How did life begin? From where did early life collect chemical energy? (The atmosphere? Extraterrestrial sources?) By what biochemical means did the original inhabitants extract energy? Where on today's earth can we find proxies for early metabolism?

- How and when did the processes of photosynthesis and respiration evolve? What drove the change to oxygen-based respiratory energy extraction from food?

- Did distinctly more complex life forms originate due to environmental, climate, and nutrient pressures or from purely random evolution? How did the rise of these organisms impact the simpler creatures that had existed until that time? How did these organisms impact their surroundings and how were these changes preserved in the geological record?

- Can we correlate major climatic effects with rapid evolutionary branching? What evidence would we seek?

- What was the impact of increasing or decreasing temperature events on the evolution of microbial communities?

- Did the types and populations of living things increase dramatically when the atmosphere first acquired significant amounts of oxygen?

- How do microbes respond to environmental change, how rapidly do they respond, and how do these changes affect geochemistry?

Another set of questions was raised about life in deep subsurface regions of the Earth's crust where, until recently, life was not thought to exist.

- What is the extent of the biosphere that exists deep below the Earth's surface? When and how did it evolve? How much biomass lies there?
- From where do organisms that are trapped inside rocks or in sediments below the Earth's surface derive their energy? Do these organisms employ very slow metabolic rates and how important is the phenomenon of slow metabolism? How long do these microbes live and for what do they use energy in unknown ways to maintain their cells? What kind of selective forces act on microbes under the severe starvation conditions of the deep subsurface?
- How do subsurface microbes affect rock weathering? Are subsurface processes similar to those involved in soil formation? How do subsurface microbes compare to the soil microbes that contribute to that process?

CATALOGING THE CAPABILITIES OF LIVING THINGS

We have only begun to chart the diversity and potential of the Earth's most abundant and diverse biological resources, the microorganisms. They compose more than half of all living matter on Earth, yet we have identified less than one percent of all the predicted microbial species. In order to tap natural communities for economic or social benefit, we will need to monitor and develop new means to more deeply probe the natural activities of microorganisms. Such an achievement should help establish links between processes associated with life and its inanimate surroundings.

The genetic content—or genome—of an organism can be used to predict its biochemical and physiological potentials, or lack thereof. For this reason, the genomic sequence provides a wealth of information about ways in which a living creature can influence the planet. Technological advances in this area have led to a situation in which the amount of DNA sequence information greatly exceeds our understanding of its meaning. Major work is needed to connect physiological functions with the ever-accumulating masses of sequence data.

Scientists must find new ways to capture the potential of species diversity in genetic terms. To this end, they must develop new means for uncovering biological processes and continue to decipher the genetic sequences that dictate these behaviors. Reaching this goal requires advances in laboratory and computational technology associated with sequence and functional analysis. This requirement calls for interdisciplinary research and tools. For example, computer scientists must grasp the relevant biological questions to create software that exploits the sequence and functional data, and biologists must learn to navigate new software that is developed. Biologists must reach beyond traditional ground and extend ways to study, for example, organisms that don't grow under conventional laboratory conditions. Geologists and biologists must collaborate in ventures that explore the impact of particular microbes on the environment and vice versa.

Finally, many microbiological scientists study physiology, but fail to put their findings in the context of the evolution of the planet. The feedback between Earth's history and microbial metabolism is important to understanding the development of both life and the environment, how organisms are currently keeping the Earth's systems in balance, and how to anticipate—and even impact—future events and trends.

These challenges can be overcome in numerous ways. Strong support should encourage new genomics efforts, particularly those aimed at linking biogeological function with sequence data. Funding agencies and professional organizations should encourage collaborations between genomics experts and others from diverse earth science fields. For example, projects that explore geobiological questions in novel ways by crossing conventional specialty lines or by employing unconventional methods to answer geobiological questions should be fostered.

Geomicrobiologists should be encouraged to move beyond descriptive surveys and move toward more mechanistic understanding of geobiological phenomena. Special emphasis should be put on efforts to culture novel microbes so that their biogeochemical functions can be investigated. In this regard, geochemists should collaborate with microbiologists in elucidating geochemical reactions that microbes might be employing.

ANALYTIC TECHNIQUES

Despite decades of study, basic information about fundamental biological and geological processes is missing. For example, while scientists realize that some microbes can persist for extended periods of time, many mechanisms of long-term survival remain mysterious. No one knows whether or how organisms endure the apparent absence of an energy source or whether apparently entombed microbes gain energy by very slow metabolism of a source that is not readily apparent. Hydrogen gas can be a major energy source and perhaps some long-lived organisms are exploiting this substance for energy—yet the mechanisms of hydrogen gas production and distribution in geological samples remain murky.

The ecological and geological importance of such "slow" metabolism remains similarly obscure. Most microbiologists are trained to conduct experiments with rapidly growing cells in the laboratory or even in the field over periods of hours or months or years; conventional scientific grants fund 3- to 5-year investigations. Studying microbes that live at a very slow pace will be essential for understanding geobiological processes, the microbes that catalyze them, and the function of environments in which they are important, such as the deep subsurface. The environmental influence of such slow-living organisms and their associated biochemical activities may be very significant over long periods of time, but only become apparent after decades or longer. Only by long-term studies will we determine how gradual changes in the local environment may lead to the gain of an ecological advantage or how to identify the potential energy sources in an environment and discern how the energy available is used or to discover whether the resident microbes actually can evolve under starvation conditions.

The hydrogen example above illustrates a general principle that affects many domains of geobiological study: scientists don't have reliable ways to measure many critical processes that they would like to measure. Beyond quantification, there is an urgent need to develop better techniques for detecting specific processes and determining how they are occurring.

Microbes themselves may serve as environmental sensors. For example, some organisms respond in predictable ways to particular chemical or physical conditions; many bacteria move toward nutrients and away from poisons. Microbes possess sophisticated systems for detecting and responding to chemicals in the environment. With enough ingenuity and application of new molecular and analytical microscopic techniques that are available today, we should be able to learn their secrets. By understanding and exploiting such microbial sensing phenomena, we can use microbiology to tell us about geochemistry.

The field also needs to develop sensors that can be deployed and used remotely to make environmental measurements on a real-time or near-real-time basis in areas of the planet that have been understudied or are relatively inaccessible. Some programs aimed at developing such tools exist, but much more development in this area is needed.

OBSERVATION ON SMALL AND LARGE PHYSICAL SCALES

In order to document the interplay between organisms and their surroundings, scientists must measure chemical reactions and products on spatial scales that range from distances between molecules to those between mountain ranges. Tools exist for accomplishing this task under some circumstances, but not all, and for some purposes, but not others.

Analyses of individual microbial cells can identify organisms and the chemicals that they are consuming and producing. Furthermore, by taking a small step backward from single cells and looking at their neighbors and their immediate surroundings, scientists can also examine the consequences of microbial processes as reflected in the local microenvironment. Bulk measurements provide only averages over large volumes and many cells, however, while the *real* action happens at the level of the individual microbial cell or small groups of microbial cells. Sometimes, for instance, two or more specific organisms in close physical association must collaborate to accomplish a particular biogeochemical transformation. The details of such processes can be measured only at the level of individual cells or small groups of cells. The problem is similar to trying to understand the basic mechanisms of forest ecology using only satellite pictures without examining the individual trees or groups of trees. The tools to address these problems of scale are only now coming on line.

Methods for analyzing environmental samples at the nano- or microscale include conventional, fluorescence, and laser scanning light microscopy; ion microprobe analysis; scanning probe microscopy; scanning and/or transmission electron microscopy; electron spectroscopic imaging and energy dispersive X-ray spectroscopy; electron energy loss spectroscopy; selected area electron diffraction; and X-ray imaging using synchrotron radiation. These tools serve as probes and chemical analyzers of the microscopic world, providing detailed biological and geological information on the scale of microns to nanometers. These techniques need to be improved and expanded in order to conduct these "single-cell" experiments because their capabilities are currently limited to only a very few dedicated facilities and because of instrumental limitations. Many promising nano- and microscale techniques are not yet well developed. They are still clumsy and inefficient. Furthermore, they generally employ large expensive instruments that cannot routinely be used in the field.

While many of these tools allow scientists to outline pieces of the geobiological puzzle, many pieces remain hazy. Sensors are needed that can measure a broader array of chemicals and other microenvironmental factors—such as pH, temperature, and light—central to the interplay between life and non-living matter. Development of such methodologies faces multiple challenges, such as detecting and quantifying the target factors in natural environments, where other conditions (the presence of minerals, for example) can interfere with measurements. Furthermore, key geobiological processes frequently occur at hard-to-reach locations—within sediments and rocks or deep in the ocean, for example. New technologies are needed that permit three-dimensional detection and mapping of microbes, minerals, chemical compounds, and their associated processes in all locations of interest.

In addition, scientists must extend their insights gained from such Lilliputian observations and extract meaningful information to be applied at much larger scales. Equally important as concentrations of a particular compound around an individual microbe are the levels of its products in the environment. Indeed some bantam scale processes—greenhouse gas formation and destruction by microbes, for example—can impact the entire planet. Global warming almost certainly results in large part from gases that are controlled by microbiological activities. In addition to utilizing microscopy, scientists must collect tools and perspectives that allow them to integrate the effects of the microscale processes on a global scale. They must expand the repertoire of available methods and develop tools that integrate observations from very small or very large scales.

OBSERVATION OVER LONG PERIODS OF TIME

To construct an accurate depiction of how our planet evolved, we must measure geobiological interactions throughout Earth's history. Scientists must find ways to identify what types of metabolism were present in different time periods, how populations swelled and dwindled, and why. Geobiologists are particularly interested in cataloguing changes in life forms as they relate to alterations in the environmental character of the Earth. Most species that have ever lived on Earth are now extinct. The geologic record provides the only window into the broad physiological variation that evolution has produced. Buried organic matter, rocks, fossils, and trapped gases (which can reveal what ancient organisms ate and breathed) provide the best record of ancient biological activities.

Fossils also provide the only direct avenue for understanding the environmental conditions present at times of major biological innovation and mass extinction. The material that holds the remains of an organism provides information about the environment at the time that creature died. Because rocks reveal their age by their chemical composition, any biological material that gets preserved in them can also be dated.

But imprints of shelled or otherwise hard-bodied creatures deposited in rocks are just one kind of fossil and provide only a partial record of former life. Soft-bodied organisms, including microbes, leave more subtle traces, and scientists have a great interest in uncovering these clues. Just as certain shapes and structures reveal what types of animals were alive at particular times and under particular conditions, the presence of certain molecules can belie the existence of living creatures and provide information about their properties. For example, some chemicals—e.g., isoprenoids or phytanyl-based lipids—in ancient sediments might reveal how cell membranes were constructed, while others provide clues about other biological characteristics and processes that occurred as life evolved. Further investigation into micropaleontology, in conjunction with studies of present day microbe-mineral interactions, will provide additional biogeochemical signatures that can be used for detecting which types of microbial activity were important, not only in paleoenvironments on ancient Earth, but in other poorly understood and difficult to sample modern environments.

Similarly, such molecular and chemical fingerprints, or biomarkers, should allow scientists to infer details about the environmental conditions at the time a particular organism lived. The development of new and more sensitive methods that detect fingerprints of life and corresponding geological processes are needed to probe the environments where life flourished and floundered and to discern how this was changed by the chemical and physical surroundings. Furthermore, scientists need these improved analytical tools to reveal high-resolution absolute and relative ages for events and species that extend back through the last three billion years.

Current analytical tools do not adequately look backward, which limits scientists' ability to look forward. Biologists would like to uncover diagnostic microbial signatures in rocks and to enhance their ability to examine microbes and biogeochemical events on a tiny scale. Improving these methodologies will enhance our understanding of the past and our ability to predict the future. Furthermore, an improved catalog of life's fingerprints will enhance our ability to detect life if it exists elsewhere in the universe.

SEARCHING FOR EXTRATERRESTRIAL LIFE

To ensure that we can detect life on other planets if it exists, we must hone our ability to uncover its hallmarks here on Earth. But the search for extraterrestrial life must incorporate the idea that living creatures on other planets may be fabricated and look and act differently from those on Earth. It would be foolish to restrict our definitions of life to Earth-based constraints. Scientists need to keep their minds open and entertain the idea that, for example, the chemical basis of life could be different on other planets. Studies of geobiology on this planet should include consideration of the fundamental constraints on life here that could help us define or look for it elsewhere. Investigations at the extremes will aid these endeavors by cataloging the permutations of life in a wide a variety of environments that we can probe here on Earth.

INFORMATICS TOOLS

To advance the field of geobiology, scientists require an understanding of a wide array of processes in a large number of organisms on tremendous scales of space and time. Progress depends on the development, manipulation, and integration of huge data sets. Computational tools must allow researchers to combine information from a variety of sources. These include databases that can be used to map microbes, minerals, geological formations, and temperatures to particular locations on the planet, to compare genomic DNA sequences, and to compile information about the cycling of particular chemical elements, for example. This informatics technology also needs to be powerful enough and user friendly enough to assist scientists as they explore what kind of life existed where and under what conditions and time periods. It should thus help researchers document the fossil record, provide tools for analyzing these data, and link this information to other relevant biological and geological databases. New informatics technology should facilitate recognition of and help establish connections, trends, and patterns that might otherwise go unnoticed. Furthermore, it should fuel researchers' findings by raising queries and providing answers that would be impossible without substantial computing power.

Scientists are rapidly uncovering genetic secrets of large numbers of organisms by sequencing their genomes. Comparisons of these sequences can highlight both shared and unique features of microbes, which can reveal clues about their physiological capabilities. DNA sequences present in all life forms, for example, point toward basic functions, while those carried only by organisms that convert one obscure compound into another or that squeeze nutrients out of rocks point toward specific biochemical talents and help link DNA sequence with function. Although seemingly simple, the task can require enormous computing power because of the huge number of genes and organisms being studied. The scientific community requires new and improved informatics tools to handle even this type of seemingly straightforward analysis.

In addition, researchers have recently set their sights on much more ambitious goals. Some are collecting not only sequences of individual organisms, but also sets of sequences that represent whole microbial communities from particular environments. By considering the added complexity of comparing entire communities, it is even easier to appreciate the tremendous need for powerful computing tools.

Information from sequencing efforts is a high-profile piece of the geobiology puzzle. In order to assemble the full picture, scientists would like to overlay physical and chemical data on the genomic sequencing data. In an imaginary example, they would construct maps that showed the types of organisms that inhabit specific areas of the globe and that allowed one to easily "see" the corresponding environments. In addition, there would be a tool that showed critical information about the content of solids, liquids, and gases in a particular location, and there would be data about, for example, specific chemical constituents, temperature, and pressure. Furthermore, the fantasy computer tools would map this information over time so scientists could examine how the various parameters are changing, and thus develop hypotheses about how components in complex geobiological webs are influencing each other. They could also learn about how species, or even specific genetic sequence variations, correlate with changes in temperature, chemicals in the environment, and so forth.

In order to achieve such imaginative goals, investigators need new ways to integrate the relevant data. This will require manipulating and combining huge data sets from different sources. To accomplish this task, new and more powerful informatics tools need to be forged and honed as more information and more questions arise.

Finally, the entire scientific community will benefit when these data and tools are available to everyone and when the tools are easily usable by scientists with a variety of backgrounds and training. Currently, there is no central site that serves as a hub and storehouse for geobiological information. This situation can lead to inefficiency and duplication of efforts. Care must also be taken to set up systems by which the data in the databases are easily accessed and manipulated by members of all sections of the geobiology community.

CULTURING TECHNIQUES

The ability to grow microorganisms in the laboratory is the only way to directly test hypotheses about their physiological and biochemical potential. Currently, it is estimated that greater than 99 % of all microbes cannot be cultivated in the laboratory. This number must be reduced. Because the diversity of microbes that are important in geobiological processes is enormous, geobiologists can make a big difference in solving this problem. While techniques for identifying microorganisms and their biological capabilities in the absence of pure cultures (such as deciphering and comparing their genetic sequence) are blossoming, geobiologists will also need to make special efforts to grow specific microbes in the laboratory.

Dedicated funding is needed to develop new culturing techniques. Scientists need to make significant headway on expanding culture methods to include more organisms. Of particular interest would be culture methods for studying interactive groups, or consortia (not just individual microbes), under conditions that mimic the natural environment as closely as possible. This goal presents

special challenges because microbial communities consist of many different microbes, each with a different function in the community. The challenges are that each individual may require different conditions for growth in the laboratory and that, in the consortium, the requirements may be different from those for any individual microbe.

SAMPLING TECHNOLOGIES

Researchers require new ways to sample organisms and their surroundings from the environment to discover and monitor biogeochemical processes. These challenges are particularly acute in remote or extreme environments, where life and its associated processes have not been adequately explored or mapped. New technologies are required that both increase access to these areas and address combined biological and geological objectives. When developing such methodologies, scientists and engineers face unique problems.

Pulling up material for geobiological studies from a lake or the ocean or beneath the Earth's surface requires care to avoid contamination by microbes and chemical compounds on the surface and to detect such adulteration if it occurs. Sampling strategies have been worked out for most of these near-surface environments, although improvements are still required. Improved methods are also required for sampling and analyzing extreme and remote locations (such as deep sea hydrothermal vents or the subsurface of Mars) to identify organisms and geobiological processes. Analytical devices that operate inside deep boreholes, for example, will facilitate subsurface monitoring of geobiological processes. However, the peculiarities of some microbes may not allow them to hold up well under conditions at Earth's surface. Microbes that have evolved at high temperatures and pressure or under other special environmental conditions might die on their journey to the environment that we consider normal. Similarly, gases that are maintained under high pressure (and the microbes that metabolize them) might escape (or die) unless transferred under appropriate pressurized conditions.

Another major challenge is the environmental relevance of a particular geobiological process. Just because a process is observed does not mean it is a major process in the environment, or that it operates to any extent in the natural setting. Geobiologists must devise strategies to determine whether the geobiological processes they observe are occurring in the same way under observation as they are in their undisturbed natural contexts.

The examples given above illustrate just a few of the challenges posed by remote sampling endeavors for geobiological research. Special technologies will be required to probe other planets for their geobiological potential. We need small and easily portable machines that require minimal maintenance. Furthermore, devices for sampling other planets must not only collect samples, but also must analyze them on the spot, e.g., *in situ*. In some cases, existing survey technology may be adaptable for geobiological surveys. For example, radar that penetrates the ground can detect subterranean liquid water on Earth and will be useful for surveying other planets remotely for water from satellites. Likewise, remote drilling methods must be developed to access environments and retrieve geobiological samples from underneath the surface of other planets.

A major issue for geobiologists who study extraterrestrial sites is whether or not life exists there, and, if it does, what is it like, and if it does not, why doesn't it? To answer these questions, scientists need to figure out how they will identify such life if it is present. This problem consists partly of finding potential life forms and partly of recognizing such life forms if they are present. If a spaceship makes contact with entities that obviously eat, move, breathe, and reproduce, we will know that they are living aliens. But more likely, life on other planets will be in the form of microbes, which are by definition invisible to the unaided eye and are most easily observed by their indirect effects and signatures they leave in their environment. Controversy is currently raging about what exactly constitutes life's molecular signatures. Improved methods are required for distinguishing products of purely geochemical processes from those with strictly biological origins. In addition to defining life's signatures, we also need methods to detect the diagnostic signs of life at distant locations.

MODEL SYSTEMS

While the major emphasis will be on understanding geobiological processes in natural environments, laboratory experiments designed to isolate and test the effects of individual physical, chemical, and biological phenomena will continue to play an important role in geobiological research programs. This is the only way to probe specific hypotheses about the interplay between life and matter. To extend these types of investigations, new technologies are needed for accurate laboratory simulation of environmental conditions. Such tools should also simulate conditions thought to exist in the early era of life on Earth, which will enable scientists to test scenarios of how life began.

Scientists would like to test possible pathways that led to the chemistry of life. The big question is how pre-biotic chemistry gave rise to reproducing organisms. A big experimental challenge is inherent to these studies. At this point in the planet's development, the Earth is so steeped in life that it is very difficult to subtract biological products. This situation poses difficulties in simulating conditions of a much younger Earth. While very simple renditions might be possible, others are more difficult. For example, some scientists propose that certain clays may have provided the physical structure on which pre-biotic chemicals met and reacted. But at this point, clays interact so strongly with existing natural biomolecules that they cannot be easily cleansed of their organic matter for accurate pre-biotic experimentation.

FIELD STUDIES

While model systems allow scientists to perform controlled experiments that probe specific questions, field studies are necessary to study the natural environment. Such endeavors reveal how different communities interact with each other and their environments in the real world. Studying complex ecosystems can elucidate activities that would remain obscure by analyzing individual organisms or sets of interactions in the laboratory. For example, microbial consortia collaborate to perform tasks and impact the environment in ways that single microbes do not.

At present, tools to accomplish this goal are lacking. In order to describe natural communities and habitats in detail, scientists face formidable challenges. Organisms and chemicals may be present at concentrations so low that they are difficult to detect, and identifying individual molecules or microbial species can be tricky when they are immersed in a soup with others. Furthermore, such systems are not static; behaviors and chemical reactions can change over minutes, days, or seasons. Because the natural environment contains a rich array of chemicals and life, *in situ* analytic techniques must be honed so that they measure the entity of interest—at the scale of interest—without interference. Scientists need improved micro-sensors that can detect small amounts of chemicals over small spatial scales. Such sensors will allow for determination of processes that play key roles in microbe-microbe and microbe-mineral interactions. Furthermore, these devices must operate under a wide variety of conditions, including at hard-to-reach or harsh locations deep beneath the Earth's surface or at the bottom of the ocean.

Such tools must also be able to sample on a micro-scale and map findings relative to each other. Key geobiological processes frequently occur unevenly within sediments and rocks, for example. Tools that document the presence of microbes and their associated activities and geological consequences in three dimensions, on fine scale but over broad areas, would be extremely valuable.

The choice of field sites is also important. Established field sites are valuable because they allow scientists to conduct long-term studies and to exploit documented geobiological history. However, colloquium participants also stressed the importance of branching out and exploring new areas and types of environments.

ETHICAL ISSUES

The pursuit of geobiological studies requires ethical, as well as technological and theoretical, consideration. Some studies may perturb natural populations or processes, which could result in undesired consequences. It is difficult to predict what problems might arise from, for example, transporting samples from a relatively sequestered environment to another, more exposed one. For this reason, effort should be directed toward developing guidelines for handling material from remote sampling sites, such as the deep underground zones that have not been exposed to the Earth's surface. Similarly, we must entertain the possibility that we could contaminate other planets with life from Earth as we explore them; along the same lines, we run a risk of introducing foreign life forms from other planets when we return them to Earth. Such possibilities must be considered when developing geobiological research programs and new methodologies. Scientists, lawmakers, and the public should engage in discussions about the stewardship of the natural universe and decide how best to care for it during these investigations.

EDUCATION, PERSONNEL, AND TRAINING

Scientists will require diverse backgrounds to traverse the traditionally non-overlapping fields that comprise the new discipline of geobiology. In addition to the conventional biological and geological university courses, new cross-disciplinary courses in geobiology must be developed. This will be best achieved by fostering collaborations between teaching faculty, as well as research faculty and students. Departmental and institutional leaders must make special efforts to help traditional geology and biology faculties work together and to create a new geobiology vocabulary that they and their students can agree on. Geobiology training programs might branch out to include, for example, in-depth exposure to mathematics, numerical modeling, and computational techniques. In addition to the need for people with strong mathematical and quantitative skills, there is also a need for improvement of observational skills and a return to the approaches of traditional naturalists. Both quantitative and qualitative approaches are necessary. The new field will benefit from cross-trained specialists with background and experience in both areas.

To introduce quality control and uniformity to this field, recommendations about what might ideally constitute degree requirements should be developed for universities. Furthermore, strong recruitment efforts at the undergraduate and graduate levels will stimulate interest among young scientists. Currently, jobs in this field outnumber applicants. This is true for both academia and industry.

While educational programs will groom students and postdoctoral fellows for full participation in this emerging field, other efforts must be made to allow established investigators to reach across disciplines. Geobiology encompasses a variety of different fields and addresses questions that span spatial and temporal scales in nontraditional ways. Such interdisciplinary and unconventional science is not necessarily compatible with academic infrastructure, such as promotion and tenure of faculty, design of undergraduate and graduate degree programs, and federal and state funding of academic institutions. Like other new and emerging disciplines, this one requires special attention at all levels of administration.

Efforts should be made to foster working collaborations and establish a common language between fields so experts from diverse specialties can communicate effectively to state and solve problems. Better integration is needed between basic research scientists in relevant disciplines and between scientists and engineers for development of appropriate conceptual and practical strategies to tackle problems in geobiology. Various approaches might build bridges between investigators who do not usually interact. Career opportunities and incentives, for example, might foster interdisciplinary ties, training opportunities, and education in geobiology.

While colloquium participants stressed the need for strengthening the breadth of scientific training, some were also concerned about the demise of microbiologists with deep roots in microbial physiology. Strong support is needed for robust research efforts aimed at understanding the physiological and biochemical repertoire of microorganisms. To this end, those with training in conventional microbiology will continue to play critical roles. They should be encouraged to delve into research questions outside the traditional arenas of medical and industrial microbiology and, as much as possible, to apply their well-developed microbiological sciences to relevant geobiological issues.

Professional societies are actively supporting geobiology. This is a positive trend, and they should be encouraged to continue fostering special educational programs, focused sessions at meetings, collaborations between members, and so on. International societies in particular should continue and increase support for conference sessions and other activities that nurture geobiology. More interdisciplinary journals might be useful. To ensure the field's success, the lay public, as well as the scientific community, need to recognize geobiology as an identifiable scientific discipline that promises practical benefits and insight into the basic processes that shape the environment and its life forms.

Colloquium participants suggested organizing an outreach program to communicate the power and promise of this field to the general public. People involved in this project might, for example, pitch story ideas to media outlets or develop Internet resources that convey how biology and geology fit together.

Finally, education should start early. Young (K-12) students need to learn about the relationship between Earth and its inhabitants, especially with microbes. Environmental issues may particularly interest children and could be used to illustrate some of the general concepts of geobiology. Furthermore, some of the basic questions of geobiology—how living things and the environment influence each other and how life evolved—may well hold appeal for children and may promote curiosity and interest in science in general.

SUPPORT FOR RESEARCH AND TRAINING

In order to tackle the challenges and realize the goals discussed by colloquium participants, there is a strong need for funding for educational, research, and technological development. This support will ensure establishment of programs that promote geobiological training and investigations at the graduate and postgraduate levels. Furthermore, it will attract and educate high school and undergraduate students. Financial support is needed for seminars, workshops, short courses, and conferences. Interdisciplinary grants that promote collaborations between specialists in different fields will be especially important to stimulate the field of geobiology, as would those directed toward development of new analytical and computer tools. In short, while limited funding has supported some special, short-term programs, more financing is needed to sustain long-term projects, training, and vigorous development of the field.

SPECIFIC RECOMMENDATIONS

- Foster development of geobiology at appropriate institutions by providing support for innovative, cross-disciplinary teaching, research, and outreach programs.

- Support and encourage basic research and engineering programs in geobiology, stressing the key issues in this report.

- Establish more field laboratories for geobiological research and continue to support existing field laboratories.

- Support laboratory studies of basic biological sciences, especially microbial diversity, physiology, and genomics, which represent the basic science backbone of the field.

- Improve methods for defining and detecting chemical signatures and other biomarkers that indicate the presence of past and present life.

- Support efforts to catalog the diversity microorganisms, including their biogeochemical capabilities and their geobiological importance.

- Establish and support centralized culture collections for organisms important to the field.

- Encourage further exploration of how human beings might exploit the geobiological capabilities of microbes for society's benefit, such as in cleaning up polluted areas or extracting valuable resources from the environment.

- Improve analytical tools for observation and measurements on small (microscopic) and large (planetary) physical scales and that operate at inaccessible sites remote from the Earth's surface.

- Develop informatics systems and computer technology infrastructure for:

    - *Easily accessible electronic databases to store geobiological information.*

    - *Management and comparison of geobiological data resources that range over wide scales of observations and across vast stretches of time and space.*

    - *Computational tools that can integrate geobiological information from genomics to global cycles of the elements.*

- Support geobiology education at all levels:

    - *Develop systems to educate the general public as well as scientists about the potential benefits of studying geobiology. Organize an outreach system that communicates the power and promise of this field.*

    - *Establish a central repository for information about geobiology on the World Wide Web.*

    - *Introduce interdisciplinary issues on geobiology into undergraduate level courses in biology and geology. Encourage programs that grant minor degrees in geobiology, with major degrees in a primary biological or geological discipline.*

    - *Develop summer field courses that will spread interactions and communications through a broad audience and enrich the experiences of graduate students, postdoctoral fellows, and principal investigators. Courses similar to the Woods Hole summer course series and Cold Spring Harbor courses represent good models for this enterprise.*

    - *Provide travel and research support for investigators to branch out into other areas for cross-training and to bring new expertise and insight into the field of geobiology.*

    - *Organize national and international scientific meetings in the field of geobiology.*

    - *Foster cross-pollination among subdisciplines of geobiology and between geobiologists and engineers.*

    - *Encourage continuing support for "classical" fields of microbiology, physiology, taxonomy, and metabolic diversity, while expanding their repertoires to include the less conventional areas that crossover into earth science disciplines.*

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