FUTURE DIRECTIONS IN GEOBIOLOGY AND LOW-TEMPERATURE GEOCHEMISTRY

Humanity is confronted with an enormous challenge, as succinctly stated by the late Steven Schneider (2001; quoted by Jantzen 2004*): "Humans are forcing the Earth's environmental systems to change at a rate that is more advanced than their knowledge of the consequences." Geobiologists and low-temperature geochemists characterize material from the lithosphere, hydrosphere, atmosphere, and biosphere to understand processes operating within and between these components of the Earth system from the atomic to the planetary scale. For this reason, the interwoven disciplines of geobiology and low-temperature geochemistry are central to understanding and ultimately predicting the behavior of these life-sustaining systems.

We present here comments and recommendations from the participants of a workshop entitled "Future Directions in Geobiology and Low-Temperature Geochemistry," hosted by the Carnegie Institution of Washington, Geophysical Laboratory, Washington, DC, on 27–28 August 2010. The goal of the workshop was to suggest ways to leverage the vast intellectual and analytical capabilities of our diverse scientific community to characterize the Earth's past, present, and future geochemical habitat as we enter the second decade of what E. O. Wilson dubbed "the century of the environment."

CHARACTERIZING EARTH SYSTEM GEOCHEMISTRY AND GEOBIOLOGY

Understanding Modern Planetary Change: The Anthropocene

Humans are transforming the physical, chemical, and biological states of as much as 50% of the Earth's land surface, the "Critical Zone" as named in the 2002 U.S. National Research Council report *Basic Research Opportunities in Earth Science*. Human-induced changes are so profound that the onset of the industrial revolution is proposed to mark a new geologic era—the Anthropocene. In this short time, soil erosion rates have accelerated, metals and toxins have been mobilized far beyond natural rates, freshwater use now exceeds recharge in major population centers, and ecosystems have been heavily impacted by fragmentation, extinction, and global-scale biogeographic shifts.

Land modification, climate change, and energy use are transforming the geochemical and geobiological landscape. We are witnessing the reorganization of elements, chemical compounds, and water cycles on a global scale. Global change in the distribution of organisms is recognized for macroflora and macrofauna but remains virtually uncharted in the microbial realm. A major research opportunity is emerging to characterize the fundamental processes at work in the Critical Zone and use this knowledge to recognize how humans and human-induced perturbations are transforming the foundation of life's habitat.

Leveraging the Deep Time Record to Understand Life and Its Geochemical Habitats

Interactions between organisms and their surroundings have played out over billions of years to define our planet's life-sustaining outer shell. These interactions continue today, shaping the Critical Zone in which we live. Our future depends on such interactions as they unfold over the coming centuries—and on our thoughtful and responsible stewardship of them. Yet, to understand our future, we need to know our geochemical and geobiological past.

The Earth's environmental systems have experienced geochemical, climatic, and biotic change in the distant past remarkably different from those in the Holocene epoch—when largely benign climatic conditions fostered human civilizations. Earth's history provides analogues to the emerging climate state of warmer temperatures and elevated atmospheric CO_2 concentrations. But life's planetary habitat has undergone even more profound geochemical transformations. For example, the advent of biological oxygen production and the expansion of plants onto land globally reorganized element fluxes in the ocean, sediments, and atmosphere. Only the geologic, geochemical, and paleontological records of Earth history can provide examples of change that rival the scale of the human-induced changes in land, biota, and climate that we are experiencing today. Understanding past biosphere–geosphere behavior is a powerful approach to anticipating impacts of human activity in the coming decades. Earth's biogeochemical history provides a major research opportunity to investigate the geologic record to unlock its messages for the future of our planet.

Powerful Insights Will Come from Integrating the Modern and Deep Time Approaches to Earth System Geochemistry and Geobiology

Geochemists and geobiologists recognize a grand challenge in modern Earth system science: to project the future state of our planet. This "Earth casting" of our future habitat requires understanding specific geochemical and geobiological mechanisms and their response to planetary drivers of change.

The response of an environmental system to human perturbation is inextricably linked to its own history. There is a major research opportunity to understand how biogeochemical legacies of past conditions or perturbations are manifest in sediment, soil, water, and associated faunal, floral, and microbial assemblages, and how they determine the resilience or vulnerability of that system to future perturbations. Because biogeochemical feedbacks operate over a range of timescales, understanding the consequences of human perturbation requires new scholarly partnerships between scientists who study modern processes and historically oriented geobiologists and geochemists. Modern and geological methods, data, and models must be integrated in order to define and quantify linkages between environmental conditions and biological function and diversity.

A REVOLUTION IN DATA AND KNOWLEDGE: MOLECULAR BIOLOGY, SPECTROSCOPY, AND COMPUTERS

Data and Knowledge in Geochemical Systems

The natural world consists of a mixture of particles, gaseous and dissolved species, and organisms, with heterogeneous properties at all scales. We can now observe the distributions of elements, isotopes, and their oxidation states, as well as crystalline and molecular structures, at the finest scales in soils and sediments. We find geochemical heterogeneity on the most intimate scales that is not represented in measurements of bulk properties. Integration of observational scales is needed to yield both new metrics of heterogeneity and new understanding of its functional role in surface environments.

The importance of the nanoscale world is literally just coming into view. What we know of the interactions between nanoparticles and microorganisms, plants, and fauna is scant, yet we face accelerating production, application, and disposal of nanomaterials manufactured by humans. A great deal of work is needed to characterize the role of nanoparticles in natural systems and to anticipate the impacts of manufactured nanoparticles in the environment.

New advances in chromatography, spectroscopy, and mass spectrometry provide an expanded analytical toolbox that reveals novel biomarkers and molecular proxies of past biogeochemical systems. Analytical advances enable mechanistic studies of metabolites, substrates, enzymes, cofactors and other molecular agents that drive geobiological processes. Coupling new tools in molecular geobiology with the power of genomics, geochemical analytical techniques, and theoretical models defines an immense new frontier in geobiology and low-temperature geochemistry.

* Jantzen HH (2004) Carbon cycling in earth systems—a soil science perspective. Agriculture, Ecosystems and Environment 104: 399-417

Molecular-scale computational models are emerging with temporal resolution down to the nano- and picosecond timescales. Ultrashort, ultraintense pulsed light and X-ray sources and time-resolved methods can track the dynamics of transient reaction species and generate "molecular movies" of fast, fundamental processes. Advances in models for liquid- and solid-phase chemistry and rapid increases in computational power provide a potent opportunity for understanding complex geochemical systems.

Data and Knowledge in Geobiological Systems

New advances in DNA sequencing allow the determination of tens of billions of bases per analysis and are opening the field of environmental genomics. Environmental RNA data reveal microbial dynamics on scales of minutes, while data derived from DNA allow characterization of geobiological evolution over billions of years. The field is poised to address challenges facing humanity, including increasing soil fertility, providing novel approaches to Earth resources and waste disposal, and attenuating the impacts of human land use and climate change.

The emerging revolution in DNA sequencing offers insights into the elusive microbial communities that mediate Earth's elemental cycles to form the foundation for all life on the planet. We can now identify where these microbes are located in relation to each other and to Earth materials, and track their activity and geochemical roles over space and time. The "meta-omics" world (metagenomics, proteomics, transcriptomics) will allow us to capture the genetic complement of nearly any geochemical environment. Gene diversity can be linked with RNA and protein expression to probe the dynamics of both diversity and function in near real time.

As DNA and protein sequencing reveal genetic and biochemical diversity, our understanding of ecological and geochemical functions in the environment must keep up the rapid pace. Much fundamental work is needed, including (1) identifying new genes and proteins using classical and novel biochemical approaches, (2) sorting out the implications of genetic and metabolic diversity within microbial taxonomic units, and (3) filling in genomic gaps with relevant microbial strains needed to test hypotheses important for tracking metabolic activities of geochemical importance.

GEOBIOLOGY AND GEOCHEMISTRY IN THE SERVICE OF SOCIETY

Earth Casting

Cross-fertilization of ideas within the community of Earth scientists will advance knowledge of our past and present needed to anticipate our future. Assembling teams of scientists to address this challenge through "observatories" will amass the tools and perspectives needed for Earth casting. A major research opportunity exists to bring together researchers across disciplines to provide new approaches to project the geobiological and geochemical impacts of environmental change. Integrated science requires integrated data. We need to make interoperable a wide array of information related to the Critical Zone.

Learning and Teaching Critical Zone Stewardship

Geobiological and geochemical systems provide essential services to planetary ecosystems and human societies. These services emerge from the geobiological and geochemical interactions that foster the availability of food, clean water, materials needed for shelter and industry, energy resources, and waste disposal. Social stability and conflict, economic health, issues of environmental justice, and national security are all closely tied to such natural services and to the human livelihoods that depend on them. The social and environmental impacts of human activities involved in resource acquisition, distribution, and disposal are profound. We need only read news report of oils spills, mining and industrial waste, and environmental change, to understand the importance of wise policy regarding Critical Zone services. Good stewardship relies on scientific understanding of highly complex systems, coupled with capable communication with decision makers and citizens.

AN ACTION PLAN: LEVERAGING THE POWER OF OBSERVATORY SCIENCE

Earth's environmental systems are under increasing stress, with potentially profound consequences for plant, animal, and human populations. The Earth science community should pursue the science needed to help societies anticipate and avoid the risks and consequences of our changing habitat. Earth system science observatories can propel us across interdisciplinary divides and help us understand our planet's past, present, and future Critical Zone.

Comprehensive Ecosystem Observatories

An existing and planned suite of Earth surface observatories provide powerful, yet not fully integrated insights into the operation of the United States' near-surface environment. These observatories include the sites within the NSF Critical Zone Observatory (CZO) and Long Term Ecological Research (LTER) programs, those identified within the Critical Zone Exploration Network (CZEN), and those proposed through the National Ecological Observatory Network (NEON). Each could be upgraded to systematically address a common suite of variables and provide data to a common data repository so that a more integrated analysis could be performed on the data.

But upgrading the existing networks would still not address the full spectrum of geochemical, biotic, climatic, and land-use complexities. Given the scale and scope of the anthropogenically driven changes to our planet, a truly comprehensive observatory configuration is called for, one that is based on an enhanced spatial coverage of the United States' natural and built ecosystems and more comprehensive investigations of Critical Zone processes. Our vision also calls for "deep time" observatories that will provide crucial insights into earlier planetary states. **The workshop participants therefore call for a suite of integrated observatories that foster the comprehensive science needed to characterize the past, present, and evolving state of the terrestrial environment. This bold initiative in observatory science would require equally bold funding to foster fundamental research in geobiology and low-temperature geochemistry.**

SUMMARY OF EMERGING MAJOR OPPORTUNITIES IN RESEARCH AND EDUCATION

- The rapidly expanding human need for land, energy, and resources is transforming the geobiological and geochemical systems that are the foundation of our planetary habitat, the Critical Zone. Basic research into the operation of these systems has been and will increasingly be a foundation of our ability to sustain human well-being.
- Major advances in analytical, molecular biological, and computational tools will provide the ability to understand fundamental biosphere–geosphere interactions at scales from atomic to planetary. Along with genomic data, the stage is set to explore the global consequences of these interactions.
- Understanding past biosphere–geosphere behavior is a powerful approach to understanding how our planet evolved, as well as anticipating how life-chemistry relationships will be impacted by human activity.
- Researchers working in teams and across disciplines can advance predictive tools to project, or "Earth cast," the geobiological and geochemical impacts of environmental change.
- Communicating scientific understanding of the Critical Zone and the services it provides to society will foster better-informed decision makers, an engaged citizenry, and the next generation of scholars.
- We call for a bold initiative in observatory science that strategically augments current efforts and establishes new observatories for characterizing the evolving state of the Critical Zone, fueled by fundamental advances resulting from basic research in geobiology and low-temperature geochemistry.

Katherine H. Freeman, Pennsylvania State University
Martin B. Goldhaber, U.S. Geological Survey
and the **workshop participants**