NEW RESEARCH OPPORTUNITIES IN THE EARTH SCIENCES

Committee on New Research Opportunities in the Earth Sciences at the National Science Foundation
Board on Earth Sciences and Resources
Division on Earth and Life Studies

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PREFACE

This report summarizes the findings and recommendations of the Committee on New Research Opportunities in the Earth Sciences (NROES). The committee was charged by the National Science Foundation (NSF) with undertaking the following tasks to advise NSF's Division of Earth Sciences (EAR)[1]:

- Identify high-priority new and emerging research opportunities in the Earth sciences over the next decade, including surface and deep Earth processes and interdisciplinary research with fields such as ocean and atmospheric sciences, biology, engineering, computer science, and social and behavioral sciences.
- Identify key instrumentation and facilities needed to support these new and emerging research opportunities.
- Describe opportunities for increased cooperation in these new and emerging areas between EAR and other government agency programs, industry, and international programs.
- Suggest new ways that EAR can help train the next generation of Earth scientists, support young investigators, and increase the participation of underrepresented groups in the field.

In keeping with its charge, the committee did not evaluate existing EAR programs or other federal research programs, and budgetary recommendations are not provided. This report focuses on new and emerging research directions that significantly intersect the portfolio of EAR research interests in surface and deep Earth processes. Research directions that are funded primarily by other NSF divisions are not addressed, but several interdisciplinary research opportunities that EAR can position itself to pursue do straddle boundaries with other organizations both within the NSF Directorate for Geosciences (GEO: Division of Ocean Sciences (OCE) and Division of Atmospheric and Geospace Sciences [AGS]) and more broadly across NSF (Office of Polar Programs, Directorate for Biological Sciences, Directorate for

[1] EAR is part of NSF's Directorate for Geosciences (GEO), which also comprises the Division of Atmospheric and Geospace Sciences (AGS) and Division of Ocean Sciences (OCE). Earth science involves the part of geosciences that addresses Earth's solid surface, crust, mantle, and core, including interactions between the solid Earth and the atmosphere, hydrosphere, and biosphere.

Mathematical and Physical Sciences). Interagency coordination with the National Aeronautics and Space Administration, U.S. Department of Energy, and U.S. Geological Survey also is of great importance for pursuing key Earth science research opportunities in the future.

The National Research Council (NRC) has issued several prior reports that have helped shape NSF activities in Earth science research. Prior to 1983, EAR directed all of its funds to individual investigators through core research programs. Pursuing the recommendations of *Opportunities for Research in the Geological Sciences*[2] and *Research Briefings*,[3] EAR created a variety of cross-disciplinary programs, including Instrumentation and Facilities and Continental Dynamics. In 1993 the NRC report *Solid-Earth Science and Society*[4] documented progress in Earth science, its technology drivers, the status of its constituent disciplines, a host of significant unsolved problems, and many outstanding research opportunities. It also described the fundamental importance of Earth science in a globalized, high-technology society. In 2001 the influential NRC report *Basic Research Opportunities in Earth Science*[5] (BROES) articulated emerging research frontiers in (1) Critical Zone studies, (2) geobiology, (3) Earth and planetary materials, (4) continental investigations, (5) studies of Earth's deep interior, and (6) planetary science, all framed in a context of the societal relevance of pursuing basic research in Earth science. NSF and EAR acted on several of the key recommendations in the BROES report, notably reorganizing the divisional structure, investing significant resources in shallow Earth dynamical and hydrological systems, critical zone observatories, and geobiology, and pursuing the EarthScope Major Research Equipment and Facilities Construction initiative. The BROES report extensively documented the value of pursuing basic research in Earth science; the arguments have only strengthened with time as issues of natural resources, natural hazards, geoscience engineering, stewardship of the environment, and terrestrial surveillance for national security have repeatedly been foci of political and societal discussion and action throughout the past decade.

A significant difference between the context of the 2001 BROES report and this 2011 NROES report is the presently improved organizational structure of EAR, with Deep Earth Processes and Surface Earth Processes sections that are now better suited to addressing evolving research opportunities in Earth science. Therefore, the goal of this report is not a major redefining of existing programs to exploit research opportunities. Rather, it builds on existing programs to support geosystem research efforts of particular promise. Another important change of context is the degree to which disciplinary and interdisciplinary science planning efforts have recently been summarized in workshop reports and white papers (see Appendix A) by various EAR research communities. The latter community efforts have been strongly encouraged by EAR program managers and have resulted in an unprecedented number of current, thoughtful, and detailed summaries of scientific opportunities spanning EAR activities, some with moderate levels of prioritization.

Given the breadth of the task assigned to this NROES committee and the huge prior investment in community planning conducted by many groups, the committee did not convene any additional symposia or workshops, preferring to draw largely on the extensive community consensus documents that had been recently produced. Not all research areas, notably

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[2] NRC, 1983, *Opportunities for Research in the Geological Sciences*, National Academy Press, Washington, D.C. 95 pp.
[3] NRC, 1983, *Research Briefings 1983*, National Academy Press, Washington, D.C., 99 pp.
[4] NRC, 1993, *Solid-Earth Sciences and Society,* National Academy Press, Washington, D.C., 346 pp.
[5] NRC, 2001, *Basic Research Opportunities in Earth Science,* National Academy Press, Washington, D.C., 168 pp.

geochemistry and structural geology, have prepared disciplinary scientific vision or "Grand Challenge" documents, and particular efforts were made to solicit input from a cross section of researchers in such fields. The committee also requested feedback on the following topics from department heads at universities and colleges, professional societies, and federal agencies with a significant Earth science component:

- the 10-year outlook for the Earth sciences, including linkages with other disciplines;
- the scale of activities suitable for conducting this science, including the roles of individual investigators, major facilities, and "system-level" research; and
- the facilities and infrastructure needed to support these research activities.

Program managers in federal agencies with major Earth science programs—NSF, U.S. Geological Survey, U.S. Department of Energy, and National Aeronautics and Space Administration—also provided programmatic information and perspectives on future research directions and agency interactions. The names of survey respondents and other individuals consulted by the committee are listed in Appendix B. Many of the conclusions and recommendations reached by the committee reflect ideas articulated in the thoughtful contributions by numerous members of the geosciences community. Finally, the committee expresses its gratitude to the NRC study director, Mark Lange, for his considerable efforts in bringing the committee together and editing its report and to NRC staff members Jason Ortego and Courtney Gibbs, who assisted the committee extensively with website development, document tracking and assembly, note taking, and meeting logistics.

Thorne Lay
Chair

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This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their participation in the review of this report:

Gregory Beroza, Stanford University, Palo Alto, California
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Marc Hirschmann, University of Minnesota, Morris
Kip Hodges, Arizona State University, Phoenix
George Hornberger, Vanderbilt University, Nashville, Tennessee
David Mohrig, University of Texas at Austin
Joan Oltman-Shay, Northwest Research Associates, Redmond, Washington

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse—nor did they see—the final draft of the report before its release. The review of this report was overseen by Raymond A. Price, Queen's University. Appointed by the Division on Earth and Life Studies, he was responsible for making certain that an independent examination of the report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the National Research Council.

CONTENTS

Summary

Earth has a suite of complex, dynamic geosystems governing the past evolution, current state, and future conditions that the planet and all humans experience. As the Earth sciences have matured over the past two centuries, developing subdisciplinary specialties that can address specific aspects of Earth's structure, processes, and history with steadily improving resolution, the interdisciplinary nature of the various dynamic geosystems has come into increasing focus. Continuing theoretical and technical improvements are advancing the capabilities of all subdisciplines of the Earth sciences to document the geological record of terrestrial change, to observe active processes in the present-day Earth from surface to inner core, and to make more realistic simulations of complex dynamic processes, and these efforts need to be sustained. However, the areas of greatest near-term research opportunity that are highlighted in this report all involve integrative interdisciplinary efforts focused on specific dynamic geosystems of the past and present.

The 2001 National Research Council (NRC) report *Basic Research Opportunities in Earth Science* (BROES) described how basic research in the Earth sciences serves five national imperatives: (1) discovery, use, and conservation of natural resources; (2) characterization and mitigation of natural hazards; (3) geotechnical support of commercial and infrastructure development; (4) stewardship of the environment; and (5) terrestrial surveillance for global security and national defense. This perspective is even more pressing today, and will persist into the future, with ever-growing emphasis. Today's world—with headlines dominated by issues involving fossil fuel and water resources, earthquake and tsunami disasters claiming hundreds of thousands of lives and causing hundreds of billions of dollars in damages, profound environmental changes associated with the evolving climate system, and nuclear weapons proliferation and testing—has many urgent societal issues that need to be informed by sound understanding of the Earth sciences.

A national strategy to sustain basic research and training of expertise across the full spectrum of the Earth sciences is motivated by these national imperatives. This assessment of research opportunities for the next decade identifies many of the ways that the Earth sciences can sustain and enhance contributions to society. The National Science

Foundation (NSF), through its Division of Earth Sciences (EAR), is the only federal agency that maintains significant funding of both curiosity-driven and strategic research in all core subdisciplines of the Earth sciences. The health and effectiveness of the EAR program are therefore central to a strong national effort in the Earth sciences, and increased investment in this arena is needed to fully capitalize on the potential contributions that the Earth sciences can make. A decade after the BROES report, the NSF again requested that the NRC form an ad hoc committee to identify new research opportunities in the Earth sciences as they relate to the responsibilities of EAR. In particular, the committee was asked to undertake four tasks:

1. Identify high-priority new and emerging research opportunities in the Earth sciences over the next decade, including surface and deep Earth processes and interdisciplinary research with fields such as ocean and atmospheric sciences, biology, engineering, computer science, and social and behavioral sciences.
2. Identify key instrumentation and facilities needed to support these new and emerging research opportunities.
3. Describe opportunities for increased cooperation in these new and emerging areas between EAR and other government agency programs, industry, and international programs.
4. Suggest new ways that EAR can help train the next generation of Earth scientists, support young investigators, and increase the participation of underrepresented groups in the field.

The committee was not asked to evaluate existing EAR programs or make budgetary recommendations.

NEW RESEARCH OPPORTUNITIES IN THE EARTH SCIENCES

Basic research in the Earth sciences encompasses a wide range of physical, chemical, and biological processes that interact and combine in complex ways to produce a spectrum of terrestrial systems. EAR is currently sponsoring investigations on geosystems that range in geographic scale from global—climate, plate tectonics, and Earth's core dynamo—to regional and local—mountain belts and sedimentary basins, active fault networks, volcanoes, groundwater reservoirs, watersheds, and soil systems—to micro-mineral interactions, microbiology, and pore fluid interactions. Research at all of these scales has been accelerated by a combination of conceptual advances and across-the-board improvements in observational capabilities and information technologies. The committee has identified seven topics involving major dynamic geosystems that can only be fully quantified by interdisciplinary approaches, organized by scale and disciplinary participation related to the EAR Deep Earth Processes and Surface Earth Processes sections: (1) the early Earth; (2) thermo-chemical internal dynamics and volatile distribution; (3) faulting and deformation processes; (4) interactions among climate, surface processes, tectonics, and deeper Earth processes; (5) co-evolution of life, environment, and climate; (6) coupled hydrogeomorphic-ecosystem responses to natural and anthropogenic change; and (7) biogeochemical and water cycles in terrestrial environments and impacts of global change. These research areas span a range of fundamental grand challenge questions from how the planet's interior works to the evolution of the surface environment. In addition, the expanding demand for accurate geological dates to support many of the research opportunities motivates consideration of restructuring how EAR supports the geochronology facilities that must innovate methodologies, train next-generation geochemists, and service burgeoning demands for what is seldom routine dating of samples.

PRINCIPAL FINDINGS AND RECOMMENDATIONS

EAR has generally done an excellent job overall in developing and maintaining a balance among programs that support investigator-driven disciplinary research, problem-focused programs involving multidisciplinary research, and equipment-oriented programs for new instrumentation and facilities. The committee offers recommendations that address the evolving science requirements in all three of these programmatic areas. These recommendations pertain primarily to new mechanisms that will allow EAR to foster new research opportunities identified in this report.

Long-Term Investigator-Driven Science

In the next decade, and likely throughout the entire century to come, the quest to quantify Earth's dynamic geosystems by establishing their history, current behavior, and future evolution will involve integrative interdisciplinary approaches that build on basic research advances in subdisciplinary capabilities. The primary recommendations in this report highlight opportunities to pursue integrative activities with high potential impact. However, as in many previous NRC reports on scientific research opportunities, this report again emphasizes the importance of sustaining subdisciplinary-based core Earth science research and facilities. Individual investigator-driven science remains the most creative and effective way to enhance the knowledge base upon which integrative efforts can build. This report gives numerous findings that reaffirm this essential need to sustain the basic Earth sciences by individual investigators, as this is the single most important mechanism for maintaining and enhancing disciplinary strength in the field. EAR is now the almost exclusive basis for supporting the full spectrum of basic Earth science research.

New Research Opportunities

The Early Earth

Many uniquely critical events occurred early in Earth's history: delivery of the material that built Earth; formation of the Moon; and the differentiation events that formed the core and earliest crust, the oceans, and the atmosphere. Earth's early history set the stage for its subsequent dynamic and geochemical evolution, from an environment dominated by impacts and magma oceans to the habitable environment dominated by the plate tectonics of today. There are multiple avenues for enhancing our understanding of this formative stage in our planet's history, including expanding the inventory of early Earth samples, fostering new technologies for analysis of ancient materials, quantification of early chronology using novel isotope systems, and developing models that simulate the highly energetic conditions of the early Earth.

Recommendation: *EAR should take appropriate steps to encourage work on the history and fundamental physical and chemical processes that governed the evolution of Earth from the time of its accretion through the end of late heavy bombardment and into the early Archaen, perhaps by establishing a specific initiative on early Earth. Specific program objectives and scope may be developed through community workshops that prepare a science plan preceding a separate call for proposals.*

Thermo-Chemical Internal Dynamics and Volatile Distribution

The huge dynamic circulation systems in Earth's mantle and core circulate heat and materials, drive the long-term evolution of continents, generate the magnetic field, and cycle volatiles into and out of the interior, maintaining bulk chemistry of the oceans and atmosphere. Resolving the present-day configuration and processes of the mantle and core convective systems with high resolution is a key undertaking for developing models of the past and future evolution of the system, the thermal evolution of Earth, and the volatile flux in Earth. Collective advances in imaging capabilities, experimental and theoretical determinations of material properties under extreme pressures and temperatures, geochemistry, and increasingly realistic representations of the dynamic circulation in the mantle and core have placed the discipline on the threshold of breakthroughs in understanding the thermo-chemical dynamics and the distribution and cycling of volatiles. Enhancing resolution of the various approaches is essential to resolving the outstanding questions about how Earth's interior works.

Recommendation: *EAR should pursue the development of facilities and capabilities that will improve spatial resolution of deep structures in the mantle and core, such as dense seismic arrays that can be deployed in various favorable locations around Earth, enhanced computational software and hardware to enable increased resolution of three-dimensional geodynamical models, and improved high-resolution experimental and theoretical mineral physics investigations. This will provide definitive tests of many hypotheses for deep Earth structure and evolution advanced over the past decade. The large scope of such facilities will require a lengthy development and review process, and building the framework for such an initiative needs to commence soon.*

Faulting and Deformation Processes

Exciting discoveries, driven by increased instrumentation around fault zones, have been made regarding the spectrum of faulting processes and mechanisms. These present an opportunity to make significant progress on understanding faulting, related deformation processes, and resulting earthquake hazards. Earthquake science involves a complex geosystem with multiscale processes from the microscale, such as the controls on surface friction, up to the regional-scale processes of sedimentary basin reverberation and excitation of tsunamis by ocean water displacements. There have been significant advances in this geosystem perspective, with interactions between researchers with expertise spanning laboratory friction experiments, observational and theoretical seismology, geodesy, structural geology, earthquake engineering, field geology, volcanology, magnetotellurics, and deep drilling. In the next decade integrative efforts built around active fault zone and subduction zone laboratories hold promise of greatly advancing our understanding of faulting and deformation processes and associated roles of fluid, volatile, and material fluxes.

> **Recommendation:** *EAR should pursue integrated interdisciplinary quantification of the spectrum of fault slip behavior and its relation to fluxes of sediments, fluids, and volatiles in the fault zone. The successful approach of fault zone and subduction zone observatories should be sustained, as these provide an integrative geosystems framework for understanding faulting and associated deformation processes. The related EarthScope project is exploring the structure and evolution of the North American continent using thousands of coordinated geophysical instruments. There is great scientific value to be gained in completing this project, as envisioned, through 2018.*

Interactions among Climate, Surface Processes, Tectonics, and Deeper Earth Processes

The broad interactions among climate, Earth surface processes, and tectonics are an area of compelling research opportunities that center on interactions among topography, hydrology and hydrogeology, physical and chemical denudation, sedimentary deposition, and deformation in tectonically active mountain belts. There is a strong need for geomorphic transport laws that account for climate and the role of biota to describe and quantify river and glacial incision, landslides, and the production, transport, and deposition of sediment. These transport laws will allow us to integrate the effects of event-based processes into long-term system behavior. New understanding of the dynamic interactions among climate, Earth's surface, and tectonics over geomorphic to geological timescales will require increased access to, and new developments in, thermochronometry, methods for dating geomorphological surfaces, Light Detection And Ranging (LiDAR), satellite imagery, modeling capabilities, experimental methods, and field instrumentation and studies. The existing EAR Continental Dynamics program[1] covers many of these themes, but a stronger link to climate and surface processes has the potential for significant advances.

> **Recommendation:** *EAR should take appropriate steps to encourage work on interactions among climate, surface processes, tectonics, and deeper Earth processes either through a new interdisciplinary program or perhaps by expanding the focus of the EAR Continental Dynamics program to accommodate the broader research agenda of these interdisciplinary subthemes.*

Co-evolution of Life, Environment, and Climate

The deep-time geological record has provided a compelling narrative of changes in Earth's climate, environment, and evolving life, many of which provide analogs, insight, and context for understanding human's place in the Earth system and current anthropogenic change. However, the complexity of this bio-geosystem is only now being fully realized, with new analytic tools from geochemistry, paleontology, and biology enabling unprecedented exploration of the coupled time-evolution of past Earth surface conditions, including temperature, atmospheric chemistry, hydroclimates, the chemical composition of the ocean, and the interrelationship and physiologies of ancient life forms. Concerted application of the interdisciplinary capabilities to the deep-time record will provide breakthrough understanding of this profound and nonlinear bio-geosystem.

> **Recommendation:** *EAR should develop a mechanism to enable team-based interdisciplinary science-driven projects involving stratigraphy, sedimentology, paleontology, proxy development, calibration and application studies, geochronology, and climate modeling at appropriately resolved scales of time and space, to understand the major linked events of environmental, climate and biotic change at a mechanistic level. Such projects could be expected to be cross program and cross directorate.*

Coupled Hydrogeomorphic-Ecosystem Response to Natural and Anthropogenic Change

Understanding the response of large scale landscapes and ecosystems to disturbance and climate change requires greater mechanistic understanding of the interactions and feedbacks among hydrological drivers, landscape morphology, and biotic processes. Advancing the science requires better theory, observations, and models relating spatial patterns and temporal variability of landscape drivers (topography, hydrology, geology) to the dynamics of biotic communities, including identification of hydrological and morphological leading indicators of landscape and ecosystem state change. This will require integrated monitoring of landscape processes and development

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[1] http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=6194&org=EAR&from=home.

of new instrumentation and data archives to support and test models—work that could take advantage of large-scale restoration efforts and documented historical change as controlled experiments.

> **Recommendation:** *EAR should facilitate research on coupled hydrogeomorphic–ecosystem response to climate change and disturbance. In particular, the committee recommends that EAR target interdisciplinary research on coastal environments. This initiative would lay the groundwork for understanding and forecasting the response of coastal landscapes to sea-level rise, climate change, and human and natural disturbance, which will fill an existing gap at NSF and should involve coordination with the Division of Ocean Sciences, U.S. Geological Survey (USGS), and National Oceanic and Atmospheric Administration (NOAA).*

Biogeochemical and Water Cycles in Terrestrial Environments and Impacts of Global Change

Humans are altering the physical, chemical, and biological states of and feedbacks among essential components of Earth's detailed surface system. At the same time, atmospheric temperature and carbon dioxide levels have increased and are impacting carbon storage in the terrestrial environment, the water cycle, and a range of intertwined biogeochemical cycles and atmospheric properties that feed back on climate and ecosystems. Advancing our understanding of integrated soil, water, and biogeochemical dynamics in the fine scale critical zone requires new theory, coupled systems models, and new data. New advances in our ability to understand and quantitatively simulate carbon, nutrient, water, and rock cycling will depend on new measurement approaches and instrumentation that capture spatial and temporal variability in atmospheric and land use inputs superimposed on complex vegetation patterns and underlying anisotropic subsurface geomedia.

> **Recommendation:** *EAR should continue to support programs and initiatives focused on integrated studies of the cycling of water, carbon, nutrients, and geological materials in the terrestrial environment, including mechanisms and reactions of soil formation; hydrological and nutrient cycling; perturbations related to human activities; and more generally the cycling of carbon between surface environments and the atmosphere and its feedbacks with climate, biogeochemical processes, and ecosystems.*

Instrumentation and Facilities to Support Research Opportunities

Each research opportunity has specific disciplinary-based data collection, instrumentation, and facilities associated with it, but there are some cross-cutting intersections of needs. The global span of the geosystems involved requires synoptic observations provided by global networks of geophysical, geochemical, petrological, and environmental facilities and data collection efforts. These include long-term observatories such as provided by seismic and geodetic networks currently supported by EAR and other agencies, as well as portable instrument facilities for hydrology, rock and fossil sampling and drilling, seismology, geodesy, and magnetotellurics, with specific findings given in Chapter 3. EAR has achieved a reasonable balance in funding of facilities, core disciplinary research programs, and interdisciplinary initiatives. Maintaining this balance as the budget grows is important; while new interdisciplinary or instrumentation initiatives often provide compelling rationale for budgetary growth, balancing the portfolio of resources (particularly with investment in the core single-investigator programs) over time is very desirable for sustaining the overall health of the effort.

Recommendation: *EAR should explore new mechanisms for geochronology laboratories that will service the geochronology requirements of the broad suite of research opportunities while sustaining technical advances in methodologies. The approaches may involve coordination of multiple facilities and investment in service facilities and may differ for distinct geochronology systems.*

Partnerships and Coordination

Agency partnerships led by EAR will continue to be essential for attaining many of the research objectives identified in this report. Well-managed partnerships can foster broadly based research communities, leverage limited resources, and promote fruitful synergies. Among the highlighted research opportunities, the Early Earth opportunities overlap with mission objectives of the National Aeronautics and Space Administration (NASA) and research activities supported by the U.S. Department of Energy; the study of Earth tectonics is enabled by measurements from NASA and U.S. Department of Defense–supported satellites, and studies of surficial processes and coastal dynamics address problems that are at the core of the missions of the USGS, NOAA, and U.S. Forest Service. Continued efforts to develop and maintain these partnerships are key to maximizing the impact of EAR funding.

Training the Next Generation and Diversifying the Researcher Community

Capitalizing on the research opportunities set out in this report will require researchers with the skills and knowledge to advance the science, but attracting new students and providing the appropriate training remain major challenges in the United States. Increasing the participation of historically underrepresented groups is an equally important and directly related challenge, and there remains an uneven minority exposure to science and math as well as a significant science knowledge disparity between poor and affluent students. The EAR division is working to enhance diversity, education, and knowledge transfer through several outreach efforts, and these efforts can continue to be enhanced. There are several important ways that EAR might do so, including establishing Advanced Placement Earth science courses in high schools, promoting early awareness of the Earth sciences on college campuses, developing place-based research and education programs that incorporate indigenous landscapes and ways of thinking, and fostering the scientist communicator.

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Earth Sciences in the 21st Century

The Earth sciences will become increasingly prominent in the 21st century as humanity confronts daunting challenges in finding natural resources to sustain Earth's burgeoning population, in mitigating natural hazards that impact huge populations and extensive built infrastructure, and in achieving sustainable environmental stewardship in the context of an evolving Earth habitat. This report adopts the National Science Foundation's (NSF) Earth science terminology: The Earth sciences involve that part of geosciences that addresses Earth's solid surface, crust, mantle, and core, including interactions between the solid Earth and the atmosphere, hydrosphere, and biosphere. Topics of the Earth sciences range from directly practical applications to society's survival—such as detecting and extracting supplies of water, minerals, and fuels to fundamental intellectual inquiry into the origin, evolution, and future of our planet—that commonly inform important societal decision making.

The stature of the Earth sciences has grown with each new decade. For the past 200 years, the Earth sciences have played prominent roles in defining the history of life; unveiling the evolution of the planetary surface; quantifying the nature of natural hazards such as earthquakes, volcanoes, and tsunamis; locating mineral and fossil fuel resources; and characterizing the history of the climate system. Looking forward to the next decade and beyond, these roles will expand substantially, driving a need for extensive basic research in the Earth sciences and training researchers and practitioners in the discipline that will expand well beyond current capacity.

While this accelerating demand is evident to many in the field, and NSF's Division of Earth Sciences (EAR) program is guided by a thorough understanding of the importance of the discipline and the many opportunities for it to contribute to the challenges humanity must confront, the reality is that the Earth sciences receive less attention than warranted at all levels in the U.S. education system and in the federal agencies that support basic and applied research and education (National Center for Education Statistics, 2011). Across the country, high school and university curricula place little emphasis on learning about Earth and environmental sciences (Hoffman and Barstow, 2007), which limits the draw of high-quality students into the field. This self-limiting situation can only be overcome by proactive efforts by federal agencies and educational institutions to recognize the value of and need for stronger education, training, and career tracking of capable students to address the Earth science challenges of the present and near future.

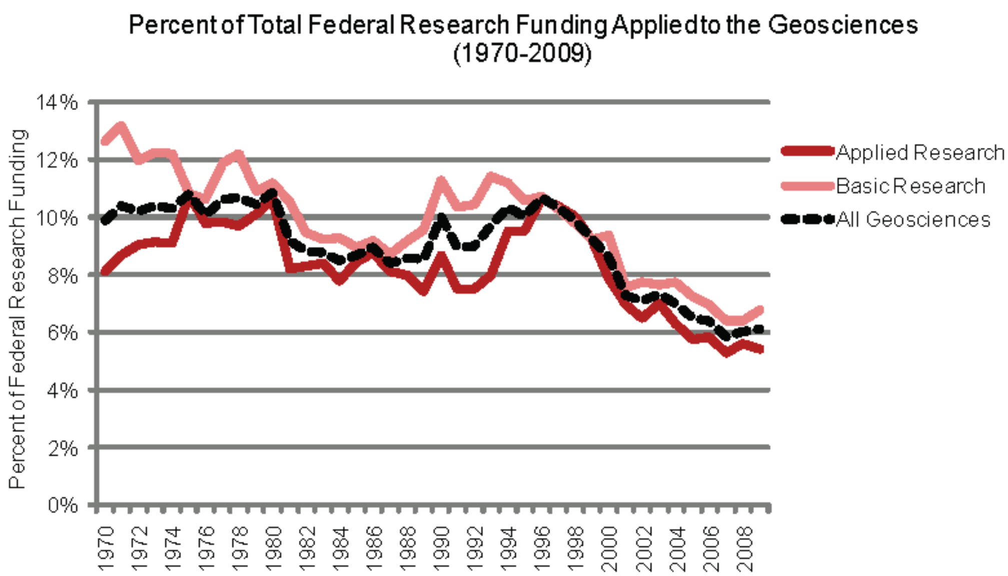
With the endorsement of the National Research Council (NRC) 2001 report, *Basic Research Opportunities in Earth Science* (BROES), EAR (and the Directorate for Geoscience, GEO) took a first major step forward in elevating the stature of the Earth sciences within NSF by pursuing EarthScope, a Major Research Equipment and Facilities Construction (MREFC) project. This project is the first GEO/EAR MREFC project that the directorate has attracted substantial external resources ($200 million) for construction of facilities from NSF resource pools that have primarily served traditional science disciplines like physics, astronomy, and biology. The EarthScope project underwent construction of facilities from 2003 to 2008 and is presently halfway through the first of at least two planned five-year operational stages (Williams et al., 2010).

EarthScope was novel for the MREFC program in creating a highly distributed facility with many data collection nodes dispersed across the United States (in contrast to typical localized facilities such as an astronomical telescope or a physics accelerator) that includes three key facilities that provide unprecedented observations of the North American continent; the Plate Boundary Observatory, USArray, and the San Andreas Fault Observatory at Depth. The EarthScope facility construction completed the five-year MREFC phase on time and on budget, a rarity in the history of large facilities' development supported by federal agencies. Scientific results from all elements of the EarthScope project are emerging rapidly, as noted later in this report, and the project is a tremendous success for EAR and GEO.

This success presents a clear opportunity for EAR to gain recognition as a sponsor of major research activity on a par with the many large efforts in physics, astronomy, and biology. Not only will the Earth sciences play a critical role in the 21st century, but the discipline has now demonstrated the internal organizational capability to rise to the tasks and funding levels for major initiatives that will be needed for the field to meet future challenges. Emerging research opportunities defined later in this report will require comparable efforts to achieve their objectives; EarthScope has demonstrated that the Earth science community and EAR can successfully meet these challenges, and NSF will need to recognize the importance and viability of enhancing investment in basic research in this discipline. Earth sciences in the 21st century must join the ranks of big science efforts pursued in the United States; it cannot remain a modest activity if new opportunities to expand basic understanding are to be pursued as a foundation for tackling the societal challenges of the upcoming century.

FUNDING TRENDS IN THE EARTH SCIENCES

This report is released against a background of declining federal funding for basic and applied Earth science research and re-enforces the importance of pursuing targeted new research opportunities that provide the greatest return on research investments. Among the several federal departments and agencies that support research in the Earth sciences, NSF is the sole agency whose primary mission is basic research and education. Only NSF, through its EAR division, provides significant funding for investigator-driven, fundamental research in all of the core disciplines of the Earth sciences. While substantial Earth science research is pursued by the U.S. Department of Energy (DOE), the U.S. Geological Survey (USGS), and the National Aeronautics and Space Administration (NASA), the emphasis of those programs is largely strategically focused and mission oriented. For example, the President's FY2011 budgets for Earth science activities in these programs emphasize climate change and renewable energy resources research. Funding for carbon capture and sequestration, climate change, and geothermal research and development is slated to increase for DOE and the USGS. NASA is set to have increased funding for Earth-observing satellites. NSF's GEO, which provides about 63 percent of all federal funding for the geosciences would receive a budget of about double the EAR funding level at the time of the 2001 BROES report.



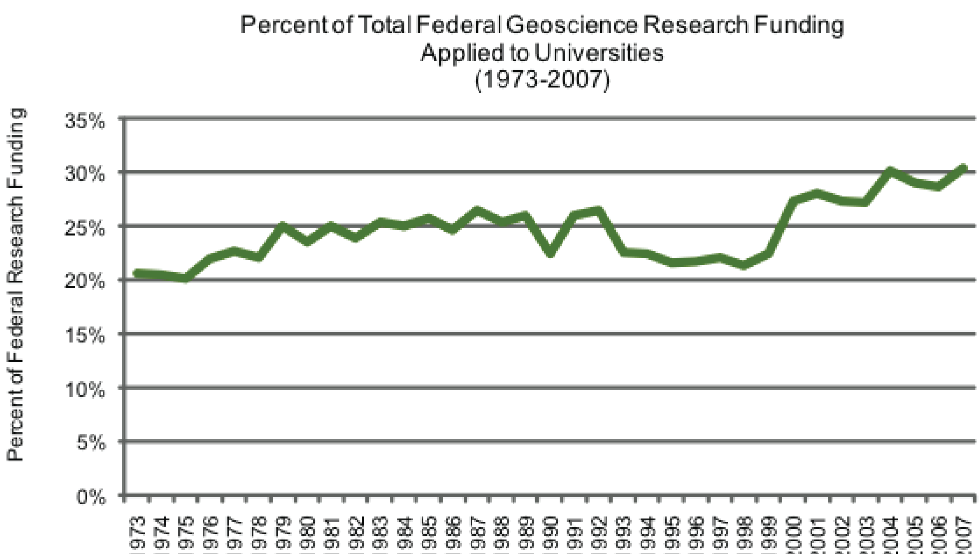


Figure 1.1 AGI summary of trends in federal research funding for geosciences. SOURCE: AGI (2009).

The trend in federal funding of geosciences research is of significant concern. Figure 1.1 displays trends in funding across all agencies and depicts a decline in funding as a percentage of total research funding for basic and applied research. This drop in overall percentage of research funding has been accompanied by a relative increase in the percentage of geosciences funding for universities, which is the domain where NSF and EAR play a predominant role.

THE COMMITTEE'S APPROACH

In this report the Committee on New Research Opportunities in the Earth Sciences (NROES) identifies new research opportunities in the Earth sciences as they relate to the responsibilities of NSF's EAR division. In particular, the committee undertook four tasks:

1. Identify high-priority new and emerging research opportunities in the Earth sciences over the next decade, including surface and deep Earth processes and interdisciplinary research with fields such as ocean and atmospheric sciences, biology, engineering, computer science, and social and behavioral sciences.
2. Identify key instrumentation and facilities needed to support these new and emerging research opportunities.
3. Describe opportunities for increased cooperation in these new and emerging areas between EAR and other government agency programs, industry, and international programs.
4. Suggest new ways that EAR can help train the next generation of Earth scientists, support young investigators, and increase the participation of underrepresented groups in the field.

The committee was not asked to evaluate existing EAR programs or make budgetary recommendations. These questions cannot be addressed without first acknowledging the context into which this report is being released, and so the following sections provide perspectives on the status of the Earth sciences that informed the committee's approach.

Grand Challenges for the Earth Sciences

The 2008 NRC report *Origin and Evolution of Earth—Research Questions for a Changing Planet* defined 10 grand research questions for the 21st century that will drive the modern Earth sciences:

1. How did Earth and other planets form?
2. What happened during Earth's "dark age" (the first 500 million years)?
3. How did life begin?
4. How does Earth's interior work, and how does it affect the surface?
5. Why does Earth have plate tectonics and continents?

6. How are Earth's processes controlled by material properties?
7. What causes climate to change—and how much can it change?
8. How has life shaped Earth—and how has Earth shaped life?
9. Can earthquakes, volcanic eruptions, and their consequences be predicted?
10. How do fluid flow and transport affect the human environment?

Answering these questions, which the NROES committee agrees are fundamental to the field, will take sustained and intense effort and the preparation of new generations of researchers capable of building on current understanding and overcoming current limitations.

The essential role of EAR is to support basic research on acquiring fundamental knowledge about the Earth system, motivated by profound questions like those above, and to foster that understanding, which can be directly applied to national strategic needs. Strong partnerships with mission-oriented agencies are critical to the flow of basic understanding into applied research and engineering. The 2001 BROES report (NRC, 2001) identified how basic research in the Earth sciences supported by EAR ultimately affects human welfare in five major areas:

1. Discovery, use, and conservation of natural resources—fuels, minerals, soils, water;
2. Characterization and mitigation of natural hazards—earthquakes, floods and droughts, landslides, tsunamis, volcanoes;
3. Geoscience-based engineering—urban development, agriculture, materials engineering;
4. Stewardship of the environment—ecosystem management, adaptation to environmental changes, remediation, and moderation of adverse human effects; and
5. Terrestrial surveillance for national security—arms control treaty verification, precise positioning, mapping, and subsurface remote sensing.

Over the past 10 years these issues have only grown in importance and relevance, and every indication is that this trend will persist through this century. The roles of basic research in the Earth sciences in each arena were described in detail in the BROES report and are not repeated here because it is clear than NSF and EAR are committed to sustaining basic Earth science research. The committee does note some issues of heightening concern as we progress into the second decade of the 21st century.

Relevance of the Earth Sciences

The world's population is expected to reach 7 billion by the end of 2011, and about 9.2 billion by 2050, relentlessly increasing the demand for food, fuel, raw materials, and water.[1] Much of this population will continue to be concentrated near dynamic coastal zones, and meeting the requirements of this population and understanding associated impacts on the environment is a key area to which the Earth

[1] U.S. Census Bureau.

sciences contribute. The energy demands of this human population are immense. In 2008 the total world energy consumption was 474×10^{18} J, equivalent to an average annual power consumption rate of 15 terawatts. For comparison, energy flux from Earth's interior to the surface is estimated at 46 terawatts. All projections anticipate steady growth of energy consumption, as long as resources can be found to accommodate it. Fossil fuels such as oil, natural gas, and coal are the primary sources of energy that will be harvested from terrestrial reservoirs. With most readily located and extracted fossil fuels largely having been exploited, there is a steadily increasing need for professionally trained Earth scientists to staff oil exploration and development companies. This includes demand for expertise in subsurface exploration and in reservoir management, with broad skills in seismology, geophysics, hydrology, rock-fluid chemical interactions, and computer modeling. Nuclear power also requires nuclear materials concentrated in geological formations, and hydrological power involves huge geoengineering efforts that require solid foundations in hydrogeology and landscape evolution. Growing energy demands will raise the importance of Earth science training and research throughout the century.

Earth scientists contribute to identifying rock materials, minerals, and ores that serve the demands of society for construction materials and critical industries. The burgeoning demands for expanded supply of materials and mitigating the long-term environmental impacts of locating and extracting them will continue throughout the century, again driving demand for Earth science expertise in the processes of petrology, fluid-rock interactions, hydrothermal systems, basin-scale hydrology, and tectonic history. Increased recognition of biological roles in ore distribution and sedimentation is further driving demand for geobiology training and expertise.

Fresh water supply is one of the greatest challenges associated with population growth, and informed decision making on water resources requires knowledge of the complex hydrological systems operating in the near-surface environment and how they respond to natural and human modifications. A broad suite of geochemical, geophysical, and geobiological approaches are central to investigation of aquifers and groundwater systems. Expanding the trained workforce and advancing the analysis tools available for water management will be a sustained need for the next century.

Soils provide essential resources for agriculture, water filtration, and construction and manufacturing activities, and understanding these biologically active, intricately structured porous media requires the fundamental physical, chemical, and biological insights provided by EAR research on the shallow Earth system. Soil management issues related to sustaining the human habitat, and issues related to land use, soil quality, and contamination are prominent in societal decision making and require fundamental Earth science foundations for ensuring long-term viability under the pressure of heightening demands. The value of training in biogeochemical cycling, sediment transport, and hydrology will only increase over the next century.

Repeated natural disasters have struck around the world over the decade since the BROES report, with floods, droughts, severe storms, volcanic eruptions, earthquakes, landslides, and tsunamis all impacting society. Great population growth in regions exposed to natural hazards has magnified the impacts of these events, and throughout the century human exposure will increase dramatically. The value of translating Earth science understanding and earthquake hazard assessments into engineering and construction implementations has been dramatically demonstrated by the contrasting impacts of the 2010 Haiti and Chile earthquake disasters. Haiti, struck by a moderately large magnitude 7.0 earthquake on January 12, 2010, had massive destruction and loss of life, primarily due to poor construction standards. In contrast, the much stronger magnitude 8.8 earthquake in Chile on February 27, 2010, caused far less damage and loss of life in the largely well-built environment of central Chile. Massive flooding events, such as that accompanying Hurricane Katrina in 2005—the costliest natural disaster in U.S. history, with about $81 billion in damages and 1,836 fatalities—and the 2010 monsoonal inundation of southern Pakistan, which flooded almost 20 percent of the country's land area, directly affecting about 20 million people, are further indicators of the upscaling of human impacts to be anticipated by natural hazards throughout the 21st century. The March 11, 2011, Tohoku great earthquake and tsunami in Japan that devastated the coast of Honshu and precipitated the Fukushima nuclear disaster is further demonstration of this expanding impact of natural disasters.

Efforts to mitigate natural hazards rely on precise observations and quantitative understanding of the phenomena that are involved. Broadly based EAR research programs that address the fundamental nature of the dynamic geosystems underlying natural hazards are essential for pursuing applied research and engineering efforts to mitigate the hazards. Most federal programs associated with natural hazards are forced by funding constraints to prioritize very directed research; without EAR basic science support, critical basic understanding of the natural hazards would lag, thereby reducing the effectiveness of mitigation efforts.

Quantifying complex geosystems requires extensive measurement of the fluxes, structures, and evolution of the systems. Recognition of this has guided EAR toward developing facilities capable of making the spatial and temporal measurements essential to understanding the dynamical geosystems. Particular progress has been made in geophysical observations with seismic, geodetic, and magnetotelluric networks being established both within the EAR Instrumentation and Facilities program and the EarthScope project. Major advances have been made in facilities for hydrological measurements and database gathering, and several Critical Zone observatories have been established for addressing the near-surface geosystem. Progress in quantifying the historical climate system and its evolution has largely stemmed from accumulation of global observations from continental and oceanic drilling, geological fieldwork, geochemical technique development, and increased understanding of the roles of geobiological processes. Essentially these endeavors probe Earth's complex environment and quantify attributes of the dynamical systems that feed into quantitative modeling efforts. While some aspects of this are intrinsic to monitoring operations conducted by mission-oriented federal programs, and numerous interagency partnerships are exploited to provide access to essential data, EAR efforts are guided by the design requirements for basic research and a strong commitment to NSF-based research facilities.

The BROES report made a compelling argument for the importance of sustaining three basic Earth science research capabilities: (1) techniques for deciphering the geological record of terrestrial change and extreme events, (2) facilities for observing active processes in the present-day Earth, and (3) computational technologies for realistic simulations of dynamic geosystems. This perspective is reinforced in the next chapter, which identifies areas of research opportunity for the near term, all of which intersect with the basic research agenda defined by the BROES study. Indeed, there are common themes manifested in all of the findings and recommendations from this updated report; technique development, observations on suitable spatial and temporal scales, and integrative simulation efforts underlie all of the frontiers in basic Earth science research.

The Earth sciences in the 21st century have great potential but also great challenges. The importance of the discipline is being propelled to high priority by the pressures of population growth, a quest for sustainability of living standards, and demonstration of the feedbacks on Earth's geosystems caused by human activities. EAR is critical to the future of basic Earth science research, and can highlight the great success of such projects as EarthScope, convey the fundamental contributions of EAR science to resource, hazards, and environmental challenges facing the nation, and promote the intellectual challenges presented by complex geosystems to be quantified by a new generation of committed Earth science researchers.

This report is organized along the structure of EAR to facilitate action by EAR on the diverse topical areas. Chapter 2 of this report describes the status and future prospects of seven primary research areas and one cross-cutting methodological area and are loosely organized by spatial and temporal scale (larger to smaller), beginning with topics related to the EAR Deep Earth Processes section, followed by Surface Earth Processes section topics. These descriptions and assessments are guided by input from across the Earth science community and provide the basis for the committee's findings and eight recommendations outlined in Chapter 3.

2

New Research Opportunities in the Earth Sciences

The vitality of the current Earth science research community is manifestly evident in the numerous strategic planning, Grand Challenges, and science vision documents that have been produced over the past decade (a list of key documents is presented in Appendix A). Any attempt at comprehensive assessment of new research opportunities across the discipline would quickly become unwieldy, and the finite expertise of any committee would result in some oversights. The committee on New Research Opportunities in the Earth Sciences (NROES), informed by personal knowledge, myriad documents produced by workshops and community organizations, and both solicited and contributed input from many researchers and program managers (see Appendix B) has attempted to identify specific areas in the basic Earth science research scope of the Division of Earth Sciences (EAR) of the National Science Foundation (NSF) that are particularly poised for rapid progress during the next decade.

Seven primary topics involving complex dynamic geosystems that can only be fully quantified by interdisciplinary approaches are highlighted in the following sections organized by scale and disciplinary participation related to the EAR Deep Earth Processes and Surface Earth Processes sections: (1) the early Earth; (2) thermo-chemical internal dynamics and volatile distribution; (3) faulting and deformation processes; (4) interactions among climate, Earth surface processes, tectonics, and deep Earth processes; (5) co-evolution of life, environment, and climate; (6) coupled hydrogeomorphic-ecosystem response to natural and anthropogenic change; and (7) interactions of biogeochemical and water cycles in terrestrial environments. These address a range of grand challenge-scale fundamental topics of both curiosity-driven and strategic Earth Science. Key to many of these topics and to many other Earth science applications are geochemical approaches to geochronology by exploiting the variety of stable and radiogenic isotopes that exist in nature to provide relative and absolute dating of geological materials and events. The expanding demand for accurate sample dating for many of the research opportunities motivates consideration of restructuring EAR-supported geochemical facilities that must simultaneously promote innovation of methodologies, training of next-generation geochemists, and servicing the burgeoning demands for what are seldom routine sample dating analyses.

THE EARLY EARTH

Much of Earth's present-day structure and significant parts of its history can be traced back to events that occurred within the first few hundreds of million years after its formation. Understanding the processes involved in Earth accretion and early chemical differentiation is essential for establishing the initial thermal conditions of the dynamical systems of the interior, the volatile content of the planet, and the origins of the continents that have led to the current Earth system. Recent progress on understanding the early Earth has been substantial, yet we have only begun the task of resolving the timing, nature, and interrelationships of the most decisive events, including cataclysmic impacts; magma oceans; segregation of the core; early forms of continents, oceans, and the atmosphere; the onset of plate tectonics; and, of course, the origin of life. Because Earth grew and differentiated rapidly, the energy available to the Earth system during its early history was far higher than today, permitting whole sets of physical and chemical processes without counterparts in the modern Earth. The overarching challenge here is to understand how Earth transitioned from its formative state into the hospitable planet of today (see Box 2.1). Lessons learned from the early Earth will help us interpret the processes occurring in the hundreds of extrasolar planetary systems now being discovered by astronomers.

BOX 2.1
Planetary Science

Earth's interior and surface environments are profoundly influenced by our position in the Solar System and interaction with the Moon and other planets. The moon stabilizes the orientation of Earth's spin axis and promotes climate stability, in stark contrast to, for example, Mars. Gravitational interactions between Earth and other planets, particularly Jupiter, cause small variations in the eccentricity, obliquity, and precession of Earth. While small, these variations are likely partly responsible for ice ages.

The discovery of hundreds of planets orbiting other stars, so-called extrasolar planets, provides a new opportunity to understand whether the architecture of our solar system and presence of an Earth-like planet in the habitable zone are common. Planets around young stars may also offer a window into the earliest Earth. Limited information, however, is available about these planets, and in the best cases we know their mass, radius, eccentricity, and temperature and are able to detect some gases.

Continued exploration of our own solar system has led to new, unexpected discoveries: an active dynamo on Mercury, eruptions on Enceladus (see Figure B2.1), and methane lakes on Titan. These discoveries provide new opportunities to test our understanding of the basic processes that govern planetary evolution and interactions between Earth systems, particularly the interior, the geodynamo, surface environments, and the atmosphere.

Understanding these new discoveries and further exploration of our solar system are activities typically supported by the National Aeronautics and Space Administration (NASA). Nevertheless, there are opportunities to better understand Earth systems and the earliest

Earth made possible by exploring other planetary objects. Collaboration between NASA and NSF in supporting such projects can only be positive.

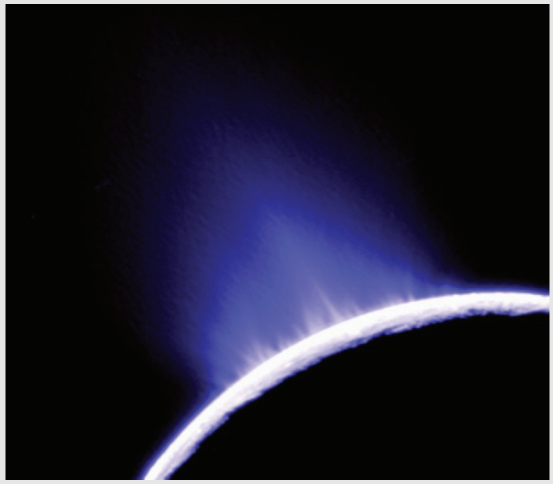


Figure B2.1 Ice geysers erupt on Enceladus, the bright and shiny inner moon of Saturn. This image presents a backlit view of the moon's southern limb, where icy plumes were discovered by the NASA *Cassini* spacecraft mission in November 2005. Cryovolcanism is evidence that the 500-km-diameter Enceladus has active internal tectonics. SOURCE: NASA Jet Propulsion Laboratory/Space Science Institute.

Accretion of Earth

The birthplace of Earth was a protoplanetary accretion disk, a cloud of gas and dust surrounding the early Sun. Modern astronomy provides a glimpse of what this environment may have been like, in the form of debris disks that surround young stars, some of which have been imaged by the Hubble Space Telescope (see Figure 2.1). Accretion disks are subject to instabilities driven by powerful gravitational and electromagnetic forces that collect dust particles into planetesimals, typically 1-kilometer-sized objects that were the fundamental building blocks of Earth and the other terrestrial planets. Once a sufficient density of planetesimals developed in the nebular cloud, increasingly violent collisions began to dominate the accretion process, forming an ever-smaller number of growing planetary embryos that swept up most of the remaining nebular debris.

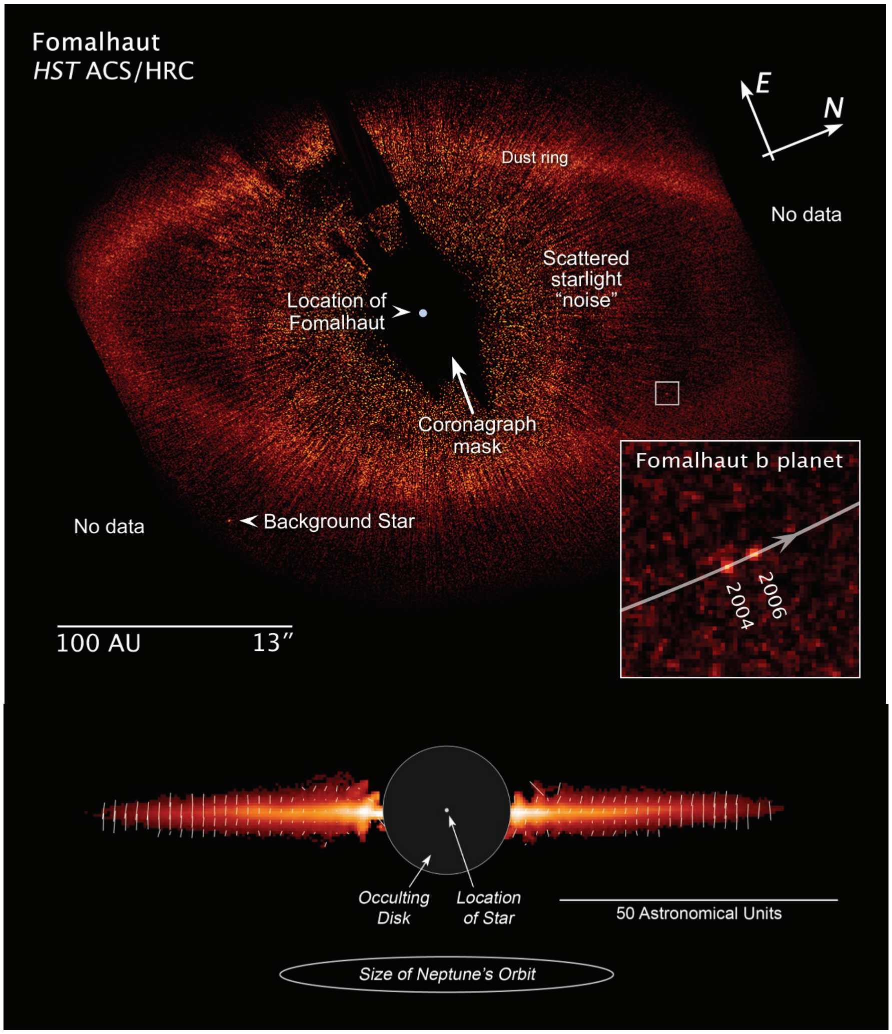


Figure 2.1 Hubble Space Telescope (HST) images showing young stars surrounded by dust rings thought to be the birthplaces of planets like Earth. *Top:* The planet Fomalhaut b orbits the star Fomalhaut (25 light-years away in the southern constellation Piscis Australis) near a ring of dust similar to the Kuiper Belt that may contain bodies ranging from dust grains to objects the size of dwarf planets. *Bottom:* Light reflected off a debris disk in cross section around the young star AU Microscopii, HD197481. SOURCES: *Top:* NASA, the European Space Agency (ESA), and Z. Levay. *Bottom:* NASA, ESA, and J. Graham.

Although much effort has been directed toward understanding accretion from the perspective of solar system dynamics, many related processes that were important for early Earth have not received the same attention. Accretion models, for example, often assume that colliding planetesimals simply adhere, ignoring effects like fragmentation, spin and precession, melting, vaporization, condensation, and differentiation (Chambers, 2004). There is mounting evidence for these processes, many of which bear directly on the final chemistry and structure of the accreting body (Halliday, 2004).

Geochemical and cosmochemical observations provide important constraints on the timing and the mechanisms of accretion and segregation of the core, although several interpretations are possible. For example, in the Hafnium-Tungsten ((Hf-W) system, the excess radiogenic 180W in the silicate Earth relative to chondritic meteorites has been interpreted as rapid accretion or alternatively as incomplete mixing of the impactor with the growing Earth (Halliday, 2008; Rudge et al., 2010). Similar interpretations have come from other short-lived isotope systems, such as 146Sm - 142 Nd (O'Neil et al., 2008), which also have implications for the earliest crust. The fusion of geochemistry and geophysics offers many promising avenues for better understanding formative processes that governed the early history of the Earth.

Based on isotopic evidence from meteorites, what originated as occasional planetesimal collisions soon began to run away, leaving a small number of rapidly growing planetary embryos. Improved chronological methods reveal that melting and differentiation occurred within a few million years of the formation of the first solids, probably driven by collisions and assisted by now-extinct radioactive heat producers such as ^{26}Al and ^{60}Fe. Accordingly, the assumption that Earth formed by a continuous influx of small particles made of pristine solar system condensates has given way to a much more dramatic model, in which Earth was assembled by a relatively small number of traumatic collisions involving larger objects, some of these already having differentiated interiors and well as their own internal dynamics (Canup and Asphaug, 2001). Future progress on the processes and timing of Earth's growth in the coming decade will rely on a diversity of approaches, including:

- Application of new isotope techniques for dating methods
- Closer integration of isotope geochemistry with astrophysical approaches to planetary formation
- More comprehensive and more realistic dynamical models of the accretion process
- Evolutionary studies of the chemistry and physics of planetesimal-sized objects and planetary embryos

Response to the Moon-Forming Impact

Although conclusive evidence is still lacking that ever-larger impacts dominated the later stages of Earth's growth, the global dynamical and thermal implications of this process are not in doubt. Once Earth reached an appreciable mass, the enormous amounts of kinetic and gravitational potential energy released by large impacts dictate widespread melting, with regional and possibly global magma oceans extending to considerable depths (Tonks and Melosh, 1993).

The compositional similarity of Earth's mantle and the Moon and realization of the importance of large impacts in the early Solar System, together with the large angular momentum present in the Earth-Moon system, have led to the theory that the Moon formed as the result of a late cataclysmic impact of a Mars-sized object with the growing Earth (Wetherill, 1990). Particle-based simulations of this giant collision (Canup, 2004; see Figure 2.2) predict that much of the preexisting layered structure of

Earth was obliterated and a substantial portion of the impacting material was thrown back into orbit, creating a post-impact accretion disk surrounding the proto-Earth, complete with its own silicate vapor atmosphere. These simulations also predict that the Moon consists primarily of material from the impacting object, and not material from proto-Earth. This computational model is challenged by remarkable similarity in oxygen isotopes found between lunar and Earth rocks, raising questions about the partitioning of material during impact.

Despite its widespread acceptance, direct evidence of a Moon-forming giant impact—the smoking gun in Earth's early history—remains elusive. Similarly, our understanding of the events accompanying giant impacts and their consequences for the chemical and physical modification of the early Earth remain sketchy. Further delineation of the Moon-forming event and its consequences for Earth are high priorities for the coming decade.

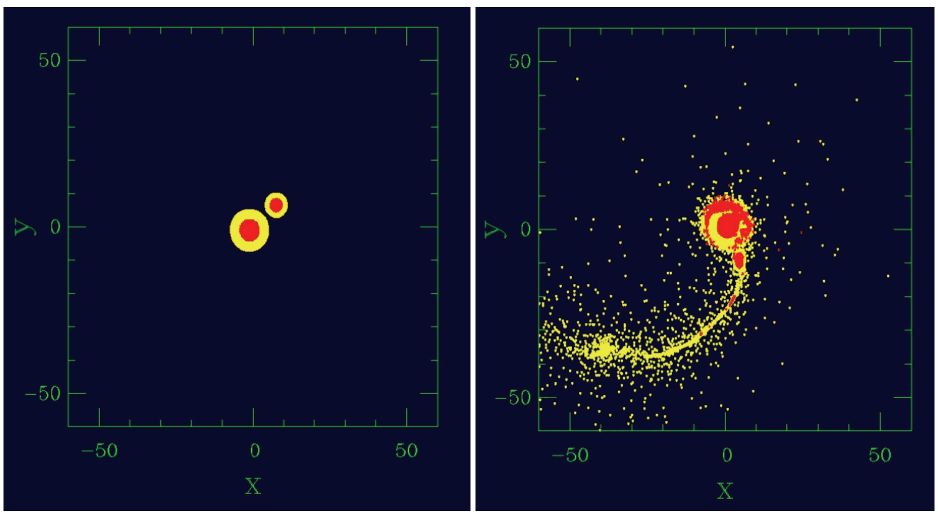


Figure 2.2 Two time slices in the animation of a glancing impact of a Mars-sized planetary embryo into the proto-Earth. The silicate mantles of both objects are shown in yellow, whereas their metallic cores are shown in red. The first image is slightly before the impact; the second is about two orbital rotations of the proto-Earth following impact. SOURCE: Reprinted from Canup (2004), with permission from Elsevier.

Terrestrial Magma Oceans

Magma oceans, an almost inevitable consequence of large planetary impacts given the energies involved, were first proposed to explain the plagioclase-dominated crust of the Moon (Warren, 1985), and differentiation in an early magma ocean on Mars is thought to be responsible for the range in source compositions of Martian meteorites (Borg and Draper, 2003). As is the case for a moon-forming impact, indisputable evidence for magma oceans and their associated early atmosphere on Earth remains elusive, although there is indirect evidence from abundance patterns of the elements affected by core formation (Kleine et al., 2004), plus some isotopic evidence for early mantle differentiation and atmosphere formation that are indicative of a magma ocean environment (Moynier et al., 2010). What is more certain, however, is that terrestrial magma oceans and the early atmosphere provided highly dynamical environments in which a wide variety of chemical and physical processes were active, ranging from shock-wave heating to fracturing and fragmentation, turbulent convection, percolation, mixing, and a host of possible redox reactions. Understanding the evolution of a terrestrial magma ocean requires answers to such basic questions as:

- What is the relationship between impact and magma ocean sizes?
- What is the lifetime of a magma ocean and how is it coupled to the early atmosphere?
- Does a terrestrial magma ocean crystallize from the bottom up or from the top down?
- Was there a deep-mantle abyssal magma ocean?
- Do deep melts rise or sink in the early mantle?
- What sequence of crystals form in a cooling magma ocean?
- As a magma ocean crystallizes, is it stably stratified, or will it overturn?
- How did metals and silicates mix and then segregate in magma oceans?
- What was the nature of mantle dynamics following magma ocean solidification?

Providing answers to these questions will probably require geodynamical modeling constrained by improved understanding of the petrology of melts and element partitioning at high pressures and temperatures, in parallel with interpretations of present-day seismic images of mantle heterogeneity in the deep mantle, where the chances are best of finding relics of this process still preserved. In addition, many of the issues raised by these questions are linked together, requiring cross-disciplinary expertise. For example, separation of immiscible liquids (in this case, iron from silicate melts) with greatly different densities happens rapidly in a low-viscosity magma ocean, whereas buoyancy-driven segregation of silicates depends on the environmental conditions. Because the moon's interior spans a small range of pressures, the crystallization sequence of a silicate lunar magma ocean is reasonably well understood (Shearer, 2006). As is the case for many shallow layered mafic intrusions on Earth, buoyancy-driven separation of lower-density Ca- and Al-rich plagioclase from denser Mg- and Fe-rich silicates occurs on the Moon. On Earth, however, the greater range of internal pressures introduces the likelihood of liquid-solid density crossovers (Mosenfelder et al., 2007; Stixrude et al., 2009), so magma oceans may stabilize at both the top and the base of the mantle (Labrosse et al., 2007), as shown in Figure 2.3, significantly complicating their evolution.

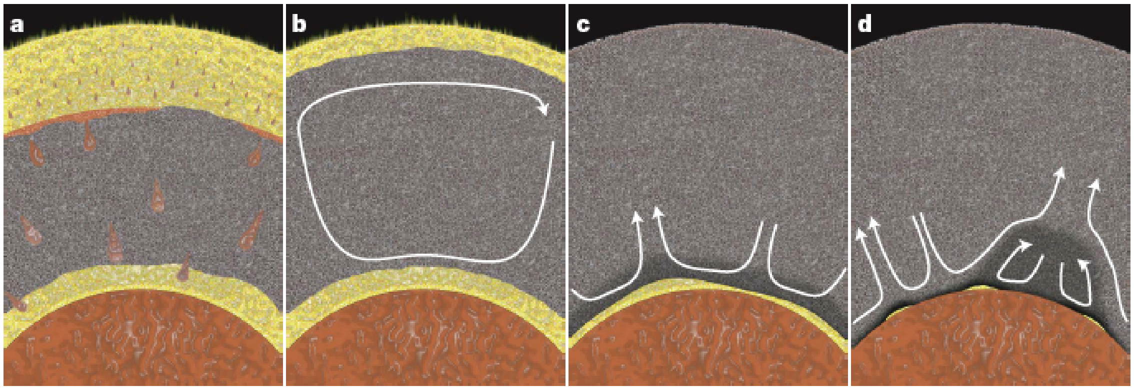


Figure 2.3 Schematic evolution of progressive crystallization of surface and basal magma oceans (yellow) following Earth accretion and core formation, based on the assumed deep-mantle density crossover between melt and solid, leading to upward segregation of melts in the upper mantle and downward migration of melts in the lower mantle. Core-forming metals are shown in orange; solid mantle is shown in gray, with circulation indicated by arrows. SOURCE: Labrosse et al. (2007). Reprinted by permission from Macmillan Publishers Ltd.

Core Formation

In addition to the energy acquired from impacts, the segregation of the core released enormous amounts of gravitational potential energy into the Earth system. Isotope evidence generally points to early core formation (Yin et al., 2002), which is consistent with the magma ocean hypothesis, wherein growth of the core essentially kept pace with growth of the mantle. There are several theories on how the core formed that are compatible with large impacts and the existence of magma oceans. One theory assumes that impacting cores fell through the magma ocean as large metal masses, directly merging with Earth's core (Halliday, 2006). Another assumes that dispersed metal rained down through the magma ocean, collected at its base, then descended through the underlying crystalline mantle by several possible mechanisms, including fracture propagation, large metal diapirs, or metal-silicate plumes (Ricard et al., 2009). The measured abundances in the mantle of moderately siderophile elements such as Nickel (Ni) and Cobalt (Co) indicate that some degree of chemical equilibration between core-forming metals and mantle silicates took place, possibly at elevated pressure and temperature conditions (Chabot et al., 2005; Wood et al., 2006). Additional geochemical and petrological constraints, better resolution of its timing and duration, and a fuller picture of the possible dynamics are needed to constrain the core segregation process.

Early Earth's Surface Environments

Evidence indicates that the accretion and major differentiation of Earth, including core formation, were largely complete within about the first 100 megayears

(Myr). The ensuing 500-Myr time interval, the Hadean Eon, is often referred to as the geological dark age, since there is little preservation of this interval in the rock record. Yet it remains a crucial stage in Earth's history because the transition to a habitable surface environment occurred during this time.

There are few solid constraints on the Hadean Earth and a host of first-order questions. Heat produced during accretion and core formation, together with the higher concentrations of heat-producing radioactive elements, point to a hot, possibly water-deficient, mantle. The consensus view is that Earth's initial atmosphere, composed mostly of hydrogen, was lost very early, perhaps during a T-Tauri phase of solar activity or through hydrodynamic escape to space aided by the strongly ultraviolet-emitting young Sun (Catling, 2006). As for the early composition of the secondary atmosphere, there is far too little in the way of direct evidence, although the decisive events in Earth's early history point to some plausible scenarios. One possible consequence of the Moon-forming impact is rapid evolution from a hot silicate atmosphere to a steam-dominated greenhouse atmosphere (Zahnle et al., 1988), and once the magma ocean solidified, liquid water could stabilize at the surface with carbon dioxide and methane dominating the climate (Kasting and Ono, 2006). A key unknown here is the capacity of the mantle to sequester water, possibly in the presence of early whole-mantle convection.

Clues from the Early Crust

Evidence for the earliest chapters in Earth's history comes from a variety of sources, including the bulk composition of Earth and the Moon, the angular momentum of the Earth-Moon system, traces of short-lived radioactive isotopes in meteorites and terrestrial rocks, terrestrial and lunar patterns of element abundances, and perhaps most importantly, the oldest crustal rocks and minerals. The discovery of increasingly old crustal rocks (see Figure 2.4) provides a few tantalizing clues on the state of Earth's surface in the late Hadean and the earliest Archean. In terms of preservation, the most diverse suite of ancient crustal rocks is found in the Isua terrane in Greenland, with ages as great as 3.8 Ga (Appel et al., 2001). These are moderately metamorphosed but contain evidence to suggest that plate tectonic processes, liquid water oceans, and perhaps life forms were present. Still older are the Acasta gneisses from north-central Canada, dated around 4 Ga (Bowring and Williams, 1999). The only known Earth materials that are unequivocally older are small zircon grains that have been removed from their parent rock, transported by fluvial systems, and deposited in sedimentary rocks of a younger age (see Box 2.2). Advances in microanalytical techniques, especially ion microprobes, have established ages around 4.3 Ga for the oldest of these. The overarching inference from these oldest crustal materials is that by the late Hadean and certainly by its end, Earth's surface environment was rather equable, perhaps not dramatically different from the present (Wilde et al., 2001; Mojzsis et al., 2001), so that some of the conditions for sustaining life were already in place. Other critical elements are more problematic, however, particularly oxygen, which does not appear to have been abundant then.

This raises several fundamental questions, such as:

- What is the critical oxygen concentration for early life forms?
- What was the role of the late heavy bombardment near 3.9 Ga on the terrestrial environment?
- At what time did the earliest continental crust stabilize?
- When did plate tectonics initiate, and what environmental effects did this transition have?

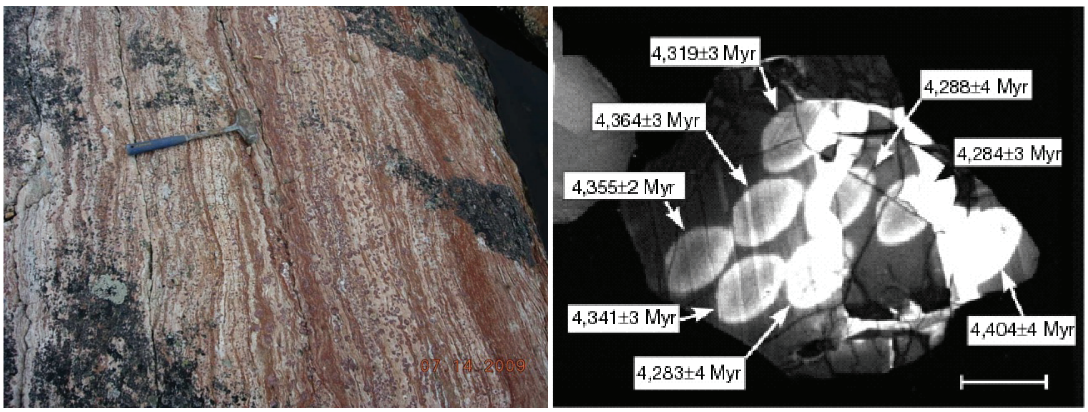


Figure 2.4 Images of Earth's oldest crustal rocks. *Left:* Acasta Gneiss of north-central Canada (Bowring et al., 1990). *Right:* The 4.28-Ga "faux-amphibolite" from the Nuvvuagittuq supracrustal belt in northern Quebec. SOURCE: O'Neil et al. (2008). Reprinted with permission from AAAS.

BOX 2.2
Earth's Oldest Solids: Hadean Zircons

The oldest known terrestrial solids are zircon crystals. Zircons are extremely resistant to both chemical and physical destruction and hence have the potential to survive billions of years of reprocessing after their formation. Fortunately, they also carry a range of mineralogical, geochemical, and isotopic tracers that document their age and environment of formation.

The oldest known zircons come from the Jack Hills region of Western Australia, where they are found in metamorphosed rocks originally deposited in a fan-delta setting (see Figure B2.2; Spaggiari et al., 2007). Although they span a range of ages, many of the Jack Hills zircons formed in the Hadean Eon (>3.8 Ga), and the oldest among them crystallized <250 million years after the birth of the solar system (e.g., Compston and Pidgeon, 1986). Because they provide a unique window into the early Earth, the Jack Hills crystals have been intensively studied in the past decade. A generally consistent story emerges from analyses of the trace element and isotopic composition of the zircons as well as the assemblage of mineral inclusions trapped within them (e.g., Wilde et al., 2001; Cavosie et al., 2005; Watson and Harrison, 2005; Trail et al., 2007; Hopkins et al., 2008; Harrison, 2009). The zircons appear to be igneous and formed at relatively low temperatures, suggesting crystallization from magma at or near water saturation. Inclusion mineralogy and oxygen isotope data indicate the magma may have formed from melting of a felsic protolith that had interacted extensively with an early hydrosphere, possibly an ocean. Geobarometry and thermometry of the inclusions and the zircons themselves suggest crystallization in an unusually cool geothermal gradient. These observations evoke an environment remarkably similar to the conditions under which modern granites form in subduction environments. Thus, it has been argued that within just a few hundred million years of the formation of the planet, a stable siliceous crust, an active hydrosphere, and a form of plate tectonics with marked similarities to the current regime had already been established.

Further advances in this field may come from identification of new localities where extremely old rocks and detrital minerals occur. This task will require application of a variety of geochemical and petrological methods, especially in geochronology. The magnitude of the undertaking is illustrated by the work invested to identify the oldest zircons from the Jack Hills. Ion microprobe analyses of more than 100,000 individual zircons were required to identify the ~100 crystals with ages >4.2 Gyr (Holden et al., 2009).

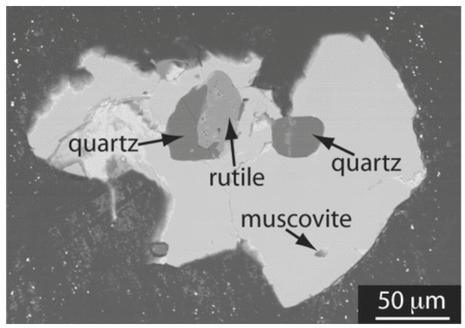


Figure B2.2 Jack Hills: a 4.06-billion-year-old Jack Hills zircon with mineral inclusions that characterize the parent magma's protolith and melting/crystallization conditions. SOURCE: Hopkins et al. (2008). Reprinted by permission from Macmillan Publishers Ltd.

The Hadean Mantle and Core

Most of the major questions posed for the early surface environment also involve the composition and dynamics of the Hadean mantle, and some of these also involve the early state of the core. For example, the thermal and compositional stratification of the mantle following the major phase of core segregation (and magma ocean solidification) constitute the "initial conditions" for subsolidus mantle convection. In the same way, conditions in the core inevitably changed once the major differentiation had occurred. Evidence for these transitions can be found in the context of the search for ancient rocks and minerals described previously. Geobarometry and geothermometry techniques can infer mantle temperatures and pressures, and magnetized samples provide information about the nature of the early geodynamo and also on the energetics of the Hadean deep Earth.

An Early Earth Initiative

This suite of topics involving the early Earth emerges as a major research opportunity because there have been significant advances in theory, observations, and modeling capabilities across all of the related areas but little coordination of the research agenda. Developing a community focus on these topics and coordination of the interdisciplinary approaches is likely to accelerate progress, much as has been the case for studies of the present-day deep Earth system. The complexity and energetics of the early Earth are distinct from today, and disciplinary approaches need to be informed by the geosystems perspective that an interdisciplinary context can provide. An Early Earth initiative could build on existing community organizations and funding programs, but distinct focus is required to catalyze coordinated momentum in this arena.

THERMO-CHEMICAL INTERNAL DYNAMICS AND VOLATILE DISTRIBUTION

The elucidation of plate tectonics over the past 50 years has provided a general framework for understanding shallow Earth structures, kinematics, and processes and for relating observations of the present Earth to those preserved in the geological record. The quests to fully quantify three-dimensional plate dynamics and to determine how distribution of materials at Earth's surface evolves with the internal dynamic system remain primary goals of the Earth sciences. The dynamic configuration, thermal and chemical fluxes, and driving forces within Earth's interior are all of central importance to understanding our planet's evolution, but these must be deduced from observations made at the surface. An improved understanding of thermo-chemical internal dynamics and volatile distribution within Earth also has important societal implications for the mitigation of volcanic and earthquake hazards and for the discovery and development of mineral and geothermal resources.

Making progress has required parallel maturation of a suite of disciplines that bring key information to light: seismology to image elastic and anelastic properties and material heterogeneity throughout the interior, mineral physics to characterize thermo-elastic properties, phase equilibria, electronic transitions, and transport properties of Earth materials over the full pressure-temperature range of the interior, geodynamics to quantify dynamic behavior of deep thermo-chemical systems and their surface manifestations, geomagnetism to probe the flow field of the outer core material and to constrain temporal evolution of the geodynamo, geochemistry to define internal chemical variability and timing of fractionation events, and geology to decipher the history of crustal formation and plate tectonics recorded by surface rocks. As observational, laboratory, and modeling capabilities of these disciplines have expanded, the prospects for major advances in our understanding of Earth's internal dynamics have increased, and a concerted interdisciplinary effort over the next decade holds the promise of significant impact on fundamental questions such as:

- How long has plate tectonics been in operation, as we see it today?
- What is the style of mantle convection and material flux between the upper and lower mantles?
- How is chemical heterogeneity distributed in the mantle, how and when was it created, and what is its role in the dynamic circulation?
- What is the volatile budget of the deep Earth?

- How have the core and geodynamo evolved over time?
- What are the driving forces of plate tectonics and internal circulation?
- When and how did the continents form?

Specific topics for which there are clear opportunities for making progress in the next decade include (1) appraisal of geochemical heterogeneities in the deep mantle and their relationship to the dynamic system, (2) quantification of volatile fluxes and their distribution in the mantle, and (3) determination of core evolution. All three topics are central to determining the thermo-chemical evolution of Earth. Progress is being made in these areas by concerted disciplinary and interdisciplinary efforts. Breakthrough advances that resolve outstanding issues will require enhanced resolution of fine-scale structures in the interior beyond what can now be achieved, and efforts to attain higher resolution from seismological, geodynamical, and mineral physics approaches will need to be undertaken.

Quantification of Geochemical Heterogeneities and Their Role in Mantle Dynamics

Earth's mantle comprises an immense convective system that circulate heat, volatiles such as water and carbon dioxide, silicate melts, former lithospheric material, and a host of other chemical and isotopic species between the interior and the surface. Throughout Earth's history chemical differentiation has produced continental and oceanic crust, much of which has been subducted or delaminated, generating compositional and isotopic mantle heterogeneity. Some chemical heterogeneities have remained sequestered in the interior for billions of years, while others have rapidly recycled to the surface. This multicomponent transport constitutes the primary interaction of the deep Earth with the ocean, atmosphere, and crust over geological timescales. The internal convective engines provide strain energy for earthquakes, heat for volcanic activity, and power for the core geodynamo. Determining the magnitude, spatial distribution, and temporal variability of geochemical heterogeneities and pinpointing the locations of internal reservoirs where they are sequestered are key to understanding how the deep interior contributes to Earth's evolution (NRC, 2008).

A profound task is to fully understand the configuration of global circulation in the mantle and its capacity to sequester chemical heterogeneities in reservoirs. Evidence from mantle-derived isotopes has long been interpreted as favoring layering of the mantle, while most geodynamic interpretations and some seismic interpretations favor mantle circulation that is at least partially continuous from top to bottom, with the transition zone providing some degree of resistance. Reconciling geochemical evidence favoring isolated mantle reservoirs, seismic evidence for down-welling slab material in the lower mantle, and geodynamic models that tend to favor extensive, although possibly intermittent, circulation remains at the heart of this long-standing controversy (Kellogg et al., 2004; Lay, 2009; Olson, 2010).

Quantifying the nature and dynamical influence of deep Earth chemical heterogeneities will require an interaction of multiple Earth science subdisciplines, including geodynamics, petrology, mineral physics, geochemistry, and seismology. New opportunities naturally arise from these interactions. For example, improved resolution of mantle seismic heterogeneity provides better constraints on candidate reservoirs and places limits on their compositions and geodynamic behavior. A dramatic example of a recent interdisciplinary advancement on this topic is provided by the discovery of two huge lower-mantle provinces with distinctive material properties (see Figure 2.5). These are the Southern Pacific and African Large Low Shear wave Velocity Provinces (LLSVPs) with several thousand-kilometer dimensions extending upward from the core-mantle boundary hundreds of kilometers (e.g., Ni et al., 2005; Wang and Wen, 2007). First detected by global seismic tomography, over the past decade these LLSVPs have been found to have abrupt lateral margins; stronger reductions of S-wave velocity than P-wave velocity, indicating anomalously high incompressibility; and anomalously high density—all suggestive of hot, chemically distinct material (Garnero et al., 2007; Garnero and McNamara, 2008; Trønnes, 2009).

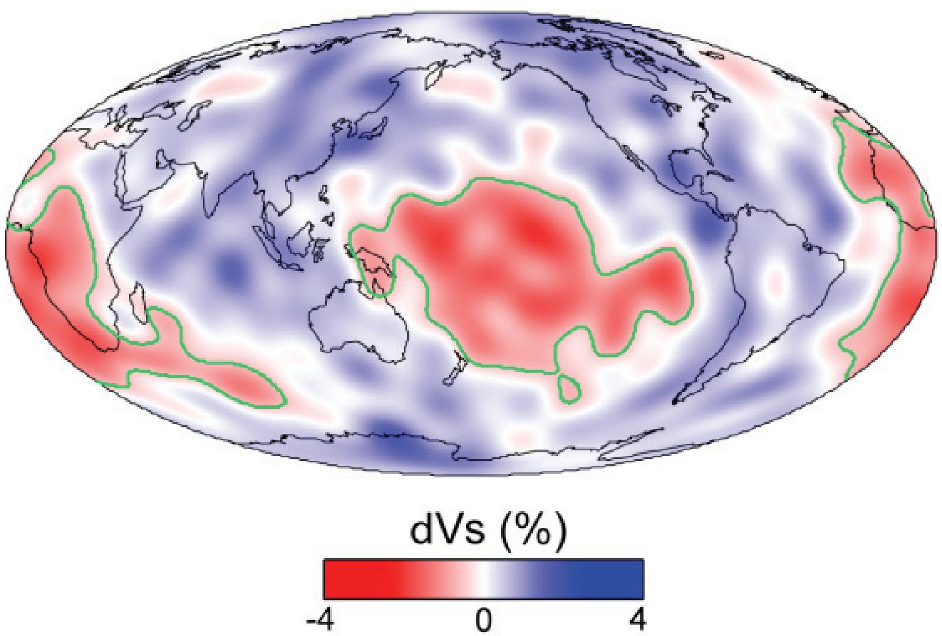


Figure 2.5 Pattern of S-wave velocity anomalies (dVs) at the core-mantle boundary for model S20RTS (Ritsema and van Heijst, 2000). Red areas have lower than average S-wave velocity, and blue areas have higher than average S-wave velocity. The green curves outline the 20 percent of the core-mantle boundary area with the lowest S-wave velocities, and this corresponds to the two LLSVPs beneath southern Africa and the south-central Pacific that have been characterized by seismic tomography and waveform modeling studies over the past two decades. SOURCE: Reprinted from Thorne et al. (2004), with permission from Elsevier.

Geodynamical modeling (see Figure 2.6) suggests that such massive hot dense piles of material can be localized by mantle circulation, with their margins possibly serving as loci for thermal boundary layer instabilities that rise through the mantle as well as accumulation zones for dense partially molten material right above the core-mantle boundary (e.g., Nakagawa and Tackley, 2004; McNamara and Zhong, 2005). Mineral physics experiments and theory now allow thermal and chemical heterogeneity of these provinces to be estimated based on predictions of elastic parameters (e.g., Murakami et al., 2004; Mao et al., 2006; Ohta et al., 2008; Duffy, 2008; Shim, 2008). Next-generation experimental facilities will provide the ability to characterize textures throughout the mantle pressure-temperature (*P-T*) range, such as crystal-liquid wetting angles and shape-preferred orientations—features that provide direct constraints on mantle evolution. The locations of large igneous provinces (LIPs) reconstructed for plate motions suggest that the deep-mantle LLSVPs may have persisted for at least 300 My, constituting a long-term connection between deep dynamics and surface geology (Burke et al., 2008; Torsvik et al., 2006). Many questions about the composition and dynamics of these huge chemical heterogeneities remain to be resolved, and petrological and geochemical investigations of surface materials are needed to evaluate possible deep compositions, but their discovery has driven models for mantle evolution in totally new directions.

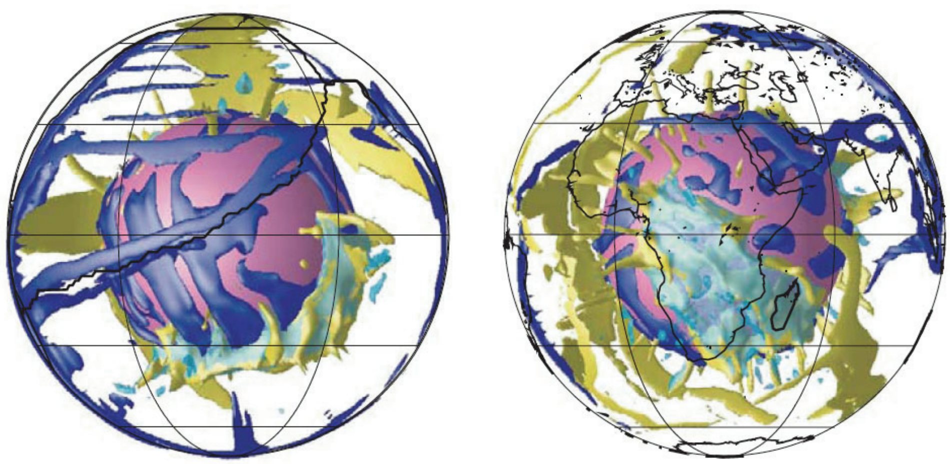


Figure 2.6 Seismic tomography indicates that the present-day lower mantle is dominated by large low-velocity provinces beneath southern Africa and the south-central Pacific, plus high-velocity regions beneath the Pacific Rim, as shown in Figure 2.5. The evolution of these structures with time is critical to deciphering the origin and composition of mantle reservoirs and their fluxes. This figure shows a simulation of whole-mantle convection with thermal and chemical heterogeneity and reconstructed plate motions since 450 Ma. *Left:* Calculated mantle structure at 230 Ma with reconstructed plate boundaries in black. *Right:* Present-day mantle structure with continent outlines in black from the same simulation. Positive and negative temperature anomalies are shown in yellow and blue, respectively; dense chemical heterogeneity is shown in green; the core-mantle boundary is shown in pink. This simulation predicts that a Paleozoic Gondwana LLSVP split to form the African and Pacific structures. It illustrates how plate and continent reconstructions can be combined with seismic tomography, LIPS paleo-reconstructions, and geodynamical modeling to trace the evolution of present-day mantle structure into the deep past. SOURCE: Zhang et al. (2010).

Disciplinary advances underlying the progress in characterizing deep chemical reservoirs include improved global seismic data sets accumulated from fixed and portable seismic networks; improved three-dimensional (3D) waveform modeling and imaging capabilities for resolving complex, deep structures; improved resolution of 3D thermo-chemical convection models enabled by faster computers and enhanced numerical codes; novel 3D petrographic analyses for lower-mantle conditions enabled by 3D x-ray tomography with nanoscale resolution; greatly expanded experimental determinations of deep-mantle properties enabled by synchrotron radiation facilities; and greatly improved molecular dynamics models implemented on fast computer networks. The rapid accumulation of new data, models, and properties positions the community to integrate the separate advances into new understanding of thermo-chemical convection throughout the upper and lower mantles, including effects of the subducted lithosphere, deep chemical piles, and thermo-chemical plumes.

While near-term progress can be anticipated based on the improved data, analysis techniques, and facilities that support research on the deep Earth system, final resolution of many of the key issues will require a significant improvement in high-resolution observational, theoretical, experimental, and modeling capabilities. On the observational end, the primary challenge is the big step to fully 3D seismic imaging with short scale-length resolution. This is achieved in the shallow oil exploration industry using very fine wavefield sampling that is not approached by current global seismic networks or even large-scale deployments of continental-scale arrays such as the EarthScope transportable array (e.g., Rost et al., 2008). There is a need for moderate aperture (~100 km) dense (100 to 200 stations) broadband arrays deployed in multiple locations around the world that can provide high-resolution imaging of specific regions of the deep mantle within the large-scale framework structures that can be imaged by existing global networks. An "Array of Arrays" concept is being developed in the seismological community as a means to achieve the high-resolution capabilities essential to resolving detailed structures in boundary layers, in deep subducting slabs, and in deep plumes as well as for improving models of statistical heterogeneity of small-scale structures that cannot be deterministically imaged. This undertaking will require strong international partnerships.

Advances in theoretical and computational capabilities for 3D seismic processing, for ab initio mineral physics calculations of material properties, and for multiscale 3D spherical geodynamics are all required to take a big step forward in resolving fine-scale structures and dynamics. Access to massive computational resources is also needed for dealing with the complexity of high-resolution seismological imaging and modeling, theoretical mineral physics, and especially global geodynamics calculations. These global geodynamics calculations will include fine-scale boundary layers on thermal and chemical boundaries, phase changes including iron (Fe) spin-state transitions, and partial melting effects, with long-time evolution. Improved experimental resolution of high *P-T* elasticity and transport properties will also be required, which will likely involve establishing new NSF-supported analysis nodes on large U.S. Department of Energy (DOE) high-energy facilities. The overall scope of facilities needed to make the next large steps in understanding the deep Earth thermo-chemical dynamic system will likely require major instrumentation initiatives and interagency partnerships. While the EarthScope project is completed over the next decade, planning efforts will need to be undertaken throughout the decade to achieve the capabilities needed for resolving key deep Earth system controversies.

Quantification of Mantle Volatile Fluxes

The stored quantity and flux of water into and out of the mantle are critical factors for sustaining life, facilitating plate tectonics (by making faults weak and lowering the viscosity of the mantle), and creating volcanism. As the universal solvent, the flux of water is intimately connected to most geochemical and volatile cycles and hence to the weathering of continents and the formation of mineral and ore deposits. A basic understanding of the dynamic Earth cannot be achieved without quantitative knowledge of the distribution and behavior of water and the feedback between the water cycle in the solid Earth and the climate system. Yet the sign of the net flux of water between Earth's interior and the near-surface hydrosphere is not even known (e.g., Hirth and Kohlstedt, 1996; Bercovici and Karato, 2003; Ohtani et al., 2004; Hirschmann, 2006; Olson, 2010).

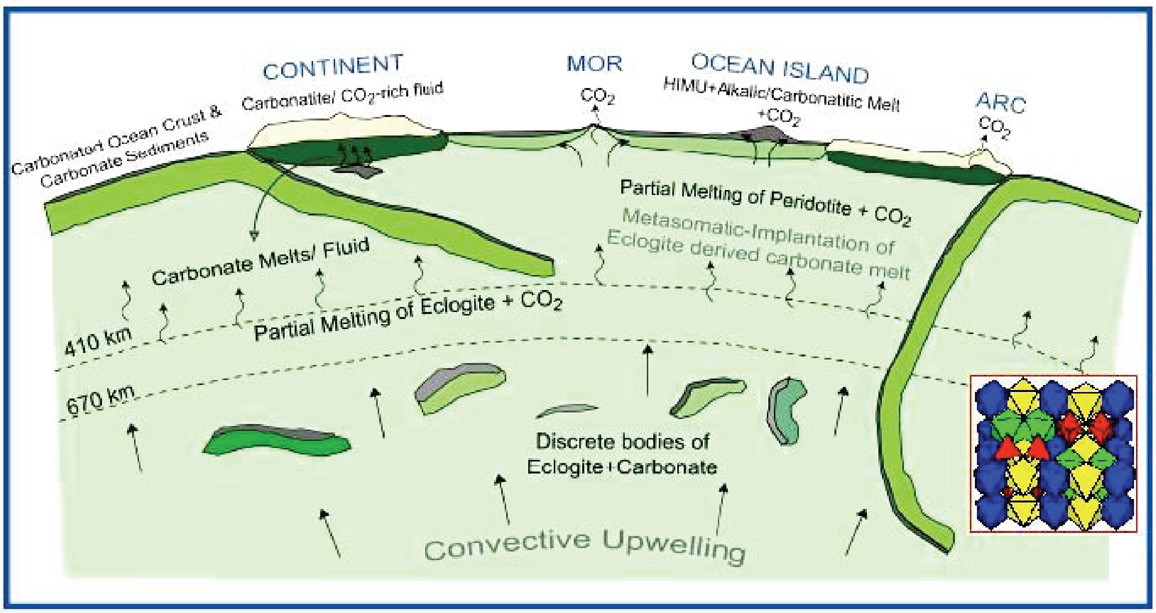


Figure 2.7 Cycling of volatile molecules through Earth's mantle is known to have an important role in regulating the level of carbon dioxide in the atmosphere. Mineralogists have discovered that many high-pressure minerals, such as the wadsleyite form of olivine present in the transition zone, can contain large amounts of water as hydrogen dissolved into their crystal structures. Current research points to a large fraction of our planet's volatile budget being locked up inside the solid Earth (Kellogg et al., 2004). SOURCE: Figure provided by R. Dasgupta and M. Hirschmann.

Likewise, the deep interior plays a critical role in the global carbon cycle and carbon can also alter physical properties of the mantle yielding feedbacks between carbon cycling and mantle dynamics (see Figure 2.7). As is true for H_2O there are great uncertainties in the distribution and flux of carbon (e.g., Dasgupta and Hirschmann, 2010). Most of Earth's carbon is stored in rocks, with much of that carbon in the mantle. Most mantle carbon is stored in high-pressure minerals, and volcanic processes provide the mechanisms for transferring some of this carbon to the atmosphere, while subduction provides the main mechanism for its return to the interior. Because the mantle carbon reservoir is thought to be large, resolving the internal component of the global carbon cycle is vital to interpreting the record of long-term climate changes. The broad scope of understanding Earth's carbon cycle from crust to core will require the expertise of geologists, physicists, chemists, and microbiologists. For example, discoveries of microbial life deep in the crust beneath both the oceans and continents indicate a rich subsurface biota that by some estimates may rival all surface life in total biomass. The subduction of tectonic plates and volcanic outgassing are primary vehicles for carbon fluxes to and from deep within Earth, but the processes and rates of these fluxes—as well as their variation throughout Earth's history—remain poorly understood. For example:

- Is biologically processed carbon represented in deep Earth reservoirs?
- What are the physical and chemical processes that govern carbon's distribution in Earth?
- How do carbon's elemental character and behaviors impact its various roles in the Earth system?

The current opportunity to improve our understanding of volatile fluxes in the interior also derives from improvements in high-resolution imaging of internal structures and material properties with seismology and magnetotellurics, especially in regions of both active and ancient subduction, in new petrological and volcanic constraints on subduction zone volatile fluxes, in high-resolution 3D geodynamical modeling capabilities for subduction zones with volatile transport and mineralogical reactions, and in mineral physics characterization of the myriad hydrous phases, dehydration processes, and influence of volatiles on rheology and the elastic properties imaged by seismology. Concerted community efforts to study subduction zones such as GeoPRISMs bring together diverse research communities that can address the volatile budget and flux problem, and large-scale studies of upper-mantle structure such as those conducted under the Continental Dynamics and EarthScope programs now regularly cast interpretations of seismic models in terms of coupled thermal, volatile, and chemical heterogeneities rather than solely thermal models (see Figure 2.8). With great expansions of seismological databases that can be anticipated over the next decade, in parallel with improved characterization of rheological and elastic attributes that reflect volatile presence and abundance, significant progress on mapping volatile distributions and resolving volatile fluxes can be anticipated with sustained research investment.

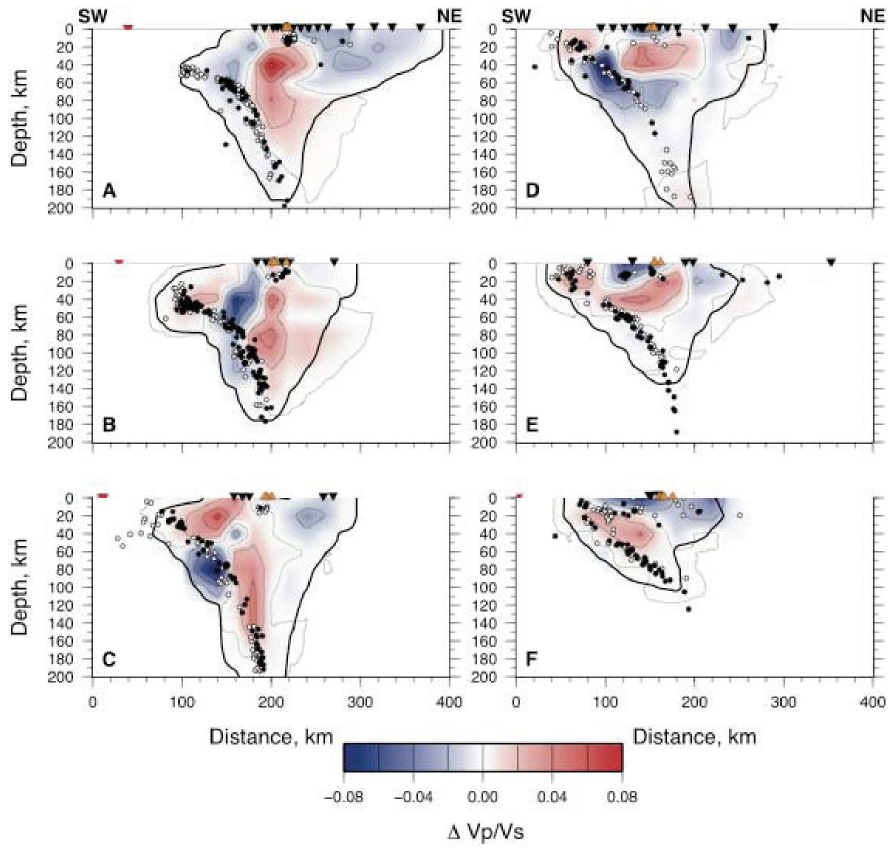


Figure 2.8 Images of Vp/Vs seismic wave velocity ratio variations in the mantle wedge beneath Central America. Low-velocity regions in the wedge may involve either fluids extracted from the slab or regions of partial melting caused by fluid-assisted reduction of melting temperature extending upward from the slab/wedge interface. SOURCE: Syracuse et al. (2008).

Quantification of Core Evolution

Our knowledge of Earth's core has advanced greatly over the past few decades, albeit with continued surprises time and again (e.g., Nimmo, 2007). As the core cools, the inner core grows by solidification of iron at its surface accompanied by a depletion of the light alloy component. It was originally assumed that this would lead to a relatively homogenous inner core structure, possibly with some thin surface transition zone. Seismology demonstrated that the inner core has both small-scale and large-scale heterogeneities that appear to reflect dynamical processes. Early characterization of the heterogeneity demonstrated the presence of anisotropic structure closely aligned with the rotation axis, but it is now recognized that there are hemispherical patterns in the inner core structure as well as changes in anisotropic pattern with depth (e.g., Ishii and Dziewonski, 2002; Song, 2007). Parallel improvements in seismological constraints on outer core structure indicate that there is a region above the inner core that has reduced velocity gradients indicative of transitional properties (Zou et al., 2008). Greatly expanded geodynamo simulation capabilities have also explored thermal, electromagnetic, and dynamic coupling of the inner and outer core regimes, seeking constraints on the inner core growth mechanism and outer core energy budget (see Figure 2.9). Coupling between the mantle and outer core and gravitational interaction between the mantle and inner core have been explored with improved geodynamic simulations constrained by orbital observations. Paleomagnetic observations have documented Earth's early magnetic field behavior back to at least 3 billion years ago (see Box 2.3), providing valuable constraints on geodynamo variations linked to inner core growth (Tarduno et al., 2007). All of these approaches to quantifying core structure and history are building an observational database on which major synthesis of core evolution should be viable over the next decade.

The committee also anticipates major developments in understanding of Earth's core through static high-pressure experiments and density functional theory calculations. With newly developing high *P-T* techniques allowing direct access to core conditions, novel experimental probes especially well suited for Fe and its alloys, and advances in theoretical techniques for treating transition metals, the time is ripe for a renaissance in studies that will provide improved understanding of the thermal evolution, seismic structure, growth mechanism, magnetic field generation, and dynamic behavior of the core.

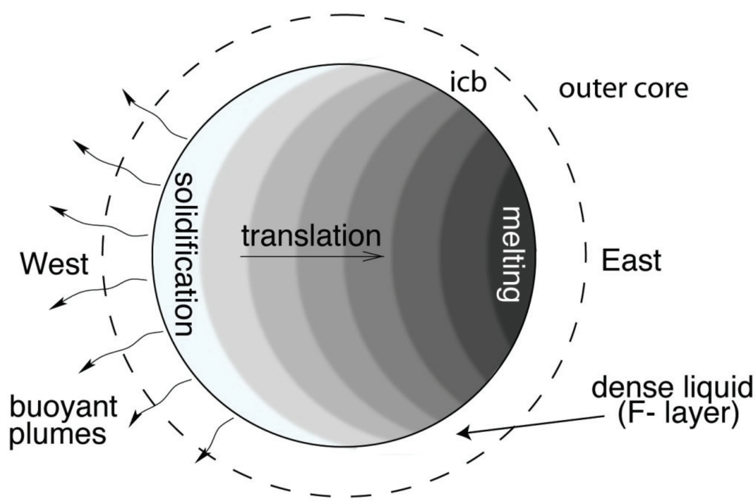


Figure 2.9 Fluxes of heat and light elements (Si, C, O, S, etc.) from the mostly solid inner core into the molten outer core provide much of the power for the geodynamo and also influence the rate of inner core growth and the thermo-chemical evolution of the core as a whole. New interpretations of these fluxes center on the significance of the seismic F-layer above the inner-core boundary (ICB), which appears to be depleted in light elements compared to the overlying outer core, and the observed dichotomy between eastern and western hemispheres of the inner core This diagram shows one interpretation, the so-called inner core translation instability, in which the inner core dynamics resemble that of a continental glacier. Freezing on the western side of the ICB releases light elements in buoyant plumes into the outer core, while melting on the eastern side of the ICB releases iron-rich liquid, forming the dense F-layer. SOURCE: Reprinted from Alboussiere et al. (2010) with permission from from Macmillan Publishers Ltd., and from Monnereau et al. (2010) with permission from AAAS.

The next decade offers the potential for building on and integrating the recent observational, computational, and experimental advances noted above into a robust model for evolution of the inner and outer cores. The thermo-chemical evolution of the core dynamic system is manifested not only in the geomagnetic field but also in the thermal history of the planet; the rate of inner core growth is determined by how rapidly the core cools, which is controlled by the mantle. Thus, a bounty of fundamental results can be harvested by developing a quantitative understanding of core evolution. The NSF's Cooperative Studies of the Earth's Deep Interior (CSEDI) program is structured to support interdisciplinary coordination on this topic, and community organizations such as the Cooperative Institute for Dynamic Earth Research (CIDER) enhance communications across the disciplines and training of graduate students in the diverse arena of core studies.

Box 2.3
New Opportunities in Rock Magnetism in the 21st century

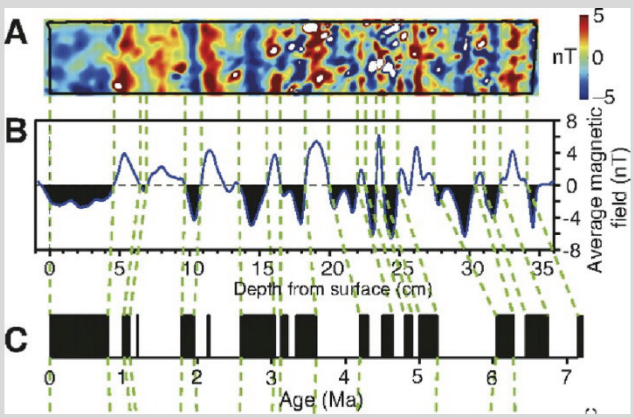


Figure B2.3 Example of current scanning SQUID microscopy with submillimeter (~100 micrometer) resolution (A) showing geomagnetic reversal stratigraphic dating of alternating polarities recorded by magnetite crystals in submillimeter layers of a seafloor manganese nodule (B). The nodule is only 35 cm thick, and the alternating magnetizations can be fit to a known polarity reversal timescale (C). SOURCE: Reprinted from Oda et al. (2011) with permission of Geological Society of America.

Rock and mineral magnetism constitute the essential connection between geomagnetic records of the past and the answers to the Grand Challenges (NRC, 2008) to understand the origin and evolution of Earth and the other planets. One such broad challenge is: How strong or weak have the internal geomagnetic and planetary magnetic fields been over the past 4.5 billion years? In particular, what can we learn from magnetism of ancient rocks that can illuminate the intertwined record of the geomagnetic field during the first billion years of Earth's existence and the formation and growth rate of the solid inner core? In the past decade the rock and paleomagnetic community have proven the feasibility of extracting reliable values of paleomagnetic intensity from one-billion-year-old single silicate crystals containing magnetite grains that have been protected from subsequent chemical alteration. Figure B2.3 shows an example of magnetic signals now being studied using current scanning Superconducting Quantum Interference Device (SQUID) sensors. But to advance the science to more precise and higher (temporal) resolution records of paleointensity, the use of submicrometer-sized, datable zircons and oxide exsolution structures from the early Archean period is needed.

There are two essential requirements for such progress, and both can be within reach if collaborative and focused efforts are now initiated on two fronts. One is the development of novel SQUID and non-SQUID sensors (e.g., spin-exchange relaxation free or Spin Exchange Relaxation-Free [SERF] method-based) that are capable of measuring submillimeter samples, and signal enhancement techniques for the very small magnetic signals that such scanning techniques will deliver. The second requirement is inherently linked to the first and involves “ground truthing” magnetic measurements that are based on submillimeter samples. Because these samples are single crystals, there are a number of rock magnetic effects that must be examined in order to ensure that they are accurate recorders of Earth’s magnetic field. These effects include remanence anisotropy due to crystallographic alignment of magnetic oxides within the silicate host, magnetostatic interactions between inclusions, and subsolidus exsolution structures within the oxides. Measuring the importance of these effects will require the use of instruments capable of imaging magnetism at scales of 10 to 1,000 nm, such as transmission electron microscopes and magnetic force microscopes. Ultimately these kinds of studies will allow researchers to select only those samples that can be confidently used for reconstruction of geomagnetic paleointensity for such ancient times.

FAULTING AND DEFORMATION PROCESSES

Plate tectonics provides a first-order description of how Earth’s surface shifts with time, with the motions near plate boundaries largely involving seismic or aseismic faulting and elastic or anelastic rock deformation. Plate motions driven by mantle flow concentrate stresses on faults at plate boundaries, powering the cycle of frictional stress accumulation, elastic and anelastic strain deformation, and slow or abrupt (earthquake) fault displacement and stress and strain release. Ground motions caused by elastic waves and surface deformations produced during rapid earthquake faulting constitute one of nature’s greatest hazards, with tremendous annual loss of life and damage on a global basis. The impact of earthquakes can be staggering; hundreds of thousands of fatalities in moderate-size events like the 2010 Haiti (magnitude M_w 7.0) earthquake or immense events like the 2004 Sumatra (M_w 9.2) earthquake and tsunami, and hundreds of billions of dollars in damage as in the 2011 Japan (M_w 9.0) earthquake. Since 2004 there have been more great earthquakes around the world than in any 6.5-year period in seismological history (back to 1900), and burgeoning population growth near plate boundaries will place ever-increasing populations and built infrastructure at risk throughout this century. Efforts to understand how faults accumulate and release stress and strain and the nature of the resulting ground motions constitute major scientific challenges highlighted in community planning documents from seismologists (Lay, 2009), geodesists (UNAVCO, 2008), geodynamicists (Olson, 2010), GEOPrisms (MARGINS Office, 2010), and the EarthScope program (Williams et al., 2010). The 2008 NRC report *Origin and Evolution of Earth* highlighted the question of whether earthquakes, volcanic eruptions, and their consequences can be predicted, as one of 10 Grand Challenges in the Earth sciences.

Earthquake science is intrinsically interdisciplinary and deals with complex multiscale dynamical systems spanning the microscale processes of friction and fluids in fault zones to the macroscale processes of elastic and anelastic crustal deformations and elastic waves in the crust and near-surface environment. Geologists provide a framework for studying deformation near plate boundaries by documenting the style and timing of faulting over geological time, and by examining exhumed faults to study frictional characteristics and evolution of fault gouge. Seismologists use the elastic wave energy radiated from dynamic fault ruptures to estimate the size of earthquakes and to determine details of the rupture process, along with quantifying seismic wave propagation and ground shaking effects. Geodesists measure deformations of the rock around a fault zone both before (interseismic), during (co-seismic), and after (postseismic) an earthquake, as well as stable sliding of some aseismic faults. Rock mechanics researchers determine frictional mechanisms and theory for rupture nucleation and arrest to guide understanding of the frictional instabilities associated with earthquakes and stable sliding. The collective scientific understanding of earthquake faulting from these endeavors feeds into earthquake engineering and emergency response efforts to mitigate the impacts of fault ruptures.

The earthquake cycle notion provides a basic framework for understanding deformation near a fault that is loaded by large-scale plate motions. Once an earthquake has occurred and the postseismic period of stress and strain transients has ended, the earthquake cycle begins anew with interseismic frictional locking of the fault and onset of fault zone strain accumulation. Geological, seismic, and geodetic data are used to evaluate the size and frequency of large earthquakes in a particular region. A catalog of historical behavior of a fault is then used to assess how large and how often fault ruptures can be expected statistically. Geodetically determined rates of strain accumulation can be evaluated relative to total plate motions and stress drop determinations for prior events on the fault to anticipate where and how much future strain release will occur. Determining the statistical likelihood of earthquakes in a region is of particular interest to society because engineering building codes are guided by the probability of experiencing various levels of ground shaking within the lifetime of a building. However, this earthquake cycle model is only useful to the extent that we can fully understand how deformation accumulates and how faults fail. The nonlinearity of frictional instabilities, the influence of dynamic and static stress perturbations by other earthquakes, and the complexity of stress heterogeneity from prior ruptures and non-uniformity of strain accumulation all add uncertainty to forecasting future earthquake occurrence.

Recent Advances—The Wide Range of Slip Velocities

The scientific view of how faults slip has evolved dramatically in the past decade. Developments in space geodesy—particularly the Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR)—allow the interseismic deformation phase of the earthquake cycle to be imaged with unprecedented temporal (GPS) and spatial (InSAR) sensitivity. Prior to the development of large GPS arrays, measurements of deformation in fault zones were either unavailable or sporadic. As GPS resolution improved to the several millimeter level, it became clear that overall strain accumulation does not always follow a simple linear model (see Figure 2.10). Instead, observations show that steady accumulation of deformation in the volume adjacent to a plate boundary can be punctuated by abrupt changes in sign, indicating non-seismic slip of portions of megathrust faults. These "slip reversals" were first observed at multiple stations in the Cascadia region within the past decade and have been termed either "slow slip" or "slow earthquakes." In Cascadia the slow slip events occur about every 14 months (Miller et al., 2002) and are thought to involve intermittent shearing displacement of the down-dip region of the megathrust in a transition zone from unstable to stable sliding, partially relaxing strain in the upper plate. It is plausible that this is a primary mechanism that helps load and initiate large earthquake ruptures on the shallower unstable sliding regime of the plate boundary.

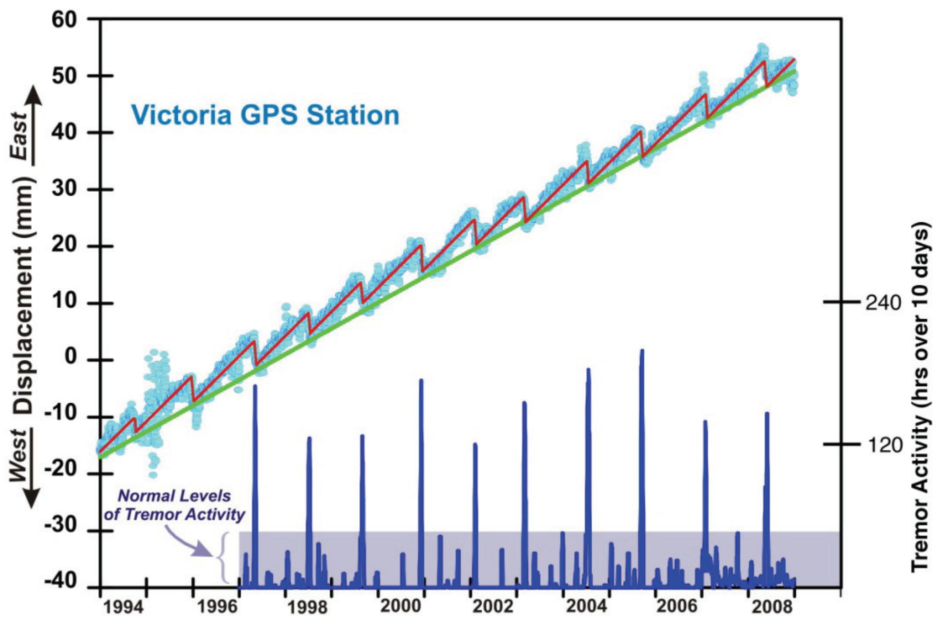


Figure 2.10 Comparison of GPS observations of upper plate displacement and seismic tremor activity levels for the Cascadia subduction zone. Cyan dots represent daily location solutions for the East-West component of the Victoria GPS station, with the overall eastward trend (green) representing the upper plate deformation caused by convergence between the frictionally locked (not slipping) shallow megathrust fault between the Juan de Fuca and North American plates. Every ~14 months the trend of the GPS locations reverses direction for ~2 weeks away from the secular trend, which is inferred to result from the deeper portion of the megathrust fault slipping slowly, relaxing some strain in the upper plate even while the shallow portion of the fault is still not slipping. Blue lines represent hours of non-volcanic tremor in each 10-day window recorded in the same region. There is a positive correlation between the times when the GPS displacement has a reversal and periods of strong tremor activity. SOURCE: Reprinted from Rubinstein et al. (2010) with permission from Springer Science+Business Media. Modified and extended from Rogers and Dragert (2003) with permission from AAAS.

Just as slow earthquakes were first being recognized, seismologists made an additional discovery, classifying a new kind of seismic signal: non-volcanic tremor

(Obara, 2002). Tremor consists of long-duration trains of weak ground motions that do not have easily identifiable body wave arrivals. Soon after slow slip events were discovered, it was shown that the slow slip episodes in Cascadia correlate with periods of enhanced seismic tremor, with the term episodic tremor and slip (ETS) being used to describe the combined phenomena (Rogers and Dragert, 2003). Efforts to establish the direct relationship between tremor and slow slip are under way, with possibilities including heterogeneous frictional conditions on the deep megathrust as well as activations of multiple faults due to fluid motions and changes in strain produced by the slow slip. ETS has now been reported in many other subduction zones but with variable manifestations. In southern Mexico the slip events are as much as five times larger than in Cascadia and less frequent (Kostoglodov et al., 2003); tremor has also been observed in the Mexican subduction zone (Payero et al., 2008). Episodic slip events have been reported in the New Zealand Hikurangi subduction zone (Douglas et al., 2005; Wallace and Beavan, 2006), while tremor was elusive (Delahaye et al., 2009) until recently observed (Kim et al., 2011). The diversity of fault slip processes has been particularly well documented in Japan, where there is high density of both geodetic and seismic instrumentation. For example, borehole tiltmeters in the Nankai Trough have been used to detect slip events that were much too small to be indentified on GPS receivers. The migration of both tremor and slip on the fault zone interface was subsequently imaged, with migration speeds of ~10 km per day (Obara et al., 2004), comparable to observations in Cascadia. Earthquakes depleted in short-period radiation (low-frequency earthquakes, or LFEs) have been identified near the down-dip edge of the unstable megathrust zone (Katsumata and Kamaya, 2003), and it currently appears that tremor involves superposition of many small LFEs (or even normal earthquakes).

Conventional earthquakes involve large amounts of energy release in small amounts of time, with rupture spreading over the fault at very high velocities of several kilometers per second (see Figure 2.11). The ETS and LFE observations make it clear that fault slip occurs on an immense variety of temporal scales that appear to scale differently than for fast ruptures. Some of the large slow slip events have the equivalent strain release of large conventional earthquakes (e.g., Kostoglodov et al., 2003). In some regions, where the total seismic slip budget falls very short of the total plate tectonic convergence budget, such as the Marianas and Tonga subduction zones, the entire megathrust may be failing in slow slip or stable sliding processes, as appears to be the case along North Island, New Zealand. This indicates the importance of understanding the full range of frictional processes that appear to play a huge role in plate motions. The simple earthquake cycle model that has been invoked for decades needs to be expanded to accommodate these new observations. Much of the effort thus far has focused on categorizing these events—where and when they occur and how big they are. And while slow slip appears to be related to a frictional behavior intermediate between that of steady sliding and stick-slip earthquakes, theoretical developments are needed in order to make advances in our understanding of these new observations of fault slip. Laboratory studies of rock mechanics spanning the full range of fault slip velocities play a key role in quantifying the observations.

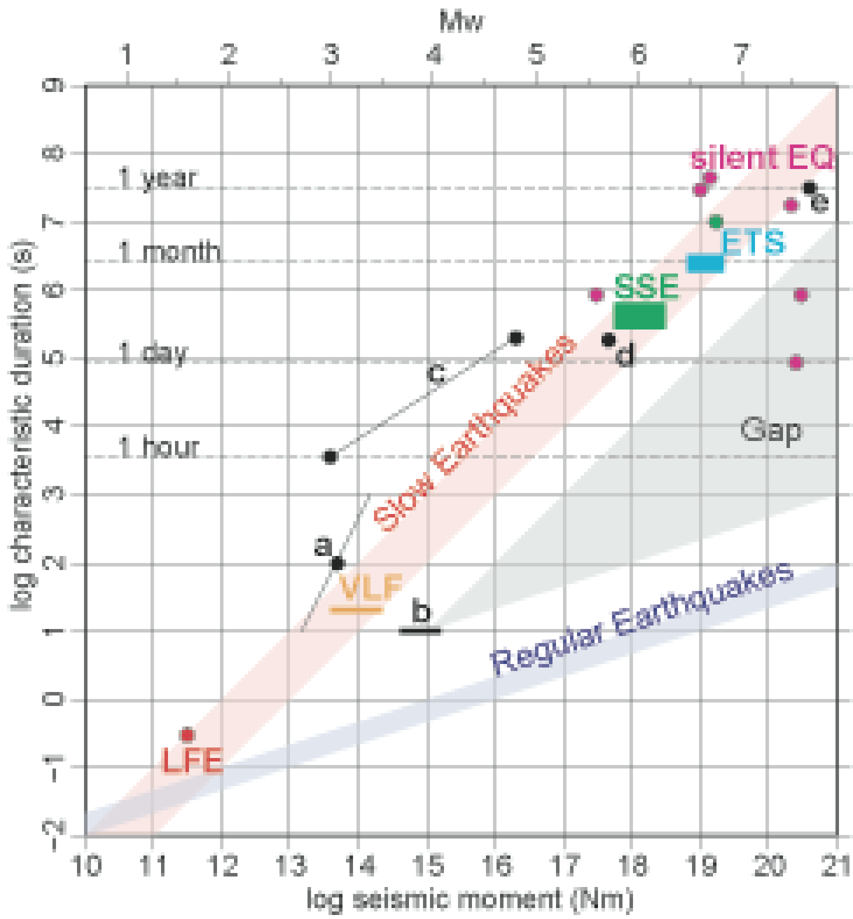


Figure 2.11 Relationship between the duration and magnitude of regular earthquakes (thick blue line) and low-frequency earthquakes (LFEs, red), very low-frequency earthquakes (VLFs, orange), and slow slip episodes (SSEs, green) in the Nankai trough off the coast of Japan and episodic tremor and slip (ETS, light blue) in the Cascadia subduction zone off the coast of the U.S. Pacific Northwest. Pink dots are silent earthquakes; black symbols are slow events. See original source for further explanation. SOURCE: Reprinted from Ide et al. (2007) by permission from Macmillan Publishers Ltd.

Rapid progress in this area can be sustained due to major observational facilities such as EarthScope being deployed with sufficient station density to capture the full spectrum of fault behavior. Organized community efforts such as GeoPRISMS and the Southern California Earthquake Center (SCEC) draw together the interdisciplinary communities working on faulting and earthquake processes at all scales, and the level of research excitement and activity provides a clear opportunity for major advances on this topic during the next 10 years.

Recent Advances—Dynamic Fault Modeling

Significant breakthroughs are also being made in our understanding of seismic radiation from earthquakes. Some of the most exciting quantifications of global earthquake ruptures in the past decade have come from innovative use of regional arrays, showing the expansion of fault rupture for the recent immense earthquakes in Sumatra, Chile, and Japan (e.g., Ishii et al., 2005; Lay et al., 2010a). Global seismic network data are now used to estimate slip distribution for all major faults; geodetic data sets using GPS, InSAR, uplift, and tsunami excitation have improved constraints on fault displacements for events around the world. Faults likely to rupture at super shear velocities have been identified (Bouchon and Vallee, 2003), and the complexity of faulting beyond simple slip pulse models has been resolved (e.g., Lay et al., 2010b). However, many fundamental questions about earthquakes remain:

- How do earthquakes initiate?
- What controls the branching of rupture or the triggering of one fault by rupture of another?
- Why does a rupture stop?
- When and why do rupture speeds exceed the seismic shear velocity?
- Can rupture attributes be anticipated based on geodetic determinations of prior fault locking and strain accumulation?

To mitigate risk from earthquakes, it is first necessary to know how strongly the ground will vibrate. This is difficult to predict given both the complexity of earthquake ruptures and the wave focusing and defocusing effects and soil interactions of seismic waves. At present, ground motions during earthquakes are usually characterized by very simple measurements, such as peak ground acceleration or velocity. These data are used by engineers to estimate the strength of ground shaking expected during an earthquake of given size by using empirical relationships based on past earthquake data in a given region (size of earthquake, distance to the rupture, and local geology). This approach seems to work adequately for moderate earthquakes, but rupture finiteness and wave directionality effects for large events greatly complicate the ground motion prediction. Because large (and very large) earthquakes occur infrequently, the empirical-based seismic hazard relationships are not well constrained, and recent earthquakes have offered repeated surprises in terms of the intensity of ground shaking actually experienced. It is desirable to move forward from empirical approaches to quantitative modeling approaches.

Most seismic and geodetic models of fault slip are kinematic in nature; simplifying assumptions are made to allow the estimation of the relevant parameters (e.g. faults are planar, slip is unidirectional). Physical properties of the fault are typically not modeled because of their complexity. However, new simulations have shown the potential to bridge the gap from standard kinematic models to physics-based models (e.g., Dunham and Archuleta, 2005). Dynamic rupture modeling considers the joint stress-slip evolution during earthquake shear failure as being driven by the redistribution of stored strain energy and can serve as the foundation for predicting both fault behavior and strong ground motion. Dynamic rupture modeling includes realistic 3D simulations of fault roughness; spatially variable frictional properties; and other effects, such as basin reverberation and focusing, soil nonlinearity, and soil-structure interactions. Quantitative modeling now provides a prospect of eliminating dependence on poorly constrained empirical models, thus linking seismic hazard analysis for the first time to physics-based concepts such as stress-time evolution.

Much of this work is currently coordinated by the SCEC, where there is a community effort to develop 3D rupture models with full 3D implementations, from finite-element codes to high-resolution 3D community crustal models (Olsen et al., 2008). These models are currently being used to predict shaking in Los Angeles, San Francisco, and other cities from ruptures on the San Andreas Fault or other regional faults. This has been an interdisciplinary effort bridging rock physics, seismology, soil mechanics, structural geology, and earthquake engineering and requires the use of today's most powerful supercomputers because representations of faults must span spatial scales covering many orders of magnitude and because physical quantities must be calculated at all causally connected points to properly account for stress and slip evolution.

Advancing earthquake source studies to a full physics-based model of initiation, propagation, and arrest requires knowledge of the stresses on faults, how those stresses change with time, and the influence of pore fluid pressure. Resolving these questions requires improvements in computational resources and support for theoretical developments so that 3D wavefields can be computed for realistic crustal environments. Furthermore, additional ground displacement records recorded near faults during large earthquakes are needed to test the results of dynamic rupture models. While much of the San Andreas Fault has been instrumented (by other government agencies) with strong motion sensors, accelerometers do not directly record ground displacements and cannot distinguish rotations from accelerations. Combining strong motion records with GPS position estimates (in the same way that GPS is often combined with more precise gyroscopes in navigation systems) would address the limitations of strong motion data. It is desirable to support collocation of strong motion sensors when GPS receivers are installed in fault zones.

The recent earthquake drills, or ShakeOuts, conducted in California (Perry et al., 2008) and since expanded[1] to Nevada, Utah, Oregon, Idaho, the Central U.S., British Columbia, and Guam have used realistic shaking simulations to guide the responses of millions of people to scenario events. The effort has just begun, and as computers, 3D methods, and the interfaces between the scientists and engineers, scientists and first responders, and societal engagement improve, this area will greatly expand (see Box 2.4). NSF's role includes interagency engagement with the U.S. Geological Survey (USGS) in SCEC, along with direct funding of many related basic research efforts in each component (theory, computational support, new observations) that feed into this hazard area. This work has the potential to transform probabilistic hazard analysis and to greatly enhance public preparedness for earthquake disasters.

With the recent demonstration that physics-based approaches to probabilistic seismic hazard analysis are both viable and important, the research opportunity is

[1] http://www.shakeout.org/regions

clear: further coordinate the interdisciplinary effort to advance understanding of dynamic failure at all scales from fault zone to remote ground shaking. This ambitious effort is under way, and sustaining it should provide major advances over the next decade.

Recent Advances—EarthScope Project

EarthScope is the first Major Research Equipment and Facilities Construction (MREFC) project conducted by the Earth sciences, receiving $200 million of NSF's MREFC support from outside of the Directorate for Geosciences (GEO) and an increase in GEO/EAR annual funding that provides ongoing Operations and Maintenance (O&M) support projected to continue through at least 2018. EAR has built up EarthScope research funding steadily by designating funds from divisional budget increases since the onset of the project. The success of EarthScope is critical to establishing a precedent for future efforts to draw MREFC funding to the discipline. The fact that the 2003-2008 EarthScope facilities construction phase was completed on time and on budget has strongly positioned EAR for future MREFC competitions and for National Science Board and congressional support of future Earth science projects. Achieving full success of the project will involve completion of the science plan defined in the original proposal and updated in the EarthScope Science Plan for 2010-2020 (Williams et al., 2010).

The scientific rationale for following through on the EarthScope program in the next decade is compelling. Densification of geodetic and seismic observations along the plate boundary on the western coast of the United States and along the Alaska-Aleutian volcanic arc has already resulted in exciting discoveries about faulting and deformation processes described above. Seismic, geodetic, magnetotelluric, and geochemical data collected by EarthScope are progressively revealing deep crustal and upper-mantle structures under North America, unveiling as the Transportable Array sweeps eastward. Fundamental questions such as the deep configuration of the Juan de Fuca plate, the fate of other subducted portions of the Farallon plate, deep crustal delamination processes under the Basin and Range and deep structure of the Colorado Plateau and Rio Grande rift, the detailed structure and mantle flow beneath the Yellowstone volcanic center, and the lithospheric contrasts across the Rocky Mountain front are all being vigorously addressed with hundreds of papers appearing (see Figure 2.12). Large-scale deformation of western North America is being revealed by the geodetic instrumentation with unprecedented resolution (see Figure 2.13). Prospects are good for resolving many long-standing large-scale framework questions about the driving processes for North American geological history. Further eastward migration of the Transportable Array will expose unknown structures beneath the eastern continental margin and then across Alaska, where there have been relatively few seismic instruments. Unraveling the complex history and processes of North American evolution has commenced but will require the synoptic framework structures anticipated from the full EarthScope program. As this framework emerges from the NSF-led effort, interagency coordination may help this understanding to penetrate into mission agencies such as the Department of

Energy, the U.S. Geological Survey, and the Nuclear Regulatory Commission, all of which have programs impacted by earthquake hazards and continental deformation related to topics such as carbon sequestration, geothermal energy, fracking for shale-gas recovery, nuclear power plant siting, and building code development.

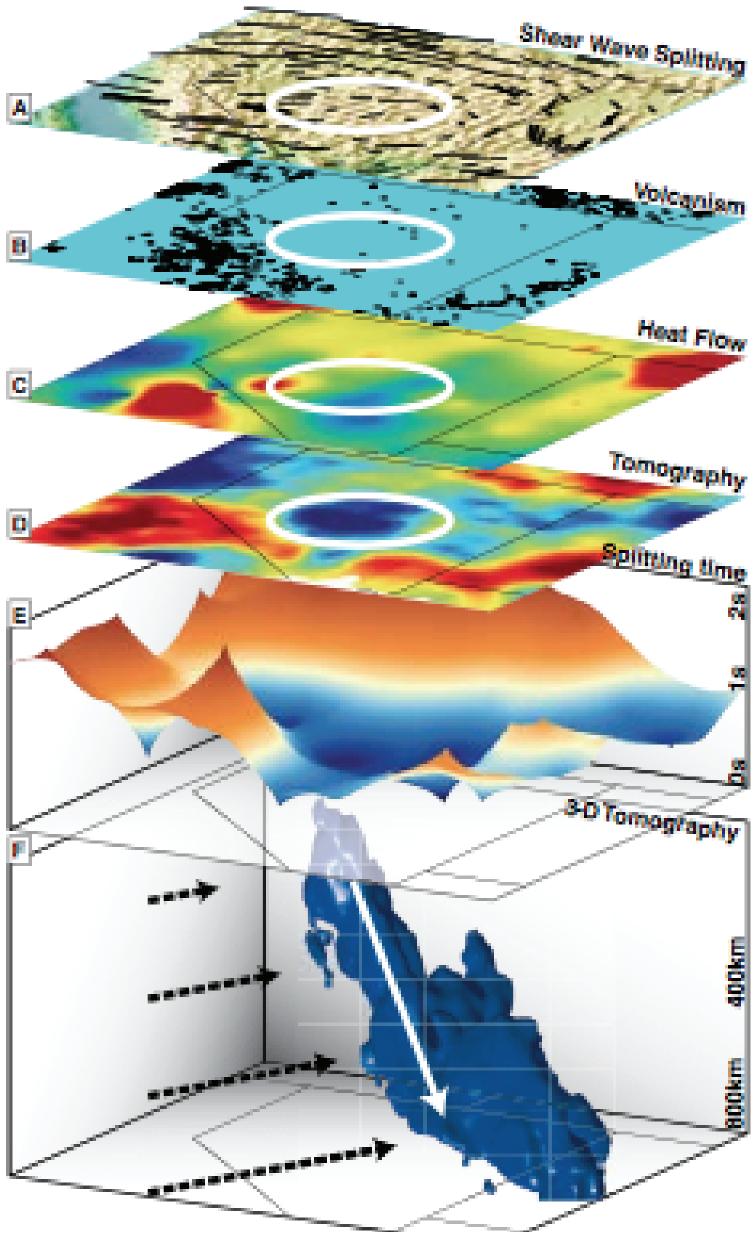


Figure 2.12 One of the goals of EarthScope is to resolve the upper-mantle structure beneath the North American continent using seismic signals and to interpret the dynamical processes by which the continent has evolved. The example shown here is the high-resolution determination of the 3D structure under the Great Basin. Source: Reprinted from West et al. (2009) by permission from Macmillan Publishers Ltd.

The economic rationale for sustaining the EarthScope project through the planned program to 2018 is equally compelling given the large investment of NSF funds in EarthScope, the superb success of the facilities in achieving the primary data collection goals to date, the exciting scientific results on first-order Earth science problems, and the excellent prospect for sustaining the flow of discoveries and resolving long-standing questions. After 2018 any continued elements of the project will need to be carefully assessed and evaluated in terms of prospects for proportionate advances. The NSF system for MREFC programs causes particular stresses for directorates that have not had prior MREFC initiatives (the need for creation of O&M and research funds within the directorate to follow up on the infusion of MREFC capitalization funds) and the successful completion of EarthScope may ease the establishment of new EAR MREFC programs. With aspirations for major new Earth sciences facilities being articulated by multiple EAR communities, future MREFC proposals should be at least one strategy considered by EAR management.

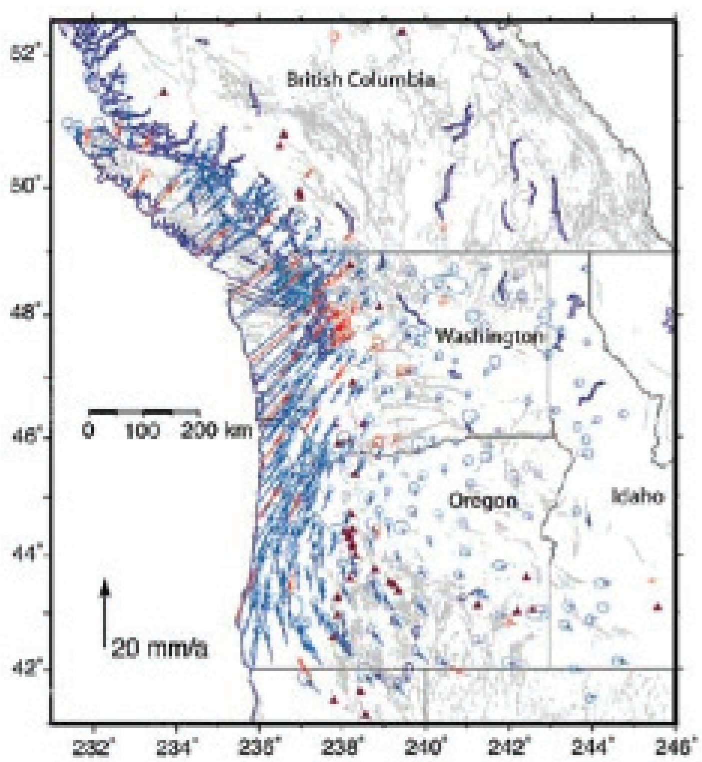


Figure 2.13 Example of the remarkable spatial resolution of the crustal deformation field in the western United States determined by the Plate Boundary Observatory geodetic instrumentation. SOURCE: McCaffrey et al. (2007). Reprinted with permission of John Wiley and Sons.

Box 2.4
Near Real-Time Analysis of Earthquakes and Volcanic Eruptions

With rapid growth of human population, society faces increasing exposure to catastrophic effects of earthquake faulting, tsunamis, and volcanic eruptions. As basic scientific investigations of these phenomena advance, a natural result is that observational and analytic procedures mature to the point where they can be robustly and rapidly applied, even while the event is under way. This exercise of scientific understanding can enable development of real-time hazard warning systems to society's great benefit, both from early warning of imminent shaking or tsunami arrivals and by providing guidance to effective post-event emergency response activities. While continuous environmental monitoring is typically the function of mission-driven agencies, development of the fundamental understanding on which real-time warning capabilities can be based involves NSF-funded research on natural phenomena.

Early warning systems rely on continuous acquisition of data from potential source regions, and real-time telemetry of the data or local analysis products for events as they occur to central processing centers where the signals enable near real-time evaluation of the process and its hazards, launching appropriate communications about the event and its potential distributed impact. For earthquakes and volcanic eruptions, such methodologies can exploit the finite velocity with which seismic, tsunami, or air-blast waves spread from the source relative to electronic communications to warn nearby regions before the waves arrive. Automated systems that sense initial signals can also activate immediate responses locally to mitigate the impact of later-arriving signals. These strategies are exemplified by ocean-scale tsunami warning systems, such as the National Oceanic and Atmospheric Administration's (NOAA) Pacific and Alaska Tsunami Warning Systems, and the Shinkansen (Japanese bullet train) accelerometer system for stopping trains when P wave ground motions exceed certain thresholds (in advance of later-arriving, stronger S wave and surface wave ground motions). The potential for many applications to mitigate shaking damage given from seconds to hours of lead time after occurrence of an event is just beginning to be explored.

Rapid analysis and warning of large earthquake ruptures can potentially be achieved with integrative approaches using geodetic (continuous, high-sample-rate GPS), seismic (rapid local network event location, mechanism, and finite faulting determination), and ocean measurements (water pressure and geodetic systems that detect tsunami waves offshore). Such applications are rapidly emerging, and over the next decade significant enhancements and impacts from these capabilities can be exploited. The Cascadia subduction zone is being instrumented onshore and offshore using EarthScope and American Recovery and Reconstruction Act funding. These regional seismic and geodetic networks within one venue of natural hazard exposure are valuable for advancing the basic science underlying rapid warning capabilities. Significant progress has been made in developing remote tsunami warning capabilities, but close-in tsunami warning, where warning response times of only tens of minutes are required, presents great challenges. This drives basic science efforts to establish what aspects of large offshore earthquakes can be reliably characterized in ground motion signals soon after an event initiates and the extent to which the ultimate size of the event can be anticipated early in its process. Similar challenges exist for developing rapid warning of volcanic eruptions that present hazards to air traffic. Development of seismic, geodetic, and infrasound analysis that can establish the occurrence of strong tropospheric and stratospheric blasts and ash clouds requires better understanding of explosive eruption processes and their manifestations.

Data from EAR facilities in seismology (IRIS), geodesy (UNAVCO), EarthScope, and community organizations (SCEC, GeoPRISMS) provide the means for coordinated efforts to rapidly analyze signals from active processes. Ultimately, monitoring and implementation of warning systems are the provenance of the USGS and/or NOAA (for Homeland Security), but developing and integrating the scientific approaches remain a basic science problem, as extensive fundamental understanding of the processes and the signals they generate lies at the core of all early warning strategies. Rapid analysis and quantification of earthquake and volcanic processes are also relevant to basic research on dynamic phenomena, especially as interactions between dynamical systems even at long ranges are now being broadly recognized.

Natural Laboratory Strategy

Research on faulting and deformation processes can be conducted over a wide range of efforts, spanning single-investigator theory and laboratory efforts to integrated field activities. It is essential to sustain the former, while the latter has become the focus of large-scale community efforts and NSF programs, exemplified by the SCEC, the Margins and Ridge initiatives, Continental Dynamics projects, and Earthscope. For the next decade several regions have been identified by GeoPRISMS as important natural field laboratories for coordinated efforts; these include Alaska and Cascadia, along with North Island, New Zealand. All of these present opportunities for increased involvement of EAR over the previous Margins program.

The Alaskan subduction zone provides a second natural laboratory to study fault zone processes. This zone is complex, with significant variations in geometry and locking and more frequent magnitude 7 to 8 earthquakes and volcanic eruptions than Cascadia (see Box 2.5). There is an existing GPS network (~150 stations) in Alaska, maintained by the Plate Boundary Observatory (PBO). The committee anticipates two significant and complementary research and instrumentation efforts in Alaska in the next decade. First, the EarthScope Transportable Array will arrive in Alaska in 2014 if the next phase of EarthScope operations is sustained, extensively increasing the on-land seismic network, which has been sparse relative to the huge tectonically active domain. Second, GeoPRISMS recently announced that the Alaskan subduction zone will be one of its primary scientific targets, which means that offshore seismic sensors will likely become available. The combination of seismic and geodetic instrumentation and the synergism with GeoPRISMS science objectives will allow unprecedented opportunities for fault zone earthquake and deformation studies. EAR collaboration with the NSF Division of Ocean Sciences (OCE) could ensure optimal usage of the scientific data collected in Alaska.

While natural laboratories in Cascadia, Alaska, and New Zealand present excellent opportunities for research on faulting processes, it is desirable to pursue an ultimate goal of instrumenting all accessible fault zones. Progress can be made by taking advantage of interdisciplinary collaborations. For example, EAR is co-sponsoring the installment of a 50-station GPS network in the Caribbean.[2] EAR's goals for this effort are to assess seismic hazards in the region. The NSF Division of Atmospheric and Geospace Sciences (AGS) is co-funding the network because the same GPS data can be used to help atmospheric scientists predict the intensification and direction of tropical storms and hurricanes. In addition to partnering within GEO and with other NSF directorates, EAR can continue collaborations to maintain networks with other government agencies that use seismic (USGS, DOE) and geodetic instrumentation (NASA, NOAA). Innovative uses of existing networks and

[2] See www.nsf.gov/news/news_summ.jsp?org=NSF&cntn_id=117808&preview=false.

facilities should be encouraged, including applications to hydrology and meteorology, to broaden the support base for these data collection efforts.

Box 2.5
Volcanic Systems

Volcanic eruptions provide spectacular and frequent (more than 70 different volcanoes erupt every year) reminders that Earth is a dynamic and evolving planet. Lava flows, pyroclastic flows, and ash fall are proximal hazards; gases and dust lofted into the atmosphere have global effects on climate, life, and air traffic. Volcanic hazard does not end with the eruption—lahars and landslides create hazards long after an eruption ends. Despite a long history of investigation, numerical models of volcanic processes, laboratory characterization of the properties of magmas, and real-time monitoring of active volcanoes are only now beginning to show their promise to both predict eruptions and quantitatively interpret volcanic deposits.

Volcanic eruptions are the end product of a complex set of interacting processes: melting Earth's interior, the storage and chemical evolution of magma, the ascent of magma through the crust, and the fragmentation of magma during explosive eruptions. Several key questions remain the subject of active research. Why do volcanoes erupt in so many different ways? Can the duration and style of eruption be predicted from pre-eruption signals? Why do supervolcanoes exist? Why do earthquakes sometime trigger volcanic eruptions? What processes govern the speed and distance traveled by pyroclastic flows?

Modern research in volcanology relies on integrating complementary approaches: remote sensing from space with InSAR and spectroradiometers; distributed high-frequency monitoring of GPS, tilt, seismic, infrasound, acoustic, and electromagnetic signals; gas sampling; measuring the rheological properties and phase equilibria of magmas in the lab; numerical simulations of conduit processes, the multiphase dynamics of eruption columns and pyroclastic flows, and the thermal and chemical evolution of magma within the crust. Additionally, large-scale laboratory experiments offer an important opportunity for validating the new generation of numerical models for conditions and properties that are well constrained. At the present time, NSF does not support either such large-scale laboratory facilities for community use or experimental facilities for studying magma properties at relevant deformation rates and temperatures.

Monitoring of volcanoes in the United States is performed by the USGS and its volcano observatories. NSF-supported research adds to these activities by supporting complementary principal investigator–led monitoring, theoretical work, and laboratory analyses. Partnerships and collaborations between NSF and other agencies, such as the USGS, may be vital for making full use of the data and addressing questions that are beyond the primary objective of hazard assessment. Support is also needed to rapidly respond to new eruptions and to ensure that instruments are available.

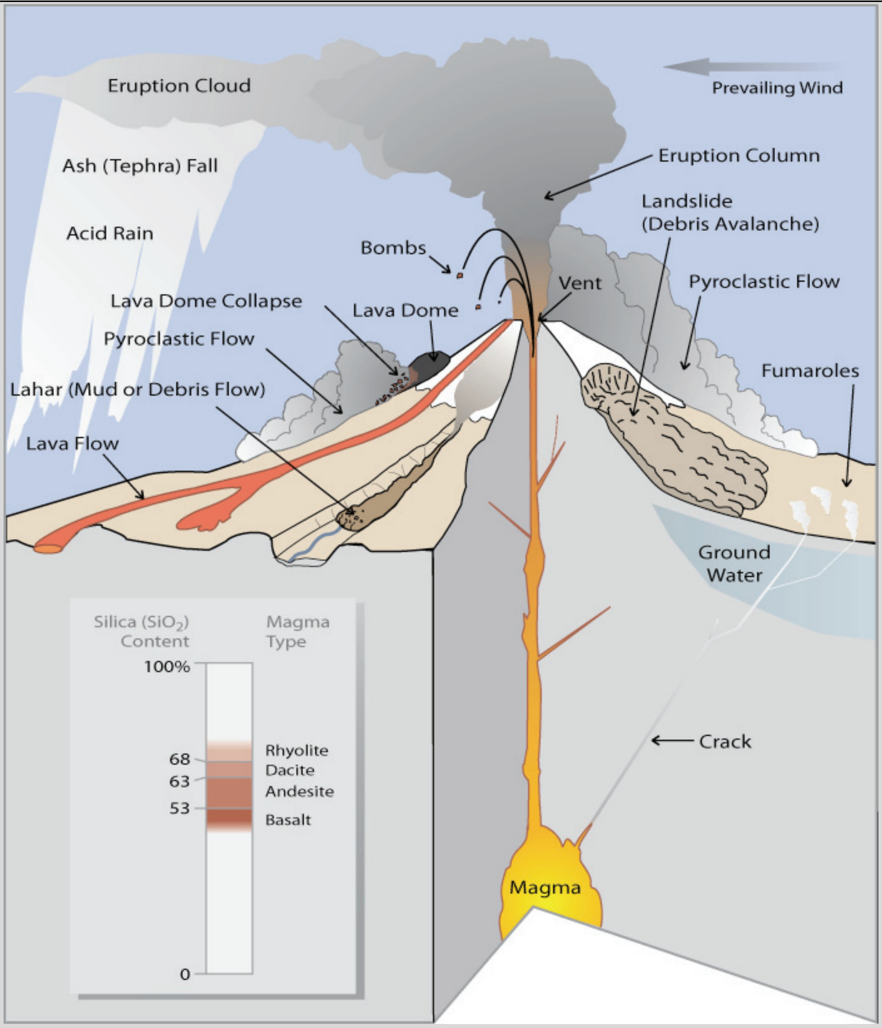


Figure B2.5 Some of the phenomena at volcanoes that transport mass and energy to the surface and create volcanic hazards. Modern volcanology seeks a quantitative understanding of these processes and their interactions. SOURCE: Myers et al. (2008).

INTERACTIONS AMONG CLIMATE, SURFACE PROCESSES, TECTONICS, AND DEEP EARTH PROCESSES

One of the major advances in the Earth sciences over the past decade was the recognition and verification of broad connections between climate, surface processes, and tectonics. The NRC *Landscapes on the Edge* (2010a) report identified research questions that center on interactions among climate, topography, hydrology and hydrogeology, physical and chemical denudation, sedimentary deposition, and rock deformation in tectonically active mountain belts as particularly intriguing. While the feedbacks between tectonics, climate, erosion, and deposition have been the focus of field studies and numerical simulations over the past decade, elucidating connections between these processes continues to drive discoveries. Such feedbacks influence the sensitivity of landscape response to climate change and involve numerous complex interactions among climatic, geological, and geomorphological processes. Our understanding of the dynamics of landscape evolution and the linkages between climate, Earth surface processes, and tectonics across a wide range of spatial and temporal scales is ripe for substantial advances now that the advent of thermochronometric methods provides data on erosion rates over geological timescales, cosmogenic methods for dating geomorphological surfaces have matured to the point of being readily accessible to researchers across the field, and high-quality digital topography (such as LiDAR) is increasingly available for regions around the world (see Figure 2.14).

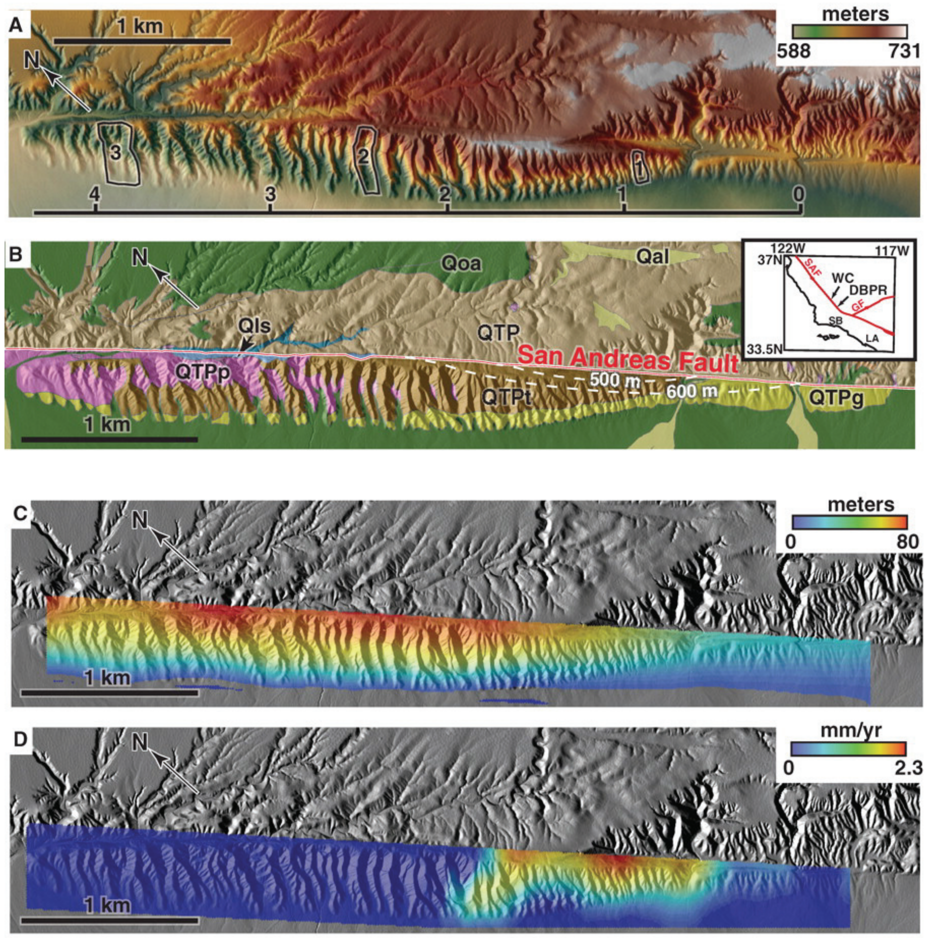


Figure 2.14 Combing LiDAR data with geological observations allows the response of erosional processes in small drainage basins to rock uplift to be determined for the first time in the field at a Dragon's Back pressure ridge along the San Andreas Fault. These types of detailed measurements were not possible prior to the advent of LiDAR mapping. (A) Airborne Laser Swath Mapping (ALSM) topography (1-m digital elevation model); (B) geology; (C) total rock uplift (~140 k.y.) inferred from distribution of geological contacts; and (D) instantaneous rock uplift rate. SOURCE: Reprinted from Hilley and Arrowsmith (2008) with permission of Geological Society of America. See original text for further explanation.

Development and elaboration of transport laws offer the potential to connect studies of active processes with their signatures in landscapes and the related sedimentary and climatic record. In addition, recent studies have highlighted the importance of regional context in sorting out controls on landscape development and evolution as competing theories are seen to have more or less explanatory power in different physiographic, tectonic, and climatic settings. For example, numerous studies have documented evidence for the operation of a so-called “glacial buzzsaw” through which efficient glacial erosion above the glacial equilibrium line altitude (ELA) limits the height of mountains (Brozović et al., 1997; Mitchell and Montgomery, 2006; Enghold et al., 2009). In contrast, glaciers in the southern Andes have the opposite effect and instead shield alpine topography from erosion and thereby enhance elevation (Thomson et al., 2010). Likewise, a recent study that reviewed global erosion rates found that, contrary to the often invoked conventional wisdom that glaciers are the most efficient erosional agents, erosion by rivers can keep up with glacial erosion in tectonically active mountain belts (see Figure 2.15). In some regions the landscape-scale pace of erosion is correlated with hillslope steepness (or local relief; Ahnert, 1970), whereas in others it is correlated with changes in river profile steepness (Wobus et al., 2003). Like these examples, many of the key controls on landscape evolution appear to have context-dependent aspects that present challenges—and opportunities—for developing integrated global understanding of the controls on landscape dynamics. Greater understanding is needed not only to identify fundamental controls on, and theory for, landscape evolution but also to understand how different circumstances and settings influence the driving forces or dominant factor(s) and how systems interact in different regional contexts. Only then can the range and limits to the applicability of theories and the strength and consequences of interactions among processes be known.

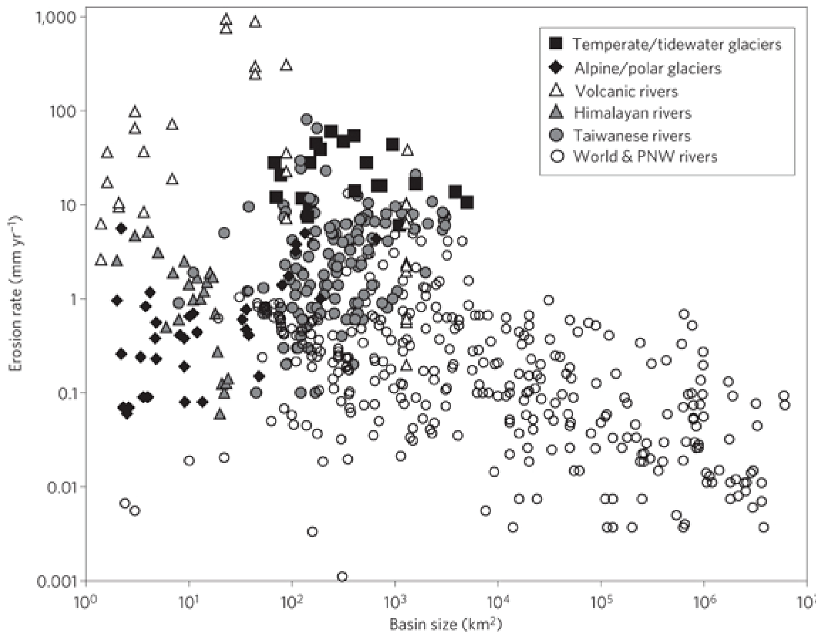


Figure 2.15 Relationship between glacial, fluvial, and composite landscape erosion rates and the contributing basin area, as measured by sediment yield data collected over a 20-year period. Black symbols refer to glaciated basins; gray and open symbols indicate river basins. PNW refers to river basins in the U.S. Pacific Northwest. SOURCE: Koppes and Montgomery (2009). Reprinted by permission from Macmillan Publishers Ltd.

To date, however, overarching theory has proven useful, and substantial progress has been achieved from studies of steady-state orogens. For example, recognition of the role of enhanced windward erosion and limited erosion on the leeward, rain-shadowed side of mountain ranges (e.g., Reiners et al., 2003) has confirmed predictions of modeling studies (e.g., Koons, 1990; Willett et al., 1993; Willett, 1999) and bolstered evidence of rock uplift and deformation patterns that matched the conceptual framework (e.g., Beaumont et al., 1996; Batt and Braun, 1999). Connections between climate, erosion, and the tectonically driven growth of orogenic wedges have been explored in coupled models (e.g., Whipple and Meade, 2004, 2006; Tomkin and Roe, 2007). Coupling of erosion, tectonic deformation, and patterns of rock uplift have also been explored at finer scales through the development of individual fold belts or geological structures (e.g., Wobus et al., 2003; Hilley et al., 2004; Simpson, 2004; Stolar et al., 2007). While there has been tremendous progress on such linkages, significant uncertainties and questions remain about the role of erosional processes on the dynamic development of geological structures in diverse tectonic settings.

Further elaboration and evaluation of such linkages and the implications for landscape response to tectonic and climatic perturbation offer tremendous research opportunities. In particular, key research opportunities include:

- The role of climate and tectonics in surface processes and landscape evolution;
- feedbacks and linkages between climate and surface processes with mountain building and decay, shoreline advance and retreat; and
- Linkages among climate, surface processes of erosion, transport, and sedimentation, and deep Earth lithospheric processes.

These linked research areas offer exciting new opportunities to broaden our understanding of the fundamental controls on Earth surface processes and their influences on the world's landscapes.

Role of Climate and Tectonics in Surface Processes and Landscape Evolution

While one could hardly imagine a more striking contrast than that between the slow evolution of hard, dense tectonic plates and the fluid, rapidly changing atmosphere, the connections between the climate and tectonic systems are far deeper and more subtle than commonly imagined (NRC, 2010a). Climate, tectonics, and erosion interact over timescales ranging from individual storm events or earthquakes to millions of years over the course of the evolution of a mountain range. The importance of climate and climate variability is central to understanding both the geomorphological impacts of shallow crustal processes over short timescales and how such processes integrate up over longer timescales to influence landscape evolution.

A quantitative, process-based understanding of the linkages among climate, hydrology, geomorphological processes, ecosystems, and landscape evolution is a primary goal of research on Earth surface processes. Fundamental to achieving this goal is the development of transport laws that mathematically characterize the controls on rates of processes shaping Earth's surface. While significant progress has been made in developing transport laws for a variety of processes (Dietrich et al., 2003), transport laws are still lacking for processes as fundamental as landslides, glacial erosion, and chemical erosion. In addition, the fundamental controls on one of the basic components of the rock cycle, the breakdown of rock into erodible debris, is poorly understood. The formulation of process laws allows quantification of the driving phenomena and thereby rigorous exploration of questions of sensitivity of landscape response to climate change and numerous feedbacks between climatic, hydrological, geological, and geomorphological processes.

The linkages among surface processes and climate with tectonics also have societal implications on human timescales in the role that sedimentation and erosion play in the distribution and rates of displacement of active faults. Landforms and sedimentary deposits preserve records of past earthquakes and deformation that are used to evaluate recurrence intervals for active faults and assessment of seismic hazard. Recent paleoseismological observations of migration of deformation between fault strands over thousands of years (Dolan et al., 2007) challenge traditional views of steady fault slip due to far-field plate motions, with important implications for seismic hazards, earthquake clustering, fault growth, and fault interactions.

Feedbacks and Linkages between Climate and Surface Processes with Mountain Building and Decay

The rugged topography of mountain environments reflects the interplay of spatially variable tectonic uplift and erosion. The consequences of rapid erosion in response to snowmelt, intense rainfall, or glacial dam-break floods are familiar to those living in mountain environments. Less widely appreciated is how rates and patterns of deformation in tectonically active mountain belts can be greatly influenced by the spatial distribution and pace of erosion by landslides, river incision, and glaciation (NRC, 2010a). Recent recognition of the strong coupling between erosion and surficial mass redistribution and deeper tectonic and structural deformation creates new opportunities for interdisciplinary research that bridge climate science, geomorphology, structural geology, and geophysics.

Precipitation and erosion induced by orogenic effects impact the distribution of deformation in mountain belts. Conversely, the size and distribution of high-elevation topography influence global, regional, and local climates (e.g., Meehl, 1992; Wu et al., 2007). While much of the work on climate-erosion linkages in the past decade has focused on steady-state landscapes, new research opportunities in transient responses of landscapes include the buildup and tearing down of mountains, the evolution of rift zones or volcanic arcs, and the role of climate variability (ranging in scale from glacial-interglacial periods to surface response to changes in storm frequency-magnitude relationships). The response of crustal-scale processes and feedback through climate linkages is central to understanding the controls on mountain building and decay and landscape response times to climatic changes and climate variability.

Erosional unloading and sediment loading of Earth's surface also influences the structural geology and rheology of the lower crust. While coupled tectonic-surface process models predict that the structural evolution of a mountain belt is sensitive to spatial and temporal variability in climate forcing (see Figure 2.16), the common assumptions that erosional efficiency increases linearly with precipitation, discharge, or stream power have not been demonstrated over orogenic timescales. Similarly, the role of lithological variability on long-term patterns of landscape evolution remains poorly constrained.

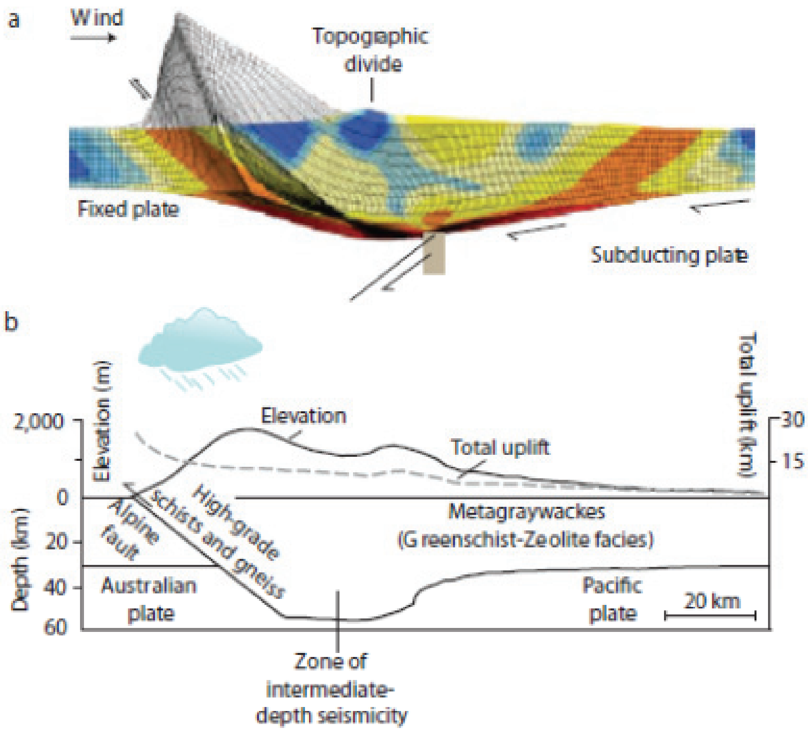


Figure 2.16 Example of unidirectional moisture flux and mountain-belt evolution. (a) Results of numerical model of the Southern Alps of New Zealand with moisture-laden winds arrive from the west (*left*). (b) The observed topography and pattern of total uplift in the Southern Alps closely match the numerical experiment shown in (a). SOURCE: Whipple (2009), modified by permission from Koons (1990). Courtesy of Macmillan Publishers Ltd.

Research opportunities under this theme also include the influence of the global distribution of topography on climate through, for example, how the location of mountain belts impacts larger-scale climate patterns. On the global scale and over geological timescales, the positions of the continents affect ocean circulation and global climate. A prominent example is the breakup of Antarctica and Australia and opening of the Drake Passage, which led to circumpolar circulation that isolated Antarctica from warmer low-latitude waters and is implicated in the cooling climate of the Cenozoic. Conversely, climate influences the deformation and structural evolution of mountain belts and the margins of continents. For example, Northern hemisphere glaciation in the late Cenozoic is linked to denudation and migration of deformation in the St. Elias range in Alaska (Berger et al., 2008; Chapman et al., 2008), with implications for mountain belts worldwide. In this research area of climate and orogenesis, empirical studies have lagged models. New observational studies are needed that integrate geomorphology with geochronological and geochemical studies to constrain timing and rates of uplift and erosion, with seismic imaging of sediment deposits adjoining mountain belts that record past conditions, and with structural geology and geophysical studies that target deeper crustal and mantle structure.

Linkages Between Climate, Surface Processes, and Deeper Earth Processes

Although it has long been recognized that lower crust and mantle processes can significantly influence landscape evolution, linkages between climate and deeper Earth processes remain largely unexplored. Climate and tectonics are fundamentally linked through the influence of sediment loading and erosion unloading on the state of stress in Earth's interior that in turn govern tectonic motions. For example, the development of large, high-elevation plateaus holds the potential for strong climate-tectonic feedbacks through rapid, localized incision on plateau margins that receive substantial precipitation. Such localized erosion creates the potential to advect hot, low-viscosity, mid-to-lower crustal rocks to the surface in either channel flow along laterally continuous belts or localized domal uplifts (e.g., Beaumont et al., 2001, 2004; Hodges et al., 2001; Koons et al., 2002; Zeitler et al., 2001). Rapid erosion in such settings can lead to a positive feedback by drawing up highly pressurized ductile rock toward the surface, resulting in isothermal decompression that may induce partial melting that further reduces viscosity and resistance to flow. Because deformation rates can respond to surface forcing with little time lag, the pace of surface erosion can drive long-term patterns of structural deformation. The response to climate variability of such tightly coupled erosion-tectonic systems has not been explored and presents an attractive opportunity for future research.

Other examples of deeper Earth response to erosion unloading and sediment loading of Earth's surface include the impact of sediment distribution on the distribution and magnitudes of subduction zone megathrust earthquakes, with important implications for the major human population centers located along subducting margins (e.g., Wells et al., 2003). Recent studies reveal linkages between climate and volcanic activity with increased volcanic activity during periods of deglaciation (e.g., Sigvaldason et al., 1992; Jellinek et al., 2004) that are attributed to enhanced decompression mantle melting due to glacial unloading (Jull and Mackenzie, 1996; MacLennan et al., 2002). Release of carbon dioxide associated with this enhanced subaerial volcanism during deglaciation may in turn play a significant role in modulating glacial/interglacial cycles (Huybers and Langmuir, 2009).

Global patterns of sea-level rise are directly linked to elastic deformation of the solid Earth and are another manifestation of the complex interactions between Earth's interior and surface. There is particular concern that accelerated melting in the modern warming world could lead to collapse of the West Antarctic Ice Sheet with meter-scale rises in sea level worldwide. Highly non-uniform sea-level rise is predicted with enhanced sea-level rise around North America as a result of the interplay between changes in gravity due to the redistribution of ice/water and rock, changes in Earth's rotation, and changes in shoreline geometry (see Figure 2.17).

In all of these research areas, significant opportunities exist for framing testable hypotheses to guide field studies of the interactions between climate and tectonics in landscape evolution. Of particular need are studies to evaluate temporal variability. Given the different timescales of climate variability and deep Earth processes, what are the sensitivities and lag times built into their interactions?

Several challenges and science objectives under the theme of climate-landscape-tectonics interactions are primed for significant advances:

- Developing theory for the interactions between climate, topography, land cover, and the deeper Earth interior at global, regional, and local scales.
- Integrating surface processes and deep Earth studies, including petrological and seismological studies, and the record of past surface environments, to explore connections between deep Earth processes and Earth surface dynamics.
- Developing geomorphic transport laws that account for climate and the role of biota to describe and quantify river and glacial incision; landslides; and the production, transport, and deposition of sediment.
- Measuring and modeling landscape evolution under diverse and varying climatic conditions, with an emphasis on identification of physiographic signatures of climate and climate variability, and evaluation of thresholds of landscape response and the limits of landscape resilience.
- Improvement of coupling between surface process and climate models, including incorporation of feedbacks and thresholds.

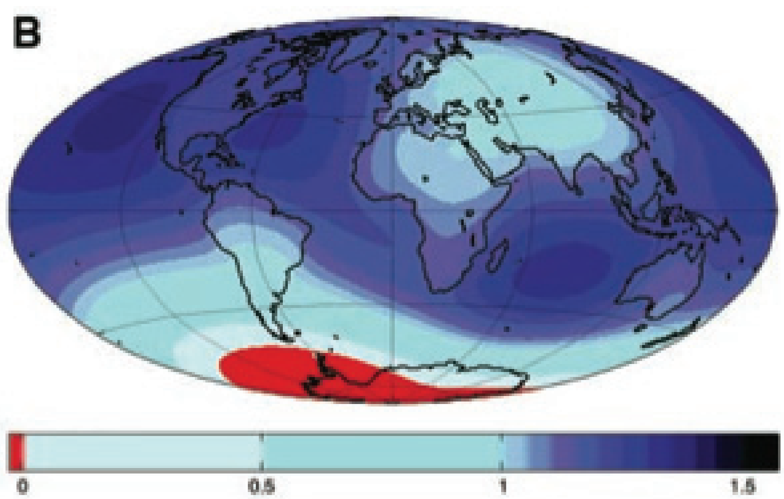


Figure 2.17 Predicted sea-level change in meters following the collapse of the West Antarctic Ice Sheet, based on theory that includes variations in ice and ocean volume, gravity, rotation, and shoreline configurations and deformation of the crust and mantle. SOURCE: From Mitrovica et al. (2009). Reprinted with permission from AAAS.

All of these promising research areas will be facilitated by recent and new developments in thermochronometry, cosmogenic methods for dating geomorphological surfaces, LiDAR, satellite imagery, modeling capabilities, experimental methods, and field instrumentation.

CO-EVOLUTION OF LIFE, ENVIRONMENT, AND CLIMATE

Earth is apparently unique in the Solar System in bearing living organisms that profoundly modify planetary processes affecting the composition and properties of the atmosphere, hydrosphere, and lithosphere. The geological record has provided a compelling narrative of major changes in Earth's climate, environment, and evolving life, played out over billions of years that has defined our planet's life-sustaining outer shell. These interactions continue to shape the world in which we live, and 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 the future, we need to know our geochemical and geobiological past.

Earth's environmental systems have experienced geochemical, climatic, and biotic change, with conditions in the distant past remarkably different from those of the Holocene epoch—the epoch when low and relatively stable atmospheric carbon dioxide and largely benign climatic conditions fostered human civilizations. Earth's deep-time record provides numerous unique analogs to the emerging climate state of dramatically warmer temperatures and highly elevated greenhouse gas contents in the atmosphere. 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 are both changes that reorganized element fluxes and concentrations in the ocean, sediments, and atmosphere on a global scale. Only the deep-time geological and paleontological record can provide examples of change that rival the scale of contemporary human-induced impacts on land, biota, oceans, and climate. Thus, understanding past biosphere-geosphere behavior is a potent approach to anticipating how linked physical, chemical, and biological processes that characterize Earth's surface may be impacted by and respond to human activity. Earth's biogeochemical history archived in the deep-time geological record thus provides a major research opportunity to investigate the future of our planet.

Understanding recent and ongoing climate change requires a full exploration of the range of climate phenomena, rates, feedbacks, thresholds, and tipping points captured over the long "experiment" of Earth history. Studies of the deep-time record have revealed that Earth's climate varies between two extremes. At one extreme is a cool, glaciated icehouse state associated with low greenhouse gas concentrations in the atmosphere and the state in which humans evolved, while at the other extreme is a warm greenhouse mode apparently associated with higher atmospheric greenhouse gas levels and small-to-no ice sheets (see Box 2.6). The geological archive has been particularly important for revealing how many physical, chemical, and biological processes operated differently or were unique to past warmer and transitional states than during the present cool state (NRC, 2011a).

Our ability to characterize and interpret the deep record has increased dramatically over the past decade and continues at an accelerating pace. New tracers (proxies) of past conditions have greatly refined our ability to extract ancient records of Earth surface conditions, including temperature, atmospheric levels of carbon dioxide, the chemical composition of and oxygen availability in the ocean, regional hydroclimate, and the interrelationship and physiologies of ancient life forms. These proxy records can now be placed in an ever more refined age context stemming from successfully coordinated efforts in the geochronological community (e.g., EARTHTIME) aimed at better, higher-resolution use of traditional methods; new and emerging techniques to accurately date nontraditional materials; and extension of orbitally tuned kilo-year-scale chronometers to the deep past. No longer is poor age control the bane of studies aimed at the past. Also, these diverse data can now be brought together into the interpretative framework of small- to large-scale numerical approaches ranging from geochemical box models to global climate models such as general circulation models (GCM; NRC, 2011a).

These advancements allow development and testing of process-based hypotheses, which in turn, are leading to major improvements in our understanding of the interplay of climate and life in molding and modulating one another. For example, mining of the geological record over the past several decades has documented feedbacks in the global climate system that appear unique to warmer conditions (e.g., the mid-Cretaceous and early Eocene; Kiehl, 2011; Zachos et al., 2001, 2008). Such mining has simultaneously revealed repeated periods of abrupt climate change that have, at times, led to accelerated warming, major change in regional hydroclimates, and major ecological disruption (e.g., the Paleocene-Eocene Thermal Maximum, or PETM; see Kennett and Stott, 1991; Zachos et al., 2001; Wing et al., 2005; Woodburne et al., 2009). A new coupling between highly resolved phylogeny reconstructions and the geochemical record of environmental change (see Box 2.7) is dramatically changing our understanding of the mechanisms behind Earth's largest biogeochemical transitions. Despite such advances, understanding Earth's spectrum of climate phenomena and the associated history of life at the temporal and spatial scales appropriate for testing specific hypotheses of mechanistic linkages and causation remains a significant challenge for nearly every major trend and event. The following discussion presents a set of deep-time research opportunities that, during the coming decade, are likely to lead to major advances in our understanding of variability in the geosphere and its interwoven interaction with the biota.

Box 2.6

CO_2-Climate Linkages Through Earth History

Warmer greenhouse conditions that have dominated Earth history have been typically associated with CO_2 levels in the atmosphere elevated over those of present-day carbon dioxide partial pressure (pCO_2; 392 ppmv) and those of cooler icehouse periods (see Figure B2.6, *top*). The widespread continental ice sheets of icehouse times have been rare during warm periods, with the exception of transient glaciations (e.g., Ordovician [~440 Ma]). The climate linkage between radiative forcing, Earth surface temperatures, and high-latitude continental glaciation is clearly delineated in the history of the buildup of the Antarctic and Northern Hemisphere ice sheets (see Figure B2.6, *bottom*). For example, the buildup of the East Antarctic Ice Sheet was initiated by the coupled effects of long-term decrease in atmospheric pCO_2 across a climate threshold and orbital climatic preconditioning (Pälike et al., 2006). During the Early Pliocene warming (3.5 to 3.2 Ma)—a time associated with CO_2 levels that may have been comparable to current levels (Pagani et al., 2010)—sea level was 15 to 25 m and possibly 36 m higher than at present day (Wardlaw and Quinn, 1991; Shackleton et al., 1995; Naish et al., 2009).

Such deep-time records also reveal how long-term (millennial timescale) and short-term (operating on a subcentury timescale) feedbacks have interacted to influence climate and sea-level dynamics under rising levels of atmospheric CO_2 and other greenhouse gases and provide insight into the duration over which elevated greenhouse gas levels have persisted in the atmosphere—both issues of direct societal relevance. For example, studies of long-term equilibrium sensitivity of surface temperatures to rising atmospheric CO_2 levels indicate temperature has been enhanced during times of higher atmospheric CO_2 due to the switching on of long-term positive feedbacks (Royer et al., 2007; Pagani et al., 2010). Feedbacks such as changes in ice sheet volume, distribution and composition of terrestrial biomes, and greenhouse gas release from soils, tundra, and ocean sediments typically operate on timescales much longer than that of humans and are projected to become increasingly more relevant on human timescales (decades) with continued global warming (Hansen and Sato, 2001; Hansen et al., 2008).

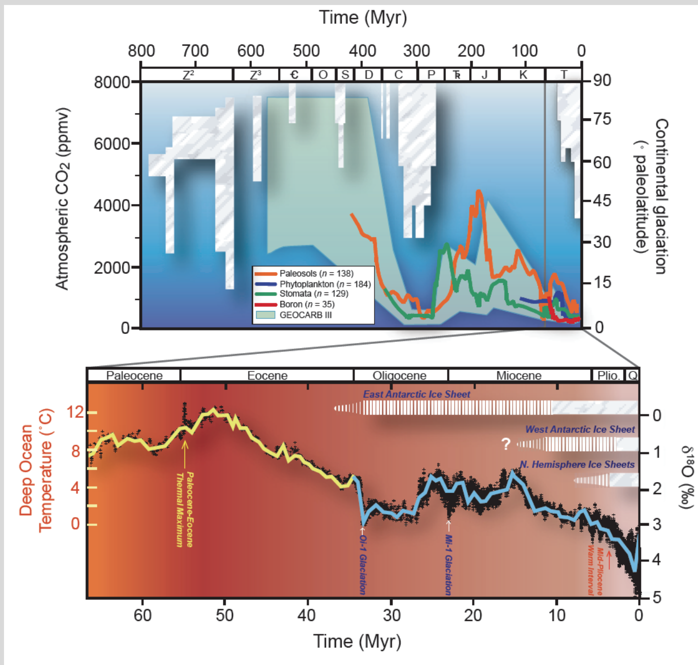


Figure B2.6 *Top:* Atmospheric pCO_2 and continental glaciation over the past 800 million years. Vertical white and gray bars indicate the timing and extent of continental ice sheets (after Crowley, 1998; Evans, 2000). CO_2 trends are inferred from mineral and biological proxies (see Royer, 2006, for details of compilation). Plausible ranges of CO_2 estimated using the GEOCARB III model are also plotted (Berner and Kothavala, 2001). All data have been adjusted to the Gradstein et al. (2004) timescale. *Bottom:* Global compilation of deep-sea benthic foraminifera ^{18}O isotope records from 40 Deep Sea Drilling Program (DSDP) and Ocean Drilling Program (ODP) sites (Zachos et al., 2001) updated with high-resolution records for the Eocene through Miocene intervals (Billups et al., 2002; Bohaty and Zachos, 2003; Lear et al., 2004). Much of the post-Oligocene $\delta^{18}O$ variability (~70 percent) reflects changes in Antarctic and Northern Hemisphere ice volume, which is represented by white and gray horizontal bars (e.g., Hambrey et al., 1991; Wise et al., 1991; Ehrmann and Mackensen, 1992). The dashed bars represent periods of ephemeral ice or ice sheets smaller than present, whereas the solid bars represent ice sheets of modern or greater size. The evolution and stability of the West Antarctic Ice Sheet (e.g., Lemasurier and Rocchi, 2005) remain uncertain and could affect estimates of future sea-level rise. SOURCE: Caption adapted from Jansen et al. (2007). Diagram courtesy of Linda Sohl and Mark Chandler.

How Have the Dynamics of the Global Climate System Varied in the Past?

Contemporary climate change can be better understood through exploration of the range of climate states, rates, feedbacks, and tipping points captured over Earth's history. The current glacial state provides an important baseline against which future climate change can be assessed. Understanding a world characterized by ice sheets at both poles and atmospheric carbon dioxide partial pressure (pCO_2) up to 30 percent less than present-day levels, however, captures only a small part of known climate variability. At current rates of concentration, by the year 2100 greenhouse gas concentrations will approach atmospheric values inferred for the greenhouse climates of the Paleogene (Kiehl, 2011; NRC, 2011a). Critical insights into how the Earth's systems have functioned in such a high CO_2 environment are archived in the records of past warm periods and major climate transitions. For example, deep-time studies reveal past periods of anomalous tropical and polar warmth that were associated with major changes in ocean and atmospheric circulation, including at times marine anoxia and acidification, and intensification of the hydrological cycle that included both increased rainfall in some areas and increased drought in others (e.g., Wilson and Norris, et al., 2001; Pagani et al., 2006). Consequences for marine and terrestrial ecosystems were dramatic. Intervals of abrupt climate change documented by the deep-time geological record—most notably, past hyperthermals—reveal how changes in greenhouse gas concentrations can abruptly and profoundly influence climate and life (Schaller et al., 2011; McElwain et al., 2005).

Deep-time geological records and the genomes of living organisms are also rich archives of Earth's deep-time history. Mineral and biological environmental indicators (proxies) record the interaction, feedbacks, and responses of physical, chemical, and biological processes under the full range that the Earth system has experienced (see Figure 2.18). A major challenge is to develop reliable proxy records of atmospheric gases, surface temperatures, precipitation, relative humidity, and marine and terrestrial productivity at a variety of temporal scales from millions to thousands of years to address the multiple scales at which the processes act. Opportunities for research exist in the development and calibration of new and existing proxies, the construction of precise and accurate long- and short-term proxy records at the requisite spatial and temporal resolution dictated by the hypotheses being tested, including next-generation paleoclimate-data and model-model comparisons.

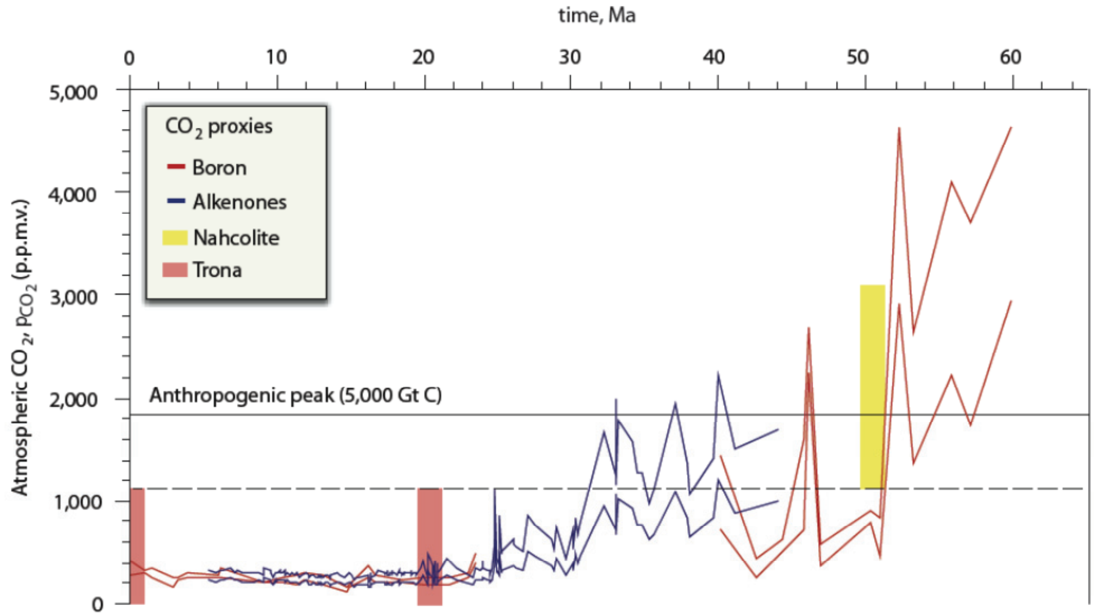


Figure 2.18 Cenozoic pCO_2 for the period 0 to 65 million years ago. Data are a compilation of marine (C isotopic composition of alkenone biomarkers and boron isotopic compositions of foraminifera) and lacustrine mineralogical records. The dashed horizontal line represents the maximum pCO_2 for the Neogene (Miocene to present) and the minimum pCO_2 for the early Eocene, as constrained by calculations of equilibrium with Na-CO_3 mineral phases (vertical bars, where the length of the bars indicates the range of pCO_2 over which the mineral phases are stable) that are found in Neogene and early Eocene lacustrine deposits (Lowenstein and Demicco, 2006). SOURCE: Zachos et al. (2008).

How Have Climate, Life, and Biogeochemical Cycling Interacted Through Time?

The deep-time geological record documents the magnitude over which the physical, chemical, and biological attributes of the ocean, continents, and atmosphere have varied over the history of Earth. There is little debate that microbial life and plant life have played a fundamental role in the evolving atmospheric concentrations of O_2 and CO_2, but the specifics of this interplay remain highly controversial. Tectonically driven changes in degassing and continental weathering are also fundamental, especially with respect to geologically transient but biologically devastating greenhouse gas increases such as during mass extinction and ecosystem reorganization events, notably those at the end-Permian, end-Triassic, Cretaceous-Paleogene, and PETM. However, it remains to be understood how new life forms changed the nature of elemental cycling (O, C, N, S), or how long-term changes in geochemical cycling have influenced the evolution of new life forms. Similarly, the oceans have fluctuated from periods of minimal oxygenation to conditions comparable to the well-ventilated ocean bodies of today. In addition to gradual, long-term shifts in baseline conditions, the oceans have at times experienced rapid perturbations that have led to transient states in ocean chemistry and circulation. These in turn have contributed to major climate change, ocean acidification and hypoxia, and consequent large-scale biotic impact.

In the tropics, integrated paleoclimate and paleoecology studies can address the fundamental question of how hot the tropics will become, and to what extent ocean chemistry will be perturbed, as atmospheric CO_2 continues to rise (NRC, 2011a). Such changes may have dire effects on tropical ecosystems, with the potential for severe declines in diversity over large areas. The penultimate deglaciation of the Late Paleozoic Ice Age is the only archival record of the tropical floral response to climate change associated with the end of a glacial epoch. How Arctic ecosystems will respond if sea ice disappears permanently—or if the Greenland ice sheet retreats significantly—can be examined though the lens of past warm periods, such as the mid-to-late Cretaceous and the early Cenozoic, when the Arctic was ice-free and supported lush rainforests, warm swamps with aquatic floating plants, and warm-water fauna.

The forcings that led to past oceanic perturbation, the rates of change and recovery, the importance of thresholds, and the connections between oceanic change and biological crises all require further investigation to be properly understood. Greatly improved dating, refinement and further development and calibration of proxy records of regional and global climate, and appropriately resolved databases will permit researchers to reconstruct past changes in Earth's surface environments, including the atmosphere, oceans, and soil systems, as well as greenhouse gas burdens (see Box 2.8). These reconstructions will permit characterization of past climates and will give insights into anthropogenic impacts. Furthermore, opportunities for new research arise from new techniques, allowing the interaction between organisms and the environment to be examined directly in living forms through molecular means and in deep time by integration of phylogenies with proxy records of environmental and climate change. This involves assessment of the origin of clades of organisms (both by phylogenetic and phylogenomic methods) and delineation of the nature of environmental feedbacks that may allow elucidation of the cause-and-effect conundrum of biotic evolution and major climate change. These connections resonate with anthropogenic effects in which the biological innovations that make humans what they are have clearly resulted in changes in carbon dioxide and other greenhouse gas concentrations, climate, and ecosystem function.

What are the Trends and Milestones in the Interaction and Co-evolution of Life and the Environment?

The deep time record has revealed events and trends of enormous magnitude and import well outside the scale of human experience. Some of these events have been the subject of long-standing inquiry, such as the origin of life, and others are relatively newly discovered, such as the bolide impact at the Cretaceous-Paleogene boundary. Opportunities exist for new research at the interface between mechanistic studies of biological processes such as proteomics, the discovery of new types of and spectacularly preserved fossils, and the application of highly accurate dating techniques linking disparate environments and processes.

A mechanistic understanding of the origin of life remains a vexing challenge and one of the great opportunities of this century. Recently, the exploration of extreme modern environments, such as hydrothermal vents, coupled with metagenomics (e.g., Grzymskia et al., 2008), phylogenomics (Delsuc et al., 2005), and proteomics (Gaucher et al., 2003), geochemical proxies (biomarkers) of various microbial groups, and analysis of the isotopic proxies of past environmental conditions has resulted not only in a better chronology of the major biotically mediated transformations of Earth but also provided a chronology of the evolutionary and physiological steps in the evolution of early life. Two surprising results from this work are (1) that our last universal common ancestor (LUCA) was plausibly a thermophile but not a hyperthermophile (Gaucher et al., 2008; Gouy and Chaussidon, 2008) in hydrothermal vents (Martin and Russell, 2007) and (2) while photosynthesis evolved very early, the early photosynthetic organisms did not produce oxygen (i.e., were anoxygenic).

Geochemists have made great progress in using the elemental and isotopic properties of ancient sediments to reconstruct the evolving redox state of the ocean and atmosphere. A decade ago Farquhar et al. (2000) established anomalous mass-independent fractionation of sulfur isotopes as the smoking gun for the near absence of O_2 in the atmosphere before the Great Oxidation Event 2.4 billion years ago. Now, frontiers for sulfur isotope approaches lie with recognition of specific microbial metabolisms in the very old record and their environmental implications (Johnston et al., 2008). Iron geochemistry calibrated in modern settings has become our most reliable inorganic fingerprint of local oxygen deficiency in the ancient ocean (Poulton and Canfield, 2005), while organic biomarkers further trace the co-evolution of life and the environment (Brocks et al., 2005). Other redox-sensitive elements, such as molybdenum, can provide a global picture of ocean oxygenation when viewed for their mass balance relationships (Scott et al., 2008) and even delineate times when biologically critical trace metals may have limited the evolutionary advance of life. At the same time, metal isotope systems, such as iron and molybdenum, are providing global perspectives on past ocean-atmosphere oxygen conditions as a backdrop to the early evolution of life (Johnson et al., 2008).

Complementary geochemical and genomic studies are informing our understanding of other major biogeochemically important paleobiological milestones. While there are too many to detail here, these milestones include the origin of animals in the late Proterozoic, the spread of grasslands and co-evolved grazers during the Neogene (Cerling, 1992; Bouchenak-Khelladi et al., 2009), and our own evolution (Feakins et al., 2005; Steiper and Young, 2006; NRC, 2010b). These examples are associated with major shifts in climate mode and variability and elemental cycling. The major challenge and opportunity is linking the evolutionary events with the environmental causes or consequences via tests of mechanistic hypotheses, and the tools to do this now exist.

What are the Patterns and Drivers in Extinction and Recovery?

The record of life on Earth is punctuated by a series of mass extinctions, including the so-called Big 5—Ordovician-Silurian, Late Devonian, end-Permian, end-Triassic, and Cretaceous-Paleogene (often called K-T)—as well as major biotic reorganization events such as the Paleocene-Eocene-Thermal Maximum (PETM). The committee's view of these extinctions and recovery has in the past been strongly dominated by records of taxonomic change (e.g., Raup and Sepkoski, 1984). But this is changing, with greater emphasis on other kinds of diversity that may have at least as much impact on function in ecosystems and the biosphere as a whole. Important approaches include analysis of morphological and physiological disparity, biotic provinciality, and the role of biodiversity in functional (and ecological) redundancy and ecosystem stability.

Box 2.7
Molecular Geobiology Data Revolution

Armed with modern capabilities in macromolecular sequencing, the structures and processes of entire microbial communities can now be characterized. New advances allow determination of tens of billions of bases per run, and this scale of capacity is jump-starting the field of environmental genomics. Genomic data derived from environmental RNA 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 to aid in feeding the world's growing population, providing novel approaches to managing Earth's resources and waste disposal and attenuating the impacts from human land use and climate change in the critical zone.

This emerging revolution offers unprecedented insight into the microbial communities that mediate Earth's elemental cycles. With our growing ability to identify the biological diversity of microbes irrespective of whether they can be cultivated, it can now be identified where these microbes are located in relation to each other and to Earth materials, and their activity and geochemical roles can be tracked over space and time. Never before has it been possible to obtain such information without having microbes in culture, and never before have so many data been collected. But this is just the tip of an immense "iceberg" in a data revolution that is beginning to show its full weight, as the "meta-omics" world (meta-genomics, proteomics, transcriptomics) becomes readily accessible. The availability of inexpensive sequencing has moved studies at the interface between geochemistry and molecular biology to a new level. Nearly limitless amounts of molecular (sequence) data can now be collected, allowing the genetic complement of nearly any environment to be seen nearly instantaneously. Billions of base pairs can be "harvested" and analyzed to provide a DNA snapshot of the biodiversity and gene diversity of an environment, while monitoring of RNA and protein expression provides new avenues for probing geobiological dynamics in near real time. From this perspective come unprecedented baselines and records of change in the face of recent environmental perturbation.

Accompanying these extraordinary opportunities is the reality that we still have a long way to go to realize the promises that new "omics" approaches hold for transforming the fields of geobiology and geochemistry. The explosion in sequencing has unveiled staggering genetic diversity, but these new vistas are matched by a widening gap between gene sequencing data and our understanding of the data's biochemical, ecological, and geochemical function. Much critical and fundamental work is needed, including (1) annotating and identifying new genes, (2) sorting out the implications of genetic diversity within microbial taxonomic units, and (3) filling the dearth of reference strains and genomes needed to test hypotheses generated via genomic and metagenomic approaches.

The sheer volume of data available at relatively low cost increasingly pushes analytical challenges into the realm of computer science—one of the major challenges of the next few years. Added to these computational challenges will be interfacing the omics data with geochemical/geological data—two data sets that are fundamentally different in terms of definition and quantification. Bringing the two fields together will ultimately allow each to make predictions about the other: omics approaches open entirely new avenues for probing geochemistry, while the geochemical community (organic and inorganic) can provide a rich context in which to understand molecular geomicrobiology. Integrating these communities has vast potential for transformative cross-disciplinary breakthroughs, including new advances at very fine temporal scales.

Among the emerging research questions and opportunities empowered by new computational, nanoscale, and DNA-based approaches are the following:

- What regulates cellular and subcellular agents in complex environmental systems?
- How does biodiversity relate to ecosystem function, stability, and resilience, and how does it respond to environmental perturbation and specifically climate change?
- What can the genetic record tell us about the history of life and its planetary habitat?
- How can we integrate genomics and the geological record to probe the emergence of metabolic processes and their impacts on the evolving geochemical states of Earth?

The deep-time record of past biotic turnovers and mass extinction events associated with warm periods (many associated with massive outgassing of carbon dioxide or methane), transient warmings, and major transitions between climate states offer an under-tapped repository from which unique insight can be obtained regarding patterns of ecosystem stress, the potential for ecological collapse, and mechanisms of ecosystem recovery (NRC, 2011a). Such periods of crisis naturally resonate with today's global warming and biotic crises. For example, the warm, low-pH, and low-oxygen ocean that will come with global warming was first experienced in the Phanerozoic and Proterozoic. It was linked to profound global climatic and biological instability. At least some Phanerozoic mass extinctions appear to be associated with a doubling to tripling of carbon dioxide concentrations that occurred over human timescales. Examples include those at the end-Triassic (McElwain et al., 1999; Schaller et al., 2011) or Cretaceous-Paleogene (Beerling et al., 2003) that were caused by massive volcanic eruptions or bolide impacts. Hot, rapidly weathering soils in the coming century have loose analogs in deglacial Permian paleosols (throughout the Pangaean paleotropics) and in the postglacial phase of Proterozoic glaciation (i.e., in the wake of the hypothesized "snowball Earth").

The recovery from mass extinction is more than just recovery of taxonomic diversity. The dynamics of recovery include coupled biological and geochemical feedbacks. They also include evolutionary responses such as rapid bursts of speciation in surviving clades, followed by increasing morphological disparity and biotic provinciality. The patterns of these different diversity changes are not well documented. However, they clearly have relevance to the present-day human-caused biodiversity crisis that appears to be causing a mass extinction that may be comparable in magnitude to the Big 5 of the Phaneozoic and perhaps larger in effect than the PETM.

How has the Global Climate System Operated under States Different from Today?

Studies of our current glacial state provide an important baseline against which future climate change can be assessed. This understanding of a world characterized by ice sheets at both poles and atmospheric $p\mathrm{CO_2}$ minimally 25 percent less than present-day levels, however, captures only a fraction of the known range of climate phenomena. Under the current rate of carbon emissions to the atmosphere, greenhouse gas contents and associated radiative forcing will, by the end of this century, reach levels that fall within the probable range of the last greenhouse period of the Paleogene and Cretaceous (see Box 2.6). Critical insights into how Earth's systems have functioned in such a high carbon dioxide environment are archived in the records of past warm periods and major climate transitions. For example, deep-time studies reveal past periods of anomalous tropical and polar warmth that were associated with major changes in ocean and atmospheric circulation, including at times marine anoxia and acidification, intensified hydrological cycling and regional drought, and consequent substantial impact on marine and terrestrial ecosystems. For many of these periods, the lack of thermostatic regulation reflects the absence of those negative feedbacks that have stabilized surface temperatures during the current icehouse climate system. These reconstructions further reveal how certain processes and positive feedbacks that typically operate on longer timescales—or not at all in glacial climates—can be accelerated under warmer conditions. Furthermore, intervals of abrupt climate change documented by the deep-time geological record—most notably, past hyperthermals of the early Cenozoic and the last greenhouse-icehouse transition of the Late Paleozoic—reveal the nonlinear dynamics associated with pushing the climate system through critical thresholds.

How does the Study of Interaction and Co-evolution of Life, Environment, and Climate Benefit Society in General?

According to a 2009 Gallup Poll, only 39 percent of the American public view evolution as the most reasonable explanation for the pattern of life on Earth, and there is a strong positive correspondence between acceptance of evolution and level of education (Newport, 2009). The United States ranks 33rd out of 34 developed countries in acceptance that species, including humans, evolved. According to the Pew Research Center (Kohut et al., 2009), only 57 percent of Americans accept the scientific evidence for atmospheric warming, down from 77 percent only two years earlier, and only 36 percent attribute global warming to the actions of humans. Many attribute contemporary change to natural cycles, such as sunspot activity, without any knowledge of the natural drivers, rates, patterns, possibilities, or consequences illuminated robustly by the short- and long-term records of Earth history.

The increasingly robust record of the co-evolution of life and the environment can be used to educate scientific and general populations about where Earth has been and where it might be heading. It is fair to conclude that NSF-EAR shoulders the responsibility of being the custodians of Earth history studies and the bridge to its future relevance. From a philosophical perspective, our understanding of geosphere-biosphere interactions in the past shapes our basic curiosity of where humans come from and our perception of human's role in the world.

Box 2.8
Proxies for Reconstructing Past Climates

Reconstructing past climates rests on our ability to indirectly infer temperature, precipitation, atmospheric greenhouse gas concentrations, and other environmental properties from sedimentary materials. The best-known proxy is $\delta^{18}O$ of biogenic $CaCO_3$ (in marine microfossils and animals), which has long been shown to reflect the combined effects of local temperature and global ice volume on seawater $\delta^{18}O$. More recently, oxygen isotope analysis of biogenic hydroxyapatite in marine and terrestrial fossils has been utilized as a proxy of seawater $\delta^{18}O$ and of continental mean annual temperatures, respectively (e.g., Fricke and Wing, 2004; Buggisch et al., 2008; Trotter et al., 2008). During the past decade, a variety of new proxies have been developed that have led to a major improvement in our ability to reconstruct past climates (summarized in *Understanding Earth's Deep Past* [NRC, 2011a]).

Despite the maturity of the stable isotope field, fundamentally new advances continue to be made—for example, by assessing the distribution or "clumping" of rare isotopes in minerals. Traditionally, the isotopic composition of a compound is determined by destroying the original structure of that compound and measuring the relative isotopic abundances of the bulk material. For example, $\delta^{13}C$ and $\delta^{18}O$ of calcite document the $^{13}C/^{12}C$ and $^{18}O/^{16}O$ ratios in the sample, retaining no record of how those isotopes were distributed. Recent advances that allow access to this distribution have ushered in a new and rich source of information contained in the stable isotopes. Most notably, Ghosh et al. (2006) showed that there is a temperature-dependent thermodynamic preference for heavy isotopes in calcite to share a bond—the lower the temperature, the stronger the preference for ^{13}C-^{18}O bonds compared to a completely random distribution. This discovery forms the basis of a completely new type of calcite paleothermometer. In particular, a measurement of the abundance of the $^{13}C\ \delta^{18}O\ ^{16}O$ variant of CO^2 evolved from calcite relative to the random distribution of isotopes, referred to as Δ47, can provide formation temperatures to a precision of $\pm 2^{\circ}C$. Importantly, unlike classical $\delta^{18}O$ calcite thermometry, this "clumped isotope thermometer" is independent of assumptions about the composition of water from which the calcite precipitated.

Recent work demonstrates that clumped isotopes accurately record paleotemperatures in a wide variety of marine biogenic carbonates (Came et al., 2007; Tripati et al., 2010), cave and soil carbonates (Affek et al, 2008; Passey et al., 2010), and carbonate-fluorapatite in vertebrate bones (Eagle et al., 2010). Ongoing work (e.g., Passey et al., 2011) reveals an apparent sensitivity of clumped isotopes in low-temperature precipitates to diagenesis requiring further calibration and assessment studies.

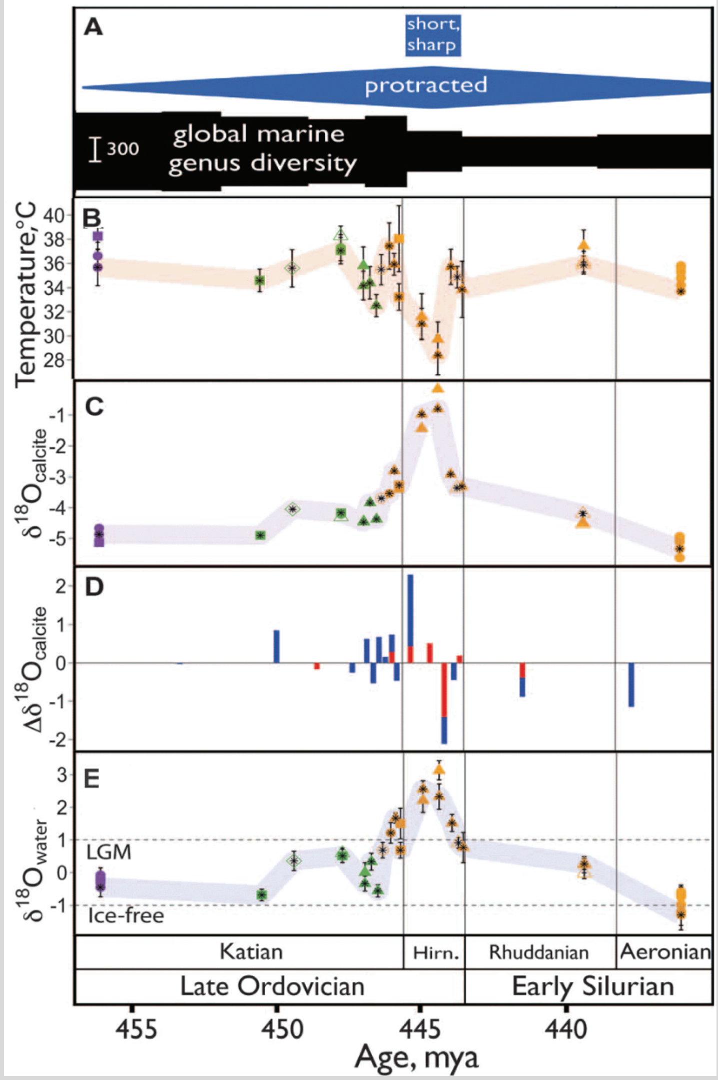


Figure B2.8 Magnitude and duration of Late Ordovician–Early Silurian glaciation based on carbonate "clumped" isotope paleothermometry (modified from Finnegan et al., 2011). (A) Hypotheses regarding the duration of the icehouse interval: restricted largely or entirely to the Hirnantian stage lasting as few as 500,000 years, with a peak in the Hirnantian interval. Both the beginning and the end of the Hirnantian stage saw a decrease in marine invertebrate genus diversity. (B) Δ47-derived near-surface ocean temperature trend for the early Katian to late Aeronian interval. (C) $\delta^{18}O$ (VPDB) trend over the same interval. (D) Relative contributions of temperature and $\delta^{18}O_{water}$ to changes in $\delta^{18}O$ ($\Delta\delta^{18}O$) between successive time intervals. Bars are scaled to the magnitude of $\delta^{18}O$, and color proportion is scaled to the relative contribution of temperature change (red) and change in the oxygen isotopic composition of seawater (blue) to $\Delta\delta^{18}O$. (E) $\delta^{18}O_{water}$ (VSMOW) trend. Dotted lines indicate $\delta^{18}O_{water}$ value during the Pleistocene LGM (10) and expected $\delta^{18}O_{water}$ value for an ice-free world. Various symbols and colors indicate various fossil organisms and locations. SOURCE: Finnegan et al. (2011).

COUPLED HYDROGEOMORPHIC-ECOSYSTEM RESPONSE TO NATURAL AND ANTHROPOGENIC CHANGE

The ways in which ecosystems and landscapes have co-evolved through time and the nature of their coupled responses to human activity and climate change present tremendous new opportunities for advancing our understanding of Earth surface processes as well as providing critical scientific input to managers tasked with finding solutions to problems associated with environmental change. This research opportunity differs from the later section on biogeochemical cycles in that its roots are more in geomorphology and materials cycling than geochemistry.

Coupled Landscape and Ecosystem Dynamics

Recognition of the magnitude of influence that hydro-geomorphological processes exert on ecological systems and ecological systems' influence on landscape processes and dynamics has opened up exciting new areas in the emerging fields of ecohydrology, ecogeomorphology, and geobiology. It is now widely documented that living systems influence the style and pace of surface processes and biogeochemical cycling and that disturbance regimes influence ecosystem trajectories and dynamics. The full scope and breadth of these linkages, however, are only beginning to be understood, in part because of the bi-directional nature of such feedbacks.

Over relatively short timescales, understanding the response of landscapes and ecosystems to disturbance requires explicit consideration of their interactions. Landslides, overgrazing, and flooding are just a few examples of disturbances in which geomorphic, hydrological, and ecological processes are inextricably coupled. Consider, for example, flooding. Vegetation on hill slopes and stream banks plays an important role in regulating the delivery of water and sediment to stream channels at the same time that overbank transport of water and sediment regulates the soil and nutrient conditions for vegetation in riparian zones and floodplains. While natural disturbances have always been an important driver of landscape and ecosystem co-evolution, humans have, in many cases, altered the frequency, intensity, and impact of disturbances. Returning to the example of flooding, through activities such as deforestation, agriculture, installation of dams and levees, and increasing nutrient and contaminant loads in runoff and streamflow, humans have modified stream and floodplain morphology, hydrology, and ecology, often in ways never anticipated and often with the effect of exacerbating the magnitude, frequency, and damage associated with floods. In a time when humans are rapidly becoming the dominant change agent, human-environmental interactions can no longer be ignored in the quest for a unified model of the Earth surface system.

A similar coupling of landscapes and ecosystems is evident on the longer timescales of climate change, particularly in rapidly changing, marginal environments like wetlands, permafrost, and desert margins. Salt marshes, for example, can become unstable when they are flooded too frequently, a potential consequence of sea-level rise. The existence of salt marshes is dependent on an adequate sediment supply and the presence of intertidal vegetation, such as *Spartina alterniflora* on western Atlantic coasts. Vegetation slows water flow, promotes sediment deposition, and inhibits erosion. Sediment deposition, along with organic matter accumulation, supplies nutrients and maintains the marsh platform at elevations beneficial for primary biological production. These feedbacks result in rates of vertical marsh accretion close to rates of contemporary sea-level rise, provided a sufficient supply of sediment and undisturbed vegetation. The likely response of marshes to accelerated sea-level rise is a complex eco-hydro-geomorphological question currently receiving considerable attention.

In the context of a changing climate, it is particularly important to understand why some regions of Earth's surface are relatively resilient to change, whereas others are not. It is reasonable to assume that long-term trends of warming temperatures will result in fundamental alterations to polar, glacial, and periglacial landscapes and ecosystems, but at what point are these changes irreversible? More frequent climate extremes are also among the expected manifestations of climate change. Drought, for example, poses severe challenges with regard to food and water resources as well as soil erosion. Yet there are regions of Earth that are able to support annual and perennial plant growth despite low water availability. In these and other landscapes, understanding the factors and processes governing landscape resilience, and in particular the nature of feedbacks and thresholds in system response that may fundamentally alter landscape and ecosystem characteristics, processes, and dynamics are essential for forecasting and interpreting landscape change. Research opportunities for such issues are found in the records of past environmental and landscape change, in studies of contemporary processes, and in model simulations of future scenarios.

Research at the intersections of geomorphology, hydrology, and ecology is providing new insight into the mechanisms of landscape-ecosystem interactions and co-evolution. For example, Roering et al. (2010) have brought an ecogeomorphic perspective to questions related to rates of soil formation in forested landscapes. Soil covers can only be maintained if rates of soil production equal or exceed rates of soil erosion. Roering et al. found that large volumes of bedrock were incorporated into the roots of large coniferous trees (>0.5 m diameter) overturned during storms in the Oregon Coast Range. They suggest that the penetration of deep root systems into bedrock is important in initiating soil formation processes (see Figure 2.19), which in turn helps maintain the mineral-rich soils that support coniferous forest ecosystems in temperate, active tectonic settings like the Pacific Northwest. In drier climates with sparse vegetation, Owen et al. (2011) have shown that bedrock erosion becomes more sensitive to precipitation.

The rapid growth in the field of ecohydrology is providing a theoretical framework and new, testable hypotheses to explain complex ecosystem dynamics and patterns (D'Odorico et al., 2010b). The dominant landscape control on most terrestrial vegetation is soil moisture through its effects on transpiration and photosynthesis. Soil moisture variations are regulated by external factors like topography and soil composition, as well as feedbacks with vegetation, microbial communities, and animal activities, including burrowing and grazing. Landforms and their associated surface-water and groundwater flows also play essential roles in structuring biotic communities. Stream networks, for example, enhance connectivity across the landscape and provide preferential pathways for transport of water, nutrients, sediment, and propagules.

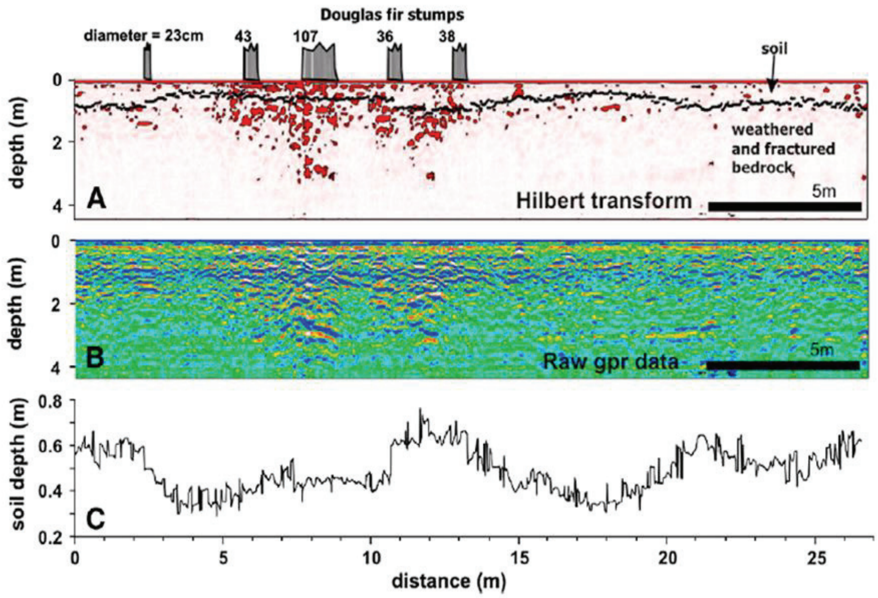


Figure 2.19 Profile of (A) filtered and transformed and (B) unprocessed ground-penetrating radar data for a hilltop in the Hadsall Creek catchment in the Oregon Coast Range. The locations of Douglas fir stumps within 1 m of the profile, and their diameters, are shown in (A). (C) Soil depth estimated from the radar data. SOURCE: Roering et al. (2010).

Changes in land use and climate can modify precipitation, runoff, and soil moisture, favoring some species over others, leading to shifts in plant, animal, and microbial composition. Examples include shifts from vegetated to bare soil during periods of extended drought and establishment of water-intolerant species following the drainage of wetland soils. These changes can, in turn, affect water and biogeochemical cycling. For example, draining and drying of wetlands can increase soil respiration and convert wetlands into a source of carbon, fueling further increases in greenhouse gas emissions (Strack and Waddington, 2007). Feedbacks among hydrological and geomorphological processes and biotic communities can allow some species to live in otherwise unfavorable conditions (e.g., water-intolerant plants in wetland environments) or the existence of alternative stable states (e.g., desert and savanna; see Figure 2.20). Improved observations and models of soil moisture variability and its feedbacks with landforms and ecosystems are needed to understand the role of landscape and hydrological change in biodiversity, species invasions, and shifts in plant functional types.

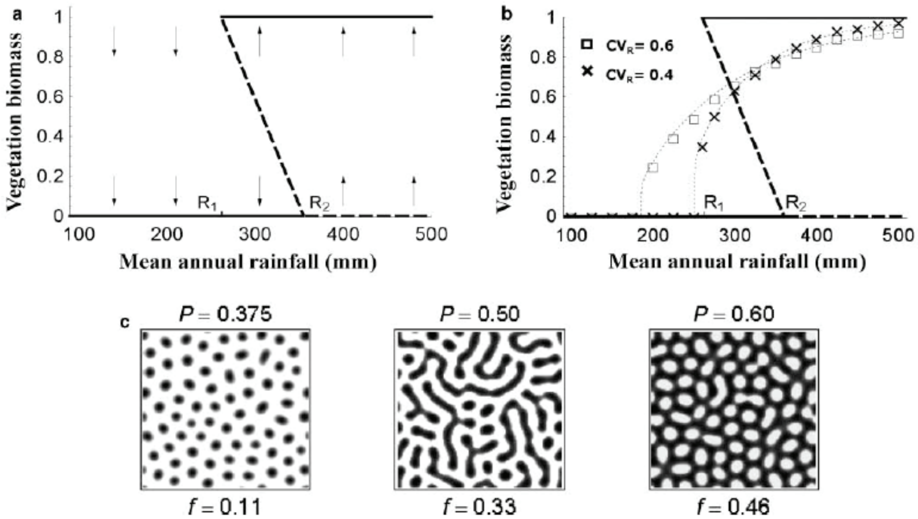


Figure 2.20 Illustration of the effects on soil moisture–vegetation feedback on vegetation patterns in a dryland ecosystem. (a) and (b) Alternate stable states (solid lines) and unstable states (dashed lines) of vegetation biomass; R is annual rainfall in millimeters, and arrows indicate convergence toward a stable state. The thin lines in (b) show stable states under randomly varying rainfall conditions characterized by the indicated coefficients of variation (CV). (c) Noise-induced patterns of vegetation cover (*f* = fraction covered) for varying precipitation conditions (*P* is the probability of no water stress). Vegetation patterning occurs at intermediate precipitation conditions when stressed and unstressed states alternate but not for lower or higher values of *P*. SOURCE: D'Odorico et al. (2010b).

Role of Humans in Landscape Change

Recognition that people are now one of the dominant forces shaping Earth's surface has opened new areas in the study of recent (i.e., historical) environmental records and in forecasting the effects of future population growth and development on environmental systems and landscapes. There is growing societal recognition that the geomorphological impacts of human land use have shaped ancient societies and continue to do so today, from the role of marsh destruction in exacerbating hurricane impacts on coastal cities to the erosion of the soil in which food is grown.

In many parts of the world, society's reaction to landscape disturbance is an engineered response: dams and levees to mitigate floods; groins and breakwaters to slow coastal erosion; various forms of hill slope stabilization to limit landslides; and more recently, restoration of rivers and wetlands that have been impaired by human activities. The frequent failure of these interventions to accomplish their goals and/or the unintended consequences of these engineered solutions highlight the critical need for better scientific understanding of the underlying processes and ability to predict the success and impacts of proposed solutions. The National Center for Earth-Surface Dynamics (NCED), an NSF Science and Technology Center, hosted at the University of Minnesota, is developing leading advances in the science and practice of stream restoration by conducting and coordinating research directed toward multidisciplinary quantitative prediction and development of improved tools to transfer this knowledge into practice (see Figure 2.21). Similarly, the USGS Grand Canyon Monitoring and Research Center and the Glen Canyon Adaptive Management Program have been spearheading high-resolution data collection and state-of-the-art model development to determine if planned water releases from Glen Canyon Dam designed to mimic natural seasonal flooding can be used to improve downstream resources in Grand Canyon National Park.

A key challenge in designing sustainable land uses, from forestry to urban drainage systems, is how to develop regional understanding of landscape history, processes, and change due to both human activity and climate change (past and future). The geography, geomorphology, and ecology of specific landscapes hold the key to understanding human influences on landscapes and therefore are central to correctly diagnosing ecosystem condition and designing effective mitigation, restoration, or adaptation techniques. In this sense the history and effects of land use in different regions could be considered as individual experiments to be probed in the search for deeper, more general, understanding. Similarly, carefully monitored restoration efforts offer case studies that can be used to test and improve quantitative models of landscape evolution. These models, in turn, suggest gaps in our understanding of the underlying processes and critical observations needed to move forward. When observations and modeling go hand in hand, rapid progress can be made in our ability to understand past change and predict future landscape response to restoration activities and other change. Such studies are important because the restoration of rivers, wetlands, and deltas is already a major enterprise, and there is a compelling need for Earth scientists to contribute to developing and evaluating methods, strategies, and insights into how to efficiently proceed in many environments.

Figure 2.21 The Outdoor StreamLab (OSL) facility at the National Center for Earth Surface Dynamics (NCED), located on the banks of the Mississippi River at the University of Minnesota, is dedicated to stream restoration research. OSL uses an abandoned flood bypass channel near St. Anthony Falls to study interactions among river channels, floodplains, and vegetation. Dams and bridge piers can be added to the OSL channel to investigate human-river interactions. SOURCE: Available at www.nced.umn.edu/content/outdoor-streamlab-osl. Courtesy of the University of Minnesota.

For these problems and many more, it is crucial to develop mechanistic models of the influence(s) of human actions on landscapes and ecosystems. The NSF-funded Community Surface Dynamics Modeling System (CSDMS) was launched in 2004 to provide the cyber-infrastructure and protocols for coupling and running a suite of numerical models representing diverse processes and scales across Earth's surface, with the goal of facilitating exploration of surface response to environmental change. CSDMS is moving toward its goal of providing a user-contributed, modular, open-source modeling environment capable of significantly advancing fundamental Earth system science. Investigators are utilizing the CSDMS modeling framework to address proof-of-concept challenges, such as dynamic coupling of fluvial and coastal processes and their evolution over time.

A critical gap in most surface process models is explicit consideration of the role of humans. Some hydrological models have accounted for such influences as the impact of humans on the flux of terrestrial sediment to the global coastal ocean (e.g., Syvitski et al., 2005); however, few have attempted to account for the active role of humans in landscape change. McNamara and Werner (2008) found that interactions of humans and surface processes might best be exhibited at intermediate timescales (years to decades). They constructed a coupled barrier island-resort model to explore emergent instabilities in the landscape induced by human behavior. Resorts and barrier islands are linked through potential resort damage by storm over wash and flooding and the resulting efforts to limit physical and economic damage through site location and size and to maximize revenue by renting many rooms at a relatively high price. Using an agent-based model of human activity coupled with a physically based model for barrier island elevation and evolution, McNamara and Werner concluded that developed barrier islands are lower lying and farther offshore than undeveloped islands, that island vulnerability increases when property is insured, and that protection measures at best postpone widespread damage. This research demonstrates the high social value of coupled mechanistic agent-based models.

Coastal Landscape Response to Sea-Level Rise and Natural and Anthropogenic Disturbance

Located at the interface between land and sea, coastal systems are particularly sensitive to changes in climate and land use because they are subject to forcings from both ocean and land processes. Climate change effects are pronounced in all coastal regions from the tropics to the poles and include accelerated sea-level rise; ocean acidification; and changes in temperature, precipitation, and storm frequency. Both urbanization and agricultural intensification in coastal watersheds lead to landscape change, including loss of habitat, nutrient buffers, and protective barriers (islands, dunes, wetlands) as well as eutrophication effects, including low-oxygen dead zones, harmful algal blooms, and fisheries' losses. With most of the world's major cities and more than 60 percent of the world's population living near the coast, these changes can be expected to have profound societal and economic consequences globally. Yet our understanding of the impacts of climate and human-induced change on coastal systems is not well developed due in part to the lack of a large, integrated coastal research program.

Coastal environments are strongly influenced by the landscape-ecosystem-human interactions discussed earlier. Close coupling of geomorphic, hydrological, ecological, climatic, and biogeochemical processes shape modern coastal landscapes and dictate their sensitivity and resilience to short-term disturbance events and longer-term trends in climate, land use, and sea level. Changing climate and land use affect coastal systems at multiple spatial and temporal scales. Understanding the effects of these external drivers as well as the interactions and feedbacks among landscape units and processes demands a unifying ecomorphodynamic framework for investigating these complex systems. Studies of specific coastal environments (e.g., barrier islands, marshes, coral reefs, mangroves, seagrasses, estuaries) and their linkages are necessary to understand impacts at regional and global scales.

Coastal systems face accelerated change associated with climate and land-use change. At high latitudes, coastal erosion is increasing in response to warming temperatures, sea-level rise, increasing storminess, and decreasing sea-ice extent (e.g., Jones et al., 2009). The thawing of coastal permafrost, with associated decomposition, is likely to result in the release of large amounts of stored carbon to the atmosphere and major ecosystem changes (Schuur et al., 2008). At mid-latitudes there is growing concern about wetlands loss and flood risk with rising sea level, changes in storm magnitude and frequency, and increased temperatures and population pressure. Nicholls et al. (1999) estimated that sea-level rise alone could lead to a loss of almost a quarter of the world's coastal wetlands by 2080; accounting for added human impacts could increase the losses to 70 percent. However, accounting for feedbacks among inundation, primary production, and accretion of organic and inorganic material on marshes suggests that marsh surface elevations may be able to keep pace with rates of sea-level rise on the low end of future projections if sufficient sediment is available. Marsh erosion rates on the high end of projections are likely to eliminate most existing marshes in this century (Kirwan et al., 2010). At lower latitudes, mangroves and coral reefs offer critical protection from storm-produced erosion to the coastal areas they fringe, and mangroves face many of the same threats as salt marshes, and coral reef systems are even more endangered. Coral reefs are part of the coastal marine ecosystem and are adversely impacted by nutrients, pollution, and sediment from terrestrial runoff (Hoegh-Guldberg et al., 2007). Globally, trapping of sediment in reservoirs and channeling of river flows by levees and other structures has significantly reduced the natural supply of terrestrial sediment to the coastal zone, resulting in sinking deltas and eroding coastlines (Syvitski et al., 2009). Barrier island systems, which make up close to 10 percent of the continental coastlines, are also highly vulnerable to the impacts of climate change and human disturbance (see Figure 2.22).

The history of human modification of coastal environments extends back at least several thousand years (e.g., Stanley and Warne, 1993; Weinstein et al., 2007), including drainage of wetlands, dredging of channels, damming of rivers, mining of sand, and coastal constructions designed to reduce wave energy and shoreline erosion. History has shown that these kinds of modifications tend to increase the vulnerability of coastal environments to catastrophic flooding and storm damage, such as was witnessed during Hurricane Katrina on the Gulf Coast of the United States. Despite the susceptibility of coastal systems to climate change, human activities are likely to be the dominant impact on coastal systems for the foreseeable future (Weinstein et al., 2007; McNamara and Werner, 2008; Kirwan et al., 2010).

Given the high value of coastal systems, both economic and environmental, it is imperative that more effective strategies be found for coastal restoration, stabilization, and adaptation. This requires an investment in fundamental science to develop a far greater understanding of the interactions and feedbacks among hydrodynamics, morphodynamics, ecosystem response, mitigation strategies, human agency, and economic valuation than is presently available. For example, beach stabilization by sand addition (beach nourishment) may have significant negative impacts on beach ecosystems, but neither the monitoring nor the understanding of the underlying physical and biological processes is adequate to evaluate the long-term risks associated with this practice (Peterson and Bishop, 2005). This lack of understanding extends to the full range of coastal environments and includes such fundamental questions as the degree and nature of coastal protection offered by mangroves, wetlands, reefs, and dunes (Barbier et al., 2008; Valiela and Fox, 2008; Feagin et al., 2009, 2010; see Figure 2.22). Several recent studies have attempted to couple models of ecogeomorphological processes with economic models (e.g., McNamara and Werner, 2008); to identify strategies for moving toward a more rational assessment of, for example, the minimum level of landscape stability needed for human occupation of coastal environments (Feagin et al., 2010); and to consider the role of human adaptation in scenarios of future coastal change (Nicholls and Cazanave, 2010).

Technical and methodological advances are also shedding new light on coastal processes. Methods that were in their infancy a decade ago, such as Acoustic Doppler Current Profilers (ADCPs), have matured to the point where they are now available as off-the-shelf technology. Near-shore currents were previously measured at discreet points that were interpolated and modeled to infer the flow field. The advent of ADCPs allows true three-dimensional flow fields to be measured for the first time and is leading to significant advances in coastal science. These technical advances and coupled ecogeomorphological-economic models represent first steps in what must be a transdisciplinary effort among scientists studying coastal processes and ecosystems, engineers, economists, and other social scientists to address the pressing problems facing coastal environments. Advances in coastal sciences would be accelerated by a dedicated NSF initiative that integrates physical, chemical, and biological processes with human activities and their interconnections across coastal watersheds, into the coastal zone, and beyond to the near-shore zone. This effort will necessarily involve several GEO divisions but is most naturally led by EAR because the majority of processes in question are solid-earth processes.

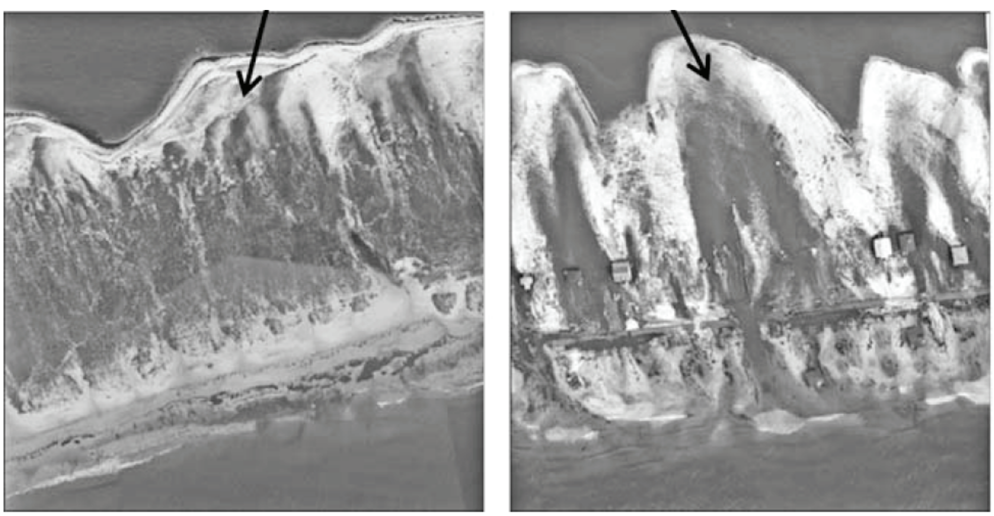


Figure 2.22 Aerial photo comparison of developed (*right images*) and undeveloped (*left images*) sections of a barrier island response to Hurricane Katrina. While areas on Dauphin Island, Alabama, covered by native vegetation (*left*) appear to have been less impacted by overwash than developed areas (*right*) during Hurricane Katrina, Feagin et al. question whether the decrease in erosion and overwash was due to the direct effects of vegetation cover or to the presence of higher coastal dunes that was indirectly built through vegetation interactions with wind-blown sediment transport processes. As noted by Feagin et al., the answer has important management implications. SOURCE: Feagin et al. (2010).

BIOGEOCHEMICAL AND WATER CYCLES IN TERRESTRIAL ENVIRONMENTS AND IMPACTS OF GLOBAL CHANGE

Human land use, climate change, and energy demand are transforming geochemical and geobiological systems and, in particular, the cycling of water, carbon, and nitrogen in these settings. Humans are now managing and altering 50 percent of Earth's land surface—dubbed the "critical zone" in the *Basic Research Opportunities in Earth Science* report (NRC, 2001)—and, in so doing, are transforming the physical, chemical, and biological states and feedbacks among essential components of the Earth surface system. Over the past century, soil erosion rates have accelerated; metals and toxins have enriched and mobilized far beyond natural rates; agriculture has industrialized the nitrogen cycle; freshwater usage has grown to exceed recharge in major population centers; and natural ecosystems have been heavily overprinted by fragmentation, extinction, global-scale biogeographic shifts, and invasive species. At the same time, atmospheric temperature and carbon dioxide levels have increased, impacting carbon storage in the terrestrial environment, the water cycle, and a range of intertwined biogeochemical cycles and atmospheric properties that feed back on climate and ecosystems (terrestrial and marine). This research opportunity differs from the earlier section on hydrogeomorphic-ecosystem response in that its roots are more in geochemistry than geomorphology.

EAR is poised to play a leadership role in comprehensive, uniquely integrated studies of the terrestrial environment in the face of human activity and climate change. This work spans diverse programs within EAR and more broadly across diverse divisions and directorates within NSF and other governmental agencies, such as the USGS and DOE. An existing suite of observatories provide insight into Earth's ecosystems and related dynamics. These natural laboratories include the NSF Critical Zone Observatory (CZO) and Long Term Ecological Research (LTER) programs and those within the National Ecological Observatory Network (NEON) and the Free-Air Carbon Dioxide Enrichment (FACE) program of the DOE. The EarthScope facility also shows potential for providing data needed for ecosystem and water cycle studies through indirect measurements of soil moisture and snow cover from the EarthScope GPS network. These programs are alike in their prioritization of integrated science, and now, increasingly, these complementary programs are philosophically and collaboratively bound together by common goals focused on common questions about terrestrial ecosystems impacted under human influence and climate change.

Integrated Soil, Water, and Biogeochemical Dynamics in the Critical Zone

The dynamics of the critical zone—the dynamic interface between the solid Earth and its fluid envelopes (NRC, 2001)—are governed by the interplay between hydrological, geomorphic, biogeochemical, and biotic processes that transform and rearrange materials in the Earth surface environment. Plant growth, for example, affects surficial weathering and hill slope form through bioturbation, fracture formation, alteration of hydrological fluxes, soil carbon dioxide generation, and profusion of organic weathering reagents. We are not yet able to weave these and other individual processes into a predictive conceptual model of critical zone evolution. This limitation is primarily due to incomplete knowledge of couplings between the physical, chemical, and biological processes in the critical zone, including both positive and negative feedbacks and their distribution in time and space.

An example of processes not adequately understood at present literally lies beneath our feet. We lack observation and theory of the weathering front (the interface between regolith and bedrock) that strongly influences processes in the critical zone. Coupled with the rapid development of soil ecology as a distinct discipline over the past several decades, this sets the stage for significant advances in our understanding of how life above ground and life below ground are adapted to each other and to spatially variable, hydrogeomorphic processes. The thin layer of weathered rock and soil that mantles Earth's surface offers exceptional opportunities for research on both fundamental processes shaping landscapes and applied issues related to the geobiological basis for soil fertility. Chemical weathering and erosion of bedrock and soil influence climate, river and groundwater chemistry, bedrock erodibility, and ecosystem properties. Despite the fundamental importance of soil formation and fertility for life on Earth's surface, soils and the breakdown of rock to form soil remain among the least understood areas of the Earth sciences. Quantifying the controls on rates of rock breakdown to form soils is needed to understand the processes of soil formation and how they vary in different landscapes, climates, and tectonic regimes.

Interdisciplinary studies of the critical zone are yielding new ideas about the interactions of weathering, erosion, and biology in the critical zone. These include hypotheses concerning the evolution of the critical zone, such as that in relatively stable landscapes where biology drives weathering in the initial stages of plant establishment while weathering drives biology over the long term (Brantley et al., 2011). This work also suggests that future land use change may impact critical zone processes more than climate change and that restoration efforts are likely to restore hydrological functions on shorter timescales (decades or less) than biogeochemical functions and biodiversity (Brantley et al., 2011).

A substantial investment in *in situ* environmental sensors, field instruments, geochemical tools, remote sensing, surface and subsurface imaging, and development of new technologies will be required to test these hypotheses. For example, geochemists now possess powerful tools that permit the characterization of fundamental processes and elemental, molecular, and isotopic properties at scales from submicroscopic to planetary, fueled in part by tremendous advances at the nanoscale and in computational and instrumental toolkits. Among these advances are abilities to date processes in the critical zone at increasingly fine resolution using cosmogenic and uranium series isotope systems.

Two interdisciplinary techniques currently supported by EAR also show significant promise. First, geodetic techniques are increasingly being used to measure changes in the components of the water cycle. Long-term and seasonal subsidence can be observed via Global Positioning Systems (GPS) and Interferometric Synthetic Aperture Radar (InSAR), providing important constraints on groundwater depletion due to withdrawals for irrigation and municipal use. Gravity data measured using satellites are being used to monitor changes in water storage at the basin-scale that cannot be observed using any other technique (Famiglietti et al., 2011). Second, GPS receivers in the EarthScope Plate Boundary Observatory (PBO) are being used to measure critical environmental parameters such as soil moisture, snow depth, biomass changes, and glacier retreat. These data are valuable to both climate scientists and water managers for drought and flood prediction. These PBO studies demonstrate how infrastructure developed for geophysical studies can simultaneously be used for water cycle studies funded through the hydrological sciences within EAR, the Division of Atmospheric and Geospace Sciences (AGS), and non-GEO directorates such as the Directorate for Biological Sciences (BIO) and the Office of Polar Programs (OPP).

The payoffs of such investments in data acquisition are potentially enormous if the fluxes of energy, water, and materials within and through the critical zone can be resolved and if fundamental insight can be provided into ecosystem and landscape evolution and resilience. The data sets and understanding developed through such measurements will form the basis for coupled systems models that allow study of interactions and feedbacks between biological and physical processes in the critical zone through assimilation of hydrological, meteorological, biogeochemical, and geomicrobiological measurements.

Quantitative estimation of watershed carbon balance provides a compelling example. Findings from the late 1980s to mid-1990s indicating that only ~30 percent of the carbon dioxide released by fossil fuel burning stayed in the atmosphere, with ocean uptake accounting for an additional ~30 percent, launched a stampede of terrestrial ecosystem and surface Earth scientists to every biome on Earth to look for the missing sink for the remaining 40 percent. However, after 15 years of effort, a consensus has yet to emerge regarding the spatial distribution of, or the processes responsible for, the 2 to 4 Pg C y^{-1} continental sink of the 1990s (Solomon et al., 2007)—or the observation that continents were likely a net carbon source in the 2000s. One roadblock is that net ecosystem production (NEP) measured at local scales does not often extrapolate well to larger scales (Ometto et al., 2005; Stephens et al., 2007), very possibly due to lack of consideration of lateral export (Chapin et al., 2006; Lovett et al., 2006) and the details of spatial and temporal variability. The importance of full watershed-scale carbon balances is illustrated by the one published study that accounted for both vertical carbon fluxes (via eddy covariance tower) and lateral carbon exports via streams, demonstrating that Net Ecosystem Exchange (NEE) went from a net sink of 0.278 Mg C ha^{-1} yr^{-1} to a net source of 0.083 Mg C ha^{-1} yr^{-1} when lateral stream fluxes were accounted for (Aufdenkampe et al., 2011).

The integrated watershed studies needed to advance our understanding of the critical zone is a distinctive feature of the CZO framework and their multidisciplinary science teams. CZOs provide essential data sets and a coordinated community of researchers who integrate hydrological, ecological, geochemical, and geomorphic processes from mineral grain to watershed scales to illuminate the rich complexity of interactions between the lithosphere, the pedosphere, the hydrosphere, the biosphere, and the atmosphere. CZO sites are establishing infrastructure for the intensive data-gathering effort required to support their science teams and the conceptual and mathematical models they develop (see Box 2.9). The development of more diverse observatory sites could facilitate comparison and sensitivity studies that might then serve with reasonable confidence in a broader predictive mode across non-observatory sites.

Box 2.9
Critical Zone Observatories

The Critical Zone concept, introduced in the 2001 NRC report *Basic Research Opportunities in Earth Science*, provides a research framework for the portion of Earth most closely linked to society and terrestrial life. A network of Critical Zone Observatories (CZOs) is being established to capitalize on this new research framework by providing locations and funding mechanisms for integrated, multidisciplinary research. Five observatories are located in the continental United States and a sixth is in Puerto Rico, and each is in a different representative landscape. This CZO network is connected to an international network through collaboration with a parallel effort in the European Union, and data and infrastructure are open to all researchers. Past studies of the Critical Zone rarely were able to conduct long-term monitoring efforts. Establishing semi-permanent observatories is allowing long-term studies to be conducted and has the potential to fill large gaps in our knowledge of Critical Zone systems. Because human agency plays such a large role in nearly every system of the Critical Zone, the traditional Earth science objective of constructing a universal model cannot be accomplished without including the influence of human activities. This is an evolution in thinking for conventional Earth sciences, but it holds promise of transformative discoveries that will be both useful to society and add value to the larger corpus of Earth science understanding. The CZO network is designed to be the mechanism for making those discoveries.

Responses and Feedbacks of Carbon, Nitrogen, and Water Cycles to Climate Change

Each year about 120 Pg of carbon is exchanged between the atmosphere and terrestrial ecosystems through photosynthesis and respiration. This is more than an order of magnitude larger than estimates of exchange directly due to human activities (8.7 Pg C/year from fossil fuel combustion and 1.2 P C/year associated with land use change in 2008; Le Quéré et al., 2009). As a result, global changes in sources and sinks of carbon due to climate change could be at least as important to global carbon cycles as the total of all direct anthropogenic fluxes. Indirectly, humans have and continue to be an important agent of past and future climate change, primarily through fossil fuel burning. Identification of carbon sources and sinks requires studies at landscape and regional scales, whereas most research to date on carbon cycling has been at global (e.g., GCM simulations) or local (e.g., flux tower) scales.

Environments in which climate change could trigger relatively rapid vegetation and landscape change, such as permafrost areas and wetlands, are of particular concern to regional and global carbon exchange. For example, there are 23×10^6 km^2 of ice-rich permafrost in the northern hemisphere, more than a third of which could be actively thawing by 2100, according to model projections (Grosse et al., 2011). An estimated 1,600 Pg C is stored in the top 3 m of ground in northern hemisphere permafrost regions (see Figure 2.23). Thawing of permafrost and associated microbial decomposition of organic carbon have the potential to transfer large quantities of carbon to the atmosphere, with estimates in the range of 50 to 100 Pg by 2100 (Schuur et al., 2008). However, assessments of the vulnerability and resilience of permafrost to warming and thawing, as well as potential carbon losses, are complicated by positive and negative feedbacks among snow cover, vegetation, soil, active layer properties, and surface water and groundwater (Grosse et al., 2011). Thawing of permafrost is also likely to produce rapid landscape degradation, including development of thermokarst, accelerated coastal erosion, channel network expansion, and mass wasting (Rowland et al., 2010). Improved understanding of the impacts of climate change on carbon, soil, ecosystem, and landscape dynamics in permafrost regions will require coordinated observation and modeling efforts by multidisciplinary teams of scientists.

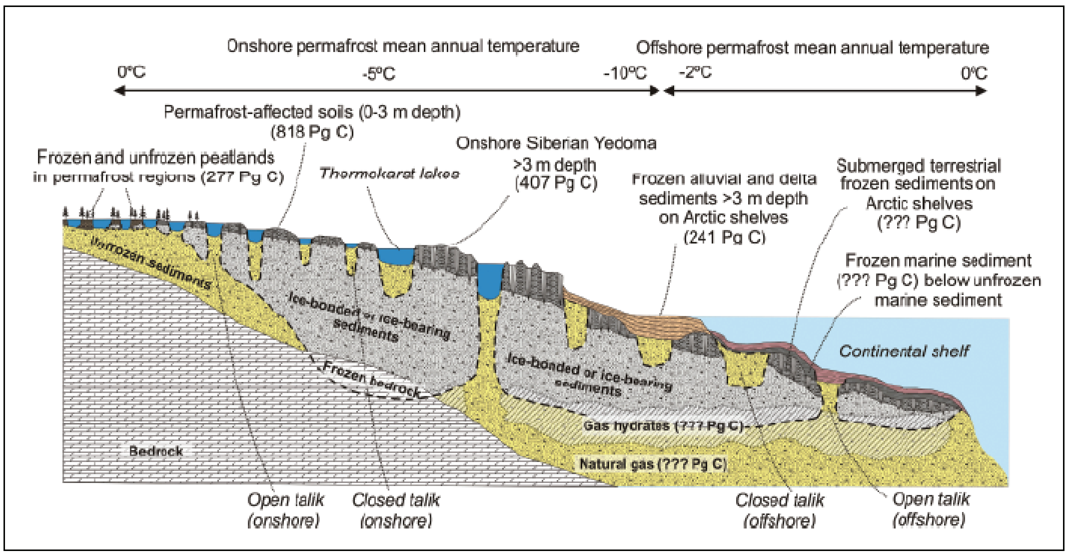


Figure 2.23 Idealized cross section through northern permafrost regions indicating significant known and assumed carbon pools, including estimated carbon storage in petagrams (Pg C) for the terrestrial and marine portions of the permafrost system. SOURCE: Grosse et al. (2011).

The elemental stoichiometry wired into living organisms guarantees that the carbon cycle is coupled with those of nitrogen and phosphorus, while processes such as biological nitrogen fixation link nitrogen cycles to those of other elements, such as iron (e.g., Finzi et al., 2011). Carbon, nitrogen, and other elemental cycles respond variously to changes in temperature and precipitation, and their coupling creates a complex system of interactions and feedbacks among elemental cycles, ecosystems, and climate. The coupling between carbon and nitrogen cycles and climate change is one aspect of this system currently receiving considerable attention owing to uncertainties as to whether feedbacks between nitrogen and carbon cycles will act to buffer or amplify the response of Earth's climate to continued anthropogenic carbon dioxide flux to the atmosphere.

The terrestrial nitrogen cycle has been dramatically accelerated by industrial production of reactive nitrogen for use as fertilizer, as well as by combustion of fossil fuels and cultivation of legumes. These three anthropogenic sources of nitrogen are estimated to have added more nitrogen (187 Tg N/year in 2005; Galloway et al., 2008) into the terrestrial environment during the past few decades than natural sources (110 Tg N/year; see Figure 2.24; Gruber and Galloway, 2008). In addition, anthropogenic emissions of nitrous oxide (N_2O, a greenhouse gas) directly contribute to stratospheric ozone depletion and tropospheric N_2O accumulation (Ravishankara et al., 2009), while emissions of nitrogen oxides (NO_x) indirectly contribute to tropospheric ozone and aerosol formation (Arneth et al., 2010).

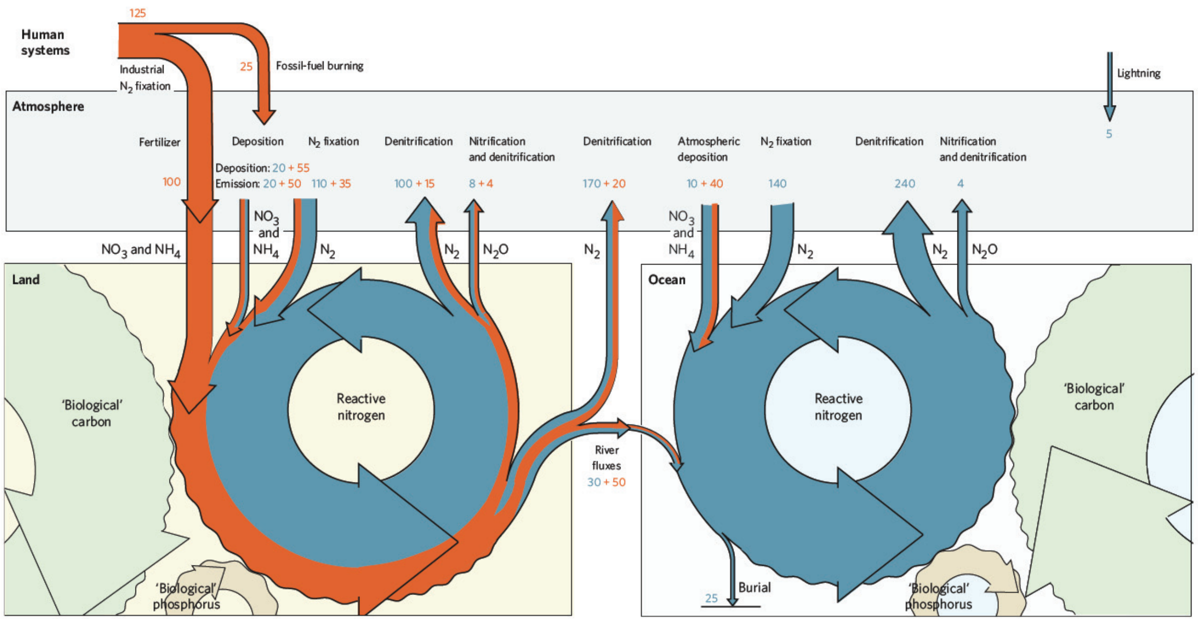


Figure 2.24 Natural (blue) and anthropogenic (orange) nitrogen fluxes for the terrestrial (*left*) and marine (*right*) nitrogen cycles. Illustrates major sources, sinks, and processes associated with production of reactive nitrogen and the coupling of the nitrogen cycles with those of carbon and phosphorus. Values are for the 1990s in Tg N/year. SOURCE: Gruber and Galloway (2008). Reprinted by permission from Macmillan Publishers Ltd.

Understanding how all of this additional nitrogen will affect climate, terrestrial ecosystems, and carbon cycling is essential as we attempt to anticipate future environmental change and possible mitigation strategies. For example, recent modeling studies indicate that nitrogen feedbacks represent an important control on changes in terrestrial carbon storage driven by increases in atmospheric carbon dioxide, though the nature of this control varies between tropical, temperate, and high-latitude ecosystems and the magnitude of the effect remains uncertain (e.g., Zaehle et al., 2010). Nitrogen-related changes in carbon storage feed back into climate by regulating atmospheric carbon dioxide levels. In addition, any changes in the C:N ratio of terrestrial plants and/or changes in rates or the geographic distribution of biological nitrogen fixation and denitrification would alter regional and global carbon cycles (Gruber and Galloway, 2008). Redistribution of nitrogen, carbon, and other elements in terrestrial systems by runoff, land-atmosphere exchange, and other surface processes connects the biogeochemical cycles operating in soil-based, freshwater, and marine systems. Quantifying changes in the water cycle associated with climate change is therefore a critical element of building an understanding of future changes in biogeochemical cycles.

Reconstruction of the monthly discharge of the largest rivers by Labat et al. (2004) indicates that global continental runoff increased during the 20th century. Changes in runoff have been linked to changes in precipitation, evapotranspiration, and land use. Modeling of the relative contributions of precipitation, temperature, carbon dioxide concentration, land cover, and land use to increases in river discharge in the 20th century indicates that increases in precipitation are the dominant driver of global increases in discharge (Gerten et al., 2008). Precipitation is expected to increase with increasing temperature, though the rate of increase may be moderated by the influence of tropospheric greenhouse gas forcing and black carbon aerosols on precipitation (e.g., Frieler et al., 2011). Land use practices also contribute to increases in discharge, particularly in watersheds characterized by extensive agriculture or deforestation. For example, there is a strong correlation between agricultural land cover in the Mississippi River basin and increased discharge under average precipitation conditions, with agricultural land use accounting for more of the increase in Mississippi River discharge in the past 50 years than do increases in precipitation (Raymond et al., 2008). This agriculturally enhanced runoff can carry high concentrations of nitrogen, phosphorus, and carbon (in the form of bicarbonate) that impact the biogeochemistry of the receiving rivers and downstream marine systems.

The role of climate-related changes in evapotranspiration in the intensification of the water cycle is more challenging to sort out, in part because of feedbacks between evapotranspiration and soil moisture. Elevated atmospheric carbon dioxide has been tied to decreases in stomatal conductance (e.g., Leakey et al., 2009), which could lead to decreased evapotranspiration and increased soil moisture (e.g., Gedney et al., 2006). However, several lines of hydrological evidence (water balance estimates, lysimeter and pan evaporation measurements, length of growing season) point to an increase in evapotranspiration in temperate regions over the past 50 years (Huntington, 2008). These results suggest that, at present, the effects of higher temperatures are generally able to offset the effects of increased carbon dioxide on evapotranspiration, though their relative effects are likely to vary geographically and may change with future changes in climate and land cover.

While there are relatively long and spatially distributed records of runoff and precipitation, fundamental hydrological parameters like soil moisture and evapotranspiration are difficult to measure and, for the most part, existing data are temporally and spatially sparse. To advance the science, measurements at points on the landscape (e.g., from networks of flux towers) will have to be integrated smoothly with areally distributed estimates derived from remote sensing (e.g., satellite measurements of soil moisture). All these measurements will have to be coordinated through new data assimilation methods with new theory appropriate for landscape and regional scales. These and other new approaches to quantifying essential hydrological parameters are necessary to resolve spatial and temporal trends in the water cycle and related biogeochemical cycles caused by climate change as well as by land use change and other human impacts.

Human Impacts on Water, Carbon, and Nitrogen Cycles

Humans have altered the terrestrial water cycle through activities like reservoir construction, agriculture, groundwater extraction, and urbanization. Over half (52 percent) of the world's largest rivers are regulated by dams, including 85 percent of the most biogeographically diverse large river systems (systems that span five or more biomes; Nilsson et al., 2005). Regulation and fragmentation of rivers by dams also strongly impact sediment storage and the discharge of terrestrial sediment to the coastal ocean. While surface freshwater resources exceed global water demand at present, variations in water availability and demand in time and place result in regions of high water stress. In these water-stressed regions, groundwater withdrawal often exceeds recharge, with recent estimates suggesting that groundwater depletion (withdrawal in excess of recharge) has more than doubled since the 1960s (Wada et al., 2010). Virtual trade of water used in the production of goods or services is likely to become increasingly important in supporting human populations in water-stressed regions, especially during drought, but may also facilitate unsupportable population growth in regions of water scarcity (D'Odorico et al., 2010a). Accurate assessments of water availability, water demand, and sustainable water use require more complete global hydrological data sets, compilations of operational data regarding water use, and advances in modeling coupled with hydrological and socioeconomic systems.

Because of the centrality of the carbon cycle to climate, it is critical that the effects of human activities on the carbon cycle be quantified, that the response of the carbon cycle to disturbance be determined, that potential future impacts on carbon cycling and carbon pools (e.g., ocean acidification and methane dynamics) be evaluated, and that possible mitigation strategies be considered (Canadell et al., 2010). The potential for rising atmospheric carbon dioxide levels to significantly impact climate, ecosystems, and human populations has given rise to a variety of ideas for slowing rates of future increases in atmospheric carbon dioxide, ranging from energy-saving measures and use of renewable energy sources to schemes for increasing terrestrial and marine carbon storage (Gussow et al., 2010). Proposed engineered approaches to reducing atmospheric carbon dioxide include ocean iron fertilization, large-scale forestation using nonnative species and injection of carbon dioxide in deep-sea sediments and aquifers. Geoengineering proposals for carbon storage can involve substantial risks, possible unintended consequences, and potentially limited benefit (Bala, 2009; Finzi, 2011). Both the American Meteorological Society (AMS) and the American Geophysical Union (AGU) have adopted position statements on geoengineering that recommend further research on the intended and unintended Earth system response to geoengineering proposals and coordinated, interdisciplinary study of the relevant scientific, social, legal, and ethical issues (AMS, 2009; AGU, 2009).

Humans have also significantly impacted other biogeochemical cycles. As noted above, industrial production of fertilizer, fossil fuel combustion, and cultivation of legumes are currently adding more new reactive nitrogen to the environment than natural terrestrial processes. Impacts of reactive nitrogen on the environment are exacerbated by its cascading effect as it moves through the environment, such that each molecule of nitrogen can contribute to multiple environmental problems. Future population increases, and improvements in standards of living, will likely add to this anthropogenic nitrogen load through growing use of energy, additional demand for food production, and improvements in diet. Policies and practices for nitrogen use must balance the excesses and inefficiencies associated with nitrogen use in much of the developed world with the need for food in other parts of the world (Galloway et al., 2008).

Understanding these and other anthropogenic impacts on the environment requires integrated, interdisciplinary studies of climate, biogeochemical cycles, water, ecosystems, and humans. In particular, it is important that Earth scientists identify processes and thresholds that, when crossed, would lead to irreversible and unacceptable environmental change. Rockström et al. (2009) suggest that this threshold has already been crossed with respect to atmospheric carbon dioxide, the nitrogen cycle, and biodiversity loss (see Figure 2.25).

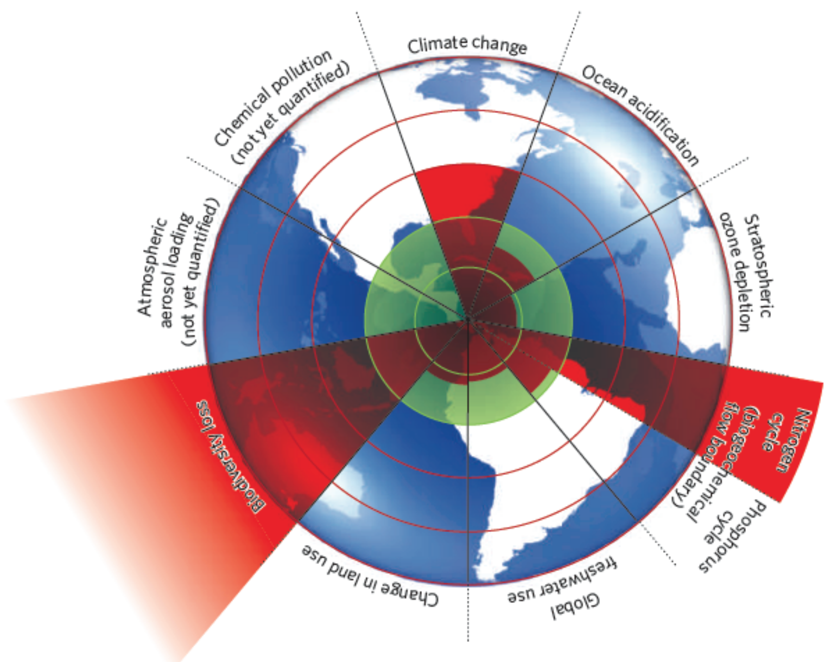


Figure 2.25 Earth-system processes and their proximity to crossing threshold conditions that lead to unacceptable environmental change. Processes are indicated outside each sector. Green colors denote safe operating conditions. The heights of the red-colored wedges represent the status of each process with respect to safe operating conditions. In this figure, climate change, the nitrogen cycle, and biodiversity loss have crossed the threshold of unacceptable environmental change. SOURCE: Rockström et al. (2009). Reprinted by permission from Macmillan Publishers Ltd.

RECENT ADVANCES IN GEOCHRONOLOGY

A common theme running through previous sections of this chapter is the growing reliance on geochronology to provide quantitative estimates of the age, duration, and rate of events and processes over many different timescales. As a result of improvements in analytical methods and in the theoretical underpinnings and calibrations of a variety of dating methods, the past few years have seen transformative advances in many approaches to geochronology. Areas of notable growth include surface exposure dating using rare isotopes produced by cosmic rays, determination of cooling histories of rocks (thermochronometry), extremely high precision dating of volcanic ashes, and high-throughput dating of detrital minerals. These geochemical techniques provide quantitative estimates of time that are an essential complement to dates and rates established using magnetostratigraphy and increasingly reliable methods of cyclostratigraphy (counting of orbitally paced oscillations recorded in sedimentary rocks).

Recent work greatly improving the ability to extract extremely precise and accurate ages from both the U/Pb and $^{40}Ar/^{39}Ar$ methods underscore recent advances and illustrate likely future directions both in terms of method development and application.

High Precision–High Accuracy Radiometric Dating

Given the wide applicability of the U/Pb and $^{40}Ar/^{39}Ar$ methods, especially to dating ashfalls in sedimentary sequences, recent improvements have had and will continue to have a major impact on the Earth sciences. In the case of U/Pb dating, a remarkable series of discoveries culminating in the work of Mattinson (2005) has revealed an analytical approach by which the consequences of Pb loss on zircon U/Pb dates can be almost entirely removed. This new approach permits routine determination of U/Pb dates with a precision of better than 0.1 percent. Geochronologists are also continuing to reduce other sources of error, including spike calibration, instrumental mass fractionation, decay constants, and the magma chamber residence time of zircon crystals prior to eruption and deposition.

Profound new insights into the rates of geochemical and biological processes are possible with ages precise to a small fraction of a percent. For example, Maloof et al. (2010) recently investigated a portion of the early Cambrian period associated with the appearance of the first calcite biomineralizing organisms and an associated dramatic change in global carbon cycling, as indicated by a large $\delta^{13}C$ shift of marine carbonate (see Figure 2.26). Dates of multiple ash fall zircons show that the event occurred at 525.34 ± 0.09 Ma, and the adjustment in global carbon cycling occurred in 506±126 kyr. The rate of this event suggests that these changes arose from biological diversification occurring at that time.

The ability to obtain extremely accurate and reliably inter-calibrated ages allows previously impossible high precision cross-correlation of events recorded in different localities. For example, Schoene et al. (2010) dated the end-Triassic mass extinction to 201.32 Ma in sedimentary sections in both Peru and Nevada and determined that the extinction was complete in <300 kyr. Additional dates from the

Central Atlantic Magmatic Province yielded precisely the same age, providing compelling evidence of a linkage between the extinction and massive volcanic eruptions.

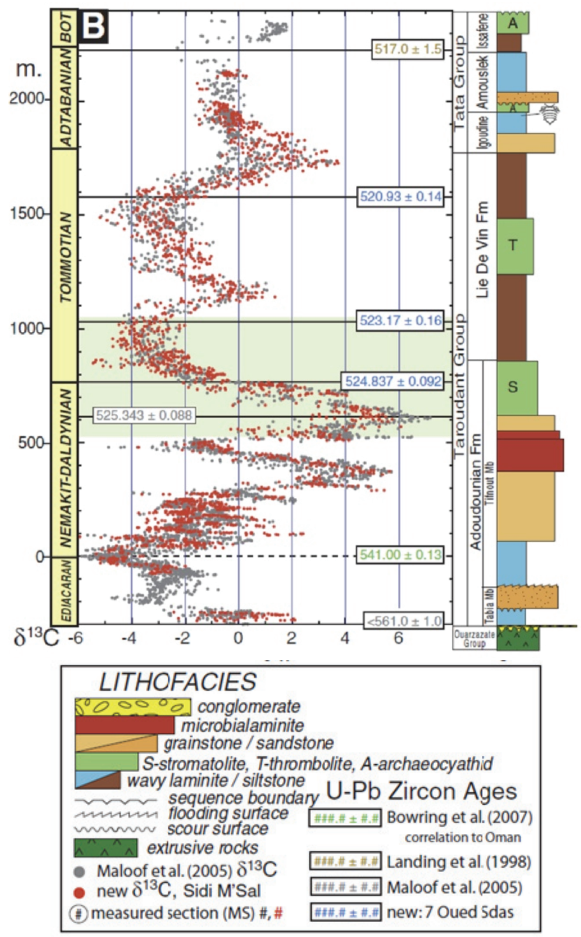


Figure 2.26 An example of the new insights possible with ages precise to a small fraction of a percent. Chart shows carbon isotope variability in marine carbonate in the early Cambrian period. High-precision U/Pb zircon ages of intercalated tuffs shown in boxed numbers (in Ma). SOURCE: Maloof et al. (2010). Reproduced with permission of Geological Society of America.

Similar advances have occurred in $^{40}Ar/^{39}Ar$ dating, which is important because not all samples of interest contain datable zircons. Furthermore, the ability to date coexisting minerals by two different high-precision methods allows the detection of possible age biases arising from such factors as daughter product loss, inheritance, and magma residence time. Much of the improvement in $^{40}Ar/^{39}Ar$ dating has arisen from refinements to the ^{40}K decay constant (Renne et al., 2010) and to the ages of the standards that are essential to the method. As an important example of standard calibration, Kuiper et al. (2008) assigned extremely precise and accurate ages from the astronomical timescale (counting of Milankovitch cycles) to ashfall sanidines in Miocene sediments. These sanidines were analyzed for $^{40}Ar/^{39}Ar$ ratio and then used to back-calculate the true age of the widely used Fish Canyon sanidine standard (the new age of this standard of 28.201 ± 0.046 Ma is remarkably more precise than the previously adopted value of 28.02 ± 0.56 Ma).

Productive interplay between astronomical dating and the improved accuracy of the $^{40}Ar/^{39}Ar$ and U/Pb chronometers is likely to continue in the coming years. Such interplay is nicely illustrated by work on the Cretaceous-Tertiary (K-T) boundary (Kuiper et al., 2008). While excellent cyclostratigraphy is apparent in some K-T boundary sections (see Figure 2.27), there is ambiguity in precisely how to map the sedimentary signals to the independently computed astronomical forcings. Improved dating accuracy has provided a new, high-accuracy-age tie point at the K-T boundary. This new tie point provides a new and more robust (but not yet definitive) age anchor on which to pin the astronomical timescale.

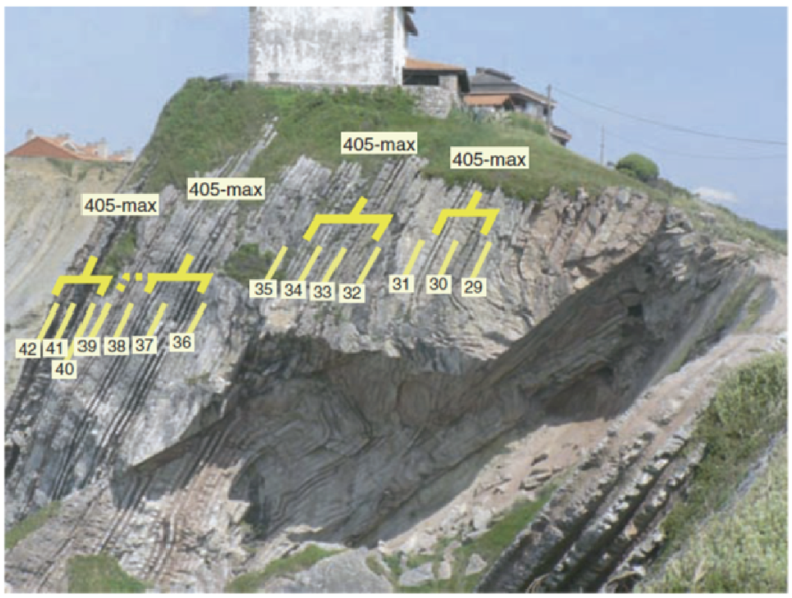


Figure 2.27 Milankaovitch cycles at the Zumaya K-T boundary section, Spain. High-precision radiometric dates permit improved assignment of the absolute ages of these cycles and hence a more accurate geological timescale. SOURCE: Kuiper et al. (2008). Reprinted with permission from AAAS.

Geochronology has its roots in analytical geochemistry and has greatly benefited from improvements in instrumentation and in a refined understanding of the underlying geochemical principles. Geochronology is a vibrant research subdiscipline, and the next decade will likely see continued advances in this area. However, as the fidelity, availability, and diversity of dating methods expand, the need for close collaboration among those who develop techniques and make the measurements with those who select key samples and interpret results is becoming increasingly apparent. In many cases—for example, in surface exposure dating and thermochronometry—sophisticated models are essential to extract the full meaning from the data. Thus, continued and robust advances in geochronology will involve a broad cross section of the Earth science community.

3

Findings and Recommendations

Basic research in the Earth sciences has numerous frontiers, with significant progress being made in both subdisciplinary arenas and interdisciplinary coordinated efforts. It is essential to sustain both types of activities, as individual-investigator research remains the most effective and innovative mechanism by which the field advances, even while the complexity and intrinsic interdisciplinarity of complex, dynamic geosystems demand coordination of multiple subdisciplinary efforts. Chapter 2 reviewed the status and prospects of basic research advancing in the next decade in seven important dynamic geosystems spanning a wide range of future research activity in the Earth sciences: (1) the early Earth; (2) thermo-chemical internal dynamics and volatile distribution; (3) faulting and deformation processes; (4) interactions among climate, surface processes, tectonics, and deeper Earth processes; (5) co-evolution of life, environment, and climate; (6) coupled hydrogeomorphic-ecosystem response to natural and anthropogenic environmental change; and (7) interactions of biogeochemical and water cycles in terrestrial environments. Chapter 2 also outlined exciting advancements in geochronology and isotope geochemistry. How to position research facilities for geochronology to better service the diverse needs of these interdisciplinary efforts while sustaining the advances of technical approaches in isotope geochemistry warrants detailed consideration.

This chapter presents the findings and recommendations of the committee regarding promising research opportunities over the next decade as relevant to the responsibilities of the National Science Foundation's (NSF) Division of Earth Sciences (EAR). Suggestions for new and enhanced instrumentation and facilities to support these research opportunities are outlined, and important partnerships and coordination between EAR and other programs and agencies engaged in Earth science research that will help pursue these opportunities are also discussed. This chapter also summarizes the committee's findings and suggestions with regard to sustaining and diversifying the Earth science research community and education in the discipline.

LONG-TERM INVESTIGATOR-DRIVEN SCIENCE

EAR funding of research projects initiated and conducted by individual investigators and small groups of investigators is the single most important mechanism for maintaining and enhancing disciplinary strength in the Earth sciences. EAR is the almost exclusive source of support for a full spectrum of basic research, not all of which is directly linked to immediate societal priorities. With all other federal support for the Earth sciences being strongly mission driven, advancing fundamental understanding of the Earth sciences falls squarely on EAR. Some basic Earth science research involves curiosity-driven inquiry into the fundamental nature of our planet and our existence as its inhabitants, but Earth research directions enhance core understanding, develop new analytic approaches, and ultimately reveal complex dynamical geosystems behavior that frequently impacts our understanding of mission-driven research efforts. It is a combination of exciting intellectual challenges as well as societal relevance that draws the best and brightest students to the field, and this is critical to bolstering Earth science expertise in the population throughout the upcoming century.

A decade ago, the *Basic Research Opportunities in Earth Science* (BROES) report (NRC, 2001) outlined many examples of the synergism between a diverse, healthy basic research program and the advances of directed research efforts. That report presented examples of how advances in basic Earth science research areas intersect with five national imperatives and, as exemplified in Chapter 2 of this report, significant progress has been made toward each of these imperatives:

1. Discovery, use, and conservation of natural resources continue to benefit from improved theory, data collection strategies, and methods developed in seismology, volcanology, magnetotellurics, geodesy, low-temperature geochemistry, geomorphology, and hydrology.
2. Characterization and mitigation of natural hazards are directly impacted by basic research on earthquake faulting, hydrology, geochemistry, geodesy, geomorphology, and surface evolution.
3. Geotechnical support of commercial and infrastructure development is strongly influenced by basic understanding of soil science, geomorphology, hydrology, seismology, and geodynamics.
4. Stewardship of the environment is informed by historical climate change, separation of secular and anthropogenic contributions, soil science, volatile fluxes, geomorphology, and coastal science.
5. Terrestrial surveillance for global security and national defense is advanced by basic research on Earth's interior; global geosystems; global seismic, geodetic, and meteorological measurements; and other remote-sensing approaches.

Further documentation of the role of basic science in contributing to these national priorities is provided by the many research community strategic plans and research summaries (see Appendix A), and full details are not repeated here. The emphasis of this report is on identifying key areas of research opportunity that can build on the foundations of sustained core subdisciplinary research to make major advances in the Earth sciences in the next decade.

THE EARLY EARTH

A large number of critical processes and events formed Earth and guided its evolution to the present state. Unique to the Hadean Eon (the first 500 million years of Earth history) were the formation of planetesimals, planetary embryos, and the moon; the mineralogy, petrology, and dynamics of magma oceans; the dynamics and chemistry of core formation and initiation of the geodynamo; formation of the earliest crust, atmosphere, and ocean; acquisition of surface volatiles; transition from an impact-dominated surface to one shaped by plate tectonics; and the terrestrial consequences of the young sun. The 2008 NRC report *Origin and Evolution of Earth* identified the question “What happened during Earth’s dark age?” as a research grand challenge in the Earth sciences.

There are multiple avenues for new insights into the early Earth. A primary objective is to increase the inventory of early Earth samples by expanding the search for yet older rocks and minerals. Still another is to quantify early Earth history using novel combinations of isotope systems and new micro and nanotechnologies. Sustained progress will require synthesizing geochronology and geochemical data with dynamical models that bridge the gap between planet formation and plate tectonics by incorporating the highly energetic conditions of the early Earth. Advances in high-performance computing hardware and parallel advances in software will make it possible to model processes such as giant impacts, magma oceans, crust, and core formation using realistic Earth parameters. The challenges of early Earth history argue for strengthening links with astronomy and astrophysics, planetary science, molecular biology, and biochemistry.

Finding 1: Organizing the diverse expertise within EAR and beyond would address major questions about the early Earth. Advances can come from collaborations with astronomy, astrophysics, planetary science, exoplanet detection and characterization, and astrobiology. EAR coordination with the research efforts of the National Aeronautics and Space Administration (NASA) is particularly relevant, as NASA supports research on detection and comparison with exoplanetary systems; origins of life and biological materials in our solar system; meteorite, asteroid, and solar system dust sampling; and large-scale modeling of planetary system formation.

Finding 2: Expanding searches for and characterization of the oldest rocks and minerals can provide new constraints on the earliest surface environments and Earth differentiation processes.

Finding 3: Refinements in early Earth chronology and rates of early Earth processes can be enabled through novel applications of short- and long-lived isotope systems.

Finding 4: Education of graduate students in venues such as the Center for Interdisciplinary Deep Earth Research (CIDER) program can be an effective strategy to foster the interdisciplinary collaborations and advanced training needed to solve early Earth problems.

> **Recommendation:** *EAR should take appropriate steps to encourage work on the history and fundamental physical and chemical processes that governed the evolution of Earth from the time of its accretion through the end of late heavy bombardment and into the early Archaen, perhaps by establishing a specific initiative on early Earth. Specific program objectives and scope may be developed through community workshops that prepare a science plan preceding a separate call for proposals.*

Instrument and Facilities Needs for the Early Earth Initiative

Finding 1: The computation challenges of studying planet formation, the impacts that influence this stage of Earth history, magma ocean dynamics, and the coupled early Earth systems are formidable: these are peta-scale applications. Activities and software development similar to those currently done by the Computational Infrastructure for Geodynamics (CIG) will be necessary. This includes developing systems that are optimized for data-intensive computations.

Finding 2: The new generation of high-resolution analytical facilities provide a combination of precision, resolution of small scales, and increased throughput, allowing geochemical measurements for extracting information from the limited number and size of early Earth samples. Modern synchrotron facilities open the possibility of doing mineral physics experiments at pressures and temperatures relevant for the full range of early Earth conditions. Continued access and training support for these community facilities will be important.

Finding 3: Databases for compiling and disseminating data relevant to the early Earth will be important. If supported by NSF, they will need to be continuously evaluated as to timeliness, effectiveness, and usefulness.

Finding 4: Continued access to labs that provide experimental capabilities at extreme pressures and temperatures under the dynamical conditions experienced during energetic collisions early in Earth's history will remain important.

THERMO-CHEMICAL INTERNAL DYNAMICS AND VOLATILE DISTRIBUTION

The most compelling problems associated with the deep Earth, of which three have been summarized in Chapter 2, are on the scale of Grand Challenges. Research frontiers and opportunities in studying the deep Earth system are explicitly highlighted in recent community research plans, such as those for geodynamics (Olson, 2010), seismology (Lay, 2009), high-pressure mineral physics (Williams, 2010), GeoPRISMS (MARGINS Office, 2010), Cooperative Studies of the Earth's Deep Interior (CSEDI) (Kellogg et al., 2004), and EarthScope (Williams et al., 2010). The NRC (2008) report, *Origin and Evolution of Earth*, also identifies corresponding Grand Challenges in how Earth's interior works, why it has plate tectonics and continents, and how the processes are controlled by material properties. Addressing these big-picture problems generally demands capabilities and resources beyond what is normally accorded a single investigator, yet "small grants"-style research remains the source of most innovation. Programs for larger-scale interdisciplinary collaborations, such as GeoPRISMs, CSEDI, CIG, and Continental Dynamics, along with community interdisciplinary activities such as CIDER will play increasingly important roles in future synthesis, but core individual investigator programs will remain important to foster the innovation found in more individualized research. Productive synergistic collaborations are often serendipitous, and specific funding mechanisms to prompt them, such as required menus of expertise on proposals, can be ineffective or at least compromised. A sounder strategy is to provide mechanisms for community cross-fertilization and communication, with intermittent bona fide collaborative undertakings being recognized and supported.

With increasing resolution of contributing methodologies and expanding data sets and modeling capabilities, there are opportunities to advance our understanding of fundamental questions such as the configuration of mantle convection, quantities and distribution of volatiles in the mantle, evolution of the core thermal regime, and growth of the inner core. These key questions lie at the heart of understanding how Earth evolves as a planet.

Finding 1: Sustaining progress in studies of the thermo-chemical dynamic system in Earth's interior requires continued data collection—archival and open distribution of seismic, geodetic, mineral physics, geomagnetic, and geochemical information on a global scale. Community-vetted open software for seismology and geodynamics calculations is very valuable for this research effort. These functions within current NSF facilities and community organizations (e.g., Incorporated Research Institutions for Seismology [IRIS], UNAVCO, EarthScope, Consortium for Materials Properties Research in Earth Sciences [COMPRES], CIG) can be evaluated regularly to ensure they are optimized and effective.

Finding 2: Focused research programs that support integrative interdisciplinary coordination on deep Earth dynamic systems (e.g., CSEDI, GeoPRISMS) are valuable for testing hypotheses and creating the synergies needed to answer long-standing questions as a supplement to innovative individual investigator programs.

Finding 3: Graduate student training across the range of interdisciplinary perspectives critical to integrative research is increasingly difficult to provide at single research institutions; thus, community efforts for focused graduate training such as provided by CIDER summer institutes can be valuable in this area. CIDER could continue to serve a function as a synthesis center for focused effort on the problems identified above.

> **Recommendation:** *EAR should pursue the development of facilities and capabilities that will improve spatial resolution of deep structures in the mantle and core, such as dense seismic arrays that can be deployed in various favorable locations around Earth, enhanced computational software and hardware to enable increased resolution of three-dimensional geodynamical models, and improved high-resolution experimental and theoretical mineral physics investigations. This will provide definitive tests of many hypotheses for deep Earth structure and evolution advanced over the past decade. The large scope of such facilities will require a lengthy development and review process, and building the framework for such an initiative needs to commence soon.*

Instrument and Facilities Needs for Deep Earth Dynamics and Volatile Distribution

Finding 1: Disciplinary-based facilities provide critical data for these major undertakings. This includes the seismological facilities of IRIS, the mineral physics facilities of COMPRES, the computational efforts of CIG, and maintenance of geochemical and petrological laboratories and databases. Sustained access to resources such as synchrotron radiation and large-volume presses along with emerging experimental technologies is also of great importance for mineral physics efforts.

Finding 2: For major deep Earth challenges, understanding follows discovery, and discovery requires new technology and improved data. For example, dense seismic and geodetic arrays such as the EarthScope facilities provide enhanced spatial resolution of mantle and core structure, but more extensive global coverage with fine-scale resolution remains a major goal. Advances in high-performance computing hardware and software will allow construction of more realistic models with improved assimilation of expanded Earth data. Current capabilities are not adequate to achieve the resolution that is needed to solve the deep Earth problems of dynamical structures and volatile distribution.

Finding 3: Strong coordination with efforts to develop and make accessible supercomputing resources such as TERRAgrid, synchrotron, neutron, and nano-probe facilities for mineral physics experiments in national laboratories, and deployments of additional seismic and geodetic sensors in oceanic and polar environments, can enhance the EAR research programs. This involves a coordination and cooperation across NSF structural entities as well as interagency coordination with the U.S. Department of Energy, NASA, and the U.S. Geological Survey (USGS).

FAULTING AND DEFORMATION PROCESSES

Rapid discoveries are being made regarding the nature of fault slip and associated deformation processes in active tectonics environments, with a huge spectrum of fault slip velocities being revealed by concerted geodetic and seismic data collection. Tremendously damaging recent earthquakes in Haiti (2010), Chile (2010), and Japan (2011) are only harbingers of the huge societal toll that could be exacted by earthquakes in the upcoming century, with burgeoning populations in seismically active areas being at risk. The combination of rapid scientific advancements and great societal relevance motivates enhanced EAR attention to the processes of faulting and deformation in active tectonic regions. Understanding the behavior of faulting and earthquake occurrence has also been deemed a Grand Challenge in the science plans of geodynamics (Olson, 2010), seismology (Lay, 2009), GeoPRISMS (Margins Office, 2010), EarthScope (Williams et al., 2010), (UNAVCO, 2009), and the NRC (2008) report *Origin and Evolution of Earth*.

The field of earthquake science is now recognized to involve a complex geosystem with multiscale processes from the microscale controls on surface friction up to the regional-scale processes of sedimentary basin reverberation and excitation of tsunamis by ocean water displacements. While single-investigator contributions remain paramount to the discovery and disciplinary advances underlying the surge of progress in earthquake science, there has been profound value in developing communities that address the geosystem perspective by bringing together researchers with expertise spanning laboratory friction experiments, observational and theoretical seismology, geodesy, structural geology, earthquake engineering, field geology, volcanology, magnetotellurics, and deep drilling. These approaches are flourishing, and in the next decade integrative efforts built around natural fault zone and subduction zone laboratories hold promise of greatly advancing our understanding of faulting and deformation processes and associated roles of fluid, volatile, and material fluxes. Large data collection and integrated analysis efforts are intrinsic to these natural laboratory investigations.

Finding 1: Completion of the envisioned Earthscope project through 2018, with the Transportable Array being deployed across Alaska and continued operation of the Plate Boundary Observatory will provide major advances in our understanding of the North American continent and deformation processes along the plate boundaries in the Aleutians, Alaska, and the western United States. Full realization of the goals of EarthScope will be a major achievement for EAR and will position the Earth sciences for future large facilities development.

Finding 2: Integrative multidisciplinary activities such as MARGINS, GeoPRISMS, and the Southern California Earthquake Center (SCEC) are particularly valuable for investigating fault zone and plate boundary environments. The SCEC has successfully bridged the earthquake science and earthquake engineering communities, including strong public outreach. The GeoPRISMS[1] community has identified three

[1] GeoPRISMS science plan.

key regions to explore in the next decade: Cascadia; the Alaskan subduction zone; and the North Island, New Zealand, subduction zone. The faulting and deformation systems and material fluxes within these regions can best be addressed with interdisciplinary programs.

Finding 3: EAR research on the multiscale nonlinear problem of earthquake faulting, seismic wave generation, and ground shaking in complex three-dimensional media is establishing understanding that can transform earthquake hazard assessment into a fully physics-based approach with potential to more effectively guide earthquake engineering decision making.

Finding 4: Understanding fault zone and plate boundary processes is strongly linked to understanding and mitigating natural hazards; thus, there is great societal relevance to understanding faulting and deformation processes as well as volcanic processes in these environments. Industry, insurance, and municipal partnerships and strong coordination with the USGS are relevant to help EAR connect science to the end user.

> **Recommendation:** *EAR should pursue integrated interdisciplinary quantification of the spectrum of fault slip behavior and its relation to fluxes of sediments, fluids, and volatiles in the fault zone. The successful approach of fault zone and subduction zone observatories should be sustained, as these provide an integrative geosystems framework for understanding faulting and associated deformation processes. The related EarthScope project is exploring the structure and evolution of the North American continent using thousands of coordinated geophysical instruments. There is great scientific value to be gained in completing this project, as envisioned, through 2018.*

Instrument and Facilities Needs for Faulting and Deformation Research

Finding 1: EAR is currently supporting numerous disciplinary facilities that are gathering essential data for understanding faulting processes and associated deformations. Facilities such as UNAVCO, IRIS, the National Center for Airborne Laser Mapping (NCALM), SCEC, CIG, and high-speed computing are important to advancing understanding of faulting processes.

Finding 2: Advances in fault rupture studies will require support for theoretical developments, new observations (combining accelerometers and global positioning systems), and high-speed computational resources.

Finding 3: InSAR data are proving to be of great value for research on faulting and associated deformation processes as well as volcanic processes. The plan for NASA to deploy an InSAR satellite as part of the EarthScope project remains a high priority.

INTERACTIONS AMONG CLIMATE, SURFACE PROCESSES, TECTONICS, AND DEEP EARTH PROCESSES

The broad interactions among climate, Earth surface processes, and tectonics are an area of growing interest and compelling research opportunities. The NRC (2010a) report *Landscapes on the Edge* identified as particularly intriguing those research questions that center on interactions among climate, topography, hydrology and hydrogeology, physical and chemical denudation, sedimentary deposition, and deformation in tectonically active mountain belts. Strong feedbacks among precipitation and erosion induced by orogenic effects play an important role in the distribution of deformation in mountain belts, whereas size and distribution of high-elevation topography in turn influence global, regional, and local climates. The recent recognition of close coupling among surficial processes of erosion and sedimentation and deeper tectonic and structural deformation creates new opportunities for interdisciplinary research questions that bridge climate science, geomorphology, structural geology, and geophysics. New understanding of the dynamic interactions among climate, Earth's surface, and the planet's tectonics over geomorphic to geological timescales will require increased access to—and new developments in—thermochronometry, methods for dating geomorphological surfaces, LiDAR, satellite imagery, modeling capabilities, experimental methods, and field instrumentation and studies.

Understanding the interplay among climatic, geomorphic, and geological/tectonic processes in governing Earth surface processes and landscape evolution requires integrating processes across a wide range of temporal and spatial domains. Addressing the most compelling problems and Grand Challenges under this theme will involve studies of the evolution and dynamics of particular physiographic regions over orogenic timescales and studies to address how to scale-up mechanistic, process-based understanding of short-term processes to quantitatively characterize and constrain system behavior and interactions over longer timescales. Developing theory for the interactions among climate, topography, land cover, and the deeper Earth interior at global, regional, and local scales represents a major research opportunity. Integrating surface processes and deep Earth studies, including petrological and seismological studies, and the record of past surface environments are needed to explore connections between deep Earth processes and Earth surface dynamics. Developing geomorphic transport laws that account for climate and the role of biota to describe and quantify river and glacial incision, landslides, and the production, transport, and deposition of sediment are needed to address how to integrate the effects of event-based processes into long-term system behavior. Measuring and modeling landscape evolution under diverse and varying climatic conditions, with an emphasis on identification of physiographic signatures of climate and climate variability, will allow for the identification of thresholds of landscape response and the limits of landscape resilience.

Finding 1: Significant opportunities exist to encourage coordination and communication within the communities engaged in research on linkages between climate, tectonics, surface processes, and deeper Earth processes such as workshops that promote community interactions around this theme.

Finding 2: New opportunities for studies of climate, tectonics, and surface processes exist within the GeoPRISMS program for research that spans the shoreline within focus areas that include Cascadia, the Aleutians, and eastern North American margin. Development of closer linkages between EAR and the Division of Ocean Sciences (OCE) within GeoPRISMS can leverage and optimize these research opportunities.

Finding 3: The acquisition of high-resolution topographic data, such as through the NCALM, is essential for continued progress in surface process studies. Maintenance of this capability and expansion to support acquisition of wider areal coverage and to provide more comprehensive distribution of these data are highly relevant for studies of climate, tectonics, and erosion processes.

Finding 4: Seismic reflection techniques provide the primary tools for imaging structure in the crustal interior at geological scales and is a highly desired capability for addressing many deep Earth to surface research questions. However, the capabilities for reflection imaging are diminishing in the academic community. Maintaining and enhancing reflection imaging capability, perhaps through new industry-academic partnerships to acquire new data sets or to obtain access to existing industry data sets for academic study, is also highly relevant for research goals in fault studies and for continental drilling.

> **Recommendation:** *EAR should take appropriate steps to encourage work on interactions among climate, surface processes, tectonics, and deeper Earth processes either through a new interdisciplinary program or perhaps by expanding the focus of the EAR Continental Dynamics program to accommodate the broader research agenda of these interdisciplinary subthemes.*

Instrument and Facilities Needs for Advancing Research on Interactions among Climate, Surface Processes, Tectonics, and Deep Earth Processes

Finding 1: Important existing facilities that support research in this area include NCALM (LiDAR data), the Community Surface Dynamics Modeling System (CSDMS), unique lab facilities (e.g., National Center for Earth-surface Dynamics [NCED]), UNAVCO permanent and portable geodetic facilities, and IRIS permanent and portable seismic facilities.

Finding 2: Access to geochronometric and cosmogenic dating to support analysis of the large sample collections intrinsic to this field-intensive research remains important.

CO-EVOLUTION OF LIFE, ENVIRONMENT, AND CLIMATE

The deep-time geological record has provided a compelling narrative of changes in Earth's climate, environment, and evolving life, many of which provide analogs, insight, and context for understanding human's place in the Earth system and current anthropogenic change. Deep-time studies document a range in variability and impact of climate phenomena far broader than archived in more recent records revealing how physical, chemical, and biological feedbacks have operated differently during past warmer and transitional climate states (NRC, 2011a). In turn, the deep-time record captures the importance of life as an agent of change in the environment affecting the composition and properties of the atmosphere, hydrosphere, and lithosphere. The complexity of this bio-geosystem is only now being fully realized, with new analytic tools from geochemistry, paleontology, and biology enabling unprecedented exploration of the coupled time-evolution of past Earth surface conditions, including temperature, atmospheric chemistry, hydroclimates, chemical composition of the ocean, and the interrelationship and physiologies of ancient life forms. Concerted application of interdisciplinary capabilities to the deep-time record will provide breakthroughs in understanding of this profound and nonlinear bio-geosystem.

Real or virtual paleoclimate/deep-time initiatives can be pursued that draw together a broad community of researchers asking critical questions about key intervals in time or key processes through time that could be evaluated using cutting-edge environmental proxies, paleobiological methods, and numerical models. Such initiatives should bridge our understanding of the geological record of past global "states" with those anticipated in the Anthropocene stemming from changing climate, growing water demand, energy exploitation, land use, habitat change, and extinction.

Finding 1: Understanding the dynamics of past warm periods and major climate transitions that have prevailed throughout most of Earth's history provides a valuable mechanism for assessing anthropogenic changes in the climate system associated with greenhouse gas emissions.

Finding 2: High-precision and accuracy geochronological tools (both radio-isotopic and astrochronological), environmental proxies, and molecular (genomic and proteomics) methods have placed the community on the cusp of a major advance in our understanding of the influence of major externally driven climate and environmental change on life and the feedbacks on climate caused by the evolution of new life forms. Proxy development and calibration studies need to be matched by complementary efforts to build more spatially and temporally resolved multiproxy paleoclimate and paleoecological time series with high precision and chronological constraints. There is an associated need for improved dynamic models and expanded data-model comparisons.

Finding 3: Major advancements in rapid and relatively inexpensive sequencing techniques and equally impressive progress in numerical analysis of the results are allowing the genome of living, and in some cases extinct, organisms to be mined for historical information of evolutionary relationships and gene products extending from the present to the origin of life itself. Coupled with geologically derived environmental information, this new source of deep-time information is bringing about profound changes in our understanding of the history of life on Earth and its origin and biogeochemical consequences. Enabling further application of genomic and proteomics methods that address deep-time origins of environmentally important clades and physiologies in conjunction with studies of environmental and climate proxies in deep time is a major opportunity for future research.

Finding 4: Sampling at appropriate spatial and temporal scales will require new continental coring and continued ocean drilling. This is a limiting factor in fully developing the deep-time archive of past climates and the co-evolution mechanisms operating through time. Drilling availability is limiting progress.

Recommendation: *EAR should develop a mechanism to enable team-based interdisciplinary science-driven projects involving stratigraphy, sedimentology, paleontology, proxy development, calibration, application, geochronology, and climate modeling at highly resolved scales of time and space to understand the major linked events of environmental, climate and biotic change at a mechanistic level. Such projects could be expected to be cross program and cross directorate.*

Instrument and Facilities Needs for Research on Co-evolution of Life, Environment, and Climate

Finding 1: Scientific advances could come from enhancing drilling activities ranging from small-scale drilling with transportable rigs to the drilling scale facilitated through Drilling, Observation and Sampling of the Earths Continental Crust (DOSECC) and the International Continental Scientific Drilling Program (ICDP). Current practice is complicated and inefficient, leading to a discouragingly long process.

Finding 2: There is high value in developing mechanisms for coordinated sampling (e.g., multiproxy sampling of the same materials), analysis, and archiving of drill core. Integrated efforts on the development of digital databases (e.g., SedDB, Macrostrat, GeoStratSys) to store proxy and genomic data and to facilitate data integration and comparison across all spatial and temporal scales are also necessary to support advances. Such an effort might incorporate a strategy to integrate databases where relevant and with paleoclimate model archives so as to make them fully interactive.

Finding 3: Progress can be made through strategic planning by NSF for expanded and coordinated efforts to make both high-precision geochronology and specialized analytical facilities available to all interested scientific parties. The current structure for access to high-precision geochronology labs creates a scientific bottleneck for obtaining geochronological constraints and can be cost prohibitive.

Finding 4: Dedicated computational resources for paleoclimate modeling focused on past warm periods and extreme and abrupt climate events are required for improved parameterization, development of higher-resolution regional-scale models to capture climate variability, and the integration of innovative paleoclimate intercomparison models and data-model comparisons consistent with Intergovernmental Panel on Climate Change (IPCC)–style assessments. Similarly, additional computational resources are needed for genomic analyses.

COUPLED HYDROGEOMORPHIC-ECOSYSTEM RESPONSE TO NATURAL AND ANTHROPOGENIC CHANGE

The ways in which ecosystems and landscapes have co-evolved through time and the nature of their coupled response to human activity and climate change present tremendous opportunities for advancing our understanding of Earth surface processes. Recognition of the degree to which hydrogeomorphological processes influence ecological systems, and ecosystems in turn influence hydrogeomorphological processes and dynamics, has opened up exciting new areas in the emerging fields of ecohydrology, ecogeomorphology, and geobiology. It is now widely recognized that climate change and disturbance, both natural and human, can have far-reaching consequences for landscapes and ecosystems. Landscape-ecosystem response to environmental change and disturbance can, in turn, affect climate and human populations. The full scope and breadth of these interactions are only beginning to be understood, in part because of the bi-directional nature of such feedbacks. Landscapes and ecosystems in relatively rapidly changing, marginal environments like coastal systems, wetlands, and permafrost regions are particularly vulnerable to changes in climate and land use.

Our ability to anticipate the response of landscapes and ecosystems to disturbance and climate change requires greater mechanistic understanding of the interactions and feedbacks among hydrological drivers, landscape morphology, and biotic processes. Advancing the science requires better theory, observations, and models relating spatial patterns and temporal variability of landscape drivers (topography, hydrology, geology) to the dynamics of biotic communities, including identification of hydrological and morphological leading indicators of landscape and ecosystem state change. Model development can continue to work toward bringing the influence of biotic processes into formal representations of geomorphological and hydrological processes and to couple these with models of climate and human-landscape dynamics.

Finding 1: There is a particularly critical need to better understand the impact of natural and anthropogenic environmental changes in coastal environments, where these changes can be expected to have profound societal and economic consequences globally. Advances in coastal sciences could be accelerated by dedicated NSF initiatives and programs.

Finding 2: Critical zone research contributes understanding essential to addressing larger-scale questions concerning co-evolution of landscapes and ecosystems and landscape response to disturbances (natural or anthropogenic).

Finding 3: Integrated monitoring of hydrogeomorphic-ecosystem processes will require development of new instrumentation, data archives, and models that can take advantage of large-scale environmental restoration efforts and documented historical change as controlled experiments.

Finding 4: The research required to address many of the priorities and opportunities related to landscape change cuts across divisional and directorate boundaries within NSF. In cases where other federal agencies such as the USGS are addressing related questions, it would be advantageous to coordinate plans, facilities, and activities.

> **Recommendation:** *EAR should facilitate research on coupled hydrogeomorphic-ecosystem response to climate change and disturbance. In particular, the committee recommends that EAR target interdisciplinary research on coastal environments. This initiative would lay the groundwork for understanding and forecasting the response of coastal landscapes to sea-level rise, climate change, and human and natural disturbance, which will fill an existing gap at NSF and should involve coordination with OCE, USGS, and National Oceanic and Atmospheric Administration (NOAA).*

Instrument and Facility Needs for Coupled Hydrogeomorphic-Ecosystem Response to Natural and Anthropogenic Change

Finding 1: Advancing our understanding of landscape response to natural and anthropogenic environmental change requires infrastructure and support for community modeling efforts, data archiving, and instrument facilities. These functions of current NSF facilities, centers, and community organizations (e.g., NCALM, UNAVCO, NCED, CSDMS, and Consortium of Universities for the Advancement of Hydrologic Science, Inc. [CUAHSI]) are valuable and can be evaluated regularly to ensure they are optimized and effective. Centralizing and disseminating a variety of data related to landscape processes (hydrological, geomorphological, geological, biogeochemical, biotic, climate) would be valuable.

BIOGEOCHEMICAL AND WATER CYCLES IN TERRESTRIAL ENVIRONMENTS AND IMPACTS OF GLOBAL CHANGE

Humans are altering the physical, chemical, and biological states and feedbacks among essential components of the Earth surface system. At the same time, atmospheric temperature and carbon dioxide levels have increased and are impacting carbon storage in the terrestrial environment, the water cycle, and a range of intertwined biogeochemical cycles and atmospheric properties that feed back on climate and ecosystems. Advancing our understanding of integrated soil, water, and biogeochemical dynamics in the critical zone and the responses and feedbacks of carbon, nitrogen, and water cycles to climate change and human impacts requires new theory, coupled systems models, and new data. Several reports and science plans underscore the need for integrated studies of biogeochemical and water cycles in terrestrial environments, particularly in the critical zone, and their response to climate and land use change, including *Landscapes on the Edge* (NRC, 2010a), *Challenges and Opportunities in the Hydrologic Sciences* (NRC, in preparation), *Frontiers in Exploration of the Critical Zone* (Brantley et al., 2006), *A Plan for a New Science Initiative on the Global Water Cycle* (USGCRP, 2001), and the BROES report (NRC, 2001).

Among the key research opportunities is development of a theoretical framework for the interactions among hydrological, geochemical, geomorphic, and biological processes in the critical zone, including the roles of climate and geological setting that have heretofore been only loosely constrained. New advances in our ability to understand and quantitatively simulate carbon, nutrient, water, and rock cycling will depend on new measurement approaches and instrumentation that capture spatial and temporal variability in atmospheric and land use inputs superimposed on complex vegetation patterns and underlying anisotropic subsurface geomedia. This will require a substantial investment in *in situ* environmental sensors, field instruments, geochemical and microbiological tools, remote sensing, surface and subsurface imaging, and development of new technologies. There is also a critical need for development of coupled systems models to explore how these systems respond to anthropogenic and climatic forcing.

Finding 1: EAR is poised to play a leadership role in comprehensive, uniquely integrated studies of the terrestrial environment in the face of human activity and climate change. New efforts could coordinate with complementary NSF programs in hydrology, geomorphology, sedimentology, climatology, atmospheric science, geodesy, geophysics, geochemistry, geobiology, and terrestrial ecology, as well as the National Ecological Observatory Network (NEON). Extending this coordination to related programs outside NSF could be valuable.

Finding 2: The Critical Zone Observatory (CZO) model provides a fruitful template for evaluation and possible expansion of integrated studies of the critical zone in complex terrestrial settings. These observatories and other integrated approaches are most valuable if they capture a broad, but differentiated, array of settings, processes, and controls (natural and anthropogenic) and are effectively coordinated. Critically evaluating the success of the CZO program at regular intervals will ensure its long-term success.

Finding 3: To advance our understanding of the cycling of water, carbon, nutrients, and geological materials in terrestrial environments, it will be valuable to have measurements at single points on the landscape integrated smoothly with more broadly distributed estimates derived from remote sensing. All of these measurements will have to be coordinated with new theory and models appropriate for landscape and regional scales to resolve spatial and temporal trends caused by climate change, land use, and other human impacts.

Finding 4: There is a major role for modern critical zone science as a bridge between ancient analogs archived in the geological record and the anticipated consequence of future changing climate, growing water demand, and greater and evolving land use.

> **Recommendation:** *EAR should continue to support programs and initiatives focused on integrated studies of the cycling of water, carbon, nutrients, and geological materials in the terrestrial environment, including mechanisms and reactions of soil formation; hydrological and nutrient cycling; perturbations related to human activities; and more generally the cycling of carbon between surface environments and the atmosphere and its feedbacks with climate, biogeochemical processes, and ecosystems.*

Instrument and Facilities Needs for Biogeochemical and Water Cycles in Terrestrial Environments and Impacts of Global Change

Finding 1: Advancing this research priority will require a substantial focus on *in situ* environmental sensors, field instruments, geochemical and microbiological tools, remote sensing, surface and subsurface imaging, and development of new technologies. There is also a need for computational facilities and community modeling efforts like the CSDMS and the Community Hydrologic Modeling Platform (CHyMP).

FACILITIES FOR GEOCHRONOLOGY

A strong theme developed in many of the previous sections of this report is the pressing need to enhance the community's capacity to produce high-quality dates. The recent pace of innovation of new methods, ranging from radiometric dating to thermochronometry to surface exposure dating, has generated exciting new scientific opportunities and a large unmet demand for measurements. New mechanisms for supporting geochronology laboratories will be required to efficiently develop these opportunities and to promote continued technical advances in the coming decade. In this regard, this aspect of EAR-funded facilities requires the special attention given in this report in how to service the expanding needs of the community relative to other core facilities noted above that underlie opportunity areas.

Traditionally, age determinations have been made in single principal investigator (PI) laboratories. These laboratories are usually funded by a combination of grants directly to the laboratory PI and to investigators with which the PI collaborates. However, as the technical complexity of the measurements and the cost of instrumentation rise, this model is becoming financially unsustainable. In addition, there is a sense among potential users that this model does not serve the community as broadly and effectively as it could. One way forward is for EAR to entertain proposals that seek funding for major new facilities capable of meeting these challenges. The committee prefers to avoid being overly prescriptive of what such a facility should look like—whether it be a single laboratory or an alliance of multiple laboratories, whether it be focused on a single method or a range of methods, and so forth. However, a collection of important objectives for such facilities is offered:

1. The best science outcomes occur when strong intellectual engagement exists between the investigators who make the measurements and those who use them. This extends all the way from the inception of a project, through sampling strategy and sample selection, to the collection and interpretation of results. The committee believes that a simple analysis-for-hire scheme is unlikely to yield results of consistent high quality.
2. It will be useful to identify mechanisms that will encourage broad community access to the facilities.
3. It would be useful if facilities were encouraged or required to routinely demonstrate that the quality of their results meet the standard expected by the community they serve. Such a demonstration would eliminate any questions regarding the integrity of ages produced.
4. The education of investigators, especially students and post-docs, is an essential goal of these facilities. The education of geochronologists and that of users of geochronology are equally important. Intellectual isolation of measurements from applications is best avoided.
5. A component of the support given to facilities could be used to innovate new or better methods.
6. Traditional single-PI laboratories doing high-quality, innovative research will remain essential to the vitality of the field.

The facilities envisioned here could be quite expensive, and the committee does not prescribe a specific funding mechanism. In its boldest implementation the committee can envision creating one or more national geochronology centers that would require capitalization and operating costs that exceed the capacity of existing NSF-EAR programs, including the Major Research Instrumentation (MRI) program. Alternatively, single PI laboratories or networks of such laboratories could potentially fulfill the same objectives but would require substantially more support and more commitment to serving community needs than if implemented through current EAR programs.

Recommendation: *EAR should explore new mechanisms for geochronology laboratories that will service the geochronology requirements of the broad suite of research opportunities while sustaining technical advances in methodologies. The approaches may involve coordination of multiple facilities and investment in service facilities and may differ for distinct geochronology systems.*

At present there is no mechanism within EAR for proposals of the large scale the committee envisions; therefore, a bold new program with appropriate goals and guidelines would need to be created.

INTERAGENCY AND INTERNATIONAL PARTNERSHIPS AND COORDINATION

All of the research opportunity areas and associated facilities identified above intersect interests and capabilities of other Federal agencies and international programs. EAR can enhance the impact of its research portfolio by encouraging and supporting interagency and international coordination of facilities, community consortia, and individual investigations. Each activity is distinctive, and in some case a formal Memorandum of Understanding (MoU) between agencies may clarify relationships, and in other cases direct EAR representation in international programs may be appropriate.

The Early Earth opportunity area overlaps with mission objectives of the National Aeronautics and Space Administration (NASA) and research activities supported by the U.S. Department of Energy. Large-scale modeling capabilities of U.S. National Laboratories offer potential points of coordination as well. Investigation of global thermo-chemical dynamics of the mantle directly engages the global seismological communities loosely organized under the Federation of Digital Seismic Networks, the in situ Global Earth Observation System of Systems, and the Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) International Monitoring System (IMS). EAR can coordinate with these international activities best through university consortia efforts such as the Incorporated Research Institutions for Seismology (IRIS). Development of increased resolution capabilities for global imaging will require international coordination on data acquisition and EAR could work together with the U.S. Geological Survey to support that international effort. Expanding data collection to oceanic and cryosphere environments remains a key challenge for global investigations, and EAR coordination with the Division on Ocean Sciences (OCE) and Office of Polar Programs (OPP) in instrument development and data acquisition in these challenging locations needs to be sustained and expanded.

Pursuing the advances in understanding faulting processes requires continued operation of GPS networks, and EAR can advocate for sustaining and upgrading these capabilities of NASA and U.S. Department of Defense–supported satellites. The broad infrastructure required for EAR science applications of geodetic data is often not appreciated and EAR can play a valuable role in sustaining this infrastructure in other agencies by communicating and, as appropriate engaging in MoU to sustain data flow. Research opportunity topics involving surficial processes and coastal dynamics address problems that are at the core of the missions of the USGS, NOAA, and U.S. Forest Service. Continued efforts to develop and maintain these partnerships are key to maximizing the impact of EAR research programs.

TRAINING THE NEXT GENERATION AND DIVERSIFYING THE RESEARCHER COMMUNITY

Capitalizing on the research opportunities set out in the preceding sections will require researchers with the skills and knowledge to advance the science. As several high-profile reports have recently laid out (e.g., CGS, 2007; NRC, 2010d), providing the appropriate training remains a major challenge in the United States, both within the Earth sciences specifically and STEM (science, technology, engineering, and mathematics) disciplines in general. Earth science K–12 education standards are still inconsistent from state to state (Hoffman and Barstow, 2007), and *The Global Competitiveness Report 2010-2011* by the World Economic Forum ranks the United States 52nd in the quality of math and science education (Schwab, 2010), continuing a downward trend that presents a significant challenge to the nation's ability to draw on domestic sources of expertise in the Earth sciences. Many of the research areas discussed above require advanced skills in computer science and information technology. The specialized skills in these areas are not typically developed in Earth science curricula and a possible approach is to foster attraction of more students with good computational skills into Earth science research through outreach to those programs and students. EAR might help this process by creating incentives for computer science participation in key research areas rather than the current focus on cyberinfrastructure, which often has Earth scientists trying to find ways to collaborate with computer science initiatives.

Most university curricula in Earth science have moved toward some level of geosystems perspective for developing the cross-disciplinary foundations needed for research in opportunity areas like those described above. EAR can build on the successful example of internship programs (notably those for IRIS, UNAVCO, and SCEC), along with interdisciplinary educational workshops like CIDER, to foster broad cross-disciplinary training in other areas. The model of summer graduate training workshops, with several weeks of lectures by diverse experts addressing a cross-disciplinary topic, developed by CIDER and several European-based organizations holds potential for all of the opportunity areas. Few, if any, university programs are now able to provide in-house expertise across the relevant areas for many of the geosystems of interest and immersive training in short-courses can be an effective way of developing awareness, understanding and competency for cross-discplinary research for undergraduates, graduates and faculty alike.

Increasing the participation of historically underrepresented groups is an equally important and directly related challenge. There remains an uneven minority exposure to science and math (NRC, 2010c), as well as a significant science knowledge disparity between poor and affluent students (National Center for

Education Statistics, 2011). A gender gap persists in the Earth sciences and, although the Earth sciences are doing better than other math and physical sciences in terms of gender equity, there remains substantial room for improvement. The female share of Earth science students at all levels has steadily increased over the past decade, but still only 35 percent of Earth sciences post-docs are women (NSF, 2011). As in other sciences, at each career step through graduate school to professorship, the number of women relative to men declines (NRC, 2006), a condition that increases women's isolation as they advance in the discipline. The committee agrees that including ideas and perspectives of underrepresented groups serves both underrepresented groups and the discipline itself.

To some extent, the disparities in training and inclusion are driven by larger social issues that are beyond the capacity of the EAR division or this committee to address. However, NSF is making progress on many of these challenges (see, e.g., NSF, 2008, 2010), and EAR is working to enhance diversity, education, and knowledge transfer through the outreach efforts of EAR-funded groups, such as IRIS and NCED, and the committee encourages EAR to continue these efforts. There are several areas in which the committee believes EAR could benefit from focusing its resources, and the following suggestions are meant to guide those efforts. The committee mentions several specific NSF initiatives as examples but does not mean to imply that these initiatives are the best vehicles for EAR efforts going forward. The EAR division will know best how to implement these suggestions, including the specific initiatives that could be expanded or developed.

Finding 1: Bringing the Earth sciences into the high school curriculum at the same level as chemistry, biology, and physics would pay large dividends to the discipline in the next generation. As an integrative discipline, the Earth sciences can be used as an umbrella course to bring together core math and science knowledge and, while other integrative disciplines such as "environmental science" and "human geography," have Advanced Placement (AP) courses available to high school students, the Earth sciences remain notably absent from the AP course list. The EAR division may also consider both laboratory and deployable scientific instruments for high school classrooms. Much of the exciting and relevant work in the Earth sciences is done using unique instrumentation, and some underrepresented minorities may prefer a laboratory setting to fieldwork (O'Connell and Holmes, 2011). Exposing students to the types of instruments they would use in a career in the Earth sciences, with an emphasis on laboratory instrumentation, could boost interest and understanding. A schoolyard version of the Long Term Ecological Research program with an Earth science emphasis would build on existing NSF programmatic infrastructure.

Finding 2: Promoting early awareness of the Earth sciences on college campuses is key. One of the best times to capture students' interest is as they are entering college. Earth science gap-year internships would incentivize early exposure to the Earth sciences for students who defer college entry for a year. Deferring college entry is becoming increasingly common, and students who take a gap year may perform better as undergraduates (Birch and Miller, 2007). Gap-year internships could be incorporated into research proposals as a supplement to encourage this specific type of pre-undergraduate outreach. An initiative to target the parents of freshmen with a kiosk and brochures during "Parents Day" events could help parents realize that the Earth sciences offer a legitimate career path for their children. Outreach to computer science majors could highlight the exciting applications of high-performance computing available in the Earth sciences. The EAR-funded Louis Stokes Alliances for Minority Participation is a valuable mechanism to attract Earth science majors as they transition from high school to undergraduate institutions. The NSF Research Experiences for Undergraduates program has also been successful and could be further geared toward underrepresented groups.

Finding 3: Place-based research that incorporates indigenous landscapes and ways of thinking is one way to attract indigenous students. Indigenous peoples are underrepresented in the Earth sciences despite these cultures having a rich sense of place when it comes to the natural world (Palmer et al., 2009). Incorporating concepts like ethnogeology (how geological features are interpreted by cultures) into lessons can increase the accessibility of the Earth sciences. Presenting the Earth sciences in a way that is commensurate with, rather than in opposition to, native perspectives of Earth systems has had some success and is worthy of EAR education resources. An initiative such as NASA's Earth Science Division's Tribal Earth Science and Technology Education Program could be partnered with or emulated. The lessons learned in developing place-based Earth science education for native cultures may also be transferable to other groups, such as teaching watershed hydrology to urban students (Endreny, 2009).

Finding 4: The decline in traditional science journalism may be partly offset by fostering the scientist communicator. Support for the Earth sciences depends on citizens and policy makers understanding the high social and economic value of the Earth sciences to the nation. Traditionally, the most effective way of communicating the results of jargon-laden Earth science articles to laypeople has been through science journalism. With the decline in the number of science journalists nationwide (Brumfiel, 2009), the capacity to communicate the Earth sciences to laypeople is diminished, and there is a danger that U.S. citizens' understanding of the Earth sciences will be further challenged. One solution is to provide training and support for scientists interested in popular science writing such as online science blogging, short videos, or nonfiction book writing. Assisting scientists in developing a narrative that explains a new science concept will enhance communication with laypeople as well as interdisciplinary communication. Writing fellowships, media training, workshops, and courses that address science communication skills in today's media climate are several mechanisms for supporting science communication.

References

Affek, H.P., M. Bar-Matthews, A. Ayalon, A. Matthews, and J.M. Eiler. 2008. Glacial/interglacial temperature variations in Soreq cave speleothems as recorded by "clumped isotope" thermometry. *Geochimica et Cosmochimica Acta* 72(22):5351-5360.

AGI (American Geological Institute). 2009. *Status of the Geoscience Workforce: Report Summary*. Alexandria, VA: AGI.

AGU (American Geophysical Union). 2009. *AGU Position Statement: Geoengineering the Climate System*. Available online at www.agu.org/sci_pol/positions/geoengineering.shtml.

Ahnert, F. 1970. Functional relationship between denudation, relief and uplift in large mid-latitude drainage basins. *American Journal of Science* 268:243-263.

Alboussiere, T., R. Deguen, and M. Melzani. 2010. Melting-induced stratification above the Earth's inner core due to convective translation. *Nature* 466:744-747.

Alvarez, L.W., W. Alvarez, F. Asaro, and H.V. Michel. 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction: Experimental results and theoretical interpretation. *Science* 208(4448):1095-1108.

AMS (American Meteorological Society). 2009. *AMS Position Statement: Geoengineering the Climate System*. Available online at www.ametsoc.org/policy/2009geoengineeringclimate_amsstatement.html.

Appel, P.W.U., C.M. Fedo, and J.S. Myers. 2001. Depositional setting and paleogeographic implications of Earth's oldest supracrustal rocks, the >3.7 Ga Isua Greenstone belt, West Greenland. *Sedimentary Geology* 141:61-77.

Arneth, A., S.P. Harrison, S. Zaehle, K. Tsigaridis, S. Memom, P.J. Bartlein, J. Feitcher, A. Korhola, M. Kulmala, D. O'Donnell, G. Schurgers, S. Sorvari, and T. Vesala. 2010. Terrestrial biogeochemical feedbacks in the climate system. *Nature Geoscience* 3:525-530.

Aufdenkampe, A.K., E. Mayorga, P.A. Raymond, J.M. Melack, S.C. Doney, S.R. Alin, R.E. Aalto, and K. Yoo. 2011. Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Frontiers in Ecology and the Environment* 9:53-60.

Bala, G. 2009. Problems with geoengineering schemes to combat climate change. *Current Science* 96:41-48.

Barbier, E.B., E.W. Koch, B.R. Silliman, S.D. Hacker, E. Wolanski, J. Primavera, E.F. Granek, S. Polasky, S. Aswani, L.A. Cramer, D.M. Stoms, C.J. Kennedy, D. Bael, C.V. Kappel, G.M.E. Perillo, and D.J. Reed. 2008. Coastal ecosystem-based management with nonlinear ecological functions and values. *Science* 319:321-323.

Batt, G.E., and J. Braun. 1999. The tectonic evolution of the Southern Alps, New Zealand: Insights from fully thermally coupled dynamical modelling. *Geophysical Journal International* 136:403-420.

Beaumont, C., P. Kamp, J. Hamilton, and P. Fullsack. 1996. The continental collision zone, South Island, New Zealand: Comparison of geodynamical models and observations. *Journal of Geophysical Research* 101:3333-3359.

Beaumont, C., R.A. Jamieson, M.H. Nguyen, and B. Lee. 2001. Himalayan tectonics explained by extrusion of a low-viscosity crustal channel coupled to focused surface denudation. *Nature* 414:738-742.

Beaumont, C., R.A. Jamieson, M.H. Nguyen, and S. Medvedev. 2004. Crustal channel flows: 1. Numerical models with applications to the tectonics of the Himalayan-Tibetan orogen. *Journal of Geophysical Research* 109:B06406.

Beerling, D.J., B.H. Lomax, D.L. Royer, G.R. Upchurch, Jr., and L.R. Kump. 2003. An atmospheric pCO_2 reconstruction across the cretaceous-tertiary boundary from leaf megafossils. *Proceedings of the National Academy of Sciences USA* 99(12):7836-7840.

Bercovici, D., and S.-I. Karato. 2003. Whole-mantle convection and the transition-zone water filter. *Nature* 425:39-44.

Berger, A.L., S.P.S. Gulick, J.A. Spotila, P. Upton, J.M. Jaeger, J.B. Chapman, L.A. Worthington, T.L. Pavlis, K.D. Ridgway, B.A. Willems, and R.J. McAleer. 2008. Quaternary tectonic response to intensified glacial erosion in an orogenic wedge. *Nature Geoscience* 1:793-799.

Berner, R.A., and Z. Kothavala. 2001. GEOCARB III: A revised model of atmospheric CO_2 over phanerozoic time. *American Journal of Science* 301(2):182-204.

Billups, K., J.E.T. Channell, and J. Zachos. 2002. Late Oligocene to early Miocene geochronology and paleoceanography from the subantarctic South Atlantic. *Paleoceanography* 17(1):1004.

Birch, E.R., and P.W. Miller. 2007. The characteristics of "gap-year" students and their tertiary academic outcomes. *Economic Record* 83:329-344.

Bohaty, S.M., and J.C. Zachos, 2003. Significant Southern Ocean warming event in the late middle Eocene. *Geology* 31(11):1017-1020.

Borg, L.E., and D.S. Draper. 2003. A petrogenetic model for the origin and compositional variation of the martian basaltic meteorites. *Meteoritics & Planetary Science* 38:1713-1731.

Bouchenak-Khelladi, Y., A. Verboom, T.R. Hodkinson, N. Salamin, O. Francois, G. Chonghaile, and V. Savolainen. 2009. The origins and diversification of C4 grasses and savanna adapted ungulates. *Global Change Biology* 15:2397-2417.

Bouchon, M., and M. Vallee. 2003. Observation of long supershear rupture during the magnitude 8.1 Kunlunshan earthquake. *Science* 301:824-826.

Bowring, S.A., T.B. Housh, and C.E. Isachsen. 1990. The Acasta gneisses; remnant of Earth's early crust. Pp. 319-343 in *The Origin of the Earth*, H.E. Newsom and J.H. Jones, eds. New York: Oxford University Press.

Bowring, S.A. and I.S. Williams. 1999. Priscoan (4.00-4.03 Ga) orthogneisses from northwestern Canada. *Contributions to Mineralogy and Petrology* 134(1):3-16.

Brantley, S.L., T.S. White, A.F. White, D. Sparks, D. Richter, K. Pregitzer,L. Derry, O. Chorover, R. April, S. Anderson, and R. Amundson. 2006. *Frontiers in Exploration of the Critical Zone.* Report of a workshop sponsored by the National Science Foundation, October 24-26, 2005, Newark, DE, 30 pp.

Brantley, S.L., J.P. Megonigal, F.N. Scatena, Z. Balogh-Brunstad, R.T. Barnes, M.A. Bruns, P. Van Cappellen, K. Dontsova, H.E. Hartnett, A.S. Hartshorn, A. Heimsath, E. Herndon, L. Jin, C.K. Keller, J.R. Leake, W.H. McDowell, F.C. Meinzer, T.J. Mozdzer, S. Petsch, J. Pett-Ridge, K.S. Pregitzer, P.A. Raymond, C.S. Riebe, K. Shumaker, A. Sutton-Grier, R. Walter, and K. Yoo. 2011. Twelve testable hypotheses on the geobiology of weathering. *Geobiology* 9(2):140-165.

Brocks, J.J., G.D. Love, R.E. Summons, A.H. Knoll, G.A. Logan, and S.A. Bowden. 2005. Biomarker evidence for green and purple sulphur bacteria in a stratified Palaeoproterozoic sea. *Nature* 437:866-870.

Brozović, N., D. Burbank, and A. Meigs. 1997. Climatic limits on landscape development in the northwestern Himalaya. *Science* 276:571-574.

Brumfiel, G. 2009. Supplanting the old media? *Nature* 458:274-277.

Buggisch, W., M.M. Joachimski, G. Sevastopulo, and J.R. Morrow. 2008. Mississippian $\delta^{13}C_{carb}$ and conodont apatite $\delta^{13}O$ records—their relation to the Late Palaeozoic glaciation. *Palaeogeography Palaeoclimatology Palaeocology* 268:273-292.

Burke, K., B. Steinberger, T.H. Torsvik, and M.A. Smethurst. 2008. Plume generation zones at the margins of large low shear velocity provinces on the core-mantle boundary. *Earth Planetary Science Letters* 265:49-60.

Came, R.E., J.M. Eiler, J. Veizer, K. Azmy, U. Brand, and C.R. Weidman. 2007. Coupling of surface temperatures and atmospheric CO_2 concentrations during the Palaeozoic era. *Nature* 449:198-201.

Canadell, J.P., P. Ciais, S. Dhakal, H. Dolman, P. Friedlingstein, K.R. Gurney, A. Held, R.B. Jackson, C. Le Quéré, E.L. Malone, D.S. Ojima, A. Patwardhan, G.P. Peters, and M.R. Raupach. 2010. Interactions of the carbon cycle, human activity, and the climate system: A research portfolio. *Current Opinion in Environmental Sustainability* 2:301-311.

Canup, R.M. 2004. Simulations of a late lunar-forming impact. *Icarus* 168:433-456.

Canup, R.M., and E. Asphaug. 2001. Origin of the moon in a giant impact near the end of Earth's formation. *Nature* 412:708-712.

Catling, D. 2006. Comment on a hydrogen-rich early Earth atmosphere. *Science* 311:38.

Cavosie, A.J., J.W. Valley, and S.A. Wilde. 2005. Magmatic delta O-18 in 4400-3900 Ma detrital zircons: A record of the alteration and recycling of crust in the Early Archean. *Earth and Planetary Science Letters* 235:663-681.

Cerling, T.E. 1992. Development of grasslands and savannas in East Africa during the Neogene. *Palaeogeography, Palaeoclimatology, Palaeocology* 97:241-247.

CGS (Council of Graduate Schools). 2007. *Graduate Education: The Backbone of American Competitiveness and Innovation*. A report of the CGS Advisory Committee on Graduate Education and American Competitiveness, Washington, DC, 30 pp.

Chabot, N.L., D.S. Draper, and C.B. Agee. 2005. Conditions of core formation in the Earth: Constraints from nickel and cobalt partitioning. *Geochimica et Cosmochimica Acta* 69:2141-2151.

Chambers, J.E. 2004. Planetary accretion in the inner solar system. *Earth Planetary Science Letters* 224:241-252.

Chapin, F., G. Woodwell, J. Randerson, E. Rastetter, G. Lovett, D. Baldocchi, D. Clark, M. Harmon, D. Schimel, R. Valentini, C. Wirth, J. Aber, J. Cole, M. Goulden, J. Harden, M. Heimann, R. Howarth, P. Matson, A. McGuire, J. Melillo, H. Mooney, J. Neff, R. Houghton, M. Pace, M. Ryan, S. Running, O. Sala, W. Schlesinger, and E.D. Schulze. 2006. Reconciling carbon-cycle concepts, terminology, and methods. *Ecosystems* 9:1041-1050.

Chapman, J.B., T.L. Pavis, S. Gulick, A. Berger, L. Lowe, J. Spotial, R. Bruhn, M. Vorkink, P. Koons, A. Barker, C. Picornell, K. Ridgway, B. Hallet, J. Jaeger, and J. MacCalpin. 2008. Neotectonics of the Yakuttat collision: Changes in deformation driven by mass redistribution. Pp. 65-82 in *Active Tectonics and Seismic Potential of Alaska*, J.T. Freymueller et al., eds. Washington, DC: American Geophysical Union.

Compston, W., and R.T. Pidgeon. 1986. Jack Hills, evidence of more very old deetrital zircons in western Australia. *Nature* 321:766-769.

Crowley, T.J. 1998. Significance of tectonic boundary conditions for paleoclimate simulations. Pp. 3-17 in *Tectonic Boundary Conditions for Climate Reconstructions*, T.J. Crowley and K.C. Burke, eds. New York: Oxford University Press.

D'Odorico, P., F. Liao, and L. Ridolfi. 2010a. Does globalization of water reduce societal resilience to drought? *Geophysical Research Letters* 37:L13403.

D'Odorico, P., F. Liao, A. Porporato, L. Ridolfi, A. Rinaldo, and I. Rodriquez-Iturbe. 2010b. Ecohydrology of terrestrial ecosystems. *BioScience* 60(11):898-907.

Dasgupta, R., and M.M. Hirschmann. 2010. The deep carbon cycle and melting in Earth's interior. *Earth and Planetary Science Letters (Frontiers)* 298:1-13.

Davis, S.J., W.R. Dickinson, G.E. Gehrels, J.E. Spencer, T.F. Lawton, and A.R. Carroll. 2010. The Paleogene California River: Evidence of Mojave-Uinta paleodrainage from U-Pb ages of detrital zircons. *Geology* 38(10):931-934.

Delahaye, E.J., J. Townend, M.E. Reyners, and G. Rogers. 2009. Microseismicity but no tremor accompanying slow slip in the Hikurangi subduction zone, New Zealand. *Earth and Planetary Science Letters* 277:21-28.

Delsuc, F., H. Brinkmann, and H. Philippe. 2005. Phylogenomics and the reconstruction of the tree of life. *Nature Reviews Genetics* 6:361-375.

Dietrich, W.E., D.G. Bellugi, L.S. Sklar, J.D. Stock, A.M. Heimsath, and J.J.

Roering. 2003. Geomorphic transport laws for predicting landscape form and dynamics. Pp. 1-30 in *Prediction in Geomorphology*. Geophysical Monograph 135. Washington, DC: American Geophysical Union.

Dolan, J.F., D.D. Browman, and C.G. Sammis. 2007. Long-range and long-term fault interactions in Southern California. *Geology* 35(9):855-858.

Douglas, A., J. Beavan, L. Wallace, and J. Townend. 2005. Slow slip on the northern Hikurangi subduction interface, New Zealand. *Geophysical Research Letters* 32:L16305.

Duffy, T.S. 2008. Mineralogy at the extremes. *Nature* 451:269-270.

Dunham, E.M., and R. J. Archuleta. 2005. Near-source ground motion from steady state dynamic rupture pulses. *Geophysical Research Letters* 32:L03302.

Eagle, R.A., E.A. Schauble, A.K. Tripati, T. Tutken, R.C. Hulbert, and J.M. Eiler. 2010. Body temperatures of modern and extinct vertebrates from ^{13}C-^{18}O bond abundances in bioapatite. *Proceedings of the National Academy of Sciences USA* 107:10,377-10,382.

Ehrmann, W.U., and A. Mackensen. 1992. Sedimentological evidence for the formation of an East Antarctic ice-sheet in Eocene Oligocene time. *Palaeogeography, Palaeoclimatology, Palaeocology* 93(1-2):85-112.

Eiler, J.M. 2007. Clumped-isotope geochemistry—the study of naturally-occurring, multiply-substituted isotopologues. *Earth and Planetary Science Letters* 262:309-327.

Elrick, M., and L.A. Scott. 2010. Carbon and oxygen isotope evidence for high-frequency (104-105 yr) and My-scale glacio-eustasy in Middle Pennsylvanian cyclic carbonates (Gray Mesa Formation), central New Mexico. *Palaeogeography, Palaeoclimatology, Palaeocology* 285:307-320.

Endreny, A.H. 2009. Urban 5th graders' conceptions during a place-based inquiry unit on watersheds. *Journal of Research in Science Teaching* 47:501-517.

Enghold, D.L., S.B. Nielsen, V.K. Pedersen, and J.-E. Lesemann. 2009. Glacial effects limiting mountain height. *Nature* 460:884-887.

Evans, D.A.D. 2000. Stratigraphic, geochronological, and paleomagnetic constraints upon the Neoproterozoic climatic paradox. *American Journal of Science* 300:347-433.

Famiglietti, J.S., M. Lo, S.L. Ho, J. Bethune, K.J. Anderson, T.H. Syed, S.C. Swenson, C.R. de Linage, and M. Rodell. 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophysical Research Letters* 38:L03403.

Farquhar, J., H.M. Bao, and M. Thiemens. 2000. Atmospheric influence of Earth's earliest sulfur cycle. *Science* 289(5480):756-758.

Feagin, R.A., S.M. Lozana-Bernard, T.M. Ravens, I. Moller, K.M. Yeager, and A.H. Baird. 2009. Does vegetation prevent wave erosion of salt marsh edges? *Proceedings of the National Academy of Sciences USA* 106:10,109-10,113.

Feagin, R.A., W.K. Smith, N.P. Psuty, D.R. Young, M.L. Martinez, G.A. Carter, K.L. Lucas, J.C. Gibeaut, J.N. Gemma, and R.E. Koske. 2010. Barrier islands: Coupling anthropogenic stability with ecological sustainability. *Journal of Coastal Research* 26:987-992.

Feakins, S.J., P.B. deMenocal, and T.I. Eglinton. 2005. Biomarker records of late Neogene changes in northeast African vegetation. *Geology* 33:977-980.

Finnegan, S., K. Bergmann, J.M. Eiler, D.S. Jones, D.A. Fike, I. Eisenman, N.C. Hughes, A.K. Tripati, and W.W. Fischer. 2011. The magnitude and duration of late Ordovician–early Silurian glaciation. *Science* 331:903-906.

Finzi, A.C., J.J. Cole, S.C. Doney, E.A. Holland, and R.B. Jackson. 2011. Research frontiers in the analysis of coupled biogeochemical cycles. *Frontiers in Ecology and the Environment* 9:74-80.

Fricke, H.C., and S.L. Wing. 2004. Oxygen isotope and paleobotanical estimates of temperature and δ^{18}O-latitude gradients over North America during the early Eocene. *American Journal of Science* 304:612-635.

Frieler, K., M. Meinshausen, T.S. von Deimling, T. Andrews, and P. Forster. 2011. Changes in global-mean precipitation in response to warming, greenhouse gas forcing and black carbon. *Geophysical Research Letters* 38:L04702.

Galloway, J.N., A.R. Townsend, J.W. Erisman, M. Bekunda, Z. Cai, J.R. Freney, L.A. Martinelli, S.P. Seitzinger, and M.A. Sutton. 2008. Transformation of the nitrogen cycle: Recent trends, questions and potential solutions. *Science* 320:889-892.

Garnero, E.J., and A.K. McNamara. 2008. Structure and dynamics of Earth's lower mantle. *Science* 320:626-628.

Garnero, E.J., T. Lay, and A.K. McNamara. 2007. Implications of lower-mantle structural heterogeneity for existence and nature of whole-mantle plumes. Pp. 79-91 in *Plates, Plumes and Planetary Processes*, G.R. Foulger and D.M. Jurdy, eds. Special Papers of the Geological Society of America, vol. 430.

Garzione, C.N., G.D. Hoke, J.C. Libarkin, S. Withers, B. MacFadden, J. Eiler, P. Ghosh, and A. Mulch. 2008. Rise of the Andes. *Science* 320(5881):1304.

Gaucher, E.A., J.M. Thomson, M.F. Burgan, and S.A. Benner. 2003. Inferring the palaeoenvironment of ancient bacteria on the basis of resurrected proteins. *Nature* 425:285-288.

Gaucher, E.A., S. Govindarajan, and O.K. Ganesh. 2008. Palaeotemperature trend for Precambrian life inferred from resurrected proteins. *Nature* 451:704-707.

Gedney, N., P.M. Cox, R.A. Betts, O. Boucher, C. Huntingford, and P.A. Stott. 2006. Detection of a direct carbon dioxide effect in continental river runoff records. *Nature* 439:835-838.

Gerten, D., S. Rost, W. von Bloh, and W. Lucht. 2008. Causes of change in 20th century global river discharge. *Geophysical Research Letters* 37:L20405.

Ghosh, P., J. Adkins, H. Affek, B. Balta, W.F. Guo, E.A. Schauble, D. Schrag, and J.M. Eiler. 2006. ^{13}C–^{18}O bonds in carbonate minerals: A new kind of paleothermometer. *Geochimica et Cosmochimica Acta* 70(6):1439-1456.

Gouy, M., and M. Chaussidon. 2008. Evolutionary biology: Ancient bacteria liked it hot. *Nature* 451:635-636.

Gradstein, F.M., J.G. Ogg, and A.G. Smith, eds. 2004. *A Geologic Time Scale*. Cambridge: Cambridge University Press, 589 pp.

Grosse, G., V. Romanovsky, T. Jorgenson, K.W. Anthony, J. Brown, and P.P. Overduin. 2011. Vulnerability and feedbacks of permafrost to climate change. *Eos, Transactions, American Geophysical Union* 92:73-74.

Gruber, N., and J.N. Galloway. 2008. An Earth-system perspective of the global nitrogen cycle. *Nature* 451:293-296.

Grzymskia, J.J., A.E. Murraya, B.J. Campbell, M. Kaplarevic, G.R. Gao, C.R. Daniel, A. Ghadiri, R.A. Feldman, and S.C. Caryb. 2008. Metagenome analysis of an extreme microbial symbiosis reveals eurythermal adaptation and metabolic flexibility. *Proceedings of the National Academy of Sciences USA* 105(45):17,516-17,521.

Guo, W., and J.M. Eiler. 2007. Temperatures of aqueous alteration and evidence for methane generation on the parent bodies of the CM chondrites. *Geochimica et Cosmochimica Acta* 71:5565-5575.

Gussow, K., A. Proelss, A. Oschlies, K. Rehdanz, and W. Rickels. 2010. Ocean iron fertilization: Why further research is needed. *Marine Policy* 34:911-918.

Halliday, A. 2004. Mixing, volatile loss and compositional change during impact-driven accretion of the Earth. *Nature* 427(6974):505-509.

Halliday, A. 2006. The origin of the Earth. What's new? *Elements* 2:205-210.

Halliday, A. 2008. A young moon-forming giant impact at 70–110 million years accompanied by late-stage mixing, core formation and degassing of the earth. *Philos. Trans. R. Soc.* A 366:4163–4181.

Hambrey, M.J., W.U. Ehrmann, and B. Larsen. 1991. Cenozoic glacial record of the Prydz Bay continental shelf, East Antarctica. Pp. 77-131 in *Proceedings of the Ocean Drilling Program: Scientific Results*, vol. 119. College Station, TX: Ocean Drilling Program.

Hansen, J.E., and M. Sato. 2001. Trends of measured climate forcing agents. *Proceedings of the National Academy of Sciences USA* 98:14,778-14,783.

Hansen, J., M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos. 2008. Target atmospheric CO_2: Where should humanity aim? *The Open Atmospheric Science Journal* 2:217-231.

Harrison, T.M. 2009. The Hadean Crust: Evidence from >4 Ga zircons. *Annual Review of Earth and Planetary Science*, pp. 479-505.

Hilley, G.E., and J.R. Arrowsmith. 2008. Geomorphic response to uplift along the Dragon's Back pressure ridge, Carrizo Plain, California. *Geology* 36:367-370.

Hilley, G.E., M. Strecker, and V.A. Ramos. 2004. Growth and erosion of fold-and-thrust belts with an application to the Aconcagua fold and thrust belt, Argentina. *Journal of Geophysical Research* 109.

Hirschmann, M. 2006. Water, melting, and the deep Earth H_2O cycle. *Annual Review of Earth and Planetary Science* 34:629-653.

Hirth, G., and D.L. Kohlstedt. 1996. Water in the oceanic upper mantle: Implications for rheology, melt extraction and the evolution of the lithosphere. *Earth and Planetary Science Letters* 144:93-108.

Hodges, K., J.M. Hurtado, and K. Whipple. 2001. Southward extrusion of Tibetan crust and its effect on Himalayan tectonics. *Tectonics* 20:799-809.

Hoegh-Guldberg, O., P.J. Mumby, A.J. Hooten, R.S. Steneck, P. Greenfield, E. Gomez, C.D. Harvell, P.F. Sale, A.J. Edwards, K. Caldeira, N. Knowlton, C.M. Eakin, R. Iglesias-Prieto, N. Muthiga, R.H. Bradbury, A. Dubi, and M.E. Hatziolos. 2007. Coral reefs under rapid climate change and ocean acidification. *Science* 14:1737-1742.

Hoffman, M., and D. Barstow. 2007. *Revolutionizing Earth System Science Education for the 21st Century: Report and Recommendations from a 50-State Analysis of Earth Science Education Standards*. Cambridge, MA: TERC Center for Earth and Space Science Education, 59 pp.

Holden, P., P. Lanc, T.R. Ireland, T.M. Harrison, J.J. Foster, and Z. Bruce. 2009. Mass-spectrometric mining of Hadean zircons by automated SHRIMP multi-collector and single-collector U/Pb zircon age dating: The first 100,000 grains. *International Journal of Mass Spectrometry* 286:53-63.

Hopkins, M., T.M. Harrison, and C.E. Manning. 2008. Low heat flow inferred from >4 Gyr zircons suggests Hadean plate boundary interactions. *Nature* 456:493-496.

Huntington, T.G. 2008. CO_2-induced suppression of transpiration cannot explain increasing runoff. *Hydrological Processes* 22:311-314.

Huybers, P., and C. Langmuir. 2009. Feedback between deglaciation, volcanism, and atmospheric CO_2. *Earth and Planetary Science Letters* 286:479-491.

Ide, S., G.C. Beroza, D.R. Shelly, and T. Uchide. 2007. A scaling law for slow earthquakes. *Nature* 447:76-79.

Ishii, M., and A.M. Dziewonski. 2002. The innermost inner core of the Earth: Evidence for a change in anisotropic behavior at the radius of about 300 km. *Proceedings of the National Academy of Sciences USA* 99:14,026-14,030.

Ishii, M., P.M. Shearer, H. Houston, and J.E. Vidale. 2005. Extent, duration and speed of the 2004 Sumatra-Andaman earthquake imaged by the Hi-net array. *Nature* 435:933-936.

Jansen, E., J. Overpeck, K.R. Briffa, J.-C. Duplessy, F. Joos, V. Masson-Delmotte, D. Olago, B. Otto-Bliesner, W.R. Peltier, S. Rahmstorf, R. Ramesh, D. Raynaud, D. Rind, O. Solomina, R. Villalba, and D. Zhang. 2007. Palaeoclimate. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds. Cambridge: Cambridge University Press.

Jellinek, A.M., M. Manga, and M.O. Saar. 2004. Did melting glaciers cause volcanic eruptions in eastern California? Probing the mechanics of dike formation. *Journal of Geophysical Research* 109:B09206.

Jones, B.M., C.D. Aro, M.T. Jorgenson, K.M. Hinkel, J.A. Schmutz, and P.L. Flint. 2009. Increase in the rate and uniformity of coastline erosion in Arctic Alaska. *Geophysical Research Letters* 36:L03503.

Johnson, C.M., B.L. Beard, and E.E. Roden. 2008. The iron isotope fingerprints of redox and biogeochemical cycling in the modern and ancient Earth. *Annual Review of Earth and Planetary Sciences* 36:457-493.

Johnston, D.T., J. Farquhar, K.S. Habicht, and D.E. Canfield. 2008. Sulfur isotopes and the search for life: Strategies for identifying sulfur metabolisms in the rock record and beyond. *Geobiology* 6:425-435.

Jull, M., and D. MacKenzie. 1996. The effect of deglaciation on mantle melting beneath Iceland. *Journal of Geophysical Research* 101:21,815-21,828.

Kasting, J.F., and S. Ono. 2006. Paleoclimates: The first two billion years. *Philosophical Transactions of the Royal Society B* 361:917-929.

Katsumata, A., and N. Kamaya. 2003. Low-frequency continuous tremor around the Moho discontinuity away from volcanoes in the southwest Japan. *Geophysical Research Letters* 30.

Kellogg, L., B. Buffett, C. Constable, R. Jeanloz, G. Masters, W. McDonough, and R. Walker. 2004. *Cooperative Studies of the Earth's Deep Interior, Developments, Discovery, Future.* Report to the National Science Foundation. Available online at CSEDI.org. 42 pp.

Kennett, J.P., and L.D. Stott. 1991. Abrupt deep-sea warming, palaeoceanographic changes and benthic extinctions at the end of the Palaeocene. *Nature* 353:225-229.

Kiehl, J. 2011. Lessons from Earth's past. *Science* 331:158-159.

Kim, M.J., S.Y. Schwartz, and S. Bannister. 2011. Non-volcanic tremor associated with the March 2010 Gisborne slow slip event at the Hikurangi subduction margin, New Zealand. *Geophysical Research Letters* 38(L14301).

Kirwan, M.L., G.R. Guntenspergen, A. D'Alpaos, J.T. Morris, S.M. Mudd, and S. Temmerman. 2010. Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research Letters* 37:L23401.

Kleine, T., K. Mezger, H. Palme, and C. Munker. 2004. The W isotope evolution of the bulk silicate earth: Constraints on the timing and mechanisms of core formation and accretion. *Earth and Planetary Science Letters* 228:109-123.

Kohut, A., S. Keeter, C. Doherty, M. Dimock, M. Remez, R. Suls, S. Neidorf, L. Christian, J. Kiley, and A. Tyson. 2009. *Modest Support for "Cap and Trade" Policy; Fewer Americans See Solid Evidence of Global Warming*. Report of the Pew Research Center for the People & the Press, Washington, DC, 22 pp.

Koons, P.O. 1990. The two-sided orogen: Collision and erosion from the sand box to the Southern Alps, New Zealand. *Geology* 18:679-682.

Koons, P.O., P.K. Zeitler, C. Chamberlain, D. Craw, and A.S. Meltzer. 2002. Mechanical links between erosion and metamorphism in Nanga Parbat, Pakistan Himalaya. *Amerian Journal of Science* 302:749-773.

Koppes, M.N., and D.R. Montgomery. 2009. The relative efficacy of fluvial and glacial erosion over modern to orogenic time scales. *Nature Geoscience* 2:644-647.

Kostoglodov, V., S.K. Singh, J.A. Santiago, S.I. Franco, K.M. Larson, A. Lowry, and R. Bilham. 2003. A large silent earthquake in the Guerrero seismic gap, Mexico. *Geophysical Research Letters* 30(15):1807.

Kuiper, K.F., A. Deino, F.J. Hilgen, W. Krijgsman, P.R. Renne, and J.R. Wijbrans. 2008. Synchronizing rock clocks of Earth history. *Science* 320(5875):500-504.

Labat, D., Y. Goddéris, J.L. Probst, and J.L. Guyot. 2004. Evidence for global runoff increase related to climate warming. *Advances in Water Resources* 27:631-642.

Labrosse, S., J.W. Herlund, and N.A. Coltice. 2007. A crystallizing dense magma ocean at the base of the Earth's mantle. *Nature* 450:866-869.

Lay, T., ed. 2009. *Seismological Grand Challenges in Understanding Earth's Dynamic Systems*. Report to the National Science Foundation, IRIS Consortium, of a workshop held September 18–19, 2008, Denver, CO. 76 pp.

Lay, T., C.J. Ammon, H. Kanamori, K.D. Koper, O. Sufri, and A.R. Hutko. 2010a. Teleseismic inversion for rupture process of the 27 February 2010 Chile (Mw 8.8) earthquake. *Geophysical Research Letters* 37:L13301.

Lay, T., C.J. Ammon, A.R. Hutko, and H. Kanamori. 2010b. Effects of kinematic constraints on teleseismic finite-source rupture inversions: Great Peruvian earthquakes of 23 June 2001 and 15 August 2007. *Bulletin of the Seismology Society of America* 100:969-994.

Le Quéré, C., M.R. Raupach, J.G. Canadell, G. Marland, L. Bopp, P. Ciais, T.J. Conway, S.C. Doney, R.A. Feely, P. Foster, P. Friedlingstein, K. Gurney, R.A. Houghton, J.I. House, C. Huntingford, P.E. Levy, M.R. Lomas, J. Majkut, N. Metzl, J.P. Ometto, G.P. Peters, I.C. Prentice, J.T. Randerson, S.W. Running, J.L. Sarmiento, U. Schuster, S. Sitch, T. Takahashi, N. Viovy, G.R. van der Werf, and F.I. Woodward. 2009. Trends in the sources and sink of carbon dioxide. *Nature Geoscience* 2:831-836.

Leakey, A.D.B., E.A. Ainsworth, C.J. Bernacchi, A. Rogers, S.P. Lon, and D.R. Ort. 2009. Elevated CO_2 effects on plant carbon, nitrogen, and water relations: Six important lessons from FACE. *Journal of Experimental Botany* 60:2859-2876.

Lear, C.H., Y. Rosenthal, H.K. Coxall, and P.A. Wilson. 2004. Late Eocene to early Miocene ice sheet dynamics and the global carbon cycle. *Paleoceanography* 19(4):PA4015.

Lemasurier, W.E., and S. Rocchi. 2005. Terrestrial record of post-Eocene climate history in Marie Byrd Land, West Antarctica. *Geografiska Annaler* 87A(1):51-66.

Lovett, G., J. Cole, and M. Pace. 2006. Is net ecosystem production equal to ecosystem carbon accumulation? *Ecosystems* 9:152-155.

Lowenstein, T.K., and R.V. Demicco. 2006. Elevated Eocene atmospheric CO_2 and its subsequent decline. *Science* 313:1928-1928.

MacLennan, J., M. Jull, D. Mckenzie, L. Slater, and K. Gronvold. 2002. The link between volcanism and deglaciation in Iceland. *Geochemistry Geophysics Geosystems* 3(11):1062.

Maloof, A.C., J. Ramezani, S.A. Bowring, D.A. Fike, S.M. Porter, and M. Mazouad. 2010. Constraints on early Cambrian carbon cycling from the duration of the Nemakit-Daldynian-Tommotian boundary delta C-13 shift, Morocco. *Geology* 38(7):623-626.

Mao, W.L., H.K. Mao, W. Sturhahn, J. Zhao, V.B. Prakapenka, Y. Meng, J. Shu, Y. Fei, and R.J. Hemley. 2006. Iron-rich post-perovskite and the origin of ultralow-velocity zones. *Science* 312:564-565.

MARGINS Office. 2010. *GeoPRISMS Draft Science Plan*. Report to National Science Foundation, 140 pp. Available online at www.nsf-margins.org/Planning_and_review/DSP_final.html.

Martin, W., and M.J. Russell. 2007. On the origin of biochemistry at an alkaline hydrothermal vent. *Philosophical Transactions of the Royal Society of London B* 362(1486):1887-1925.

Mattinson, J.M. 2005. Zircon U-Pb chemical abrasion (“CA-TIMS”) method: Combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. *Chemical Geology* 220(1-2):47-66.

McCaffrey, R., A.I. Qamar, R.W. King, R. Wells, G. Khazaradze, C.A. Williams, C.W. Stevens, J.J. Vollick, and P.C. Zwick. 2007. Fault locking, block rotation and crustal deformation in the Pacific Northwest. *Geophysical Journal International* 169:1315-1340.

McElwain, J.C., D.J. Beerling, and F.I. Woodward. 1999. Fossil plants and global warming at the Triassic-Jurassic boundary. *Science* 285:1386-1390.

McElwain, J.C., J. Wade-Murphy, and S.P. Hesselbo. 2005. Changes in carbon dioxide during an oceanic anoxic event linked to intrusion into Gondwana coals. *Nature* 435:479-482.

McNamara, A.K., and S. Zhong. 2005. Thermochemical structures beneath Africa and the Pacific Ocean. *Nature* 437:1136-1139.

McNamara, D.E., and B.T. Werner. 2008. Coupled barrier island—resort model: 1. Emergent instabilities induced by strong human-landscape interactions. *Journal of Geophysical Research* 113:F01016.

Meehl, G.A. 1992. Effect of tropical topography on global climate. *Annual Reviews of Earth and Planetary Science* 20:85-112.

Miller, M.M., T.I. Melbourne, D.J. Johnson, and W.Q. Sumner. 2002. Periodic slow earthquakes from the Cascadia subduction zone. *Science* 295:2423.

Mitchell, S.G., and D.R. Montgomery. 2006. Influence of a glacial buzzsaw on the height and morphology of the Cascade Range in central Washington state, USA. *Quaternary Research* 65:96-107.

Mitrovica, J.X., N. Gomez, and P.U. Clark. 2009. The sea-level fingerprint of West Antarctic collapse. *Science* 323:753.

Mojzsis, S.J., T.M. Harrison, and R.T. Pidgeon. 2001. Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 MYr ago. *Nature* 409:178-181.

Monnereau, M., M. Calvet, L. Margerin, and A. Souriau. 2010. Lopsided growth of Earth's inner core. *Science* 328:1014-1017.

Mosenfelder, J.L., P.D. Asimow, and T.J. Ahrens. 2007. Thermodynamic properties of Mg_2SiO_4 liquid at ultra-high pressures from shock measurements to 200 GPa on forsterite and wadsleyite. *Journal of Geophysical Research* 112:B06208.

Moynier, F., Q.-Y. Yin, K. Irisawa, M. Boyet, B. Jacobsen, and M.T. Rosgin. 2010. Coupled $182W\text{-}142^{Nd}$ constraint for early Earth differentiation. *Proceedings of the National Academy of Sciences USA* 107:10,810-10,814.

Murakami, M., K. Hirose, K. Kawamura, N. Sata, and Y. Ohishi. 2004. Post-perovskite phase transition in $MgSiO_3$. *Science* 304:855-858.

Myers, B., S.R. Brantley, P. Stauffer, and J.W. Hendley II. 2008. *What Are Volcanic Hazards?* USGS Fact Sheet 002-97. Vancouver, WA: U.S. Geological Survey.

Naish, T., R. Powell, R. Levy, G. Wilson, R. Scherer, F. Talarico, L. Krissek, F. Niessen, M. Pompilio, T. Wilson, L. Carter, R. DeConto, P. Huybers, R. McKay, D. Pollard, J. Ross, D. Winter, P. Barrett, G. Browne, R. Cody, E. Cowan, J. Crampton, G. Dunbar, N. Dunbar, F. Florindo, C. Gebhardt, I. Graham, M. Hannah, D. Hansaraj, D. Harwood, D. Helling, S. Henrys, L. Hinnov, G. Kuhn, P. Kyle, A. Läufer, P. Maffioli, D. Magens, K. Mandernack, W. McIntosh, C. Millan, R. Morin, C. Ohneiser, T. Paulsen, D. Persico, I. Raine, J. Reed, C. Riesselman, L. Sagnotti, D. Schmitt, C. Sjunneskog, P. Strong, M. Taviani, S.

Vogel, T. Wilch, and T. Williams. 2009. Obliquity-paced Pliocene West Antarctic ice sheet oscillations. *Nature* 458:322-328.

Nakagawa, T., and P.J. Tackley. 2004. Effects of thermo-chemical mantle convection on the thermal evolution of the Earth's core. *Earth and Planetary Science Letters* 220:107-119.

National Center for Education Statistics. 2011. *The Nation's Report Card: Science 2009*. NCES 2011-451. Washington, DC: U.S. Department of Education, 79 pp.

Newport, F. 2009. *On Darwin's Birthday, Only 4 in 10 Believe in Evolution*. Gallup poll, February 6-7, 2009. Available online at www.gallup.com/poll/114544/darwin-birthday-believe-evolution.aspx.

Ni, S., D.V. Helmberger, and J. Tromp. 2005. Three-dimensional structure of the Africa superplume from waveform modeling. *Geophysical Journal International* 161:283-294.

Nicholls, R.J., and A. Cazenave. 2010. Sea-level rise and its impact on coastal zones. *Science* 328:1517-1520.

Nicholls, R.J., F.M.J. Hoozemans, and M. Marchand. 1999. Increasing flood risk and wetland losses due to global sea-level rise: Regional and global analysis. *Global Environmental Change* 9:S65-S87.

Nilsson, C., C.A. Reidy, M. Dynesius, and C. Revenga. 2005. Fragmentation and flow regulation of the world's large river systems. *Science* 308:405-408.

Nimmo, F. 2007. Thermal and compositional evolution of the core. *Treatise on Geophysics,* G. Schubert, main ed., vol. 9, *Evolution of the Earth*, D. Stevenson, vol. ed., pp. 217-242. New York: Elsevier B. V.

NRC (National Research Council). 2001. *Basic Research Opportunities in Earth Science*. Washington, DC: National Academies Press.

NRC (National Research Council). 2006. *To Recruit and Advance: Women Students and Faculty in U.S. Science and Engineering*. Washington, DC: National Academies Press.

NRC (National Research Council). 2008. *Origin and Evolution of Earth*. Washington, DC: National Academies Press, 137 pp.

NRC (National Research Council). 2009. *Evaluation of NSF's Program of Grants and Vertical Integration of Research and Education in the Mathematical Sciences (VIGRE).* Washington, DC: National Academies Press.

NRC (National Research Council). 2010a, *Landscapes on the Edge: New Horizons for Research on Earth's Surface*. Washington, DC: National Academies Press.

NRC (National Research Council). 2010b. *Understanding Climate's Influence on Human Evolution*. Washington, DC: National Academies Press, 128 pp.

NRC (National Research Council). 2010c. *Expanding Underrepresented Minority Participation: America's Science and Technology Talent at the Crossroads.* Washington, DC: National Academies Press.

NRC (National Research Council). 2010d. *Rising Above the Gathering Storm, Revisited.* Washington, DC: National Academies Press.

NRC (National Research Council). 2011a. *Understanding Earth's Deep Past: Lessons for Our Climate Future*. Washington, DC: National Academies Press.

NRC (National Research Council). 2011b. *Successful K-12 STEM Education: Identifying Effective Approaches in Science, Technology, Engineering, and Mathematics*. Washington, DC: National Academies Press, 48 pp.

NRC (National Research Council). In preparation. *Challenges and Opportunities in the Hydrologic Sciences*. Washington, DC: National Academies Press.

NSF (National Science Foundation). 2008. *Broadening Participation at the National Science Foundation: A Framework for Action*. Washington, DC: NSF. 47 pp.

NSF (National Science Foundation). 2010. *Earth Science Literacy Principles: The Big Ideas and Supporting Concepts of Earth Science*. Washington, DC: NSF, 11 pp.

NSF (National Science Foundation). 2011. *Women, Minorities, and Persons with Disabilities in Science and Engineering: 2011*. Report 11-309. Washington, DC: NSF.

O'Connell, S., and A. Holmes. 2011. Obstacles to the recruitment of minorities into the geosciences: A call to action. *GSA Toda*y 21:52-54.

O'Neil, J., R.W. Carlson, D. Francis, and R.K. Stevenson. 2008. Neodymium-142 evidence for Hadean mafic crust. *Science* 321:1828-1831.

Obara, K. 2002. Nonvolcanic deep tremor associated with subduction in southwest Japan. *Science* 296:1679-1681.

Obara, K., H. Hirose, F. Yamamizu, and K. Kasahara. 2004. Episodic slow slip events accompanied by non-volcanic tremors in southwest Japan subduction zone. *Geophysical Research Letters* 31.

Oda, H., A. Usui, I. Miyagi, M. Joshima, B.P. Weiss, C. Shantz, L.E. Fong, K.K. McBride, R. Harder, and F.J. Baudenbacher. 2011. Ultrafine-scale magnetostratigraphy of marine ferromanganese crust. *Geology* 39:227-230.

Ohta, K., K. Hirose, T. Lay, N. Sata, and Y. Ohishi. 2008. Phase transitions in pyrolite and MORB at lowermost mantle conditions: Implications for a MORB-rich pile above the core-mantle boundary. *Earth and Planetary Science Letters* 267:107-117.

Ohtani, E., K. Litasov, T. Hosoya, T. Kubo, and T. Kondo. 2004. Water transport into the deep mantle and formation of a hydrous transition zone. *Physics of the Earth and Planetary Interiors* 143:255-269.

Olsen, K.B., S.M. Day, J.B. Minster, Y. Cui, A. Chourasia, D. Okaya, P. Maechling, and T. Jordan. 2008. TeraShake2: Spontaneous rupture simulation of Mw 7.7 earthquakes on the Southern San Andreas Fault. *Bulletin of the Seismological Society of America* 98(3):1162-1185.

Olson, P., ed. 2010. *Grand Challenges in Geodynamics: Outstanding Geodynamics Problems and Emerging Research Opportunities for the Earth Sciences*. Report to the National Science Foundation, 109 pp.

Ometto, J., A. Nobre, H. Rocha, P. Artaxo, and L. Martinelli. 2005. Amazonia and the modern carbon cycle: Lessons learned. *Oecologia* 143:483-500.

O'Neil, J., Carlson, R.W., Francis, D., and Stevenson, R.K. 2008. Neodymium-142 evidence for Hadean mafic crust. *Science*, 321:1828-1831.

Owen, J.J., R. Amundson, W.E. Dietrich, K. Nishiizumi, B. Sutter, and G. Chong. 2011. The sensitivity of hillslope bedrock erosion to precipitation. *Earth Surface Processes and Landforms* 36:117-135.

Pagani, M., N. Pedentchouk, M. Huber, A. Sluijs, S. Schouten, H. Brinkhuis, J.S. Sinninghe Damsté, G.R. Dickens, and others. 2006. Arctic hydrology during global warming at the Palaeocene/Eocene thermal maximum. *Nature* 442(7103):671-675.

Pagani, M., Z. Liu, J. LaRiviere, and A.C. Ravelo. 2010. High Earth-system climate sensitivity determined from Pliocene carbon dioxide concentrations. *Nature Geoscience* 3:27-30.

Pälike, H., R.D. Norris, J.O. Herrle, P.A. Wilson, H.K. Coxall, C.H. Lear, N.J. Shackleton, A.K. Tripati, and B.S. Wade. 2006b. The heartbeat of the Oligocene climate system. *Science* 314:1894-1898.

Palmer, M.H., R.D. Elmore, M.J. Watson, K. Kloesel, and K. Palmer. 2009. Xoa:dau to Maunkaui: Integrating indigenous knowledge into an undergraduate Earth systems science course. *Journal of Geoscience Education* 57:137-144.

Passey, B.H., N.E. Levin, T.E. Cerling, F.H. Brown, and J.M. Eiler. 2010. High temperature environments of human evolution in East Africa based on bond ordering in paleosol carbonates. *Proceedings of the National Academy of Sciences USA* 107:11,245-11,249.

Passey, B., G. Henkes, E. Grossman, and T. Yancey. 2011. *Deep-time paleoclimate reconstruction using carbonate clumped isotope thermometry: A status report.* Programme and Abstracts: The XVII International Congress on the Carboniferous and Permian, Perth, Australia, July 2011.

Payero, J.S., V. Kostoglodov, N. Shapiro, T. Mikumo, A. Iglesias, X. Perez-Campos, and R.W. Clayton. 2008. Nonvolcanic tremor observed in the Mexican subduction zone. *Geophysics Research Letters* 35:L07305.

Perry, S., D. Cox, L. Jones, R. Bernknopf, J. Goltz, K. Hudnut, D. Mileti, D. Ponti, K. Porter, M. Reichle, H. Seligson, K. Shoaf, J. Treiman, and A. Wein. 2008. *The Shake-Out Earthquake Scenario—A Story That Southern Californians Are Writing*. California Geological Survey Special Report 207. U.S. Geological Survey Circular 1324. Available online at http://pubs.usgs.gov/circ/1324/.

Peterson, C.H., and M.J. Bishop. 2005. Assessing the environmental impacts of beach nourishment. *BioScience* 55:887-896.

Poulton S.W., and D.E. Canfield. 2005. Development of a sequential extraction procedure for iron: Implications for iron partitioning in continentally derived particulates. *Chemical Geology* 214:209-221.

Raup, D.M., and L.J. Sepkosko. 1984. Periodicity of extinctions in the geologic past. *Proceedings of the National Academy of Sciences USA* 81:801-805.

Ravishankara, A.R., J.S. Daniel, and R.W. Portman. 2009. Nitrous oxide (N_2O): The dominant ozone-depleting substance emitted in the 21st century. *Science* 326:123-125.

Raymond, P.A., N.-H. Oh, R.E Turner, and W. Broussard. 2008. Anthropogenically enhanced fluxes of water and carbon from the Mississippi River. *Nature* 451:449-452.

Reiners, P.W., T.A. Ehlers, S.G. Mitchell, and D.R. Montgomery. 2003. Coupled spatial variations in precipitation and long-term erosion rates across the Washington Cascades. *Nature* 426:645-647.

Renne, P.R., R. Mundil, G. Balco, K.W. Min, and K.R. Ludwig. 2010. Joint determination of K-40 decay constants and Ar-40*/K-40 for the Fish Canyon sanidine standard, and improved accuracy for Ar-40/Ar-39 geochronology. *Geochimica et Cosmochimica Acta* 74(18):5349-5367.

Ricard, Y., O. Sramek, and F. Dubuffet. 2009. A multi-phase model of runaway core-mantle segregation in planetary embryos. *Earth and Planetary Science Letters* 284(1-2):144-150.

Ritsema, J., and H.-J. van Heijst. 2000. Seismic imaging of structural heterogeneity in Earth's mantle: Evidence for large-scale mantle flow. *Sci Prog* 83:243-259.

Rockström, J., et al. 2009. A safe operating space for humanity. *Nature* 461:472-475.

Roering, J.J., J. Marshall, A.M. Booth, M. Mort, and A. Jin. 2010. Evidence for biotic controls on topography and soil production. *Earth and Planetary Science Letters* 298:183-190.

Rogers, G., and H. Dragert. 2003. Episodic tremor and slip on the Cascadia subduction zone: The chatter of silent slip. *Science* 300:1942-1943.

Rost, S., E.J. Garnero, and Q. Williams. 2008. Seismic array detection of subducted oceanic crust in the lower mantle. *Journal of Geophysical Research* 113:B06303.

Rowland, J.C., C.E. Jones, G. Altmann, R. Bryan, B.T. Crosby, G.L. Geeernaert, L.D. Hinzman, D.L. Kane, D.M. Lawrence, A. Mancino, P. Marsh, J.P. McNamara, V.E. Romanovsky, H. Toniolo, B.J. Travis, E. Trochim, and C.J. Wilson. 2010. Arctic landscapes in transition: Responses to thawing permafrost. *Eos, Transactions, American Geophysical Union* 91:229-230.

Royer, D.L., R.A. Berner, and J. Park. 2007. Climate sensitivity constrained by CO_2 concentrations over the past 420 million years. *Nature* 446:530-532.

Rubinstein, J.L., D.R. Shelly, and W.L. Ellsworth. 2010. Non-volcanic tremor: A window into the roots of fault zones. In *New Frontiers in Integrated Solid Earth Sciences*, S. Cloetingh and J. Negendank, eds. New York: Springer Science+Business Media B.V.

Rudge, J., Kleine, T., Bourdon, B. 2010. Broad bounds on earth's accretion and core formation constrained by geochemical models. *Nat. Geosci.* 3:439–443.

Ruhl, K.W., and K.V. Hodges. 2005. The use of detrital mineral cooling ages to evaluate steady state assumptions in active orogens: An example from the central Nepalese Himalaya. *Tectonics* 24(4).

Schaller, N., I. Mahlstein, J. Cermak, and R. Knutti. 2011. Analyzing precipitation projections: A comparison of different approaches to climate model evaluation. *Journal of Geophysical Research* 116:D10118.

Schoene, B., J. Guex, A. Bartolini, U. Schaltegger, and T.J. Blackburn. 2010. Correlating the end-Triassic mass extinction and flood basalt volcanism at the 100 ka level. *Geology* 38:387-390.

Schuur, E.A.G., et al. 2008. Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *BioScience* 58:701-714.

Schwab, K., ed. 2010. *The Global Competitiveness Report 2010-2011*. Geneva: World Economic Forum, 501 pp.

Scott, C., T.W. Lyons, A. Bekker, Y. Shen, S.W. Poulton, X. Chu, and A.D. Anbar. 2008. Tracing the stepwise oxygenation of the Proterozoic ocean. *Nature* 452:456-459.

Semken, S. 2005. Sense of place and place-based introductory geoscience teaching for American Indian and Alaska Native undergraduates. *Journal of Geoscience Education* 53:149-157.

Shackleton, N.J., M.A. Hall, and D. Pate. 1995. Pliocene stable isotope stratigraphy of Site 846. Pp. 337-355 in *Proceedings of the Ocean Drilling Program, Scientific Results*, *Vol. 138*, N.G. Pisias, L.A. Mayer, and T.R. Janecsek et al., eds. College Station, TX: Ocean Drilling Program, Texas A&M University.

Shearer, C.K. 2006. Thermal and magmatic evolution of the moon. *New Views of the Moon, Reviews in Mineralogy and Geochemistry* 60:365-518.

Shim, S.-H. 2008. The postperovskite transition. *Annual Reviews in Earth and Planetary Science* 36:569-599.

Sigvaldason, G.E., K. Annertz, and M. Nilsson. 1992. Effect of glacier loading/deloading on volcanism: Postglacial volcanic production rate of the Dyngjufjok ll area, central Iceland. *Bulletin of Volcanology* 54:385-392.

Simpson, G. 2004. Dynamic interactions between erosion, deposition, and three-dimensional deformation in compressional fold belt settings. *Journal of Geophysical Research* 109:F03007.

Solomon, S., D. Qin, M. Manning, R.B. Alley, T. Berntsen, N.L. Bindoff, Z. Chen, A. Chidthaisong, J.M. Gregory, G.C. Hegerl, M. Heimann, B. Hewitson, B.J. Hoskins, F. Joos, J. Jouzel, V. Kattsov, U. Lohmann, T. Matsuno, M. Molina, N. Nicholls, J. Overpeck, G. Raga, V. Ramaswamy, J. Ren, M. Rusticucci, R. Somerville, T.F. Stocker, P. Whetton, R.A. Wood, and D. Wratt. 2007. Technical summary. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth IPCC Report*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds.

Song, X.D. 2007. Inner core anisotropy. Pp. 418-420 in *Encyclopedia of Geomagnetism and Plaeomagnetism*, D. Gubbins and E. Herroro-Bervera, eds. New York: Kluwer Academic Publishers B.V.

Spaggiari, C.V., R.T. Pidgeon, and S.A. Wilde. 2007. The Jack Hills greenstone belt, Western Australia—Part 2: Lithological relationships and implications for the deposition of >4.0 Ga detrital zircons. *Precambrian Research* 155:261-286.

Stanley, D.J., and A.G. Warne. 1993. Nile Delta: Recent geological evolution and human impact. *Science* 260:628-634.

Steiper, M.E., and N.M. Young. 2006. Primate molecular divergence dates. *Molecular Phylogenetics and Evolution* 41:384-394.

Stephens, B.B., K.R. Gurney, P.P. Tans, C. Sweeney, W. Peters, L. Bruhwiler, P. Ciais, M. Ramonet, P. Bousquet, T. Nakazawa, S. Aoki, T. Machida, G. Inoue, N. Vinnichenko, J. Lloyd, A. Jordan, M. Heimann, O. Shibistova, R.L. Langenfelds, L.P. Steele, R.J. Francey, and A.S. Denning. 2007. Weak northern and strong tropical land carbon uptake from vertical profiles of atmospheric CO_2. *Science* 316:1732-1735.

Stixrude, L., N.D. Koker, N. Sun, M. Mookherjee, and B.B. Karki. 2009. Thermodynamics of silicate liquids in the deep Earth. *Earth and Planetary Science Letters* 278:226-232.

Stock, G.M., T.A. Ehlers, and K.A. Farley. 2006. Where does sediment come from? Quantifying catchment erosion with detrital apatite (U-Th)/He thermochronometry. *Geology* 34(9):725-728.

Stolar, D.B., G.H. Roe, and S. Willett. 2007. Controls on the patterns of topography and erosion rate in a critical orogen. *Journal of Geophysical Research* 112: F04002.

Strack, M., and J.M. Waddington. 2007. Response of peatland carbon dioxide and methane fluxes to a water table drawdown experiment. *Global Biogeochemical Cycles* 21:GB1007.

Syracuse, E.M., G.A. Abers, K. Fischer, L. MacKenzie, C. Rychert, M. Protti, V. Gonzalez, and W. Strauch. 2008. Seismic tomography and earthquake locations in the Nicaraguan and Costa Rican upper mantle. *Geochemistry Geophysics Geosystems* 9:Q07S08.

Syvitski, J.P.M., C.J. Vörösmarty, A.J. Kettner, and P. Green. 2005. Impacts of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* 308:376-380.

Syvitski, J.P.M., A.J. Kettner, I. Overeem, E.W.H. Hutton, M.T. Hannon, G.R. Brakenridge, J. Day, C. Vorosmarty, Y. Saito, L. Giosan, and R.J. Nicholls. 2009. Sinking delta due to human activities. *Nature Geoscience* 2:681-686.

Tarduno, J.A., R.D. Cottrell, M.K. Watkeys, and D. Bauch. 2007. Geomagnetic field strength 3.2 billion years ago recorded by single silicate crystals. *Nature* 446:657-660.

Thomson, S.N., M.T. Brandon, J.H. Tomkin, P.W. Reiners, C. Vasquez, and N.J. Wilson. 2010. Glaciation as a destructive and constructive control on mountain building. *Nature* 467:313-317.

Thorne, M.S., E.J. Garnero, and S.P. Grand. 2004. Geographic correlation between hotspots and deep mantle lateral shear-wave velocity gradients. *Physics of the Earth and Planetary Interiors* 146:47-63.

Tomkin, J.H., and G.H. Roe. 2007. Climate and tectonic controls on glaciated critical-taper orogens. *Earth Planetary Science Letters* 262:385-397.

Tonks, W.B., and H.J. Melosh. 1993. Magma ocean formation due to giant impacts. *Journal of Geophysical Research* 98:5319-5333.

Torsvik, T.H., M.A. Smethurst, K. Burke, and B. Steinberger. 2006. Large igneous provinces generated from the margins of the large low-velocity provinces in the deep mantle. *Geophysical Journal International* 167:1447-1460.

Trail, D., S.J. Mojzsis, T.M. Harrison, A.K. Schmitt, E.B. Watson, and E.D. Young. 2007. Constraints on Hadean zircon protoliths from oxygen isotopes, Ti-thermometry, and rare earth elements. *Geochemistry Geophysics Geosystems* 8:Q06014.

Tripati, A.K., R.A. Eagle, N. Thiagarajan, A.C. Gagnon, H. Bauch, P.R. Halloran, and J.M. Eiler. 2010. ^{13}C-^{18}O isotope signatures and "clumped isotope" thermometry in foraminifera and coccoliths. *Geochimica et Cosmochimica Acta* 74:5697-5717.

Trønnes, R.G. 2009. Structure, mineralogy and dynamics of the lowermost mantle. *Mineral and Petrology* 99(3-4):243-261.

Trotter, J.A., I.S. Williams, C.R. Barnes, C. Lecuyer, and R.S. Nicoll. 2008. Did cooling oceans trigger Ordovician biodiversification? Evidence from conodont thermometry. *Science* 321:550-554.

UNAVCO. 2009. *Strategic Plan 2009-2013: Positioning UNAVCO, Advancing Science Through Geodesy*. Boulder: University NAVSTAR Consortium. 25 pp.

USGCRP (U.S. Global Change Research Program). 2001. *A Plan for a New Science Initiative on the Global Water Cycle*. Washington, DC: USGCRP. 118 pp.

Valiela, I., and S.E. Fox. 2008. Managing coastal wetlands. *Science* 319:290-291.

Wada, Y., L.P.H. van Beek, C.M. van Kempen, J.W.T.M. Reckman, S. Vasak, and M.F.P. Bierkens. 2010. Global depletion of groundwater resources. *Geophysical Research Letters* 37:L20402.

Wallace, L.M., and J. Beavan. 2006. A large slow slip event on the central Hikurangi subduction interface beneath the Manawatu region, North Island, New Zealand. *Geophysical Research Letters* 33:L11301.

Wang, Y., and L. Wen. 2007. Geometry and P and S velocity structures of the "African Anomaly." *Journal of Geophysical Research* 112:B05313.

Wardlaw, B.R., and T.M. Quinn. 1991. The record of Pliocene sea-level change at Enewetak Atoll. *Quaternary Science Reviews* 10(2/3):247-258.

Warren, P.H. 1985. The magma ocean concept and lunar evolution. *Annual Reviews of Earth and Planetary Science* 13:201-240.

Watson, E.B., and T.M. Harrison. 2005. Zircon thermometer reveals minimum melting conditions on earliest Earth. *Science* 308:841-844.

Weinstein, M.P., et al. 2007. Managing coastal resources in the 21st century. *Frontiers in Ecology* 5:43-48.

Wells, R.E., R. Blakely, Y. Sugiyama, D.W. Scholl, and P.A. Dinterman. 2003. Basin-centered asperities in great subduction zone earthquakes: A link between slip, subsidence, and subduction erosion? *Journal of Geophysical Research* 108:2507.

West, J.D., M.J. Fouch, J.B. Roth, and L.T. Elkins-Tanton. 2009. Vertical mantle flow associated with a lithospheric drip beneath the Great Basin. *Nature Geoscience* 2:439-444.

Wetherill, G.W. 1990. Formation of the Earth. *Annual Reviews in Earth and Planetary Science* 18:205-256.

Whipple, K.X. 2009. The influence of climate on the tectonic evolution of mountain belts. *Nature Geoscience* 2:97-104.

Whipple, K.X., and B.J. Meade. 2004. Controls on the strength of coupling among climate, erosion, and deformation in two-sided, frictional orogenic wedges at steady state. *Journal of Geophysical Research* 109.

Whipple, K.X., and B.J. Meade. 2006. Orogen response to changes in climatic and tectonic forcing. *Earth and Planetary Science Letters* 243:218-228.

Wilde, S.A., J.W. Valley, W.H. Peck, and C.M. Graham. 2001. Evidence from detrital zircons for the existence of continental crust and oceans on Earth 4.4 Gyr ago. *Nature* 409:175-178.

Willett, S.D. 1999. Orogeny and orography: The effects of erosion on the structure of mountain belts. *Journal of Geophysical Research* 104:28,957-28,981.

Willett, S., C. Beaumont, and P. Fullsack. 1993. Mechanical model for the tectonics of doubly vergent compressional orogens. *Geology* 21:371-374.

Williams, Q., ed. 2010. *Understanding the Building Blocks of the Planet: The Materials Science of Earth Processes*. Report to the National Science Foundation, COMPRES Consortium. Long-Range Planning for High-Pressure Geosciences Workshop, March 2–4, 2009, Tempe, AZ. Available online at compres.us/index.php?option=com_docman&task=doc_download&gid=256&Itemid.

Williams, M.L., K.M. Fischer, J.T. Freymueller, B. Tikoff, and A.M. Tréhu et al. 2010. *Unlocking the Secrets of the North American Continent: An EarthScope Science Plan for 2010-2020*. 78 pp. Available online at www.earthscope.org/ESSP.

Wilson, P.A., and R.D. Norris. 2001. Warm tropical ocean surface and global anoxia during the mid-Cretaceous period. *Nature* 412:425-429.

Wing, S.L., G.J. Harrington, F.A. Smith, J.I. Bloch, D.M. Boyer, and K.H. Freeman. 2005. Transient floral change and rapid global warming at the Paleocene-Eocene boundary. *Science* 310:993-996.

Wise, S.W.J., J.R. Breza, D.M. Harwood, and W. Wei. 1991. Paleogene glacial history of Antarctica. Pp. 133-171 in *Controversies in Modern Geology: Evolution of Geological Theories in Sedimentology, Earth History and Tectonics*, D.W. Müller, J.A. McKenzie, and H. Weissert, eds. Cambridge: Cambridge University Press,.

Wobus, C.W., K. Hodges, and K. Whipple. 2003. Has focused denudation at the Himalayan topographic front sustained active thrusting near the main central thrust? *Geology* 31:861-864.

Wood, B.J., M.J. Walter, and J. Wade. 2006. Accretion of the Earth and segregation of its core. *Nature* 441:825-833.

Woodburne, M.O., G.F. Gunnell, and R.K. Stucky. 2009. Climate directly influences Eocene mammal faunal dynamics in North America. *Proceedings of the National Academy of Sciences USA* 106:13,399-13,403.

Wu, G., Y. Lui, Q. Zhang, A. Duan, T. Wang, R. Wan, X. Lui, W. Li, Z. Wang, and X. Liang. 2007. The influence of mechanical and thermal forcing by the Tibetan Plateau on Asian climate. *Journal of Hydrometeorology* 8:770-789.

Yin, Q., S.B. Jacobsen, K. Yamashita, J. Blichert-Toft, P. Telouk, and F. Albarede. 2002. A short timescale for terrestrial planet formation from Hf-W chronometry of meteorites. *Nature* 419:949.

Zachos, J., M. Pagani, L. Sloan, E. Thomas, and K. Billups. 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science* 292(5517):686-693.

Zachos, J.C., G.R. Dickens, and R.E. Zeebe. 2008. An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics. *Nature* 451:79-283.

Zaehle, S., P. Friedlingstein, and A.D. Friend. 2010. Terrestrial nitrogen feedbacks may accelerate future climate change. *Geophysical Research Letters* 37:L01401.

Zahnle, K.J., J.F. Kasting, and J.B. Pollack. 1988. Evolution of a steam atmosphere during Earth's accretion. *Icarus* 74:62-97.

Zeitler, P.K., et al. 2001. Crustal reworking at Nanga Parbat, Pakistan: Metamorphic consequences of thermal-mechanical coupling facilitated by erosion. *Tectonics* 20:712-728.

Zhang, N., S.J. Zhong, W. Leng, and Z.X. Li. 2010. A model for the evolution of the Earth's mantle structure since the Early Paleozoic. *Journal of Geophysical Research* 115:B06401.

Zou, Z., K. Koper, and V.F. Cormier. 2008. The structure of the base of the outer core inferred from seismic waves diffracted around the inner core. *Journal of Geophysical Research* 113:B05314.

Appendix A

List of Background Materials

Ad Hoc Committee and Technical Working Group for a Petascale Collaboratory for the Geosciences. 2005. *Establishing a Petascale Collaboratory for the Geosciences: Scientific Frontiers*. Report to the Geosciences Community. University Corporation for Atmospheric Research/Joint Office for Science Support (UCAR/JOSS).

AGI (American Geological Institute). 2009. *Status of the Geoscience Workforce: Report Summary*. Alexandria, VA: AGI.

Anderson, R.S., S. Anderson, A.K. Aufdenkampe, R. Bales, S. Brantley, J. Chorover, C.J. Duffy, F.N. Scatena, D.L. Sparks, P.A. Troch, and K. Yoo. 2010. *Future Directions for Critical Zone Observatory (CZO) Science: Report Prepared by the CZO Community*, 6 pp. Available at criticalzone.org/CZO-FutureDirectionsReport_v3-1.pdf.

Bass, J., ed. 2004. *Current and Future Research Directions in High-Pressure Mineral Physics.* Consortium for Materials Properties Research in Earth Sciences (COMPRES). Available at www.compres.us/index.php?option=com_docman&task=doc_download&gid=170&Itemid.

Bottjer, D.J., ed. 2006. *Future Research Directions in Paleontology*. Report of a workshop held April 8–9, 2006, sponsored by the National Science Foundation. Boulder, CO: The Paleontological Society.

Brantley, S.L., T.S. White, A.F. White, D. Sparks, D. Richter, K. Pregitzer,L. Derry, O. Chorover, R. April, S. Anderson, and R. Amundson. 2006. *Frontiers in Exploration of the Critical Zone.* Report of a workshop sponsored by the National Science Foundation, October 24-26, 2005, Newark, DE, 30 pp.

Brodsky, E.E., K.-F. Ma, J. Mori, and D.M. Saffer. 2009. *Rapid Response Drilling: Past, Present, and Future*. Report of the ICDP/SCEC (Intercontinental Scientific Drilling Program/Southern California Earthquake Center) International Workshop on Rapid Response Drilling, Tokyo, Japan, November 2008.

Burbank, D., K. Hudnut, R. Ryerson, C. Rubin, D. Schwartz, B. Wernicke, and S. Wesnousky. 2001. *The Plate Boundary Observatory: Results of the First Workshop on Geological Research*. Submitted by the PBO Geology Committee. Workshop held in Pasadena, CA, May 22–25, 2001.

Carbotte, S., K. Lehnert, S. Tsuboi, W. Weinrebe, and workshop participants. 2007. *Building a Global Network for Studies of Earth Processes*. Report of the International Data Exchange Workshop, May 9–11, 2007, Kiel, Germany. Available at www.nsf-margins.org/Datawkshp07.

Cohen, R.E., ed. 2005. *High-Performance Computing Requirements for the Computational Solid Earth Sciences*. Available at www.geo-prose.com/computational_SES.html.

DUSEL (Deep Underground Science and Engineering Laboratory). 2010. *Science Inquiry in Biology, Geosciences, and Engineering at DUSEL*. Prepared by the DUSEL Science Community. Available online at www.dusel.org/PDFs/bge_science-at-dusel_community_report_20101118.pdf.

EarthLab Steering Committee. 2003. *EarthLab: A Subterranean Laboratory and Observatory to Study Microbial Life, Fluid Flow, and Rock Deformation*. Report to the National Science Foundation. Available online at www.dusel.org/PDFs/earthlab_5.30.03.pdf.

Erwin, D., et al. 2006/2011. *DETELON: Future Research Directions in Paleontology.* Workshop sponsored by the National Science Foundation, Washington, DC. Available at detelon.org/.

MARGINS. 2010. *GeoPRISMS Draft Science Plan*. Prepared by the MARGINS Office and submitted to the National Science Foundation. Available at www.nsf-margins.org.

Gonzales, L., C. Keane, and C. Martinez. 2009. *Effects of the Global Economic Crisis on Geoscience Departments*. Alexandria, VA: American Geological Institute.

Hornberger, G. 2001. *A Plan for a New Science Initiative on the Global Water Cycle*. Report to the U.S. Global Change Research Program (USGCRP) from the Water Cycle Study Group. Available online at www.usgcrp.gov/usgcrp/Library/watercycle/wcsgreport2001/default.htm.

Kellogg, L., B. Buffett, C. Constable, R. Jeanloz, G. Masters, W. McDonough, and R. Walker. 2004. *CSEDI: Cooperative Studies of the Earth's Deep Interior*. Report of the CSEDI Workshop held February 22–23, 2004, La Jolla, CA. Available online at www.csedi.org/CSEDI.Sept29.04.pdf.

Lay, T., ed. 2009. *Seismological Grand Challenges in Understanding Earth's Dynamic Systems*. Report to the National Science Foundation, IRIS Consortium, of a workshop held September 18–19, 2008, Denver, CO. 76 pp.

Marshall, C., and I. Montanez. 2010. *Grand Challenges in Sedimentary Geology, Geochemistry and Paleobiology*. Report of a workshop held July 26–27, University of California–Davis Tahoe Environmental Research Center, Incline Village, NV, 7 pp.

McPherson, B.J., and the EarthLab Steering Committee. 2003. *EarthLab: A Subterranean Laboratory and Observatory to Study Microbial Life, Fluid Flow, and Rock Deformation*. Report to the National Science Foundation by

Geosciences Professional Services, Inc. Available online at www.dusel.org/PDFs/earthlab_5.30.03.pdf.

Merritts, D., G. Hilley, J.R. Arrowsmith, B. Carter, W. Dietrich, J. Jacobs, S. Martel, J. Roering, R. Shrestha, and N.P. Snyder. 2008. *Workshop on Studying Earth Surface Processes with High-Resolution Topographic Data*. Report of a workshop held by the National Science Foundation, June 15–18, Boulder, CO. Available online at opentopo.sdsc.edu/docs/NCALM_workshop report_June2008.pdf.

Montañez, I.P., et al. 2010. *Grand Challenges in Sedimentary Geology*. Report of a workshop held July 23-25, Incline Village, NV, sponsored by the National Science Foundation.

National Committee for Earth Sciences. 2003. *National Strategic Plan for the Geosciences: Geoscience—Unearthing Our Future*. Canberra: Australian Academy of Science.

NRC (National Research Council). 1999. *Hydrologic Science Priorities for the U.S. Global Change Research Program: An Initial Assessment*. Washington, DC: National Academies Press.

NRC (National Research Council). 2001. *Basic Research Opportunities in Earth Science*. Washington, DC: National Academies Press.

NRC (National Research Council). 2001. *Review of EarthScope Integrated Science*. Washington, DC: National Academies Press.

NRC (National Research Council). 2002. *Assessment of the Usefulness and Availability of NASA's Earth and Space Science Mission Data*. Washington, DC: National Academies Press.

NRC (National Research Council). 2002. *Geoscience Data and Collections: National Resources in Peril*. Washington, DC: National Academies Press.

NRC (National Research Council). 2002. *Review of USGCRP Plan for a New Science Initiative on the Global Water Cycle Research*. Washington, DC: National Academies Press.

NRC (National Research Council). 2003. *Living on an Active Earth: Perspectives on Earthquake Science*. Washington, DC: National Academies Press.

NRC (National Research Council). 2003. *Review of NOAA's Geophysical Data Center*. Washington, DC: National Academies Press.

NRC (National Research Council). 2004. *Partnerships for Reducing Landslide Risk: Assessment of the National Landslide Hazards Mitigation Strategy*. Washington, DC: National Academies Press.

NRC (National Research Council). 2004. *Review of NASA's Solid-Earth Science Strategy*. Washington, DC: National Academies Press.

NRC (National Research Council). 2005. *The Geological Record of Ecological Dynamics: Understanding the Biotic Effects of Future Environmental Change*. Washington, DC: National Academies Press.

NRC (National Research Council). 2006. *Geological and Geotechnical Engineering in the New Millennium: Opportunities for Research and Technological Innovation*. Washington, DC: National Academies Press.

NRC (National Research Council). 2006. *Improved Seismic Monitoring—Improved Decision Making: Assessing the Value of Reduced Uncertainty*. Washington, DC: National Academies Press.

NRC (National Research Council). 2006. *To Recruit and Advance: Women Students and Faculty in Science and Engineering*. Washington, DC: National Academies Press.

NRC (National Research Council). 2007. *Assessment of NASA Applied Sciences Program*. Washington, DC: National Academies Press.

NRC (National Research Council). 2007. *Coal: Research and Development to Support National Energy Policy*. Washington, DC: National Academies Press.

NRC (National Research Council). 2007. *Earth Materials and Health: Research Priorities for Earth Science and Public Health*. Washington, DC: National Academies Press.

NRC (National Research Council). 2007. *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. Washington, DC: National Academies Press.

NRC (National Research Council). 2007. *Evaluating Progress of the U.S. Climate Change Science Program: Methods and Preliminary Results*. Washington, DC: National Academies Press.

NRC (National Research Council). 2007. *The Scientific Context for Exploration of the Moon: Final Report*. Washington, DC: National Academies Press.

NRC (National Research Council). 2008. *Increasing Capacity for Stewardship of Oceans and Coasts: A Priority for the 21st Century*. Washington, DC: National Academies Press.

NRC (National Research Council). 2008. *Integrating Multiscale Observations of U.S. Waters*. Washington, DC: National Academies Press.

NRC (National Research Council). 2008. *Minerals, Critical Minerals, and the U.S. Economy*. Washington, DC: National Academies Press.

NRC (National Research Council). 2008. *Origin and Evolution of Earth: Research Questions for a Changing Planet*. Washington, DC: National Academies Press.

NRC (National Research Council). 2009. *Ensuring the Integrity, Accessibility, and Stewardship of Research Data in the Digital Age*. Washington, DC: National Academies Press.

NRC (National Research Council). 2009. *Evaluation of NSF's Program of Grants and Vertical Integration of Research and Education in the Mathematical Sciences (VIGRE).* Washington, DC: National Academies Press.

NRC (National Research Council). 2009. *Rising Above the Gathering Storm Two Years Later: Accelerating Progress Toward a Brighter Economic Future. Summary of a Convocation*. Washington, DC: National Academies Press.

NRC (National Research Council). 2009. *Toward a Sustainable and Secure Water Future: A Leadership Role for the U.S. Geological Survey*. Washington, DC: National Academies Press.

NRC (National Research Council). 2010. *Adapting to Impacts of Climate Change*. Washington, DC: National Academies Press.

NRC (National Research Council). 2010. *Advancing the Science of Climate Change*. Washington, DC: National Academies Press.

NRC (National Research Council). 2010. *Assessment of Impediments to Interagency Collaboration on Space and Earth Science Missions*. Washington, DC: National Academies Press.

NRC (National Research Council). 2010. *Expanding Underrepresented Minority Participation: America's Science and Technology Talent at the Crossroads*. Washington, DC: National Academies Press.

NRC (National Research Council). 2010. *Landscapes on the Edge: New Horizons for Research on Earth's Surface.* Washington, DC: National Academies Press.

NRC (National Research Council). 2010. *Limiting the Magnitude of Future Climate Change.* Washington, DC: National Academies Press.

NRC (National Research Council). 2010. *Rising Above the Storm, Revisited: Rapidly Approaching Category 5*. Washington, DC: National Academies Press.

NRC (National Research Council). 2010. *Understanding Climate's Influence on Human Evolution.* Washington, DC: National Academies Press.

NRC (National Research Council). 2011. *Understanding Earth's Deep Past: Lessons for Our Climate Future*. Washington, DC: National Academies Press.

NSF (National Science Foundation). 2007. *Women, Minorities, and Persons with Disabilities in S&E: 2007*. Report 07-315. Washington, DC: NSF.

NSF (National Science Foundation). 2009. *GEO Vision Report: Unraveling Earth's Complexities Through the Geosciences*. Washington, DC: NSF.

NSF (National Science Foundation). 2009. *Women, Minorities, and Persons with Disabilities in S&E: 2009.* Report 09-305. Washington, DC: NSF.

NSF (National Science Foundation). 2011. *Women, Minorities, and Persons with Disabilities in Science and Engineering: 2011*. Report 11-309. Washington, DC: NSF.

Olson, P., ed. 2010. *Grand Challenges in Geodynamics: Outstanding Geodynamics Problems and Emerging Research Opportunities for the Earth Sciences*. Geodynamics White Paper, Computational Infrastructure for Geodynamics, University of California, Davis.

Raymond, A., S. Bowring, C. Badgley, and L. Park. 2010. *DETELON Workshop Report*. Report of the workshop held April 23–25, Washington, DC, organized through the Paleontological Society and the Society of Vertebrate Paleontology.

Robinson, D.A., J. Duncan, and J. Selker. 2006. *The CUAHSI Hydrological Measurement Facility Community Survey 2005*. Technical Report #8 to the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc.

Sadoulet, B., E. Beier, C. Fairhurst, T.C. Onstott, R.G.H. Robertson, and J. Tiedje. 2006. *Deep Science: A Deep Underground Science and Engineering Initiative*. Washington, DC: National Science Foundation.

Schofield, O., and M.K. Tivey. 2005. *ORION: Ocean Research Interactive Observatory Networks*. Report of a workshop held January 4–8, 2004, San Juan, Puerto Rico.

Studinger, M., D. Bromwich, B. Csatho, R. Muench, T.R. Parish, and J. Stith. 2005. *Scientific Opportunities for a Long-Range Aircraft for Research in Antarctica (LARA).* Report of a workshop held September 27–29, 2004, Herndon, VA.

Technical Working Group and Ad Hoc Committee for a Petascale Collaboratory for the Geosciences. 2005. *Establishing a Petascale Collaboratory for the Geosciences: Technical and Budgetary Prospectus*. Report to the Geosciences Community, University Corporation for Atmospheric Research/Joint Office for Science Support (UCAR/JOSS).

The Hydrologic Science Standing Committee. 2002. *A Vision for Hydrological Science Research*. Technical Report #1. Washington, DC: Consortium of Universities for the Advancement of Hydrologic Science, Inc.

UNAVCO. 2008. *Strategic Plan 2009–2013: Positioning UNAVCO*, Advancing Science Through Geodesy. Boulder, CO: UNAVCO.

Walton, T.W., et al. 2009. *The Future of Continental Scientific Drilling: US Perspective*. Proceedings of a workshop held June 4-5, Denver, CO, sponsored by the National Science Foundation and DOSECC, Inc.

Williams, Q., ed. 2010. *Understanding the Building Blocks of the Planet: The Materials Science of Earth Processes*. Report to the National Science Foundation, COMPRES Consortium. Long-Range Planning for High-Pressure Geosciences Workshop, March 2–4, 2009, Tempe, AZ. Available online at compres.us/index.php?option=com_docman&task=doc_download&gid=256&Itemid.

Williams, M.L., K.M. Fischer, J.T. Freymueller, B. Tikoff, and A.M. Tréhu et al. 2010. *Unlocking the Secrets of the North American Continent: An EarthScope Science Plan for 2010-2020*. 78 pp. Available online at www.earthscope.org/ESSP.

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Thorne Lay (*Chair*) is distinguished professor of earth and planetary sciences at the University of California, Santa Cruz, where he was founding director of the Institute of Geophysics and Planetary Physics and is currently director of the Center for the Study of Imaging and Dynamics of the Earth. His primary research interests involve analysis of seismic waves to interrogate the deep structure of the Earth's interior and to study the physics of earthquake faulting. This involves imaging structures associated with internal dynamics of the mantle, particularly the core-mantle boundary region and the vicinity of the subducting lithosphere. Earthquake-related investigations include waveform modeling of body and surface waves to determine the nature of faulting and to develop seismic models for the entire rupture process. He also studies nuclear explosion sources to provide improved means for monitoring low-threshold test ban treaties. Dr. Lay has over 240 peer-reviewed publications, he received the Macelwane Medal from the American Geophysical Union in 1991, and he is a Lifetime National Associate of the National Academy of Sciences. Dr. Lay is a fellow of the American Geophysical Union, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences. He is also past chair of the Board of Directors of Incorporated Research Institutions for Seismology and previously held a faculty position at the University of Michigan from 1984 to 1989. Dr. Lay received a B.S. from the University of Rochester in 1978 and an M.S and a Ph.D. from the California Institute of Technology in 1980 and 1983, respectively.

Michael L. Bender (NAS) is a professor of geosciences at Princeton University, where he has been since 1997. His research focuses on glacial-interglacial climate change and the global carbon cycle. This involves measuring gas properties in ice cores to date critical climate changes of the ice ages. His carbon cycle research involves characterizing the fertility of ecosystems at the global scale, at the scale of ocean basins, and at regional to local scales within the oceans. Dr. Bender is a fellow of the American Geophysical Union and is a recipient of the Patterson Medal of the Geochemical Society. He has served on numerous editorial boards and committees, including as chair of the National Oceanic and Atmospheric Administration's CO_2 Observations Advisory Group (1999-2001) and the National Science Foundation's (NSF's) Ice Core Working Group (1990-1997). Prior to joining Princeton, he was a professor of oceanography at the University of Rhode Island (1972-1997). Dr. Bender received a B.S. in chemistry from the Carnegie Institute of Technology in 1965 and a Ph.D. in geology from Columbia University in 1970.

Suzanne Carbotte is the Heezen Lamont Research Professor at the Lamont-Doherty Earth Observatory at Columbia University, where she has been since 1993. Her research focuses on the formation of oceanic crust at the global midocean ridge, using a variety of marine geophysical techniques. Current work involves application of seismic methods to study the alteration of the crust that occurs as a result of fluid-rock interactions on the Juan de Fuca plate and the origin of the segmentation of midocean ridges. Nearer to shore, Dr. Carbotte applies marine geophysical techniques to study sedimentary processes and to characterize benthic habitats in the estuarine setting, including the linkages between rising sea level and climate fluctuations with the changing faunal populations documented in the river sediments. She has served on numerous national committees, including the NSF–funded Ridge 2000 steering committee (2002-2007), ORION Cyberinfrastructure Committee (2005-2007), and the Ocean Observing Science Committee (2010-present). Dr. Carbotte received a B.S. in geology and physics from the University of Toronto in 1982; an M.Sc. in geophysics at Queen's University, Kingston, Ontario, in 1986; and a Ph.D. in marine geophysics from the University of California, Santa Barbara, in 1992.

Kenneth A. Farley is chair of the Division of Geological and Planetary Sciences and W. M. Keck Foundation Professor of Geochemistry at the California Institute of Technology, where he has been since 1993. His research is focused on the use of noble gas concentrations and isotopic ratios and addresses problems in a range of disciplines of the Earth sciences. Current interests include (1) development and application of techniques for assessing the cooling history of rocks from the in-growth and diffusion of radiogenic helium-4, (2) improved analytical techniques for measurement of cosmogenic noble gases and experimental investigation of the processes by which these isotopes are produced, and (3) identifying major events in the recent history of the solar system using extraterrestrial helium-3 in seafloor sediments. He was director of the CalTech Tectonic Observatory and received the Macelwane Medal from the American Geophysical Union in 1999 and the National Academy of Sciences Award for Initiatives in Research in 2000. Dr. Farley received a B.S. in chemistry from Yale University in 1986 and a Ph.D. in earth science from the Scripps Institution of Oceanography, University of California, San Diego, in 1991.

Kristine M. Larson is a professor of aerospace engineering sciences at the University of Colorado, Boulder. Dr. Larson's research focuses on using high-precision global positioning system (GPS) techniques to address a range of geophysical issues that include measuring and interpreting crustal deformation as well as using geodetic techniques for measuring soil moisture variations, snow depth, and vegetation. She has studied plate boundary zone deformation in Alaska, Nepal, Tibet, Ethiopia, California, and Mexico. Dr. Larson's research has also emphasized engineering development by pushing the temporal sampling of GPS to subdaily intervals for studies of earthquakes, volcanoes, and ice sheet dynamics. She served as editor of *Geophysical Research Letters* from 2002 to 2004. She was elected a fellow of the American Geophysical Union in 2011. Dr. Larson received her A.B. in engineering sciences from Harvard University in 1985 and her Ph.D. in geophysics from the Scripps Institution of Oceanography, University of California, San Diego, in 1990.

Timothy Lyons is a professor of biogeochemistry in the Department of Earth Sciences at the University of California, Riverside, where he has been since 2005. His research interests are in marine geochemistry and geobiology; biogeochemical cycles through time; earth history and paleoclimate; and astrobiology linked to career-long interests in anoxic marine environments, early atmospheric oxygenation, and co-evolving life. His research includes the development and refinement of diverse geochemical proxies in modern settings for study of the ancient ocean. Dr. Lyons is a fellow of the Geological Society of America and the American Association for the Advancement of Science and the recipient of an NSF CAREER Award. He has been a visiting scholar at the Royal Netherlands Institute of Sea Research, the University of Queensland, the University of Tasmania (Comet Fellow), the Max Planck Institute for Marine Microbiology (Hanse Fellow), and Cambridge University (Leverhulme Visiting Professorship), and he was the first Agassiz Lecturer at Harvard University. Dr. Lyons has served on numerous steering and organizing committees, including service to the Goldschmidt Conference of the Geochemical Society, the Integrated Ocean Drilling Program, and funding panels spanning four programs within NSF, two within the National Aeronautics and Space Administration (NASA) and one within the American Chemical Society. Dr. Lyons has served in eight editorial positions, including a long-standing affiliation with *Geochimica et Cosmochimica Acta* and a new relationship with *Global Biogeochemical Cycles*, and he has served on an American Geological Union editorial advisory board. He is active within the NASA Astrobiology Institute, the Agouron Institute, and the Southern California geobiology community. Dr. Lyons received a B.S. in geological engineering from the Colorado School of Mines, an M.S. in geology from the University of Arizona, and a Ph.D. in geology/geochemistry from Yale University.

Michael Manga is a professor in the Department of Earth and Planetary Science at the University of California, Berkeley, where he has been since 2001. His research focuses on processes involving fluids, including problems in physical volcanology, geodynamics, and hydrogeology using combinations of theoretical, numerical, and experimental approaches. His research integrates laboratory and field observations (both of active processes and recorded in the geological record) with theoretical and model results and typically involves new contributions in applied fluid mechanics. He received the Macelwane Medal from the American Geophysical Union in 2002, the Donath Medal from the Geological Society of America in 2003, and a MacArthur Fellowship in 2005. He has served on numerous editorial boards (*Reviews of Geophysics*, *Journal of Geophysical Research, Geology*). He was an assistant professor at the University of

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Ho-kwang (Dave) Mao (NAS) is a geophysicist and senior staff scientist at the Carnegie Institution of Washington, where he has been for his entire career. His research involves the development and application of ultra-high-pressure technology to physics, chemistry, materials science, geophysics, geochemistry, and planetary sciences. He is the recipient of numerous awards, including the 2007 Inge Lehmann Medal from the American Geophysical Union and the 2005 Roebling Medal from the Mineralogical Society of America. Dr. Mao earned a B.S. in geology from the National Taiwan University in 1963 and an M.S. and a Ph.D. in geology from the University of Rochester in 1966 and 1968, respectively.

Isabel P. Montañez is a professor in the Department of Geology at the University of California, Davis. Dr. Montañez is a field geologist and geochemist whose research focuses on the sedimentary archive of paleoatmospheric composition and paleoclimatic conditions, in particular in reconstructing records of greenhouse gas-climate linkages during periods of major climate transitions. Her past work has involved study of marine and terrestrial successions of the Cambrian through Pleistocene ages. Dr. Montañez received her Ph.D. in geology from Virginia Polytechnic Institute and State University. She is a fellow of the Geological Society of America and a current Guggenheim Fellow. She chaired the National Research Council Committee on the Importance of Deep-Time Geologic Records for Understanding Climate Change Impacts (2010-2011).

David R. Montgomery is professor of geomorphology in the Department of Earth and Space Sciences at the University of Washington, where he has been since 1991. His research focuses on fluvial and hillslope processes in mountain drainage basins, the evolution of mountain ranges (Cascades, Andes, and Himalaya), analysis of digital topography, interpretation of martian landforms, and linkages between geomorphological processes and ecological systems. Dr. Montgomery has authored over 100 peer-reviewed scientific papers and two award-winning popular books, *Dirt: The Erosion of Civilizations* (University of California Press, Berkeley, 2007) and *King of Fish: The Thousand-Year Run of Salmon* (Basic Books, New York, 2003). He received a B.S. in geology from Stanford University in 1984; a Ph.D. in geomorphology from the University of California, Berkeley, in 1991; and a MacArthur Fellowship in 2008.

Paul E. Olsen (NAS) is the Storke Memorial Professor of Earth and Environmental Sciences at Columbia University's Lamont Doherty Earth Observatory, where he has been since 1984. His research focuses on the evolution of continental ecosystems, especially the pattern, causes, and effects of climate change on geological timescales, mass extinctions, effects of evolutionary innovations on biogeochemical cycles, and evolution of the solar system as revealed by geological records. He has authored over 170 publications and has appeared in numerous documentaries on the history of life and climate. He serves on the Board of Directors of the Drilling, Observation and Sampling of the Earths Continental Crust organization and has served on numerous NSF panels and steering committees. He received a B.A. in geology and a Ph.D. in biology from Yale University in 1978 and 1984, respectively.

Peter L. Olson (NAS) is a professor of geophysical fluid dynamics in the Department of Earth and Planetary Sciences at Johns Hopkins University, where he has been since 1977. Dr. Olson combines theory, numerical models, and laboratory fluid dynamics models to interpret global geophysical data pertaining to the Earth's deep interior in order to better understand how the mantle and core interact to produce plate tectonics, deep mantle plumes, and the geomagnetic field. Dr. Olson has served on numerous national and international committees, including the Computational Infrastructure for Geodynamics Executive Committee and the U.S. National Committee on Studies of Earth's Deep Interior. Dr. Olson is a fellow of the American Geophysical Union, an honorary fellow of the European Union of Geosciences, and a fellow of the American Academy of Arts and Sciences. Dr. Olson received a B.A. in geology from the University of Colorado, Boulder, in 1972 and an M.A. and a Ph.D. in geophysics from the University of California, Berkeley, in 1974 and 1977, respectively.

Patricia L. Wiberg is professor and chair of the Department of Environmental Sciences at the University of Virginia, where she has been since 1990. Her research focuses on sediment transport dynamics on the continental shelf and tidal salt marshes and in lagoons and the effects of climate change on coastal systems. This includes post-depositional alteration and preservation of sedimentary strata, transport of sediment-associated contaminants, and evolution of lagoon bottom habitat. Dr. Wiberg has served as associate editor for the *Journal of Sedimentary Research* and *Journal of Geophysical Research–Earth Surface*, has served on the MARGINS steering committee, and is a member of the Executive Committee and chair of the Marine Working Group of Community Surface Dynamics Modeling System. She also chaired the American Geophysical Union's Information Technology Committee. Dr. Wiberg received a B.A. in mathematics from Brown University and an M.S. and a Ph.D. in oceanography from the University of Washington.

Dongxiao (Don) Zhang is the Marshall Professor of Water Resources and Petroleum Engineering in the Department of Civil and Environmental Engineering, Department of Chemical Engineering and Materials Science, University of Southern California, Los Angeles, where he has been since 2007. His research focuses on the stochastic uncertainty quantification for hydrology and petroleum reservoir simulations, multiscale modeling and simulation of flow in porous media, and geological sequestration of carbon dioxide. He is a fellow of the Geological Society of America, the author of two books, and serves as associate editor for five journals, including *Water Resources Research* and the *Journal of Computational Geosciences*. Dr. Zhang was a senior scientist at Los Alamos National Laboratory (1996-2004) and held the Miller Chair at the Mewbourne School of Petroleum and Geological Engineering at the University of Oklahoma (2004-2007). He also served as a Chang Jiang (guest chair) Professor at Nanjing University and is a founding associate dean at the College of Engineering of Peking University in China. Dr. Zhang received a B.S. in engineering from Northeastern University, Shenyang, People's Republic of China, and an M.S. and a Ph.D. in hydrology from the University of Arizona.

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