NATIONAL ACADEMY OF SCIENCES
NATIONAL ACADEMY OF ENGINEERING
INSTITUTE OF MEDICINE
NATIONAL RESEARCH COUNCIL

REPORT IN BRIEF

New Research Opportunities in the Earth Sciences

A national strategy to sustain basic research and training across all areas of the Earth sciences would help inform the response to many of the major challenges that will face the planet in coming years. Issues including fossil fuel and water resources, earthquake and tsunami hazards, and profound environmental changes due to shifts in the climate system could all be informed by new research in the Earth sciences. The National Science Foundation's Division of Earth Sciences, as the only federal agency that maintains significant funding of both exploratory and problem-driven research in the Earth sciences, is central to these efforts, and coordinated research priorities are needed to fully capitalize on the contributions that the Earth sciences can make.

With Earth's population expected to reach 7 billion by the end of 2011, and about 9.2 billion by 2050, demand for resources such as food, fuel, and water is increasing rapidly. At the same time, humans are changing the landscape and the temperature of the atmosphere is increasing. Expanding basic research in the Earth sciences—the study of Earth's solid surface, crust, mantle and core, and the interactions between Earth and the atmosphere, hydrosphere, and biosphere—could make real progress toward meeting these growing demands and reaching a better understanding of the changing environment.

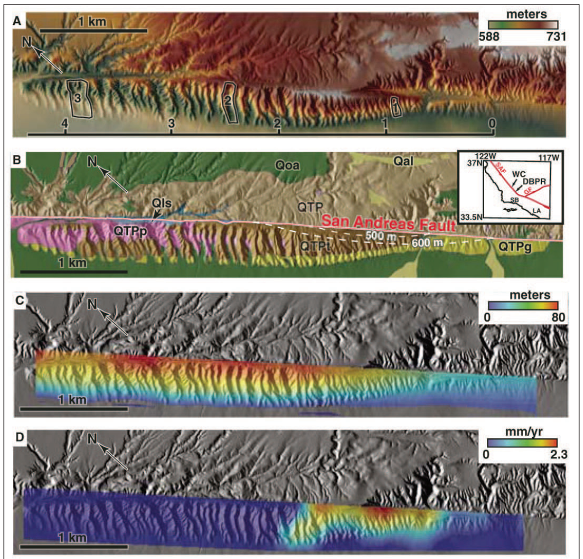

Figure 1. Combining LiDAR data with geological observations helps determine how erosional processes respond to rock uplift at Dragon's Back pressure ridge along the San Andreas Fault. A. Airborne Laser Swath Mapping topography; B. Geological observations; C. total rock uplift; D. instantaneous rock uplift rate. Source: Hilley and Arrowsmith, 2008, Geological Society of America

Overall, the National Science Foundation, through its Division of Earth Sciences, has done an excellent job in developing and maintaining a balance among programs that support investigator-driven, disciplinary research, problem-driven multidisciplinary research, and equipment-oriented programs to develop new instrumentation and facilities. Because all areas of the Earth system are interconnected, scientists and researchers in different Earth science disciplines will need to work together to advance understanding of the planet. However, it's important to note that this collaborative work builds on basic research in specific disciplines. Core Earth science research carried out by individual investigators, or small groups of scientists, remains the most creative and effective way to enhance the knowledge base upon which integrative efforts can build.

Key Research Opportunities

Conceptual advances in basic Earth science theory and technological improvements in data gathering and observational capabilities have boosted progress in the Earth sciences in recent years. In particular, seven Earth science topics promise rapid progress over the next decade. These topics represent a blend of exploratory research to increase understanding of fundamental Earth processes and problem-driven research to meet specific needs.

1. 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 million years of the planet's formation. These events include the formation of Earth's crust, atmosphere, and ocean, and the formation of the moon. A better understanding of this "early Earth" is essential for establishing the events and processes that allowed Earth to transition from its formative state to the hospitable planet of today.

Research directions to expand knowledge of the early Earth include expanding the search for older rock and mineral samples, developing new technologies to analyze ancient materials, and developing models that better simulate the conditions of the early Earth.

Recommendation: The Division of Earth Sciences should take appropriate steps to encourage work on the history and fundamental physical and chemical processes that governed the evolution of the early Earth, 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.

2. The Dynamics of Heat, Chemicals, and Volatiles in Earth's Interior

Huge, dynamic systems circulate heat in Earth's mantle and core. This circulation drives the movement of Earth's tectonic plates that generate earthquakes, form volcanoes, and lead to the accumulation of resources such as mineral ores. Developing a better understanding of the systems that circulate heat and materials beneath Earth's surface will help scientists reconstruct how these systems operated in the past, and predict how they will function in the future. Advances in imaging capabilities, a better understanding of how materials react under extreme heat and pressure, and increasingly realistic representations of the circulation of heat and pressure in Earth's mantle and core have helped advance the field.

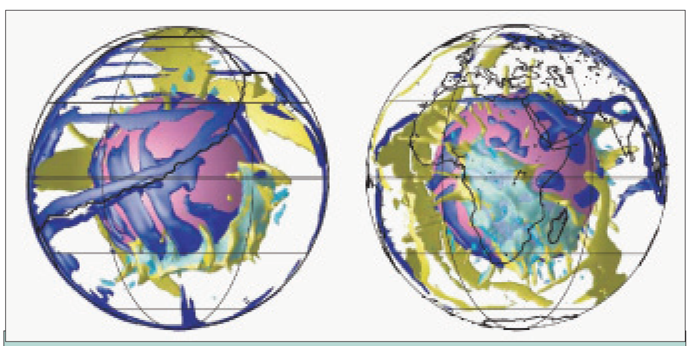

Figure 2. Understanding large low-velocity mantle provinces beneath southern Africa and the south-central Pacific could help decipher the origin and composition of mantle reservoirs and their fluxes. This simulation of whole-mantle convection shows, on left: calculated mantle strucutre 230 million years ago with reconstructed plate boundaries in black; and on right: present-day mantle structure with continent outlines in black. Positive and negative temperature anomalies are shown in yellow and blue; chemical heterogenetity in green, and the core mantle boundary in pink. Source: Zhang et al, 2010.

Figure 3. The Outdoor StreamLab (OSL) facility at the National Center for Earth Surface Dynamics (NCED) 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. Source: University of Minnesota.

Recommendation: The Division of Earth Sciences should pursue the development of facilities and capabilities that will improve the spatial resolution of deep structures in the mantle and core, such as dense seismic arrays that can be deployed in locations around Earth, and enhanced computational software and hardware to enable increased resolution of three-dimensional models. These 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.

3. Faulting and Deformation Processes

Studying fault zones and deformation—the twisting, bending and fracturing of rock— can help scientists predict when and where Earthquakes will occur, and how big earthquakes will be. Over the past few years, increased instrumentation around fault zones has allowed scientists to learn more about faulting processes and mechanisms. These findings present an opportunity to make significant progress on understanding faulting, related deformation processes, and resulting earthquake hazards.

Earthquake science is, by its nature, interdisciplinary. For example, geologists provide a framework for studying the deformation near plate boundaries; seismologists estimate the size of earthquakes and quantify ground shaking effects; and rock mechanics researchers determine frictional mechanisms.

Recommendation: The Division of Earth Sciences 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 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.

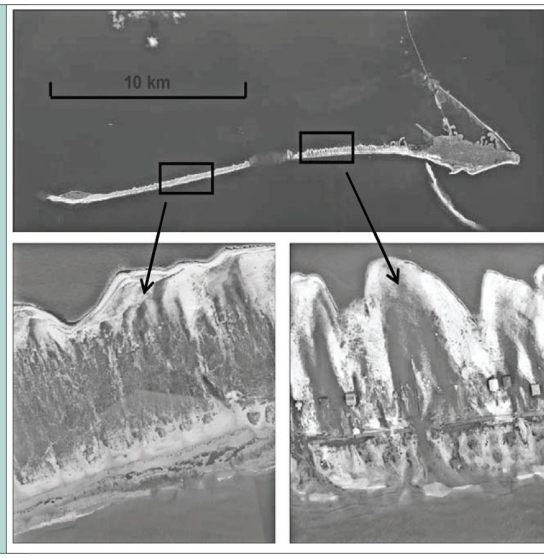

Figure 4. Aerial photo comparison of developed and undeveloped sections of barrier island response to Hurricane Katrina. Areas covered in vegetation (left) appear less impacted than developed areas (right). Understanding if this was due to the vegetation or to the prescence of higher coastal dunes built through vegetal interactions with sediment has signifcant environmental management implications.
Source: Feagin et al, 2010.

4. Interactions Among Climate, Surface Processes, Tectonics, and Deep Earth Processes

Over geologic spans of time, Earth's shifting tectonic plates, atmosphere, freezing water, thawing ice, flowing rivers, and evolving life have shaped Earth's surface features. These surface and deep Earth processes form a complex network of interactions and feedbacks that currently are not well understood. A more complete understanding of the influence of deep Earth processes that shape Earth's surface will require new developments in technologies such as satellite imagery, modeling capabilities, and field instrumentation and studies.

Recommendation: The Division of Earth Sciences 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 Continental Dynamics program to accommodate the broader research agenda of these interdisciplinary subthemes.

5. Co-evolution of Life, Environment, and Climate

The deep-time geological record provides a narrative of changes in Earth's climate, environment, and the evolution of life. This record provides analogs, insight, and context for understanding the role of people in the Earth system and the impacts of human-caused change on the planet. New analytic tools are now allowing scientists to put changes in Earth's landscapes in context with changes in other parameters such as temperature, atmospheric conditions, and the chemical composition of the ocean. These findings could provide new insight on the co-evolution of life, the environment, and climate.

Recommendation: The Division of Earth Science should develop a mechanism to enable interdisciplinary science-driven projects involving stratigraphy, sedimentology, paleontology, proxy development, calibration and application studies, geochronology, and climate modeling at appropriates resolves scales of time and space, in order 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.

6. Coupled Hydrogeomorphic-Ecosystem Response to Natural and Human-caused Change

It is now widely recognized that climate change and disturbance, both natural and human-caused, can have far-reaching consequences for landscapes and ecosystems. Building the ability to anticipate the response of landscapes and ecosystems to change will require a better understanding of the mechanisms of interactions and feedbacks among landscapes, ecosystems, and the flux and flow of water. Coastal environments are particularly important areas in which to understand these coupled responses due to their location at the interface of major terrestrial and oceanic systems. This will require monitoring of landscape processes, and the development 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: The Division of Earth Science should facilitate research on coupled hydrogeomorphic-ecosystem response to natural and human-caused change and disturbance. In particular, the committee recommends that the Division of Earth Science 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 the National Science Foundation, and should involve coordination with the Division of Ocean Sciences, the United States Geological Survey, and the National Oceanic and Atmospheric Administration.

7. 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 the cycling of water, carbon, and nitrogen. Advances in abilities to understand and quantitatively simulate these cycles will depend on new theories, models, and data. Among the key research opportunities is development of a theoretical framework for the interactions among processes. This will require an investment in environmental sensors, field instruments, geochemical and microbiological tools, remote sensing, and surface and subsurface imaging tools.

Recommendation: The Division of Earth Science should continue to support programs and initiatives focused on integrated studies of the cycling of water, nutrients, carbon and geological materials. These studies should include the 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

Although each research opportunity has specific data collection, instrumentation, and facilities associated with it, there are some cross-cutting intersections of needs. For example, understanding Earth system processes requires global networks to collect data, such as long-term observatories and portable instrument facilities for hydrology, rock and fossil sampling and drilling. The Division of Earth Science has achieved a balance of funding facilities, core research programs, and interdisciplinary initiatives. Maintaining this balance in the future will be important.

A strong theme throughout all the research topics identified in this report is the need to enhance geochronology—the science of determining the age of rocks, fossils, and sediments— in order to produce more accurate estimates of the age, duration, and rate of events and processes in earth's past. As a result of improvements in analytical methods and in the theoretical underpinnings and calibrations of a range of dating methods, the past few years have seen transformative advances in many approaches to geochronology. Areas of notable growth include more accurate dating of structures on Earth's surface using the rare isotopes produced by cosmic rays, determining the cooling histories of rocks, and the high precision dating of volcanic ash.

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

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Committee on New Research Opportunities in the Earth Sciences at the National Science Foundation: Thorne Lay, *Chair,* University Of California, Santa Cruz; **Michael L. Bender**, Princeton University, New Jersey; **Suzanne Carbotte**, Columbia University, New York; **Kenneth A. Farley**, California Institute Of Technology, Pasadena; **Kristine M. Larson**, University Of Colorado, Boulder; **Timothy Lyons,** University Of California, Riverside; **Michael Manga**, University Of California, Berkeley; **Ho-Kwang (Dave) Mao**, Carnegie Institution Of Washington, DC; **Isabel P. Montañez**, University Of California, Davis; **David R. Montgomery**, University Of Washington, Seattle; **Paul E. Olsen,** Columbia University, New York; **Peter L. Olson**, Johns Hopkins University, Baltimore, Maryland; **Patricia L. Wiberg**, University Of Virginia, Charlottesville; **Dongxiao (Don) Zhang**, University Of Southern California, Los Angeles; **Mark D. Lange**, *Study Director;* **Jason R. Ortego,** *Research Associate;* **Courtney R. Gibbs,** *Program Associate,* **National Research Council.**

The National Academies appointed the above committee of experts to address the specific task requested by the National Science Foundation.The members volunteered their time for this activity; their report is peer-reviewed and the final product signed off by both the committee members and the National Academies. This report brief was prepared by the National Research Council based on the committee's report.

For more information, contact the Board on Earth Sciences and Resources at (202) 334-2744 or visit http://dels.nas.edu/besr. Copies of *New Research Opportunities in the Earth Sciences* are available from the National Academies Press, 500 Fifth Street, NW, Washington, D.C. 20001; (800) 624-6242; www.nap.edu.