Free Executive Summary

Basic Research Opportunities in Earth Science

Committee on Basic Research Opportunities in the Earth Sciences, Board on Earth Sciences and Resources, National Research Council

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Executive Summary

Earth science is a quest for fundamental knowledge about the origin, evolution, and future of the natural world. Opportunities in this science have been opened up by major improvements in techniques for reading the geological record of terrestrial change, capabilities for observing active processes in the present-day Earth, and computational technologies for realistic simulations of dynamic geosystems. The agenda for the next decade of basic research is to explore the planet—decipher its history, understand its current behavior, and predict its future—by exploiting and extending these capabilities. This research will contribute to 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. Progress on these practical issues depends on basic research across the full spectrum of Earth science. The National Science Foundation (NSF), through its Earth Science Division (EAR), is the only federal agency that maintains significant funding for basic research in all the core disciplines of Earth science. The health of the EAR program is therefore central to a strong national effort in Earth science.

OPPORTUNITIES FOR BASIC RESEARCH

Basic research in Earth science encompasses a wide range of physical, chemical, and biological processes that interact and combine in complex ways to produce a hierarchy of terrestrial systems. EAR is currently sponsoring investigations on geosystems that range in geographic scale from global—climate, plate tectonics, and the core dynamo—to regional and local—

mountain belts and sedimentary basins, active fault networks, volcanoes, groundwater reservoirs, and soil systems. 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 six specific areas, organized here by proximity and scale, in which the opportunities for basic research are especially compelling:

1. *Integrative studies of the "Critical Zone"* the heterogeneous, near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources. Many science disciplines—hydrology, geomorphology, biology, ecology, soil science, sedimentology, materials research, and geochemistry—are bringing novel research tools to bear on the study of the Critical Zone as an integrated system of interacting components and processes. During the next decade, basic research will be able to address a wide spectrum of interconnected problems that bear directly on societal interests:

   - terrestrial carbon cycle and its relationship to global climate change, including the temporal and spatial variability of carbon sources and sinks and the influence of weathering reactions,
   - quantification of microbial interactions in mineral weathering, soil formation, the accumulation of natural resources, and the mobilization of nutrients and toxins,
   - dynamics of the land-ocean interface, which governs how coastal ocean processes such as tides, waves, and currents interact with river drainage, groundwater flow, and sediment flux,
   - coupling of the tectonic and atmospheric processes through volcanism, precipitation, fluvial processes, glacier development, and erosion, which regulate surface topography and influence climate on geological time scales, and
   - formation of a geological record that encodes a four-billion-year history of Critical-Zone processes, including environmental variations caused by major volcanic episodes, meteorite impacts, and other extreme events.

2. *Geobiology,* the study of how life interacts with the Earth and how it has changed through geological time. By combining the powerful tools of genomics, proteinomics, and developmental biology with new techniques from geochemistry, mineralogy, stratigraphy, and paleontology, geobiologists are now better equipped to investigate a variety of fundamental problems:

- prebiotic molecules, origin of life, and early evolution,
- biological and environmental controls on species diversity, including ecological and biogeographic selectivity, causes of extinction and survival, and the nature of evolutionary innovation,
- response of organisms, communities, and ecosystems to environmental perturbations, including the role of extreme events in reshaping ecosystems and climate,
- biogeochemical interactions and cycling among organisms, ecosystems, and the environment, with applications to monitoring and remediating environmental degradation, and
- effects of natural and anthropogenic environmental change on the habitability of the Earth.

3. *Research on Earth and planetary materials,* which uses advanced instrumentation and theory to determine properties at the molecular level for understanding materials and processes at all scales relevant to planets. This field is being stimulated by enhanced research capabilities, such as synchrotron-beamlines for micro-diffraction and spectroscopy, experimental apparatus for accessing ultra-high pressures and temperatures, resonance techniques for precise measurements of elastic properties, quantum-mechanical simulations of complex minerals, and novel approaches to geomicrobiology and biomineralogy. A number of opportunities for basic research can be identified:

- biomineralization—natural growth of minerals within organisms, with applications to the development of synthetic analogs,
- characterization of extraterrestrial samples from Mars, comets, and interplanetary space,
- super-high pressure (terapascal) research, with applications to planetary and stellar interiors,
- nonlinear interactions and interfacial phenomena in rocks—strain localization, nonlinear wave propagation, fluid-mineral reactions, and coupling of chemical reactions to fracturing,
- nanophases and interfaces, including microbiology at interfaces and applications to the physics and chemistry of soils,
- quantum and molecular theory applied to minerals and their interfaces, and
- studies of granular media, including the nonlinear physics of soils and loose aggregates.

4. *Investigations of the continents.* New space-based geodetic techniques—the Global Positioning System and interferometric synthetic aperture

radar (InSAR)—are capable of mapping crustal deformation with centimeter-level precision, paving the way for advances in earthquake mechanics, volcano physics, and crustal rheology. Seismic tomography can now image the subsurface with enough horizontal resolution to observe how individual surface features are expressed at depth. These remote-sensing techniques, in combination with field mapping, deep continental drilling for in situ sampling and experimentation, and advanced laboratory analysis of rocks brought up from great depths, offer major opportunities to address basic questions regarding the three-dimensional structure and composition of the continents, the geologic record of continental formation and assembly, and the physical processes in continental deformation zones. Targets of this research include:

- mechanisms of active deformation, earthquake physics, coupling between brittle and ductile deformations, and fault-system dynamics and evolution,
- role of fluids in chemical, thermal, magmatic and mechanical processes, deep circulation systems in hydrothermal areas and sedimentary basins, and fluxes from the mantle,
- nature of the lower continental crust, its average composition and fluid content, processes of formation and development, and role as a mechanical decoupling layer, and
- deep structure of the continental lithosphere, its coupling to the underlying mantle, and implications for Earth evolution.

5. *Studies of the Earth's deep interior,* to define its structure, composition, and state, and to understand the machinery of mantle convection and the core dynamo. The quality and quantity of data are expanding at an extraordinary rate in many related fields—seismology, geomagnetic studies, geochemistry, and high-pressure research. Increased computational speeds and high-bandwidth networks have greatly facilitated the processing of very large data sets and the realistic modeling of deep-interior dynamics. Laboratory studies conducted at mantle and core conditions are now able to provide constraints on the physical and chemical conditions essential for the interpretation of numerical simulations. There are four primary areas of investigation:

- complex time-dependent flow patterns of solid-state mantle convection, which can be inferred by reconciling seismic tomographic and geochemical data using high-resolution numerical simulations,
- operation and interaction of mantle convection and the core dynamo over Earth history, which can be studied through multidisciplinary investigations of the core-mantle boundary,

- generation of the geomagnetic field, which can be investigated through realistic numerical simulations of the core dynamo, combined with recently available satellite and paleomagnetic data, and
- origin and evolution of the inner core and its role in the core dynamo, as revealed by the strong seismic heterogeneity and anisotropy discovered in the past few years.

6. *Planetary science,* which uses extraterrestrial materials, as well as astronomical, space-based, and laboratory observations, to investigate the origin, evolution, and present structure of planetary bodies, including the Earth. Telescopic observations of primitive objects in the solar system and of the planets orbiting distant stars are beginning to furnish unique data regarding the origin and evolution of the solar system. Current and planned space missions will provide unprecedented detail and coverage of the geology, topography, structure, and composition of many solar-system bodies. Within a decade, the first samples collected from Mars, a comet, an asteroid, and the Sun (via solar wind particles) will be returned to Earth for direct investigation. A proper interpretation of these data will require the application of Earth-science techniques and appropriate terrestrial comparisons. Such comparisons promise improved understanding of the Earth and solar system as a whole:

- Other planets furnish new environments for investigating the basic geological and geophysical processes operating on and within the Earth.
- Most planets preserve physical and chemical records of the early solar system that contains data on planetary evolution that no longer exists on Earth.
- Distinctive chemical and isotopic signatures from extraterrestrial samples are critical for furthering the understanding of the mixing, accretion, and differentiation of meteorite parent bodies and planets, including the Earth.

PRINCIPAL FINDINGS AND RECOMMENDATIONS

EAR has done an excellent job in maintaining the balance among core programs supporting investigator-driven disciplinary research, problem-focused programs of 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 exploit research opportunities identified by the committee.

Long-Term Support of 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 Earth science. Major investments are now justified in two promising fields. EAR should seek new funds for the long-term support of:

1. geobiology, to permit studies of the interactions between biological and geological processes, the evolution of life on Earth, and the geologic factors that have shaped the biosphere, and
2. investigator-initiated research on Earth and planetary materials to take advantage of major new facilities, advanced instrumentation and theory in an atomistic approach to properties and processes.

Outstanding research opportunities related to the study of the Critical Zone also warrant additional resources for established programs in hydrology and geology. The committee offers two primary recommendations:

- Owing to the significant opportunities for progress in the understanding of hydrologic systems, particularly through coordinated studies of the Critical Zone, EAR should continue to build programs in the hydrologic sciences.
- EAR should enhance multidisciplinary studies of the Critical Zone, placing special attention on strengthening soil science and the study of coastal zone processes.

To coordinate support for multidisciplinary studies, EAR should take the lead within NSF in devising a long-term strategy for funding research on the Critical Zone.

Mechanisms for Multidisciplinary Research

Understanding the behavior and evolution of complex terrestrial systems requires cooperative efforts in data collection as well as integrative studies to pull together diverse data sets and construct explanatory models. EAR has a very good record of sponsoring multidisciplinary research through its long-term core programs, particularly the Continental Dynamics Program, and a number of fixed-term special emphasis areas. The committee has identified several opportunities for strengthening the multidisciplinary aspects of Earth science.

EarthScope. This major NSF initiative, already in the advanced planning stage, will deploy four new observational systems: (1) *USArray,* for high-resolution seismological imaging of the structure of the crust and mantle beneath North America; (2) *San Andreas Fault Observatory at Depth,* for probing and monitoring the San Andreas Fault by deep drilling into the fault zone; (3) *Plate Boundary Observatory,* for measuring deformations of the western United States using strainmeters and ultraprecise geodesy; and (4) *InSAR,* for using satellite-based interferometric synthetic aperture radar to map surface deformations. EarthScope will contribute substantially to understanding the active tectonics and evolution of the continents, earthquake and volcanic hazards, and basic geodynamic processes operating in the Earth's deep interior. The scientific vision and goals of EarthScope are well articulated and have been developed with a high degree of community involvement.

- The committee strongly endorses the four observational components of the EarthScope initiative.

Existing programmatic elements within EAR furnish the mechanisms to support the basic science required for a successful EarthScope initiative, but only if funding is adequately augmented for basic disciplinary and multidisciplinary research.

Natural Laboratories. Demands are rising for EAR investments in natural laboratories, where terrestrial processes and systems can be studied through detailed field observations and in situ measurements in specially designated areas. This type of cooperative research is particularly suitable for studies of the Critical Zone, in which techniques from several disciplines must be coordinated to collect data sets that are spatially dense and temporally extended.

- EAR should establish an Earth Science Natural Laboratory (ESNL) Program, open to all problem areas and disciplines, with the objective of supporting long-term, multidisciplinary research at a number of promising sites within the United States and its territories.

Special Areas of Multidisciplinary Research. In addition to major facility-oriented initiatives, the committee suggests that EAR initiate fixed-term programs in two research areas—microorganisms in the environment and planetary science—that offer particular promise for significantly advancing scientific understanding through multidisciplinary studies:

- EAR should seek new resources to promote integrative studies of the way in which microorganisms interact with the Earth's surface environment, including present and past relationships between geological processes and the evolution and ecology of microbial life.

- To promote increased interactions between the Earth and planetary science research communities and to exploit the basic research opportunities arising in the study of solar and extrasolar planets, EAR should initiate a cooperative effort with the National Aeronautics and Space Administration (NASA) and NSF-Astronomy in planetary science.

Instrumentation and Facilities

The EAR Instrumentation and Facilities (I&F) Program has been highly successful, but it is under increasing stress from the rising costs of purchasing, operating, and maintaining state-of-the-art research equipment. To take advantage of novel technologies, EAR will have to expand the resources devoted to major facilities and observatories, as well as to individual laboratories. Technologies targeted for future investments might include neutron-scattering facilities, smart synchrotron beamlines, laser-based materials analysis, geochemical and geochronometric instrumentation, and mobile instrumentation for ground-based remote-sensing and biogeochemical analyses.

- EAR should seek more resources to support the growing need for new instrumentation, multiuser analytical facilities, and long-term observatories, and for ongoing support of existing equipment.
- The I&F program should encourage its user communities to identify research priorities and develop a consensus regarding how many laboratories are needed and how their operational costs should be apportioned among the EAR core programs, the I&F program, and participating academic institutions.

Education

To maintain its vitality, Earth science must attract talented new practitioners. The educational requirements for these practitioners are becoming more demanding, especially given the need to keep pace with the cross-disciplinary aspects of Earth science. Within EAR, there are many opportunities for blending education with basic research.

- EAR should institute training grants and expand its fellowship program to facilitate broad-based education for undergraduate and graduate students in the Earth sciences.

- EAR should establish postdoctoral and sabbatical-leave training programs to facilitate development of the cross-disciplinary expertise needed to exploit research opportunities in geobiology, climate science, and other interdisciplinary fields.
- EAR should take advantage of the broad appeal of field work, its modest cost, and its ability to capture the enthusiasm and research effort across a wide range of institutions by providing sufficient funding for graduate and undergraduate field work.

PARTNERSHIPS IN EARTH SCIENCE

Agency partnerships led by EAR will 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. Cooperation with mission-oriented agencies can also be an effective mechanism for transferring NSF-sponsored basic research into practical applications. Geobiology, integrative studies of the Critical Zone, and paleoclimatology are obvious areas in which collaborations should be developed among a number of NSF divisions (e.g., the Atmospheric and Ocean Sciences Divisions, the Biological Sciences Directorate) and mission-oriented agencies (e.g., the U.S. Geological Survey, Department of Energy, National Oceanic and Atmospheric Administration, Environmental Protection Agency, and U.S. Department of Agriculture). The EarthScope project should also benefit from interagency cooperation on several levels: with the Ocean Sciences Division in gathering offshore data and linking to the Continental Margins Research program; with the Division of Civil and Mechanical Systems on earthquake research relevant to the Natural Earthquake Hazards Reduction Program and the Network for Earthquake Engineering Simulation; with the U.S. Geological Survey in deploying the Advanced National Seismic System; and with NASA in developing a satellite-based interferometric synthetic aperture radar system for observing active deformation. An effective initiative in planetary science will require careful coordination with NSF's Astronomical Science Division as well as with NASA. Improved core support for the study of Earth and planetary materials could be the basis for strengthening EAR's participation in the National Nanotechnology Initiative, and an EAR program on microorganisms in the environment should provide an appropriate Earth science focus for the NSF's cross-cutting program on Biocomplexity in the Environment. An ESNL program could solicit the cosponsorship of natural laboratories by other agencies, including state and local government agencies.

Continuing progress in Earth science will depend heavily on improvement to the computational infrastructure, including the development of community models that can function as virtual laboratories for the study of complex geosystems. EAR should be particularly aggressive in fostering substantive partnerships between Earth and computer scientists through the multiagency initiative on Information Technology for the Twenty-First Century and other programs.

REQUIRED RESOURCES

The committee's recommendations, taken together, lay out a basis for the manner in which the EAR Division can respond to major Earth science challenges and opportunities in the next decade. The committee estimates that the new funding needed to implement these recommendations would increase the EAR budget by about two-thirds. This increase would help to offset the recent decline in federal support of basic Earth science and would substantially strengthen the national effort in this important area of fundamental research.

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