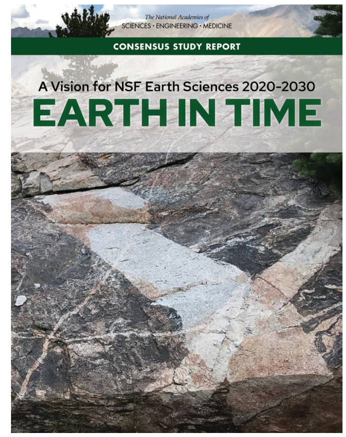
Consensus Study Report

May 2020

HIGHLIGHTS

A Vision for NSF Earth Sciences 2020-2030: Earth in Time



The Earth system functions and connects in unexpected ways—from the microscopic interactions of bacteria and rocks to the macro-scale processes that build and erode mountains and regulate Earth's climate. Efforts to study Earth's intertwined processes are made even more pertinent and urgent by the need to understand how the Earth can continue to sustain both civilization and the planet's biodiversity. This report identifies 12 priority research questions and provides recommendations to help the National Science Foundation (NSF) plan and support the next decade of Earth science research.

NSF's Division of Earth Science (EAR) is the primary federal research program funding Earth science. The EAR portfolio is diverse, including investigator-based research projects, multi-investigator programs, investments in facilities, and initiatives within NSF's Directorate for Geosciences (GEO). EAR also collaborates with other NSF divisions and directorates through cross-cutting programs, as well as with other federal agencies and international partners to provide essential research and infrastructure capabilities to Earth scientists.

SCIENCE PRIORITY QUESTIONS

To develop research priorities to guide future EAR research, the committee convened by the National Academies chose to identify specific questions that are poised for major advances in the next 10 years. The committee received input from an online community questionnaire, expert discussions at committee meetings, discussions with colleagues in the EAR research community, listening sessions and town halls at scientific conferences, and a comprehensive literature review of community-generated reports, scientific articles, and other sources of information.

These 12 compelling, high-priority research questions reflect the importance of geological time, connections between Earth's surface and interior, the co-evolution of geology and life, and the effects of human activities:

1. How is Earth's internal magnetic field generated?

Understanding what has powered the geodynamo through time and what controls its rate of change is crucial for understanding interactions from Earth's interior to the atmosphere.

2. When, why, and how did plate tectonics start?

There remains a lack of understanding of when plate tectonics developed on Earth, why on Earth and not elsewhere, and how plate tectonics has developed through time.

3. How are critical elements distributed and cycled in the Earth?

Fundamental questions remain about how critical elements essential for geologic processes are transported within the Earth, across a range of spatial and temporal scales.

4. What is an earthquake?

Deformation of the Earth occurs over a spectrum of rates and in a variety of styles, leading Earth scientists to reconsider the nature of earthquakes.

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5. What drives volcanism?

The effects of volcanic eruptions create an urgent need for research on how magma forms, rises, and erupts around the world and how these systems have operated throughout geologic time.

6. What are the causes and consequences of topographic change?

New technology for measuring topography over geologic to human timescales makes it possible to address questions linking the deep and surface Earth as well as societal challenges.

7. How does the critical zone influence climate?

The reactive skin of the terrestrial Earth influences many exchanges between the land and atmosphere and its influence on climate is a vital component of understanding the Earth system.

8. What does Earth's past reveal about the dynamics of the climate system?

Both long-term and rapid environmental change in Earth's history helps to elucidate Earth system dynamics and plays a critical role in predicting future change.

9. How is Earth's water cycle changing?

Understanding current and future changes to the water cycle requires knowledge of the hydro-terrestrial system and how the water cycle interacts with other processes.

10. How do biogeochemical cycles evolve?

A deeper understanding of biogeochemical cycles is needed to quantify the role of biology through time in rock and mineral formation and weathering and carbon cycling.

11. How do geological processes influence biodiversity?

Understanding how and why the diversity of life on Earth has varied over time, environment, and geography, including major events like extinctions, is needed.

12. How can Earth science research reduce the risk and toll of geohazards?

A predictive and quantitative understanding of geohazards is essential to reduce risk and impacts and to save lives and infrastructure.

These questions underscore the fundamentally intertwined nature of Earth processes, integrated by three overarching themes. First, the Earth is an active, dynamic, open system in which all components interact to shape the state of the planet. Second, the complex geological, geochemical, geophysical, hydrological, and biological processes that govern Earth-system interactions operate over exceptionally broad temporal and spatial scales. Finally, a clear understanding of how the Earth evolved and how it works as an integrated system is central to predicting how current and future changes are likely to influence human society.

INFRASTRUCTURE AND FACILITIES

Earth scientists use instruments and facilities to collect observations across the globe and analyze these data for new insights. Infrastructure supported by EAR consists of the instruments that are used to make observations and take measurements; the cyberinfrastructure (e.g., software, models, high-performance computing) that is needed to gather, analyze, integrate, and archive acquired information; and the human expertise needed to develop, maintain, and operate the instruments and software tools. To facilitate more transparent evaluation of EAR-supported infrastructure, from individual facilities to the entire EAR infrastructure portfolio, the committee encourages EAR to consider establishing a metrics-based system that can assess the effectiveness and impact of existing facilities.

Recommendation: EAR-supported facilities and the entire portfolio of EAR-supported infrastructure should be regularly evaluated using stated criteria in order to prioritize future infrastructure investments, sunset facilities as needed, and adapt to changing science priorities.

INSTRUMENT-BASED INFRASTRUCTURE

The study of the core and the magnetic field, plate tectonics, critical elements, earthquakes, and volcanoes would benefit from enhanced instrumentation to observe and monitor current geologic processes, especially at finer spatial and temporal resolution. This includes seismic and geodetic facilities, rapidly deployable instruments, laboratory facilities to carry out experiments under a range of environmental conditions, and analytical instrumentation to obtain improved records of igneous/metamorphic/tectonic processes operating through Earth history.

The study of topography, critical zone, climate, water cycle, and geohazards needs high-resolution and repeat survey data for change detection; subsurface characterization of material properties; long-term observatories and experimental watersheds to investigate processes; precipitation and runoff monitoring stations; satellite-based monitoring data; the ability to quantify chronologies and rates over geologic timescales; and proxy measurements of past environmental conditions.

The study of biodiversity and biogeochemical cycles depends on spatio-temporally constrained paleontological, geochemical, genomic, stratigraphic, and sedimentological records; precise geochronology; and a process-oriented understanding of environmental proxies.

POSSIBLE NEW INITIATIVES

New initiatives provide potentially transformative capabilities to support the science priority questions, while addressing gaps between existing and needed infrastructure. Several of these initiatives are well developed, following years of community involvement and support. Other possible initiatives have varying levels of community engagement and program development and may require broader involvement of the Earth science community. In most cases, funding of these possible new initiatives will require either injection of new funds and/or sunsetting of current programs.

Recommendation: EAR should fund a National Consortium for Geochronology. Improved constraints on the ages and rates of geologic processes are essential for current and future research in Earth science.

Recommendation: EAR should fund a Very Large Multi-Anvil Press Facility. Quantifying the physical and mechanical properties of rocks, minerals, and melts is a cornerstone of EAR research, but the United States still lacks certain technological capabilities needed to synthesize novel samples and to conduct key physical properties and deformation experiments.

Recommendation: EAR should fund a Near-Surface Geophysics Center. Geophysical surveys of Earth's near-surface region have become an essential tool for many Earth science fields. A near-surface geophysics center would enable novel observations and new insights for several of the science priority questions.

Recommendation: EAR should support continued community development of the SZ4D initiative, including the Community Network for Volcanic Eruption Response. This initiative seeks a deeper understanding of subduction processes that drive the evolution of Earth's interior and that create devastating geohazards such as earthquakes, tsunamis, and volcanic eruptions.

Recommendation: EAR should encourage the community to explore a Continental Critical Zone initiative. Characterizing the critical zone over large areas could advance understanding of water, carbon, and nutrient cycles; landscape evolution and hazards prediction; and land-climate interactions.

Recommendation: EAR should encourage the community to explore a Continental Scientific Drilling initiative. Improved mechanisms to support U.S. researchers' involvement in continental drilling would enhance access to continuous geologic records of the deep history of the Earth and monitoring of active subsurface processes.

Recommendation: EAR should facilitate a community working group to develop mechanisms for archiving and curating currently existing and future physical samples and for funding such efforts. New questions and analytical methods are continually introduced, making physical archives invaluable to scientists many years after the relevant materials were collected.

CYBERINFRASTRUCTURE

Addressing the science priority questions will require advanced computational capabilities and new methods of data integration to enable high-resolution imaging of Earth structure and of Earth materials; innovative modeling of physical, chemical, and biological processes; and better constraints on Earth's dynamical evolution.

Recommendation: EAR should initiate a community-based standing committee to advise EAR regarding cyberinfrastructure needs and advances. EAR needs regular guidance about the needs of its researchers, opportunities in cyberinfrastructure, and the rapidly evolving computational landscape.

Recommendation: EAR should develop and implement a strategy to provide support for FAIR (Findable, Accessible, Interoperable, Reusable) practices within community-based data efforts. FAIR data standards will improve the longevity, utility, and impact of EAR-funded data. The financial cost makes EAR support for long-term, compliant data storage difficult in times of level budgets.

HUMAN INFRASTRUCTURE

Highly trained individuals in STEM are an essential part of Earth science infrastructure and are central to future breakthroughs and the continued relevance of geoscience to societal issues.

Recommendation: EAR should enhance its existing efforts to provide leadership, investment, and centralized guidance to improve diversity, equity, and inclusion within the Earth science community. Improved inclusion of diverse perspectives in all aspects of research and collaboration benefits team innovation, problem solving, and effectiveness, and can enhance the relevance of science to currently underrepresented communities.

Recommendation: EAR should commit to long-term funding that develops and sustains technical staff capacity, stability, and competitiveness. Preparing the next generation of Earth scientists for an increasingly technological field requires strengthening financial support for technical staff.

PARTNERSHIPS

EAR has established strong relationships in order to meet the needs of advancing research across the Earth system, not just within the Earth sciences.

Recommendation: EAR should collaborate with other GEO divisions and other agencies to fund geoscience research that crosses boundaries, such as shorelines, high latitudes, and the atmosphere-land interface. Pursuing these opportunities not only advances research objectives, but also allows for more efficient leveraging of relevant facilities and infrastructure.

Recommendation: EAR should proactively partner with other NSF divisions and other federal agencies to advance novel societally relevant research. Cross-division collaboration and cross-agency partnerships work best when there is a strong common interest and robust community input.

A DECADAL VISION FOR EARTH SCIENCES

EAR's mission is more important and urgent than ever before, with profound opportunities for discovery and potential for immense societal consequences. Continued progress in scientific understanding will make society better prepared to meet the challenges of a changing Earth, especially if these advances can be effectively communicated to the public.

COMMITTEE ON CATALYZING OPPORTUNITIES FOR RESEARCH IN THE EARTH SCIENCES (CORES): A DECADAL SURVEY FOR NSF'S DIVISION OF EARTH SCIENCES

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For More Information . . . This Consensus Study Report Highlights was prepared by the National Academies of Sciences, Engineering, and Medicine based on the Consensus Study Report *A Vision for NSF Earth Sciences 2020-2030: Earth in Time* (2020). The study was sponsored by the National Science Foundation. Any opinions, findings, conclusions, or recommendations expressed in this publication do not necessarily reflect the views of any organization or agency that provided support for the project. Copies of the Consensus Study Report are available from the National Academies Press, (800) 624-6242; http://www.nap.edu or via the Board on Earth Sciences and Resources web page at http://www.nationalacademies.org/besr.

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