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A Vision for NSF Earth Sciences 2020–2030
EARTH IN TIME

Committee on Catalyzing Opportunities for Research in the Earth Sciences (CORES):
A Decadal Survey for NSF's Division of Earth Sciences

Board on Earth Sciences and Resources

Division on Earth and Life Studies

A Consensus Study Report of

The National Academies of
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This Consensus Study Report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the National Academies of Sciences, Engineering, and Medicine in making each published report as sound as possible and to ensure that it meets the institutional standards for quality, objectivity, evidence, and responsiveness to the charge. The review comments and draft manuscript remain confidential to protect the integrity of the process.

We thank the following individuals for their review of this report:

Susan Brantley (NAS), The Pennsylvania State University
Michelle Coombs, U.S. Geological Survey
Karen Fischer, Brown University
Gordon Grant, U.S. Forest Service
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Jack Williams, University of Wisconsin–Madison

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the content of the report nor did they see the final draft before its release. The review of this report was overseen by **Norman Sleep (NAS)**, Stanford University, and **George Hornberger (NAE)**, Vanderbilt University. They were responsible for making certain that an independent examination of this report was carried out in accordance with the standards of the National Academies and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee and the National Academies.

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Many individuals assisted the committee and the National Academies of Sciences, Engineering, and Medicine staff in their task to create this report. Over the course of five meetings, town halls and listening sessions, and webinars, the committee engaged with interested colleagues in academia, industry, and government. The committee greatly appreciated the chance to learn not only from the participants of these meetings and webinars, but also from each of the respondents to the questionnaire and from the facility operators, who kindly answered many questions.

Preface

I would like to briefly introduce the report with my personal observations as an outsider to the Earth science field, in that my background is in oceanography. However, I spent a few years at both the National Aeronautics and Space Administration and the National Science Foundation, and have served on two other recent decadal surveys—*Sea Change: 2015-2025 Decadal Survey of Ocean Sciences* and *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*. Because of this, I have experience with the process of developing a decadal report and insights into its potential impact.

During the committee discussions, I was so impressed with the importance of Earth science research. Much of the science was new to me, and I soon learned to appreciate the excitement of Division of Earth Sciences (EAR)-supported research over such a broad range of topics. I also learned just how much of EAR research is at the heart of what society needs to know from scientists: volcanic eruptions, earthquakes, landslides, distribution of essential elements across and below the Earth's surface, climate change, changes to the global water cycle, and relations between geology and biology, just to mention a few research areas that are reflected in our report's scientific questions. Such research is not only compelling; it is essential for our well-being here on Earth. As I write this, the committee is working on the final draft of the report during the coronavirus pandemic. Years ago, Dr. Rita Colwell and colleagues demonstrated how environmental processes helped spread the bacteria that caused cholera. Perhaps research that strengthens the connections between Earth sciences and human health may eventually help us to better understand the processes that spread other harmful pathogens.

I was very pleased with how well the committee worked together and how seriously they took their task. There were of course disagreements at times on content, wording, and organization, although these discussions were always professional and with respect for other members' points of view. In addition, committee members were cognizant of their responsibility to represent the broader Earth science research community and paid close attention to input we received at meetings and from questionnaires, town halls, and listening sessions.

There was the anticipated tension of trying to stay within the task guidance of working with a level EAR budget, and yet have the report reflect an optimistic view of the future. As one would expect, we likely erred a bit on the optimistic side.

On behalf of the committee, I thank those who took the time to meet with the committee and to otherwise provide us with much needed information. Finally, a special thanks goes to the National Academies staff who worked to keep us on time and on message. Without that discipline, this report could not have been written in the time allowed.

James A. Yoder, *Chair*
Committee on Catalyzing Opportunities for Research in the Earth Sciences (CORES): A Decadal Survey for NSF's Division of Earth Sciences

Contents

Summary

The Earth system interacts and connects in unexpected ways—from the interactions of bacteria and rocks to the convective and tectonic processes that build mountains, from the core to the atmosphere, and from the time of Earth's formation to the present day. While understanding Earth's interconnected processes is intrinsically interesting and of inherent scientific value, these efforts are made urgent by the need to understand how the Earth can continue to sustain civilization and the planet's biodiversity. During the past decade, Earth scientists have made conceptual, technological, computational, and observational advances in the study of the Earth as an integrated system. This rapid pace of discovery is likely to accelerate in the future.

The Division of Earth Sciences (EAR) at the National Science Foundation (NSF) is the primary federal research agency funding Earth science research, a foundation for fundamental scientific advances and for better understanding of the value and relevance of Earth science to society. The EAR research portfolio is diverse, including investigator-based research projects, multi-investigator programs, investments in facilities, and initiatives within NSF's Directorate for Geosciences (GEO; which encompasses EAR, the Division of Ocean Sciences, the Division of Atmospheric and Geospace Sciences, and the Office of Polar Programs). EAR also collaborates with other NSF divisions and directorates in cross-cutting programs, as well as with other federal agencies and international entities to provide essential research and infrastructure capabilities to Earth scientists.

In 2018, EAR asked the National Academies of Sciences, Engineering, and Medicine's Board on Earth Sciences and Resources to undertake a decadal survey that provides guidance on future Earth science research priorities, infrastructure and facilities, and partnerships (see Box 1-1 for the full Statement of Task). This report responds to these tasks, presenting a compelling and vibrant vision of the future of Earth science research.

PRIORITY SCIENCE QUESTIONS

The first task of the committee was to develop priority science questions to guide future EAR research. An important consideration was to develop questions that represent the broad and varied interests of the EAR research community. The committee looked to the community for its visions of the research, infrastructure, partnerships, and training that are needed to sustain and grow vibrant Earth science research. The committee received this input from an online community questionnaire, expert discussions at committee meetings, discussions with colleagues in the EAR research community, listening sessions at scientific conferences, and a comprehensive literature review of community-generated reports, scientific articles, and other sources of information. Guided by this input, the committee identified 12 compelling, high-priority research questions that reflect the importance of geological time, connections between Earth's surface and interior, the co-evolution of geology and life, the effects of human activities, and societal relevance. These questions are presented below in spatial order from Earth's core to the clouds:

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, as well as the human activities that are impacted by the geomagnetic field.

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

Plate tectonics produces and modifies the continents, oceans, and atmosphere, but there remains a lack of fundamental understanding of when plate tectonics developed on the Earth, why on the Earth and not on other planetary bodies, and how plate tectonics developed through time.

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

The cycling of critical elements essential for geologic processes creates suitable conditions for life and provides the ingredients for materials necessary for modern civilization, yet fundamental questions remain about how elements are transported within the Earth across a range of spatial and temporal scales.

4. What is an earthquake?

Earthquake rupture is complex, and the deformation of the Earth occurs over a spectrum of rates and in a variety of styles, leading Earth scientists to reconsider the very nature of earthquakes and the dynamics that drive them.

5. What drives volcanism?

Volcanic eruptions have major effects on people, the atmosphere, the hydrosphere, and the Earth itself, creating an urgent need for fundamental research on how magma forms, rises, and erupts in different settings 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 time scales now makes it possible to address scientific questions linking the deep and surface Earth and urgent societal challenges related to geologic hazards, resources, and climate change.

7. How does the critical zone influence climate?

The reactive skin of the terrestrial Earth influences moisture, groundwater, energy, and gas exchanges between the land and atmosphere, and its influence on climate is therefore a vital component of understanding the Earth system and how it has responded and will respond to global change.

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

Evidence of both long-term and rapid environmental change in Earth's history provides key baselines for comparison to modern change, helps to elucidate Earth system dynamics, provides magnitudes and rates of change, 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 fundamental knowledge of the hydro-terrestrial system and how the water cycle interacts with other physical, biological, and chemical processes.

10. How do biogeochemical cycles evolve?

To quantify the role of biology through time in the formation and weathering of rocks and minerals, the cycling of carbon, and the composition of the very air we breathe requires a deeper understanding of biogeochemical cycles.

11. How do geological processes influence biodiversity?

The diversity of life on the Earth is a major characteristic of the planet and yet we do not fully know how it came to be. We need to understand how and why diversity has varied over time, environment, and geography, including major events like extinctions.

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's processes. Several overarching themes integrate the individual research questions. 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, and biological processes that govern Earth-system interactions operate on wide temporal and spatial scales. Finally, a clear understanding of how the Earth currently works as an integrated system (including people as geological agents) and how it has worked in the past is central to predicting how present-day changes, both natural and anthropogenic, are likely to influence human society. For EAR to respond to these priorities requires maintenance of the core disciplinary program strength, with a balance between both individual investigator-driven research and larger programs.

INFRASTRUCTURE AND FACILITIES

Future observations of the Earth and its constituent materials will rely more than ever on integrating emerging technology, data analysis, and human infrastructure. Infrastructure required to support EAR-funded research consists of the instruments used to make observations and take measurements; the software to gather, analyze, and archive acquired information; the cyberinfrastructure required to model Earth system processes; and the expertise needed to develop, maintain, and operate the instruments and software tools. This report describes the existing infrastructure used by EAR-supported researchers, as well as the future infrastructure needed to accomplish the science priorities described above.

EAR supports 30 multi-user facilities that provide infrastructure and expertise for the Earth science research community. The larger facilities support researchers through a combination of instrumentation, cyberinfrastructure, and training, whereas most of the smaller facilities emphasize either instrument-based infrastructure or cyberinfrastructure. The committee found many connections among the existing EAR-supported infrastructure and facilities and the infrastructure needs envisioned for the science priority questions (see Table S-1). In addition, a suite of facilities used by EAR researchers is supported by other divisions within GEO, other parts of NSF, and other federal agencies.

A range of instruments, facilities, and capabilities will be needed to fully address the science priority questions over the next decade. Studies 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 for quick response, laboratory facilities to carry out experiments under a range of environmental conditions, and analytical instrumentation (e.g., high-precision geochronology) to obtain improved records of igneous/metamorphic/tectonic processes operating through Earth's history.

The topography, critical zone, climate, water cycle, and geohazards questions need 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; field instrumentation to document water and solid fluxes and their drivers, and moisture, gas, and solute content; satellite-based monitoring data; the ability to quantify chronologies and rates over geologic time scales; and proxy measurements of past environmental conditions.

For questions concerning biodiversity and biogeochemical cycles, progress depends on spatiotemporally constrained paleontological, geochemical, genomic, stratigraphic, and sedimentological records; precise geochronology; and a process-oriented understanding of environmental proxies.

All of the questions will require advancements in high-performance computing, improved modeling capabilities, enhanced data curation and standardization, and robust cyberinfrastructure that link together observations across many types of records.

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.

TABLE S-1 Connections Between the Science Priorities and Existing Infrastructure and Facilities

	Geomagnetism	Plate Tectonics	Critical Elements	Earthquakes	Volcanoes	Topography	Critical Zone	Climate	Water Cycle	Biogeochemistry	Biodiversity	Geohazards
Geophysics												
SAGE	■	■	●	■	■	■	●		●			■
GAGE	●	■	●	■	■	■			■			■
IRM	■	■	●	●	●							●
ISC	■	■		■	■							■
CMT	●	■		■	●							■
Material Characterization												
GSECARS	■	■	■	■	■		■	■	■	■	●	
COMPRES	■	■	■	●	■					●	●	
Biogeochemistry/Geochronology												
PRIME		●	●	■	■	■	■	■		■	■	●
Wisc SIMS	■	■	■	●	■	●		●		■	■	●
UCLA SIMS	■	■	■	●	■	■		●		■	■	●
ASU SIMS	■	■	■	●	■	●		●		■	■	●
NENIMF		■	■	●	■	■		●		■	■	●
ALC		■	■	●	■	■		●		■	■	●
Support for Continental Drilling												
CSDCO	●	■	●	●	●		●	■	●	■	■	●
LacCore	●	■	●	●	●			■	●	■	■	●
ICDP	●	■	●	●	●			■	●	■	■	●
Other Disciplines												
NCALM		●		■	■	■	■	●	■			■
CTEMPS							■	●	■			
UTCT	●	■	●	●	●			●		●	■	●
NanoEarth			●				■	■	■			
Cyberinfrastructure												
IEDA	●	■	●	●	●	●		●		●	●	●
CSDMS						■	■	■	■			●
CUAHSI						■	■	■	■			●
CIG	■	■	●	■		●						■
Open Topo		●		■	■	■	■					■
MagIC	■	■	●	●	●			●				●
Neotoma								●	●	■	■	
Open Core Data	■	■	●	●	●			●	●	■	■	●
Alpha-MELTS		■	■		■							
GMT	●	■	●	■	■							■

Abbreviations in first column:
SAGE: Seismological Facilities for the Advancement of Geoscience; GAGE: Geodetic Facility for the Advancement of Geoscience; IRM: Institute for Rock Magnetism; ISC: International Seismological Center; CMT: Global Centroid-Moment-Tensor Project; GSECARS: GeoSoilEnviroCARS Synchrotron Radiation Beamlines at the Advanced Photon Source; COMPRES: Consortium for Materials Properties Research in Earth Sciences; PRIME: Purdue Rare Isotope Measurement Laboratory; Wisc SIMS: University of Wisconsin SIMS Lab; UCLA SIMS: University of California, Los Angeles, Ion Probe Lab; ASU SIMS: Arizona State University Ion Probe Lab; NENIMF: Northeast National Ion Microprobe Facility; ALC: Arizona LaserChron Center; CSDCO: Continental Scientific Drilling Coordination Office; LacCore: National Lacustrine Core Facility; ICDP: International Continental Scientific Drilling Program; NCALM: National Center for Airborne Laser Mapping; CTEMPS: Center for Transformative Environmental Monitoring Programs; UTCT: University of Texas High-Resolution Computed X-Ray Tomography Facility; NanoEarth: Virginia Tech National Center for Earth and Environmental Nanotechnology Infrastructure; IEDA: Interdisciplinary Earth Data Alliance; CSDMS: Community Surface Dynamics Modeling System; CUAHSI: Consortium of Universities for the Advancement of Hydrological Science, Inc.; CIG: Computational Infrastructure for Geodynamics; OpenTopo: OpenTopography High Resolution Data and Tools Facility; MagIC: Geo-Visualization and Data Analysis using the Magnetics Information Consortium; Neotoma: Neotoma Paleoecology Database and Community; GMT: Generic Mapping Tools.

NOTES: Science priorities identified in the report are across the top and existing infrastructure and facilities are down the side. A fully colored box denotes a facility that provides essential capabilities needed to address a priority science question, while a colored circle denotes a facility that is relevant for a question. Determinations were made based on descriptions provided by the facilities, NSF award abstracts, and information taken from the community input questionnaire.

Possible New Initiatives

The committee offers suggestions of possible new initiatives that EAR and the Earth sciences community may wish to consider. These initiatives were chosen because they provide potentially transformative capabilities to support the science priorities, while addressing some of the gaps between existing and needed infrastructure. All of these initiatives originate from EAR research communities, and are based on either community input responses, community white papers or reports, and/or presentations in public sessions.

Several of these initiatives—creating a national consortium for geochronology, establishing a near-surface geophysics center, and funding a U.S.-based very large multi-anvil press user facility—are well developed, with years of community involvement and support, including white papers, endorsement in previous community reports, and/or proposals to NSF. The SZ4D initiative has developed strong community support in recent years, including a well-attended NSF-sponsored workshop and three funded research coordination networks (RCNs), but is still developing its program plan. Other possible initiatives discussed, such as those involving continental drilling, establishing an archive of Earth materials and associated data, and study of the continental critical zone, have various levels of community engagement and program development. Further exploration of these initiatives would need broad involvement of the Earth science community via workshops, white papers, and coordinating mechanisms such as RCNs.

In all cases, the committee strongly believes that these initiatives cannot be developed at the expense of EAR's core disciplinary research programs. EAR's annual budget has been roughly constant since FY2010 and therefore, because of inflation, has declined in real terms. The initiatives highlighted in this report will be extremely challenging to pursue if the decline in EAR's budget continues.

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. A consortium for geochronology will better support EAR-funded researchers while enabling discovery through the development of innovative new instruments, techniques, and applications.

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, yet the United States still lacks certain technological capabilities needed to synthesize novel samples and to conduct key physical properties and deformation experiments. Modest investment would enable advances in experimental rock and mineral physics and drive current and future EAR research.

Recommendation: EAR should fund a Near-Surface Geophysics Center. Geophysical surveys of the near-surface region (from the ground surface to depths of tens to hundreds of meters) of the Earth have become an essential tool in many Earth science fields. A center would provide access to instrumentation, technical support, and training required to address several of the science priority questions and enable novel observations that lead to new questions and insights.

Recommendation: EAR should support continued community development of the SZ4D initiative, including the Community Network for Volcanic Eruption Response. This community-led 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 subsurface critical zone to its full depth at the continental scale is needed to 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 needed to address many of the priority questions.

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 and associated metadata invaluable to scientists many years after the relevant materials were collected. Even if time and funding were available, it would not always be possible to replicate a physical collection, as some materials are unique or ephemeral or were found only at localities that are no longer accessible.

Recommendations for Cyberinfrastructure

The committee also presents a series of recommendations that aim to advance EAR research through improvements to cyberinfrastructure that support computing and modeling capabilities, as well as data integration, synthesis, and curation. Earth science is experiencing an explosion of data acquisition capability and rapidly increasing computational demands as models advance to exploit these data and ever-increasing hardware capabilities. 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. In order to make optimal investments of resources in the coming decade, 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 practices within community-based data efforts. FAIR[1] data standards will improve the longevity, utility, and impact of EAR-funded data. Although NSF promotes FAIR data practices in spirit, the financial cost makes EAR support for long-term, compliant data storage difficult in times of level budgets.

Recommendations for Human Infrastructure

Finally, the committee emphasizes the need for human infrastructure. Highly trained individuals in science, technology, engineering, and mathematics (STEM) fields are an essential part of Earth science infrastructure and are central to future breakthroughs and the continued relevance of geoscience to societal issues, yet there are challenges to recruit and retain a highly competent and inclusive STEM workforce with expertise in both Earth and data sciences.

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. Highly

[1] FAIR stands for findable, accessible, interoperable, reusable. See Wilkinson, M. D., M. Dumontier, I. J. Aalbersberg, G. Appleton, M. Axton, A. Baak, N. Blomberg, J.-W. Boiten, L. B. da Silva Santos, P. E. Bourne, J. Bouwman, A. J. Brookes, T. Clark, M. Crosas, I. Dillo, O. Dumon, S. Edmunds, C. T. Evelo, R. Finkers, A. Gonzalez-Beltran, A. J. G. Gray, P. Groth, C. Goble, J. S. Grethe, J. Heringa, P. A. C. 't Hoen, R. Hooft, T. Kuhn, R. Kok, J. Kok, S. J. Lusher, M. E. Martone, A. Mons, A. L. Packer, B. Persson, P. Rocca-Serra, M. Roos, R. van Schaik, S.-A. Sansone, E. Schultes, T. Sengstag, T. Slater, G. Strawn, M. A. Swertz, M. Thompson, J. van der Lei, E. van Mulligen, J. Velterop, A. Waagmeester, P. Wittenburg, K. Wolstencroft, J. Zhao, and B. Mons. 2016. The FAIR guiding principles for scientific data management and stewardship. *Scientific Data* 3(1):160018. DOI: 10.1038/sdata.2016.18.

skilled staff are needed to help tackle the questions about the complex Earth system at analytical, computational, and instrumentation development facilities. Preparing the next generation of Earth scientists for an increasingly technological field requires strengthening financial support for technical staff.

Implementing the recommendations for cyberinfrastructure and human infrastructure will require not just a commitment of funding, but significant changes for the Earth science community in terms of policies and practices.

PARTNERSHIPS

EAR has established strong relationships across the GEO Directorate in order to meet the needs of advancing research across the Earth system, not just within Earth sciences. Components of the Earth system do not adhere to the administrative boundaries of GEO. To meet the continued and growing need to work across disciplines, EAR plays an active role in ongoing and new NSF cross-division and cross-directorate activities (e.g., Coastlines and People; Innovations at the Nexus of Food, Energy, and Water Systems).

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. The points of intersection for basic and applied research among multiple NSF divisions and directorates, federal agencies, and international partners present many opportunities for partnership and collaboration. Seizing these opportunities not only advances research objectives, but also allows for more efficient leveraging of relevant facilities and infrastructure.

As research becomes more inter- and transdisciplinary, there will be continued opportunities to strengthen and expand both formal and informal collaborations. A nimble EAR can quickly take advantage of the shifting frontiers in basic science and interdisciplinary research. There is a continued need to better articulate and publicize the important benefits of EAR research to policy makers and the public. In discussions with other NSF units and federal agencies, two repeated themes were the successful relationships that EAR has built with other directorates and EAR's involvement in productive cross-directorate, cross-agency, and international partnerships.

The National Aeronautics and Space Administration (NASA), the U.S. Department of Energy (DOE), and the U.S. Geological Survey (USGS) provide important capabilities supporting EAR research. Multiple opportunities exist to continue and expand partnerships with other federal agencies. Partnerships with NASA and USGS could include quantifying water storage in aquifers and reservoirs; understanding processes affecting sea-level rise; exploring fundamental research related to volcanoes, earthquakes, and landslides (and implications for risks to people and places); and investigating effects of biogeochemical processes. All of these are relevant to EAR research and suggest possibilities for partnerships that combine satellite and aircraft remote sensing with detailed process studies and ground-based observations. Additionally, DOE invests significantly in infrastructure that supports Earth science research at synchrotron radiation facilities.

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 a strong common interest and robust community input and involvement exist. Determining which areas of research might be valuable for collaboration between NSF and other agencies can be challenging, because mission agencies generally have less flexibility in funding research topics than does NSF. However, there are important advantages when it is possible to converge on a research partnership. Developing and sustaining partnerships do require time and effort of program officers, and the extra administrative workload is a potential obstacle to partnering.

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. Today's Earth science landscape is vastly different from what it was only a decade ago. Continued progress in understanding will make society better prepared to meet the challenges of a changing Earth, especially if scientific advances can be effectively communicated to the public. In this "all hands on deck" moment a demographically and scientifically diverse group of Earth scientists is needed, working both individually and in collaborative networks, to create and deploy cutting-edge analytical, computational, and field-based research methods in an open environment where success builds expeditiously on success.

1
Introduction

Earth's surface, interior, oceans, atmosphere, cryosphere, and biosphere form a complex, interacting system connected by physical, chemical, and biological processes that operate over spatial scales from the atomic to the planetary and over temporal scales from milliseconds to billions of years. Apparent terra firma is in fact constantly changing: steadily through biological processes, chemical reactions, and physical erosion, and over geologic time as plate tectonics creates, deforms, and destroys Earth's lithosphere; suddenly and catastrophically through large extraterrestrial impacts, glacial outburst floods, mega-tsunami, and flood basalt volcanism; and most recently through the actions of humans.

Earth's geologic record reveals multiple and profound transformations that affect the planet's character and habitability (see Figure 1-1). These include:

- Earth's accretion and differentiation 4.5 billion years ago, which formed the iron-rich core and bulk silicate Earth;
- the subsequent development of the geodynamo in Earth's liquid outer core, which generates the magnetic field and by doing so deflects plasma radiation from eroding the atmosphere and oceans;
- the emergence of plate tectonics (at an as-yet unknown time), which led to the differentiation of Earth's crust and mantle;
- the emergence of life followed by the Great Oxidation Event, which permanently changed Earth's surface chemistry 2.4 billion years ago and ultimately led to an increase in the anatomical and physiological diversity of life;
- states of Snowball Earth that sporadically encased the globe in ice, most recently 630 million years ago;
- the emplacement of large igneous provinces, for example, the Siberian Traps, which coincided with Earth's most extreme known extinction event 252 million years ago;
- the demise of the dinosaurs in the end-Cretaceous extinction, whether triggered by the impact of a large extraterrestrial body and/or the massive Deccan Trap eruptions, 66 million years ago;
- the Paleocene-Eocene Thermal Maximum, when temperatures and atmospheric carbon spiked in an ice-free world 56 million years ago;
- the repeated ice ages of the past several million years that covered large continental landmasses with mile-thick ice as recently as 11,000 years ago; and
- the ongoing Anthropocene, in which humans have emerged as geologic agents.

Such events have profoundly transformed the Earth and underscore the fact that we live on a remarkable and dynamic planet.

"The present is the key to the past" is a fundamental tenet of Earth science that remains obvious and important. The converse is also true: the wide range of conditions represented in Earth's past provides essential clues for understanding the Earth at present. Understanding Earth's long history is also critical for the urgent task of anticipating Earth's future. The committee chose Earth in Time as the subtitle of the report because it reflects the urgency of understanding Earth processes and how they affect habitability and expresses the importance of understanding how the Earth has evolved over geologic time.

That future is uncertain as humanity profoundly modifies the Earth system in ways that are consequential to the entwined fates of the natural world and civilization. The Earth is subject to a variety of hazards

FIGURE 1-1 Earth's deep time history is marked by dramatic and profound changes that altered Earth's future. This timeline presents some of the major transformational events in Earth's history from its initial formation as a planet to the ongoing transformation by humans in the Anthropocene. SOURCES (from left to right): Don Davis; Committee; WikiCommons; National Aeronautics and Space Administration (NASA); Benjamin Black; Adobe Stock by Anibal; NASA; Pixabay.

that are far from understood but increasing in their impact as exposure to risk grows dramatically through urbanization. This is particularly true in hazard-prone areas such as the world's coastal areas, seismically and volcanically active areas, and climatically vulnerable regions. This century will see Earth's finite nature become more apparent as a growing population that relies on the availability of freshwater, soil, energy, and critical minerals will find these resource needs more difficult to address. A rapidly changing climate heightens these challenges and introduces new stresses stemming from sea-level rise, drought, extreme precipitation, intensifying storms and wildfires, and abruptly changing ecosystems.

It is the work of geoscientists to develop a comprehensive scientific understanding of the complex Earth system. The task is intrinsically interesting, and worth pursuing for that reason alone. It is made urgent by the need to understand how the Earth can continue to sustain civilization and the planet's biodiversity. Each component—the atmosphere, hydrosphere, cryosphere, biosphere, and Earth's surface and interior—is itself complex. Moreover, these components do not operate independently. Most of Earth's interior is, and will remain, inaccessible to direct observation, such that knowledge of the deep subsurface must be inferred through imaging and laboratory and computational experiments. While more accessible, the shallow region of the terrestrial Earth, meters to tens of meters below the surface, is still poorly documented.

Novel sensor technologies, as well as new field and laboratory capabilities, are transforming observations from the atomic to the global scale (see Figure 1-2). Computer simulations are increasingly rapid and accurate and representative of Earth's true multi-scale complexity. New field and laboratory capabilities are transforming observations from the atomic to the global scale. Breakthroughs in geochronology, geochemistry, molecular biology, and phylogenetics are revolutionizing the understanding of geological and geochemical processes. Recent advances in data science, such as machine learning, have the potential to extract new insights from large, high-dimensional datasets and simulations that would otherwise be elusive.

No less important in the understanding of Earth systems are conceptual breakthroughs. The plate tectonics revolution, for example, suddenly brought order to a disparate array of previously puzzling and seemingly unrelated observations. The mega-tsunami that have repeatedly occurred in Hawaii and other volcanic islands through sudden collapse of their flanks, the for-

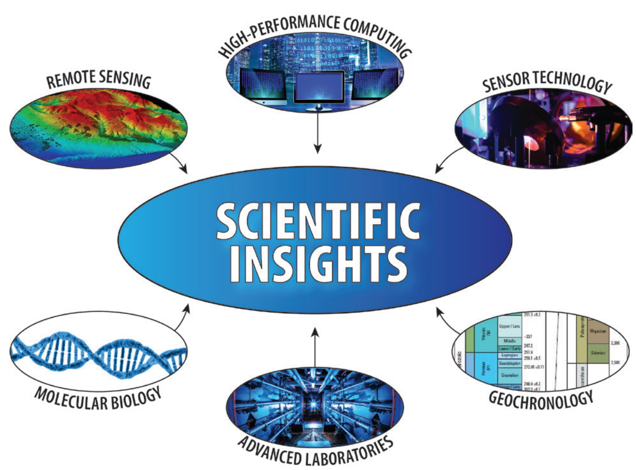

FIGURE 1-2 Advances in remote sensing, high-performance computing, sensor technology, and laboratory and field methods (such as molecular biology and geochronology) are rapidly transforming scientists' ability to resolve details of the Earth and its deep-time history. SOURCES: Image of remote sensing, National Oceanic and Atmospheric Administration; high-performance computing, Pixabay; sensor technology, National Energy Technology Laboratory; molecular biology, Pixabay; advanced laboratories, U.S. Department of Energy; geochronology, U.S. Geological Survey.

mation of eastern Washington's Channeled Scablands by major Pleistocene flooding events, and the realization that the modern structure of the Chesapeake Bay is profoundly influenced by an extraterrestrial impact 35 million years ago are all examples of how puzzling observations have come to be understood through conceptual breakthroughs. Research breakthroughs, by nature, are difficult to anticipate; however, this report highlights frontier research opportunities that are poised to accelerate understanding of the geosystem and that the National Science Foundation's (NSF's) Division of Earth Sciences (EAR), which has as its research focus Earth's surface and interior, may wish to pursue.

NSF DIRECTORATE FOR GEOSCIENCES AND DIVISION OF EARTH SCIENCES

EAR supports research addressing "the structure, composition, and evolution of the Earth, the life it supports, and the processes that govern the formation and behavior of the Earth's materials."[1] The divisions within NSF's Directorate for Geosciences (GEO) largely align with the spheres as defined in an integrated Earth systems context (atmosphere, ocean, cryosphere, and Earth's surface and interior; see Figure 1-3). The EAR research portfolio includes investigator-based research projects, multi-investigator programs, investments in facilities, and GEO and cross-directorate initiatives. EAR also collaborates with other units within NSF, as well as with other federal agencies and international entities, to provide essential infrastructure capabilities to Earth scientists. EAR's basic research programs also help federal mission agencies improve the use of applied science to serve societal needs.

EAR's organizational structure consists of two sections: Disciplinary Programs and Integrative Activities. Disciplinary Programs (often called the "core programs") encompasses Geobiology and Low-Temperature Geochemistry, Geomorphology and Land Use Dynamics, Geophysics, Hydrologic Sciences, Petrology and Geochemistry, Sedimentary Geology and Paleobiology, and Tectonics. Integrative Activities includes EAR Education and Human Resources, Earth Sciences Instrumentation and Facilities, Frontier Research in Earth Sciences, and NSF Earth Sciences Postdoctoral Fellowships. EAR disciplinary programs leverage significant infrastructure capabilities developed and operated by other federal agencies.

[1] See https://www.nsf.gov/geo/ear/about.jsp (accessed January 29, 2020).

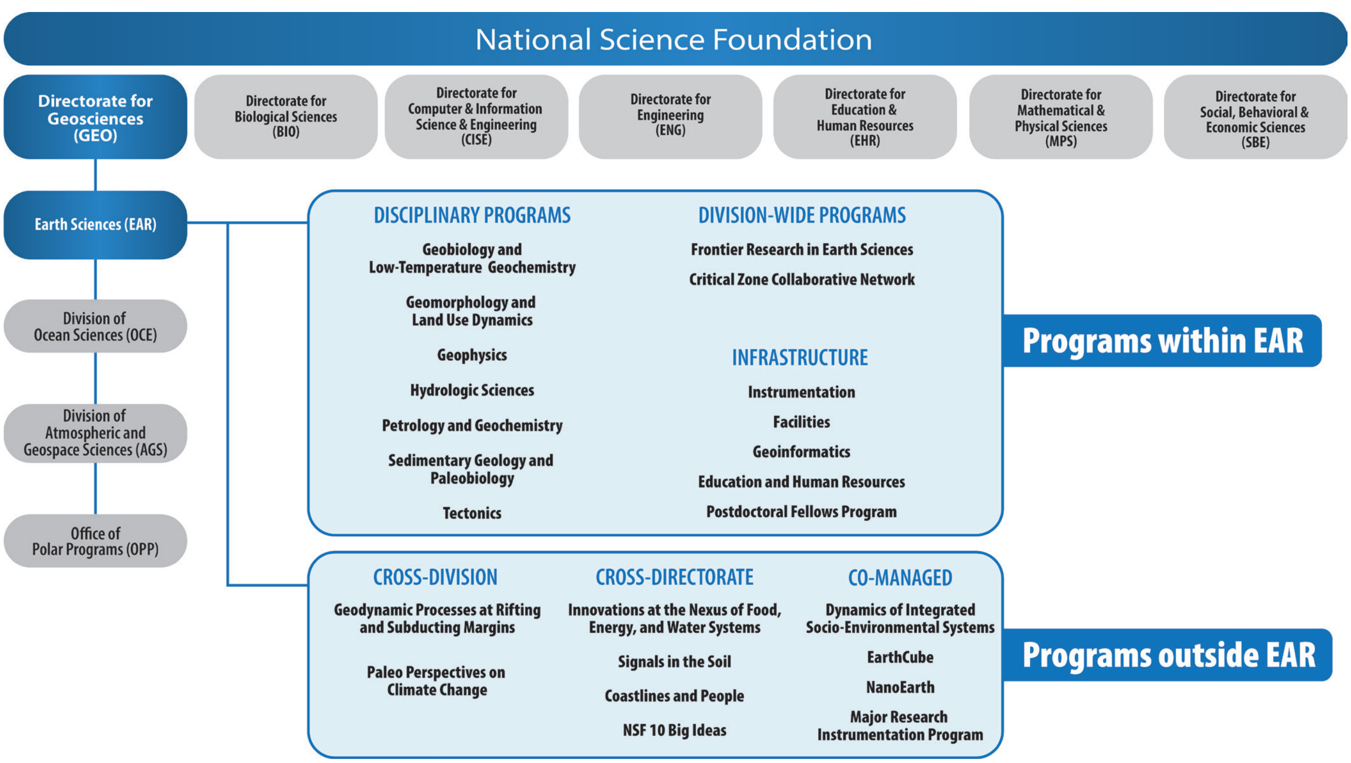

FIGURE 1-3 The organizational structure of the National Science Foundation, the Directorate for Geosciences, and the Division of Earth Sciences. SOURCE: Information provided by NSF.

In addition, there are cross-cutting programs in which EAR participates with other divisions and/or directorates. These include cyberinfrastructure and data management programs such as Cyberinfrastructure of Sustained Scientific Innovation, Geoinformatics, and Advancing Digitization of Biodiversity Collections; education programs such as Improving Undergraduate STEM Education: Pathways into Geoscience; Partnerships between Science and Engineering Fields and the NSF TRIPODS Institutes; and interdisciplinary and convergent programs such as Signals in the Soil, Critical Zone Collaborative Network, Critical Aspects of Sustainability, Origin of Life, and Paleo Perspectives on Climate Change. Since 2017, NSF has been building a foundation for U.S. research leadership through the 10 Big Ideas,[2] which encompasses a combination of research and pilot activities. In 2019, for example, NSF planned to invest $30 million per Big Idea.

EAR's annual budget has been roughly constant since fiscal year (FY) 2010, varying from a low of $173 million to a high of almost $184 million (see Figure 1-4a). While its current budget is approximately half that of the Division of Ocean Sciences (OCE) and about 70% of the Division of Atmospheric and Geospace Sciences (AGS) (see Figure 1-4a), the amount of funding that EAR devotes to research (see Figure 1-4b) is approximately equal to AGS and about 70% of OCE's funding. EAR's investment in infrastructure has been fairly consistent since FY2010 (see Figure 1-4c), accounting for 31-34% of the total yearly budget. Due to inflation, EAR's level budget necessarily supports less research today than in past years (see Figure 1-5). A decade of level-funded budgets creates challenges not only for EAR to continue to support its current successful research programs, but to consider new opportunities for programs and infrastructure.

STUDY ORIGIN

EAR relies on community input to develop long-term strategies for research priorities. From time to time, EAR examines its portfolio to evaluate the kinds of research, programs, and facilities to prioritize for funding opportunities for the research community. This prioritization of research and associated infrastructure is also important for workforce development to help train the next generation of Earth scientists. In 2018, EAR asked the National Academies of Sciences,

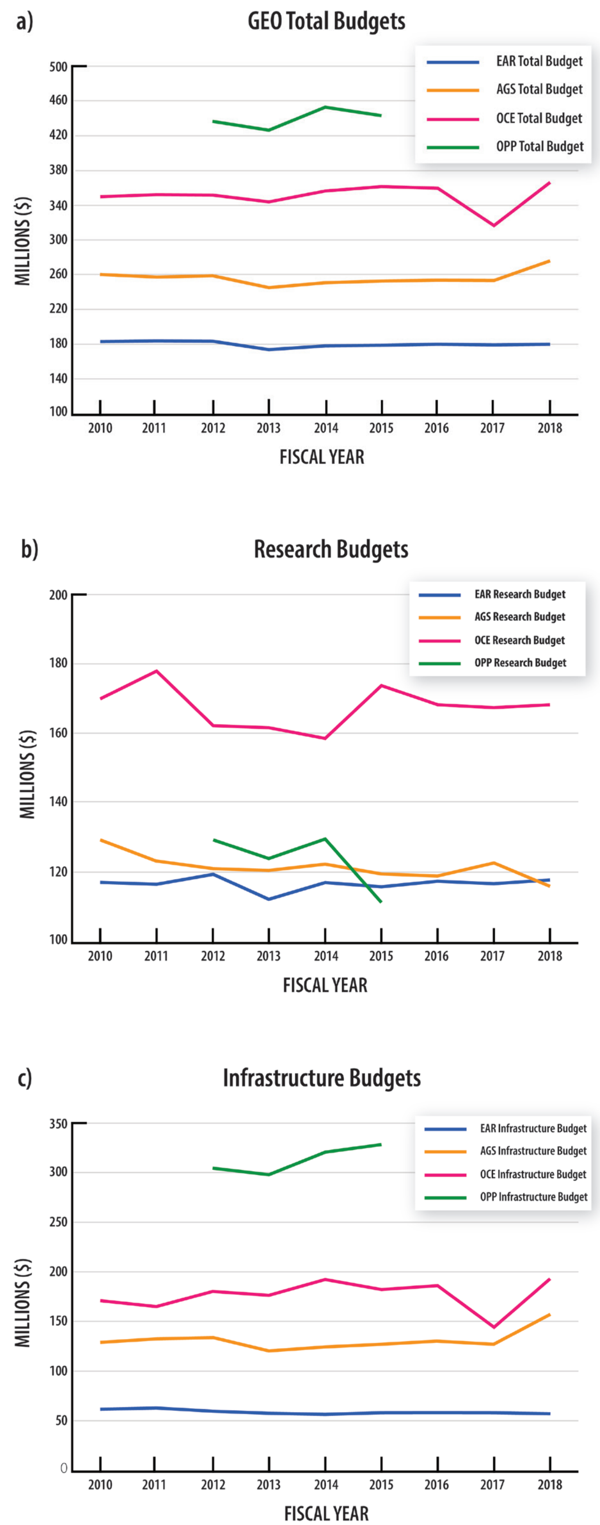

FIGURE 1-4 GEO budgets broken up by division. (a) Shows total budgets for each division from 2010-2018. (b) Presents investments in research per division. (c) Presents investments in infrastructure, per division. NOTE: The Office of Polar Programs was part of the Directorate in 2012-2015. SOURCE: Data from NSF budget requests, https://www.nsf.gov/about/budget (accessed April 16, 2019).

[2] See https://www.nsf.gov/news/special_reports/big_ideas (accessed March 23, 2020).

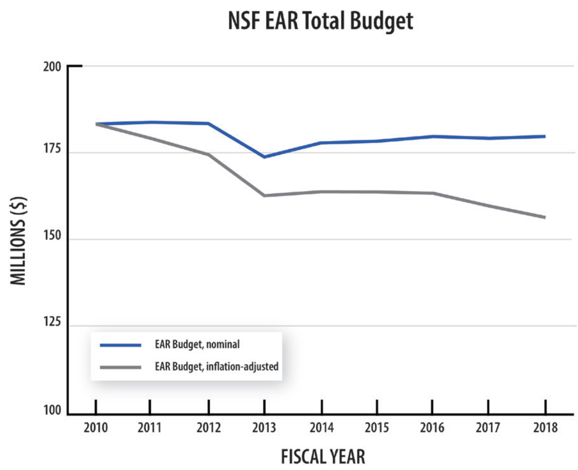

FIGURE 1-5 EAR's inflation-adjusted and unadjusted budgets from 2010-2018. The inflation-adjusted numbers were calculated using the Bureau of Labor Statistics Consumer Price Index for All Urban Consumers. SOURCES: Data from NSF budget requests, https://www.nsf.gov/about/budget (accessed April 16, 2019) and committee.

Engineering, and Medicine's Board on Earth Sciences and Resources to undertake a decadal survey that provides guidance on future Earth science research priorities and supporting facilities and infrastructure. The request was initiated by Carol Frost, EAR Division Director at the time. The full Statement of Task is provided in Box 1-1.

THE COMMITTEE PROCESS

The Committee on Catalyzing Opportunities for Research in the Earth Sciences (CORES): A Decadal Survey for NSF's Division of Earth Sciences was convened by the National Academies at the request of NSF. In response to concerns about the initial composition of the provisional committee, three additional members were added after the first committee meeting. The final committee consisted of 20 members, working on a volunteer basis from November 2018 through April 2020, with expertise in a broad range of Earth science as well as geographic diversity, career-stage breadth, and gender balance. Committee member and staff biographies are provided in Appendix A.

The committee felt strongly that active participation from the Earth sciences community was essential to the study process. It organized listening sessions at major conferences, meetings and interviews with early- and mid-career scientists, presentations at community meetings, and an online questionnaire that called

BOX 1-1
STATEMENT OF TASK

This National Academies of Sciences, Engineering, and Medicine study will help provide advice that NSF EAR can use to set priorities and strategies for its investments in research, infrastructure, and training in the coming decade. An ad hoc committee will prepare a report that includes the following elements:

1. A concise set of high-priority scientific questions that will be central to the advancement of Earth sciences over the coming decade and could help to transform our scientific understanding of the Earth. Identification of these questions may derive from consideration of relevance to societal benefits, new technological breakthroughs, potential for fruitful interaction and collaboration with other disciplines, emerging subjects poised for rapid development, or other drivers.

2. (A) Identification of the infrastructure (e.g., physical infrastructure, cyberinfrastructure, and data management systems) needed to advance the high-priority Earth science research questions from task #1, (B) discussion of the current inventory of research infrastructure supported by EAR and other relevant areas of NSF, and (C) analysis of capability gaps that would need to be addressed in order to align B with A.

3. A discussion of how EAR can leverage and complement the capabilities, expertise, and strategic plans of its partners (including other NSF units, federal agencies, domestic and international partners), encourage greater collaboration, and maximize shared use of research assets and data.

The ad hoc committee will consider these tasks within the context of the present EAR budget. It also will consider potential adjustments in priorities identified in task #1 or approaches to implementing those priorities that could be applied if future budgets were to increase or decrease.

In addition, the National Academies will convene a workshop (as an additional, integrated part of the CORES study) to address different management models for future seismological and geodetic facility capabilities such as instrumentation, user support services, data management, education/outreach, and workforce development for the Division of Earth Sciences. This workshop will provide additional information for Task #2 of the CORES study. [*Management Models for Future Seismological and Geodetic Facilities and Capabilities: Proceedings of a Workshop* was released in September 2019.]

on the Earth sciences community to offer individual views on future research priorities (see Appendix B for the questionnaire). There were almost 350 responses to the online questionnaire, which provided robust community input.

The committee held five meetings with public information-gathering sessions, a workshop on management models for future seismological and geodetic facility capabilities, and two meetings in closed session to develop this report. Public meeting agendas are listed in Appendix C.

PREVIOUS DECADAL STUDIES

This study follows two previous reports that the National Research Council produced for EAR: *Basic Research Opportunities in Earth Science* (BROES) and *New Research Opportunities in the Earth Sciences* (NROES) (NRC, 2001, 2012). The recommendations of these reports are summarized in Box 1-2. As a prologue to this study, we briefly review the legacy of these community-driven, forward-looking reports on priorities for Earth science research.

BROES and NROES both had lasting impact. The BROES recommendation for multidisciplinary studies of the critical zone led to the establishment of a network of nine critical zone observatories that serve as a platform for research at the catchment/watershed scale and focus on chemical, physical, and biological processes that connect life, water, climate, and bedrock in the dynamic skin of the Earth. The BROES endorsement of the EarthScope initiative was acted on, and all three components of EarthScope—the geodetic Plate Boundary Observatory, the USArray seismological capability, and the San Andreas Fault Observatory at Depth—were successfully completed, providing new insights into the deformation and architecture of the North American continent and on the nature and properties of the San Andreas Fault at depth. Another lasting impact stemming from the BROES report was the establishment of EAR's Geobiology and Low-Temperature Geochemistry program.

BROES was published in 2001, at a time when the NSF budget was expected to grow. NROES, on the other hand, was published in 2012, at a time when the NSF budget was flat. Despite these headwinds, the NROES recommendations led to the transformation of the Continental Dynamics program into Integrated Earth Systems,[3] which supported multidisciplinary research

[3] The Integrated Earth Systems program recently evolved into Frontier Research in Earth Sciences. See https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504833 (accessed March 31, 2020).

BOX 1-2
SUMMARY OF RECOMMENDATIONS FROM PREVIOUS NATIONAL RESEARCH COUNCIL REPORTS FOR EAR

Basic Research Opportunities in Earth Science **(2001) Findings and Recommendations:**

- Maintain support for individual-investigator-driven science
- New funds for support of research in geobiology and in Earth and planetary materials
- Continue to build programs in hydrologic sciences
- Enhanced multidisciplinary studies of the critical zone
- Strong endorsement of the EarthScope initiative
- Establish an Earth Science Natural Laboratories Program
- Promote studies of interactions between microorganisms and surface environment
- Increase interactions between Earth and planetary science communities
- Increased support of new instruments, multi-user facilities, and existing equipment
- Enhance training grants, fellowship opportunities, post-doc and sabbatical-leave programs for interdisciplinary research, and support for students to conduct field work

New Research Opportunities in the Earth Sciences **(2012) Findings and Recommendations:**

- Importance of investigator-driven science
- Study fundamental physical and chemical processes of the early Earth
- Encourage work in thermo-chemical internal dynamics and volatile distribution
- Pursue interdisciplinary quantification of faulting and deformation processes
- Encourage work on interactions among climate, surface processes, tectonics, and deeper Earth processes
- Develop science projects around co-evolution of life, environment, and climate
- Facilitate research on coupled hydrogeomorphic-ecosystem response to natural and anthropogenic change
- Support programs on biogeochemical and water cycles in terrestrial environments and impacts of global change
- Explore new mechanisms for geochronology laboratories
- Improve interagency partnerships and coordination
- Increase training opportunities and a more diverse research community

from Earth's core to the critical zone at a budgetary scale larger than that of a typical disciplinary program. The NROES recommendations also led NSF to increase technician support, addressing a long-standing research sustainability issue that continues to be a concern of the EAR-supported community.

These examples illustrate specific, tangible impacts of the BROES and NROES reports; however, both reports emphasized and began their recommendations with an appeal to the importance of continuing support for individual investigator-driven science. A good idea or discovery can rapidly advance a field in an unexpected direction, with impacts that could not have been anticipated. For example, GPS data from the Plate Boundary Observatory were used for the unexpected purpose of tracking soil moisture content. The BROES report could not foresee the discovery of a broad spectrum of deformation events, including tremor and slow slip. This spectrum of deformation events featured prominently in the NROES report; however, NROES in turn did not predict more recent developments, such as the accelerating impact of data science in the study of Earth science problems. Future decadal studies will no doubt be able to draw similar conclusions about this report. Such important but unanticipated developments attest to the continuing need for EAR to support investigator-driven science.

We also note that basic research in Earth science can have profound and unexpected impacts. A compelling example stems from the quest to determine the age of the Earth, which was driven by curiosity rather than strategic objectives, through lead-lead isotope dating. Lead-lead dating (Patterson, 1956) requires extremely clean laboratory conditions, which led to the recognition of ubiquitous industrial lead contamination (Patterson, 1965). This recognition motivated increased research focus on the human-health effects of environmental lead, and culminated in the banning of lead from household paint, gasoline, and food containers (NRC, 1980). A more recent example concerns the increasing appreciation for the role of clay minerals in fighting bacteria and other health hazards, catalyzing the emergent, interdisciplinary field of geohealth, including medical mineralogy and geochemistry. These examples demonstrate that curiosity-driven research can have far-reaching, unanticipated impacts and further attests to the continuing need for EAR to maintain a diverse research portfolio that includes research with no immediate societal relevance.

Earth science research is essential to understanding how we got here and is critical to anticipating Earth's future. This report covers many ways that NSF can maintain and strengthen programs to enable a creative and diverse population of geoscientists who will strive to attain a new level of understanding of Earth's materials, processes, and history, now and in future generations. The committee offers its recommendations with that goal in mind. The report outline is as follows: Science Priority Questions (Chapter 2), Infrastructure and Facilities (Chapter 3), Partnerships (Chapter 4), and A Decadal Vision for Earth Sciences (Chapter 5).

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2
Science Priority Questions

The committee's first task was to identify "a concise set of high-priority scientific questions that will be central to the advancement of Earth sciences over the coming decade and could help to transform our scientific understanding of the Earth." This chapter identifies and discusses these key research priority questions. These questions are exemplars that the committee believes, based on its extensive data gathering and deliberation, are important and timely topics for research. However, they are not meant to be exhaustive or to include all research questions that will arise from the Earth science community over the coming decade. It is likely that some of the best ideas for future research will come from creative thinking within areas not highlighted, or not even currently contemplated, in this report.

APPROACH TO SELECTING QUESTIONS

The committee relied on literature review, community input, workshops, interviews with colleagues, and open discussions during committee meetings to develop the list of priority questions in this report. Themes that repeatedly emerged during these discussions are as follows: Exactly what constitutes a priority question and what is the appropriate scope of a question? Should priorities be specific questions or general areas of research? Should questions that appear poised for major advances in the next decade take priority over questions that are clearly important but for which progress is likely to be further in the future? A consensus emerged that the committee could best address the Division of Earth Sciences' (EAR's) charge by identifying specific questions that are ripe for major advances in the next 10 years. These include some questions that have long been of great interest to Earth scientists. In such cases, the committee identified reasons why these questions are now poised for transformative advancement.

Literature Review

To support this task, the committee was initially provided with a bibliography created by EAR that included reports and white papers ranging from all-encompassing Earth science research agendas to overviews of the status of a particular discipline. This bibliography was augmented with additional reports, white papers, and peer-reviewed literature identified by members of the committee. Committee members divided the literature and read several items each, taking care that most items were read by more than one committee member. The readers compiled lists of priority research questions and general research themes identified in the literature surveyed, as well as lists of infrastructure and facility needs that were explicitly or implicitly identified in the literature. These lists were shared with and discussed by the whole committee.

Community Input

The committee used a variety of methods to obtain input from the Earth science community. The committee organized a listening session at the 2018 Fall Meeting of the American Geophysical Union (AGU; December 13, 2018, Washington, DC). The purpose of this meeting was to announce the work of the committee and to seek direct input on science priority questions and infrastructural needs. A similar listening session was arranged for the 2019 Annual Meeting of the Geological Society of America (September 22, 2019, Phoenix, Arizona). In both instances, the number of participants allowed the committee to have in-depth, small-group discussions (approximately two to three participants per committee member).

To reach a broader audience, the committee developed a web-based community input survey and advertised it via professional-society, disciplinary-based, and interest-based email distribution lists, community forums, and social media. EAR included the announcement in their email newsletters and at their AGU Town Hall, and committee members, National Academies staff, and EAR representatives also handed out cards with the website listed. The questionnaire asked for input regarding important topics for future Earth science research, ideas for infrastructure needed to address those topics, possible collaborations between EAR and other partners, and workforce and training. The questionnaire also invited additional, open-form comments and included questions on career stage and discipline of the respondent. The questionnaire can be found in Appendix B. The committee received approximately 350 responses to the questionnaire. In addition, several letters and white papers were submitted directly by members and organizations within the Earth science community. Committee members also contacted colleagues to explain the study and seek direct input on priority questions and other aspects of its charge.

Additionally, participants invited to the open sessions of the committee's meetings contributed their thoughts on key research priorities for the coming decade. The open sessions included focused groups of early-career scientists, those who identify with historically underrepresented groups, and those with private industry interests and connections. A small number of open sessions were held to gather data on specific EAR facilities and programs. EAR program officers were also asked to identify recent trends in research areas that are being supported by the National Science Foundation (NSF).

It became clear early in the committee's work that some disciplines within Earth science are better organized and more vocal than others. The committee therefore took care during every stage of identifying and selecting questions to consider all disciplines, whether or not there was a recent report or white paper.

Developing the Priorities

The process to develop and articulate a concise set of science priority questions included several stages:

- generating a comprehensive list of questions that had been identified from the literature review, community input, and interviews;
- merging similar or largely overlapping questions;
- eliminating or rephrasing questions that had not been clearly articulated;
- examining the scientific importance and likelihood of transformative impact for the remaining questions; and
- framing the questions in a broad context and articulating the scientific importance and potential impact.

The committee endeavored to consider Earth science broadly, without limiting discussions to fields classically funded by EAR. This effort to broaden discussions stemmed in part from community input that showed concern about research that "crosses the coastline" and that could be of interest to either EAR or the Division of Ocean Sciences (OCE), as well as other examples of cross-disciplinary research. One exception concerned areas that EAR leadership explicitly stated in the committee's first open session are not in its purview, such as planetary science, even though these areas may have been previously identified as high priorities for Earth science (e.g., Basic Research Opportunities in Earth Science; NRC, 2001).

SCIENCE PRIORITY QUESTIONS

An extensive program of omnivorous reading, careful listening, and vigorous discussion resulted in the following list of priority questions. These questions are numbered only for convenience and do not denote a priority ranking. To the extent that there is an order, it is planetary, from Earth's core to the clouds. Icons next to the questions are used in this and following chapters to show the connections among questions, infrastructure and facilities, and partnerships.

Several overarching themes integrate the individual research questions. The Earth is an active, dynamic, open system in which all components interact to shape the state of the planet at any moment in time and its secular evolution over billions of years (see Figure 2-1). Many of the priority research questions involve connections between spheres of the Earth system, and future research progress can be anticipated to feature these connections. A clear understanding of this system, including people as geological agents, is fundamental to predicting how present-day changes, both natural and anthropogenic, will influence the Earth and civilization. Earth's processes operate over exceptionally broad spatial and temporal scales, with complex, multi-scale interactions and feedbacks. Recent technological advances enable observation and modeling that can explore across these scales to an extent never before possible. Key opportunities include understanding surface- and deep-Earth interactions and the co-evolution of Earth's solid, fluid, and living components. The priority questions incorporate the societal relevance of fundamental Earth science research and the urgent need to understand a rapidly changing Earth.

While many of the key priorities can be answered in large part within EAR's core disciplinary research programs, robust cooperation among the programs within the Directorate for Geosciences (GEO) and with other directorates and other agencies will be needed to support increasingly interdisciplinary and transdisciplinary research topics. As exemplified in the science priority questions below, there are numerous connections among EAR disciplines, as well as with other NSF domains and non-NSF agencies, including material and biological science, and research on the atmosphere, oceans, and cryosphere. A challenge for EAR and GEO will be to create or maintain funding mechanisms that recognize the importance of the science that falls between traditional program boundaries.

As in other decadal reports, the committee also recognizes the importance of sustaining a strong core research program driven by independently funded, individual investigators. A recent study of 65 million papers, patents, and software products produced over a 60-year period showed that individual investigators or small teams tended to "disrupt" a field by yielding new results and ideas, while larger teams tended to further develop existing ideas (Wu et al., 2019). This study underscores the importance of supporting both individual investigators and/or small teams and large/multi-partner teams to yield influential science in a given field.

The questions are:

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

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

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

4. What is an earthquake?

5. What drives volcanism?

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

7. How does the critical zone influence climate?

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

9. How is Earth's water cycle changing?

10. How do biogeochemical cycles evolve?

11. How do geological processes influence biodiversity?

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

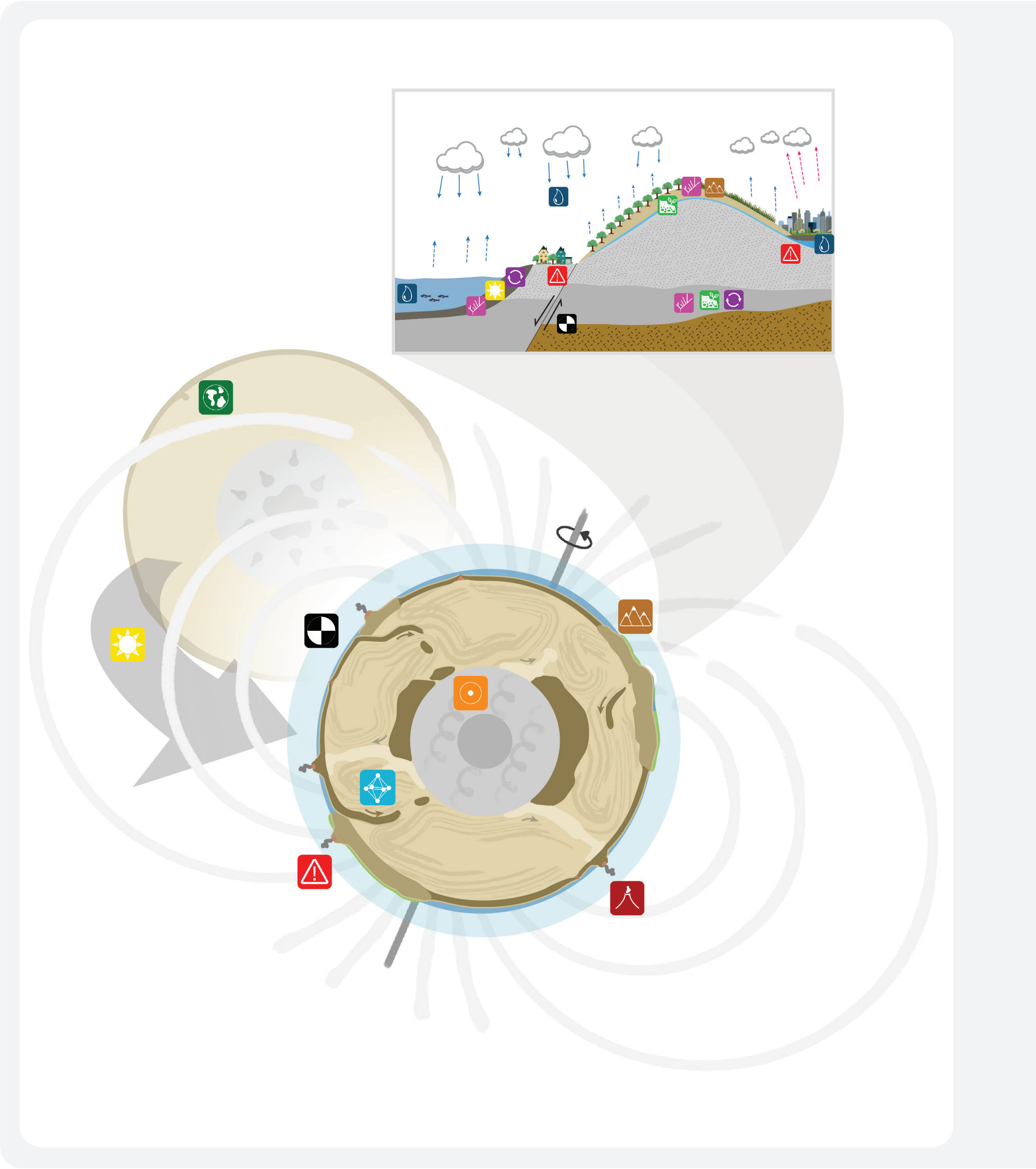

FIGURE 2-1 The science priority questions are illustrated by an early Earth (without a fully developed solid inner core, left) that evolves into a dynamic Earth, which generates and erases geologic records of its transforming states and is now experiencing unprecedented environmental change (figure not to scale). The questions are spread throughout the Earth system and are connected by processes of today and the past. The arcuate lines surrounding Earth illustrate the protective geomagnetic field that arises from the fluid dynamics within the outer core (light grey, illustrated with curled lines). The solid inner core is shown to scale as a darker grey. The mantle and crust (continental rocks are light brown, ocean floor basalts are dark brown; thicknesses greatly exaggerated, with mantle thickness to scale and variably lighter toned to represent its heterogeneity) is a single system driven by convection within the mantle that arises from radioactive decay of heat-producing elements and the loss of the deeply buried planet's formational energy through cooling of the core. The lithosphere (crust and coldest mantle) is broken into separating and colliding plates whose distribution influence critical element distribution, earthquakes, volcanism, topography, critical zone, climate, water cycle, biogeochemistry, and biodiversity. The Earth is blanketed in a thin atmosphere (light blue). In the inset, the profile of a landscape highlights Earth surface processes, the sedimentary record of Earth's history, human influence, and geohazards to people. Displacement on the fault may produce sudden strong earthquakes (creating significant hazards) or develop slowly with virtually imperceptible earthquakes. Landslides from the adjacent hill and coastal retreat, sea-level rise, and tsunamis also present hazards to the coastal community. The uplifted hill will erosionally evolve and experience weathering (light brown) such that dense bedrock develops porosity and holds moisture and groundwater (light blue) that is exploited by vegetation. Deep groundwater aquifers such as that shown under the city (blue) are key water resources. Precipitation (downward-pointing blue dashed arrows) is returned to the atmosphere by evaporation and transpiration (upward-pointing blue dashed arrows) with excess water recharging groundwater or running off. Biologically mediated gas exchange with the atmosphere occurs across the planet. Older sedimentary rocks (stippled brown) and young to contemporary sediments (stippled grey) provide records of Earth's evolving climate, biogeochemistry, and biodiversity. Humans are acting as geologic agents and affecting Earth processes in many ways, including through climate change (via urbanization, release of greenhouse gases [pink dashed arrows], and vegetation change); nutrient input to terrestrial aquatic systems and the oceans (from agriculture and urban wastewater); changes in erosion and sedimentation (from land-use change, dams, and other influences on river flow and sediment load); modification of the geographic distribution of biodiversity (from climate and land-use change); and exacerbation of hazards (through rising sea level, more intense storms, land-use change, and drought-induced wildland fires). SOURCES: Illustration courtesy of Fabio Crameri and the committee.

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

The geomagnetic field is one of the most ancient features of our planet, revealed in paleomagnetic measurements of rocks at least 3.4 billion years old (Biggin et al., 2009). The field is thought to be essential for life because it keeps the solar wind from stripping away the atmosphere (Tarduno et al., 2010). Although it is ancient, it is also changeable, reversing polarity on average a few times every million years, and varying in strength and shape on human time scales, thereby influencing navigation and satellite communications (Korte and Mandea, 2019). The field is produced by fluid motions in Earth's liquid metallic outer core. The geodynamo requires tremendous energy, which in its later history was boosted by latent heat of fusion from crystallization of the inner core. Organized and vigorous motions of a large, rotating body of conducting liquid are an essential ingredient of all planetary magnetic fields (Elsasser, 1946), including the many other examples in our solar system (Stevenson, 2010).

For the recent history of the Earth, a consensus has emerged on the process by which the magnetic field is produced. As the core cools, the solid inner core freezes out, releasing latent heat and gravitational energy. This energy powers the dynamo and creates the field that we see today. Yet, this consensus also presents a profound challenge to our understanding. If the core loses heat at the rate necessary to produce the magnetic field, as we go back in time, the core rapidly becomes so hot that inner core freezing is no longer possible (Labrosse et al., 2001). The inner core may only be 1 billion years old, leaving most of the paleomagnetic record unexplained by inner core freezing. Recent mineral physics determinations point to a core that has a higher thermal conductivity than previously thought, a result that pushes the age of the inner core even younger (Pozzo et al., 2012).

If not via inner core freezing, how was the magnetic field produced over most of geologic history? Immediately after accretion, the core was so hot that it may have dissolved significant amounts of mantle material. If so, as the core cooled, these oxide components would have frozen out and underplated the mantle, releasing large amounts of gravitational energy (Badro et al., 2016). An underplated layer should produce distinctive seismic signatures, although they may be hard to detect if the layer is thin. Perhaps the ancient field was not produced in the core, but in another part of Earth's interior. For example, it has been proposed that the Archean field may have been produced in the magma ocean overlying the core (Ziegler and Stegman, 2013). Or it may be that cooling of a fully molten core is sufficient to produce a magnetic field, although most models indicate that this mechanism can explain only a fraction of the paleomagnetic record prior to inner core growth (O'Rourke et al., 2017).

A challenge to understanding the geodynamo is to explain the contrast in seismic structure between the inner and outer core. The outer core is largely homogeneous and spherically symmetric, while the inner core is both anisotropic and heterogeneous. This contrast in structures may contain important clues as to how the field has been generated over the past billion years. The inner core's anisotropy suggests deformation and flow and is seismically heterogeneous up to hemispheric length scales (Deuss et al., 2010). How these features are produced and what they tell us about the interaction of the inner core with the dynamo (Aubert et al., 2013) are still unclear.

The core cools only as quickly as the mantle can carry its heat away. Mantle convection is therefore likely to have exerted a profound influence on the geodynamo, affecting, for example, the frequency of geomagnetic reversals (Courtillot and Olson, 2007). Recent discoveries of mantle structure have changed our view of core dynamics. The thermal and chemical properties of large, low-shear-velocity provinces at the base of the mantle are debated, but variations in temperature and/or buoyancy associated with these regions could modify heat loss from the core. The possible effect of such heterogeneous boundary conditions on the dynamo (Gubbins et al., 2011) and the overall dynamics of the planet (Greff-Lefftz and Besse, 2014) are only beginning to be explored.

Would a change in driving mechanism be visible in the rock record? If the initial nucleation of the inner core resulted in an increase in magnetic field intensity, this increase could be detected with paleomagnetic methods (Biggin et al., 2015). Measurements of tungsten and osmium isotopes in plume lavas (Mundl-Petermeier et al., 2017; Rizo et al., 2019) may shed light on inner core crystallization, and particularly to a much older inner core than current thermal models imply. It is also possible that the shape of the field has changed with time. Today, Earth's field is one of the most dipolar in the solar system (Stevenson, 2010; Moore et al., 2018). But this may not always have been the case. It may be possible through paleomagnetic observations to constrain the first order shape of the field (dominantly dipolar or not) in the deep past (Landeau et al., 2017).

Observations of the current field also provide important clues. The period of human observation has revealed changes in the field occurring over a vast range of time scales, from the gradual westward drift, to so-called magnetic jerks (see Figure 2-2). These observations give insight into the balance of forces that generate the field and the relative importance of different length scales in driving fluid flow and magnetic field generation (Aurnou and King, 2017; Aubert and Finlay, 2019). They also suggest new avenues of observation, linked, for example, to variations in Earth's rotation rate via electromagnetic coupling to the overlying mantle.

Recent developments promise substantial progress in addressing these questions in the coming decade. New computational and analytical tools are making it possible to derive thermodynamic properties of core materials from first principles, while emerging micro- and nano-beam methods of fabrication and analysis are creating ways to perform direct experiments on stability, composition, and other material properties at core conditions. Advances in synchrotron radiation facili-

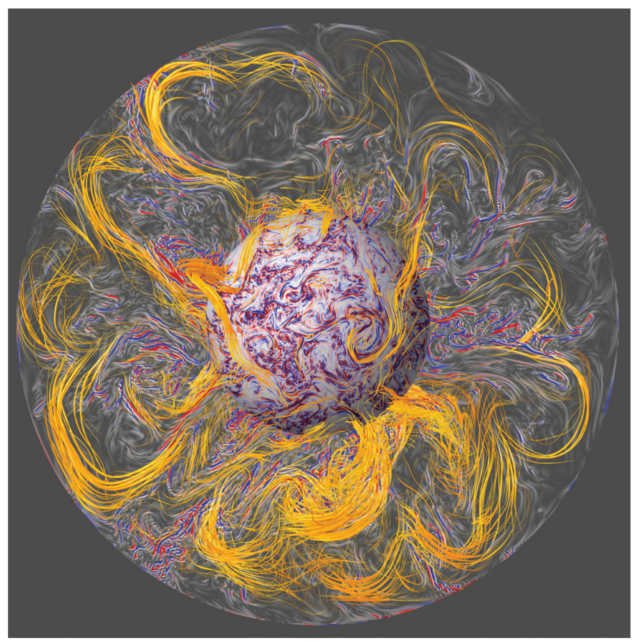

FIGURE 2-2 Cross-section of the core (inner core, solid white) from a numerical geodynamo simulation. Magnetic field lines (orange) are stretched and twisted by the turbulent core flow, whose streamlines move both up (red) and down (blue). The figure shows the interaction between the slow core convection and the rapid hydrodynamic waves that give rise to sudden accelerations in the geomagnetic field (jerks), reflecting sudden buoyancy releases inside the core. SOURCE: Image courtesy of Julien Aubert, Institut de physique du globe de Paris/National Centre for Scientific Research.

ties will drive new types of measurements on materials relevant to the core, while developments in ramp compression with laser drive and pulsed power are making accessible an entirely new pressure–temperature regime. The ability to measure the magnetic field of individual mineral grains in the deep past is improving (Weiss et al., 2018; Tarduno et al., 2020), as is the understanding of biases in recordings of the ancient field (Tauxe, 2005). Satellite data are available at finer temporal and spatial scales than ever before, and we have seen advances in the fluid dynamics of rotating magnetoconvection (Adams et al., 2015) and powerful computational and data assimilation techniques (Aubert, 2015). Improvements in seismic imaging will illuminate core and deep mantle structure. Thus, a deeper, more integrated understanding of the magnetic field and its evolution will be possible. Further progress will be aided by data from planetary missions such as Juno,[1] which has revealed in more detail the different geometries and magnitudes of magnetic fields that various bodies in the solar system have or once had (Moore et al., 2018). The varying mechanisms of planetary formation, structure, and evolution are key to understanding what controls the amplitude and structure of a given field and may be relevant to understand the origin and evolution of our own.

Success will depend on instrumentation and facilities as well as intra- and interagency partnerships. Facilities for the measurement of material properties at extreme conditions (e.g., beamline facilities, dynamic compression facilities, a very large multi-anvil press), as well as atomic force microscopy for field intensity, will be necessary for determining the age of the inner core. Data and records on polarity and intensity variations will require systematic field and continental scientific drilling campaigns, enhanced tools for measuring magnetic properties of minerals (e.g., Tarduno et al., 2020), and archiving of data in interoperable formats. Potential partners include those covering material science and computation. For example, the interaction of the internal and external magnetic fields and the importance for space weather and characterization of cosmogenic isotopes (beryllium, carbon) indicates the need for more integration between EAR and the Division of Atmospheric and Geospace Sciences (AGS), as well as with the U.S. Geological Survey (USGS) Geomagnetism Program.

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

As humans explore the solar system, the Earth emerges with a unique signature: plate tectonics. Even as geoscientists use the plate tectonic framework to interpret the surface of solar system bodies, the Earth remains the only planet with well-defined plate boundaries whose motions and evolution frame nearly all geological phenomena—as recorded in Earth's crust and imaged in the deep interior—and provide basic controls on Earth's atmosphere and oceans. Although many aspects of plate tectonic behavior and geometry are clear, there is a lack of fundamental understanding of when plate tectonics developed on the Earth, why on the Earth and not elsewhere, the interconnections with elemental cycling on the Earth, and the processes that explain how it developed (NRC, 2008; Huntington and Klepeis, 2018).

The early stages of Earth's evolution are deeply tied to planetary formation (Hawkesworth and Brown, 2018; Lock et al., 2018). Critical to the questions of why and how is a more comprehensive definition of what plate tectonics actually is and was (Joel, 2019). Is it today's plate tectonics world with ridges and one-sided subduction dominated by oceanic plates? Or is plate tectonics any type of lithospheric mobility and recycling? The answer to what also becomes central to when.

The view today is that plate tectonics and mantle convection are one and the same (Coltice et al., 2019). Plates, particularly oceanic, are the upper thermal boundary layer of the convecting system (see Figure 2-3)—the product of melting and differentiation of the mantle, and the crystallization and cooling of these materials near Earth's surface. Their distinct dynamic and kinematic behavior arises directly from the intrinsic material properties of rocks. The continuous recycling of plates and the compositional, thermal, and rheological heterogeneity acquired through their life cycle are key to understanding the present-day mantle. This view of what plate tectonics is today has evolved over the past two decades, made possible by advances in seismic imaging and analysis, computation, damage theory, and rheological measurements that have shown the promise of a tightly integrated fluid dynamical view of plates and mantle (Bercovici and Skemer, 2017; Coltice et al., 2019).

The nature of plate tectonics has broad impacts beyond geology and geophysics. It underpins efforts to better understand the physical processes that determine the surface deformation and magmatism

[1] See https://www.nasa.gov/mission_pages/juno/main/index.html (accessed March 23, 2020).

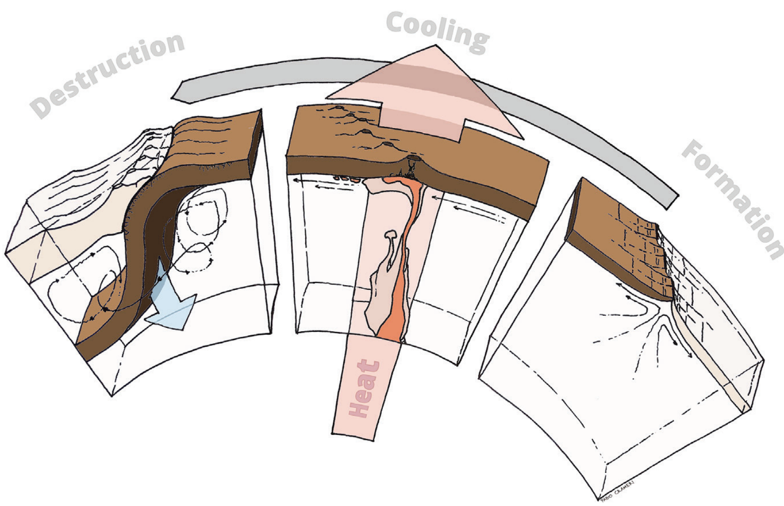

FIGURE 2-3 Schematic diagram highlighting how plate formation, cooling, and destruction are integral parts of convection. Oceanic plates are shown in dark brown. They form at a mid-ocean ridge (far right), and seamounts are emplaced on the older part of the plates (middle). Plates are subducted into the mantle, where they may stagnate at mid-depths or penetrate and sink to the core-mantle boundary. The plates reflect a single system of motion, not just horizontal surface movements (gray arrow) on a passive mantle. For example, distinct flow patterns are induced by subduction, including vertical motions (blue arrow), which support topography that can affect river drainage patterns and inundation (continental basin on far left) and even present-day sea level. Driving forces are supplied by heat from the interior. SOURCE: Crameri et al., 2019.

responsible for geohazards, the storage and evolution of elements critical to biological activity and modern society, the evolution of life and biogeochemical cycles, long-term climate change, and the extent of flooding due to present-day sea-level rise.

Understanding of plate tectonics with its broader implications is poised for revolutionary progress in the next 10 years. The problem of obtaining enough precise and accurate data to answer the question of when is being transformed by developments in geochemistry (e.g., Hawkesworth et al., 2017), the acquisition of geological records of plate motion (e.g., Holder et al., 2019), and geochronology. The history of plate tectonics is but one of many questions () whose answers would be advanced by reaching a community goal (Harrison et al., 2015) of achieving 0.01% precision on dating throughout Earth's history (see Chapter 3 for more discussion). The questions of how plate tectonics evolved and why on the Earth are also progressing. For example, understanding of the earliest stages of Earth's evolution, which was dominated by a magma ocean, giant impacts, and likely a vastly different convective mode prior to the onset of plate tectonics, has been expanded by analysis of geochemical properties of Hadean minerals (e.g., Harrison et al., 2017), measurements and simulations of materials at extreme conditions, and models of planetary formation (Kraus et al., 2012; Scipioni et al., 2017). Moreover, advances in fluid dynamics, computation, and characterization of Earth's material properties now make it possible to simulate the evolution of the mantle–plate system in detail (e.g., Bocher et al., 2018). These geophysical developments leveraged advances in seismic imaging, which have revealed mantle and core structure and illuminated Earth's subsurface dynamics (see Figure 2-4). The development of new chronometers and novel isotopic systems have continued to open paths of understanding from the age of core formation to elemental chemical exchanges.

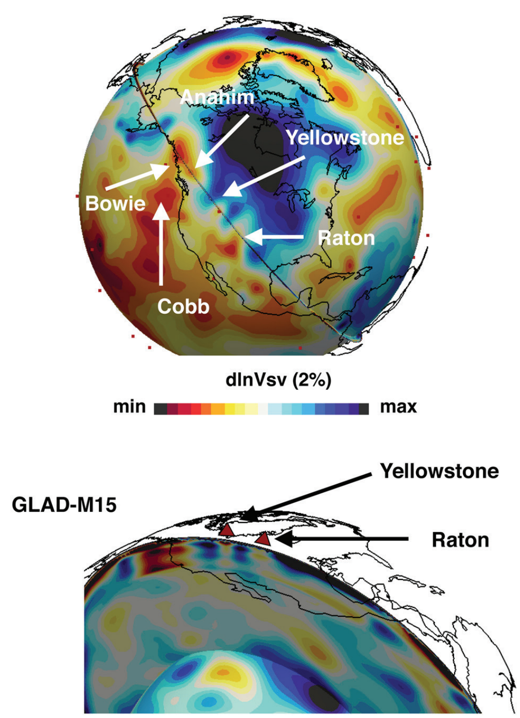

FIGURE 2-4 Map views underneath North America at 250 km depth and vertical cross-sections of shear-wave-speed perturbations (color bar labeled "dlnVsv") in GLAD-M15, a tomographic model using full waveform inversions and adjoint methods. SOURCE: Bozdağ et al., 2016.

New instruments that can make geochemical and structural observations at fine spatial scales (e.g., individual atoms with transmission electron microscopy and atom probe tomography) and can also recover geochronologic information are good examples of the rapidly accelerating technical capabilities to probe the minerals that preserve the record of plate tectonics in the crust. The measurements they enable will be essential to determining the signatures of plate tectonics in the geological record, from the rise of the first continents to their emergence above sea level. Other emerging fields such as nontraditional stable isotope geochemistry (Teng et al., 2017) are advancing quickly to provide new insights into relevant cosmochemical, geological, and biological processes. Similarly, experimental and computational investigations of material properties at extreme conditions can reveal chemical reactions, measure kinetics, and determine the properties of liquids (Sanloup et al., 2013; Millot et al., 2019). Computational advances also promise much higher-resolution imaging of Earth's structure and better constraints on dynamical evolution (Bozdağ et al., 2016; Bocher et al., 2018). The combination of material property measurements, imaging, and state-of-the-art physical modeling with data assimilation will be crucial to answering a central question of plate tectonics: How did (and does) subduction initiate?

Facilities and partnerships will be essential to the answers that emerge in the next 10 years. Partnerships that highlight synergies in computation and material characterization include coordination within NSF and between NSF and the National Aeronautics and Space Administration (NASA), the U.S. Department of Energy (DOE), and USGS. Progress in characterizing materials and documenting the history of plate kinematics will depend on continued expansion of data collection, including seismic and geodetic efforts (as anticipated by the SZ4D initiative[2] [see Chapter 3]); chemical, geochronological, and paleomagnetic analyses; and geological endeavors such as scientific drilling.

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

More than 5,000 known minerals, as well as many yet to be discovered, hold the chemical diversity and history of the Earth. These minerals, along with associated melts and fluids, host and transport critical elements—defined here as elements that are essential for geologic processes such as those that have created suitable conditions for biological activity, and those that provide the raw ingredients for materials essential to the functioning, prosperity, and security of modern society, such as low-carbon or carbon-free energy and elements for electronics, defense, medicine, and advanced manufacturing (see Table 2-1). These elements are concentrated in certain parts of the Earth by processes that geoscientists are beginning to understand on a planetary scale.

The distribution of critical elements in the outermost solid layers of the planet—the continental and oceanic crust and underlying mantle—is determined by the processes that have influenced element cycling between Earth's interior and surface environments throughout Earth's history. Dramatic redistribution of critical elements at various times in Earth's history can be tied to explosions in mineral and biological diversity, the Great Oxidation Event, oceanic anoxic events, and associated changes in atmospheric composition, influencing the history of climate and life through time. The minerals that constitute Earth's crust and mantle, and consequently the composition of the biosphere and atmosphere, evolved from processing of original materials accreted during the planet's formation, with

TABLE 2-1 Examples of Critical Elements and Their Significance

Critical Elements	Significance
H, C, N, O, P, S, K, Ca, Fe	Needed for a habitable world (Anbar, 2008)
C, S, Fe	Govern redox conditions of the mantle and crust (Armstrong et al., 2019)
B, S, halogens (F, Cl, Br, I), noble gases (He, Ne, Ar, Kr, Xe, Rn), transition metals, REEs, Re, Os	Tracers of recycling processes between the crust and mantle (Widom, 2011; Smith et al., 2018)
Li, Co, Cu, Cd, REE, U	Low-carbon or carbon-free energy (Sovacool et al., 2020)
Be, Mg, Al, Ti, V, Mn, Co, Zn, Zr, Mo, REEs, Hf, platinum group metals, precious metals, U	Materials for modern society (e.g., electronics, defense, medicine, advanced manufacturing) (DOI, 2018)

[2] See https://www.sz4d.org (accessed December 27, 2019).

additions by comets (Hirschmann, 2016). Earth materials were further transformed by differentiation and crustal formation, the co-evolution of life and plate tectonics (Cox et al., 2018), and catastrophic events such as large-meteorite impacts and volcanic episodes. Ongoing, present-day processes such as melting, re-crystallization, metamorphism, hydrothermal activity, and release or sequestration of gases continue to redistribute critical elements. Some elements are particularly effective tracers of modern and ancient processes of element cycling (see Table 2-1).

Surface processes are also an important part of the whole-Earth cycling of elements, interacting with deep-seated chemical and physical mechanisms that operate over a range of spatial and time scales. Thus, understanding the distribution of critical elements means mapping the details of a global plumbing system that extends from the core to the clouds (see Figure 2-5).

Carbon, hydrogen, iron, nitrogen, oxygen, phosphorus, and sulfur are among the bio-critical elements that create a habitable world. In the coming years, geoscientists will build on recent advances in understanding the global hydrogen and carbon cycles (Orcutt et al., 2019), with the aim of understanding how the deep sulfur, phosphorous, nitrogen, and other element cycles operate, and how halogens such as fluorine and chlorine and other elements partition into melts and fluids in metamorphic and magmatic systems (e.g., Farquhar and Jackson, 2016; Dalou et al., 2017; Hanyu et al., 2019; Smit et al., 2019).

Critical elements that are required for the materials and energy needs of modern society, such as for low-carbon energy resources, include cobalt, lithium, and rare earth elements (REEs), along with precious metals, manganese, titanium, uranium, vanadium, hafnium, and zinc (see Table 2-1). Elements that act as tracers of recycling processes between the crust and the mantle include boron, halogens, and noble gases, in addition to REEs and other elements (Smith et al., 2018). Critical elements and their compounds, such as water, significantly affect the physical properties of Earth materials, from melting temperature to strength, rheology, and seismic velocity. Multi-valence elements such as iron, sulfur, and carbon govern redox conditions of the mantle and crust (e.g., Evans et al., 2017; Cline et al., 2018). Critical elements vary widely in abundance in different parts of the crust and mantle, but many low-abundance elements have a disproportionately large influence on geological processes and physical properties of Earth materials.

Some elements partition strongly into fluids and melts that move along conduits at many scales, including the vast network of mineral grain boundaries and structures that develop during flow of fluid or melt (see Figure 2-6). Minerals and their accompanying melts and fluids are the dynamic connection between the deep interior and the surface of the planet, and minerals that form at great depth in the Earth provide clues to the evolution of the atmosphere, oceans, and surface. For example, some superdeep diamonds have been found to contain hydrous minerals (Pearson et al., 2014), traces of water-ice (Tschauner et al., 2018), and biogenic carbonate produced at or near Earth's surface (Li et al., 2019b). Despite this cycling, Earth's interior retains major chemical heterogeneities, which can be imaged with advanced seismological methods (Wang et al., 2019). For example, some deep-sourced magmas contain hydrogen and helium that have been largely isolated since the segregation of the core (Loewen et al., 2019). The persistence of long-lived chemical reservoirs within the dynamic planet has not yet been adequately explained.

Knowledge of processes that catalyze the most influential chemical reactions in the planet is only beginning to emerge and be incorporated into geodynamic models of Earth's interior (Li et al., 2019a). For example, controls on the reduction-oxidation (redox) state of different crust and mantle domains are central to planetary evolution. Among other effects, redox reactions of iron-controlled segregation of the core and the oxidation of the mantle help determine the composition of the atmosphere (Armstrong et al., 2019). Interactions among geothermal, hydrologic, geobiological, and geochemical processes at the interface between the subsurface and atmosphere will require more sophisticated, multicomponent reactive transport models (e.g., Li et al., 2017).

By integrating technological advances in experimental and computational methods with thermodynamic modeling, high-precision micro-analysis of geologic samples, and geophysical data, geoscientists are on the verge of a new understanding of how minerals and fluids react, recycle, and redistribute critical elements from atomic to planetary scales (see Figure 2-7). For example, we can now start to understand the mechanisms and timing underlying the formation and transformation of the crust and the emplacement of large igneous bodies, as well as how these processes have altered climate (Lee et al., 2017), influenced the distribution of

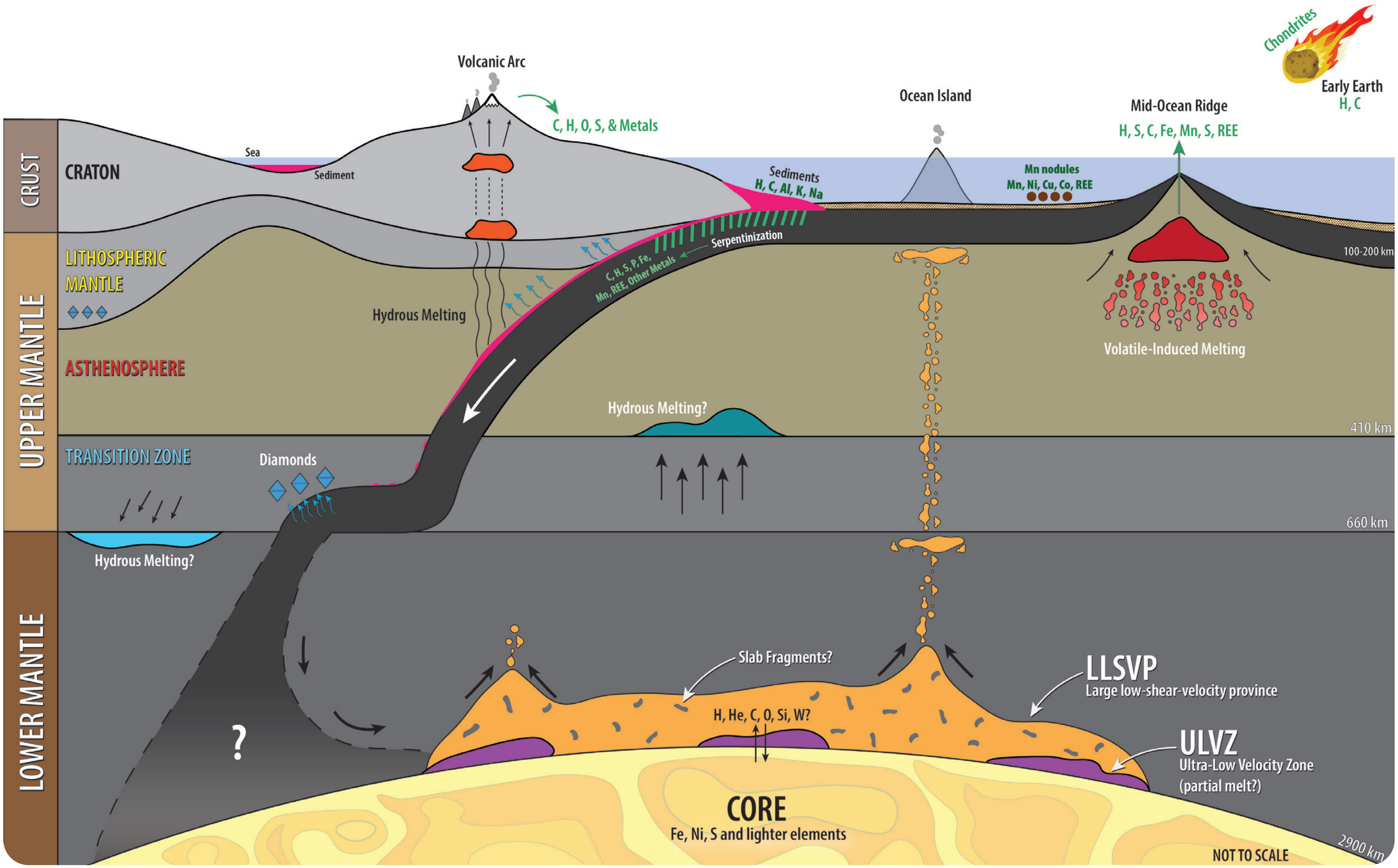

FIGURE 2-5 Volatile and incompatible elements partition strongly into partial melts, creating a global plumbing system of melts and fluids that concentrate, fractionate, and mobilize critical elements from the oceans to the core. Interdisciplinary efforts are needed to unravel how and why distinct geochemical reservoirs persist in a planet with whole-mantle convection. Upwelling fertile mantle undergoes volatile-induced melting and decompression melting at shallow levels to form basaltic crust at mid-ocean ridges (red shaded region). This magma is compositionally distinct from more enriched melts forming ocean islands (orange shaded region) and possibly related to the large low shear velocity provinces (LLSVPs) imaged by seismological methods and flanked by ultra-low velocity zones (ULVZs) that may host partial melts (purple region). Near the mid-ocean ridge, associated hydrothermal systems add volatiles and other elements to oceanic lithosphere and fractionated metals and REEs to seawater, which may precipitate and concentrate in economically valuable manganese nodules across the seafloor. On bending at convergent plate boundaries, oceanic lithosphere further hydrates (e.g., through serpentinization along deep faults [steep green lines]). These serpentinites, along with sediments (pink) and hydrated oceanic crust, carry water, carbon, and other volatiles and alkali elements into the mantle, forming hydrous melting zones that feed volcanic arcs and emplace magmas (orange shaded region) associated with metasomatism and hydrothermal systems that concentrate rare metals in the crust. Some volatiles in subducted slabs may reach deeper (>300 km) into the mantle, where the higher water storage capacity of the transition zone relative to the uppermost and lower mantle may produce dehydration melting above and below the seismic discontinuities at 410 and 660 km (blue shaded regions), and these regions could therefore act as chemical filters in mantle convection. Diamonds and their inclusions from the lithospheric mantle and from >300 km (superdeep diamonds) contain geochemical clues to whole-mantle critical element cycles.

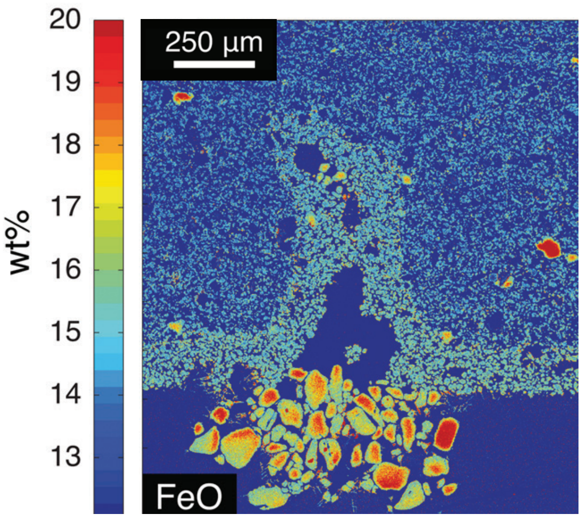

FIGURE 2-6 Variation in iron concentration in the vicinity of a melt-rich channel (dark blue region) developed during a high-temperature experiment to simulate melting in the mantle. The crystals are olivine. There is a reaction layer (light blue) surrounding the melt-rich channel. Experimental results such as this provide quantitative insights into how melt-mineral reactions create pathways for melts and fluids enriched in volatile and incompatible elements as they fractionate and are transported from source regions to emplacement or eruption. SOURCE: Modified from Pec et al., 2017.

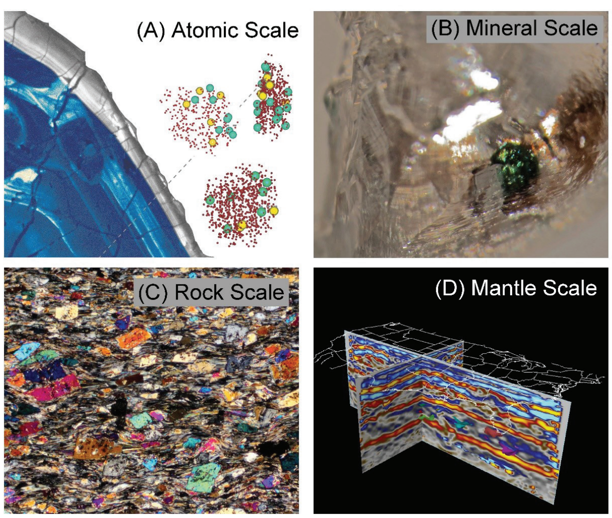

FIGURE 2-7 The redistribution and cycling of critical elements occur from atomic to global scales over geologic time. (A) Atom probe tomography for nano-geochronology maps individual lead atoms diffused over billions of years in a 4.4 Ga zircon crystal (Valley et al., 2014). (B) Green-colored REE mineral ($KNbO_3$), ~0.2 mm across, recently discovered and named goldschmidtite, trapped as an inclusion in diamond, linking extreme mantle metasomatism with the carbon cycle (Meyer et al., 2019). (C) Photomicrograph of a highly deformed blueschist from Turkey (field of view ~2 cm) showing the hydrous Ca-Al silicate lawsonite as bright-colored rectangular crystals under crossed polarized light. Lawsonite is an important mineral in the cycling of sediments and water between the crust and mantle in subduction zones. (D) At regional and mantle scales, seismic waveform imaging reveals negative scattering anomalies indicative of compositional and lithological heterogeneities associated with crust–mantle cycling. SOURCES: A–image courtesy of John W. Valley; B–image courtesy of Nicole A. Meyer; C–image courtesy of Donna L. Whitney; D–Wang et al., 2019.

economically significant elements at various stages of Earth's history, and ultimately determined habitability of the surface.

Because the definition of critical elements is broad, encompassing materials required by modern societies for security, prosperity, and health and for low to carbon-free energy sources, as well as for long time- and spatial-scale planetary processes such as volatile cycling between Earth's interior and surface (see Table 2-1), a broad range of infrastructure and partnerships is needed to optimize research opportunities. DOE synchrotron radiation facilities are needed to conduct highly specialized geochemical analyses and measurements of physical and mechanical properties of Earth materials under a wide range of physical conditions including variable pressure, temperature, oxygen fugacity, and strain rate (Dera and Weidner, 2016). Rapidly developing capabilities to link geochronology with petrology and geochemistry (Rubatto, 2002; Kohn et al., 2017), and the latest generation of micro- and nano-analysis techniques provide opportunities to determine the pressure–temperature–fluid-deformational evolution of minerals from their formation in deep time to their present exposure at Earth's surface. Cyberinfrastructure is needed to enhance training and research in data science, develop geochemical and thermodynamic databases, and create new routes of network analysis and machine learning to search for patterns in the time and age of mineral and biogeochemical evolution (Hazen et al., 2019). New partnerships and collaborations involving novel dynamic compression methods (DOE), programs related to critical minerals (USGS), and EAR core disciplinary programs as well as other divisions of GEO (e.g., OCE for processes in the marine realm), combined with infrastructure provided by the Instrumentation and Facilities Program, will be especially valuable in promoting research on critical elements.

4. What is an earthquake?

In textbooks and even for most Earth scientists, earthquakes are sudden motions of the Earth caused by rapid slip on planar faults. Recent observations, however, show that earthquake rupture is not simple and that deformation of the Earth occurs over a broad range of spatial and temporal scales, from the seconds and minutes associated with rapid slip to the million year scale of plate tectonics. For example, recent earthquake ruptures have expressed exceptional geometric complexity (Hamling et al., 2017), and dramatic improvements in monitoring have led to discoveries of a far broader spectrum of slow, transient deformation than represented by ordinary earthquakes (Beroza and Ide, 2011; see Figure 2-8). Increasingly comprehensive geological records of exhumed faults and their surroundings demonstrate that deformation and its localization are multi-faceted and strongly depth dependent (Rowe and Griffith, 2015).

This realization has led Earth scientists to reconsider the very nature of earthquakes and the dynamics that drive them, and to pose the deceptively simple question, "What is an earthquake?" Motions and deformation, regardless of scale, are Earth's responses to the internal stresses that give rise to plate tectonics, mountains, and topography. We know the form of the equations governing deformation, but not the flow laws that govern the relevant material properties for deformation.

The promise of the coming decade is that advances in characterizing material properties, coupled with high-performance computing to carry out increasingly accurate simulations of crust, lithosphere, and mantle deformation processes, will lead to a more fundamental understanding of the full spectrum of observed deformation. With such an understanding it will be possible to construct a new comprehensive framework, rooted in the forces that drive the system and the material behavior that controls deformation at all relevant scales.

In this new view of the Earth, plate boundaries would not simply be described by their relative motions, but by their origin, nature, complexity, and evolution as fault systems in terms of the convective forces that control them. This view would represent a new comprehensive theory of plate tectonics that features a dynamic, physics-based understanding to supersede the current kinematic, descriptive framework. Plate

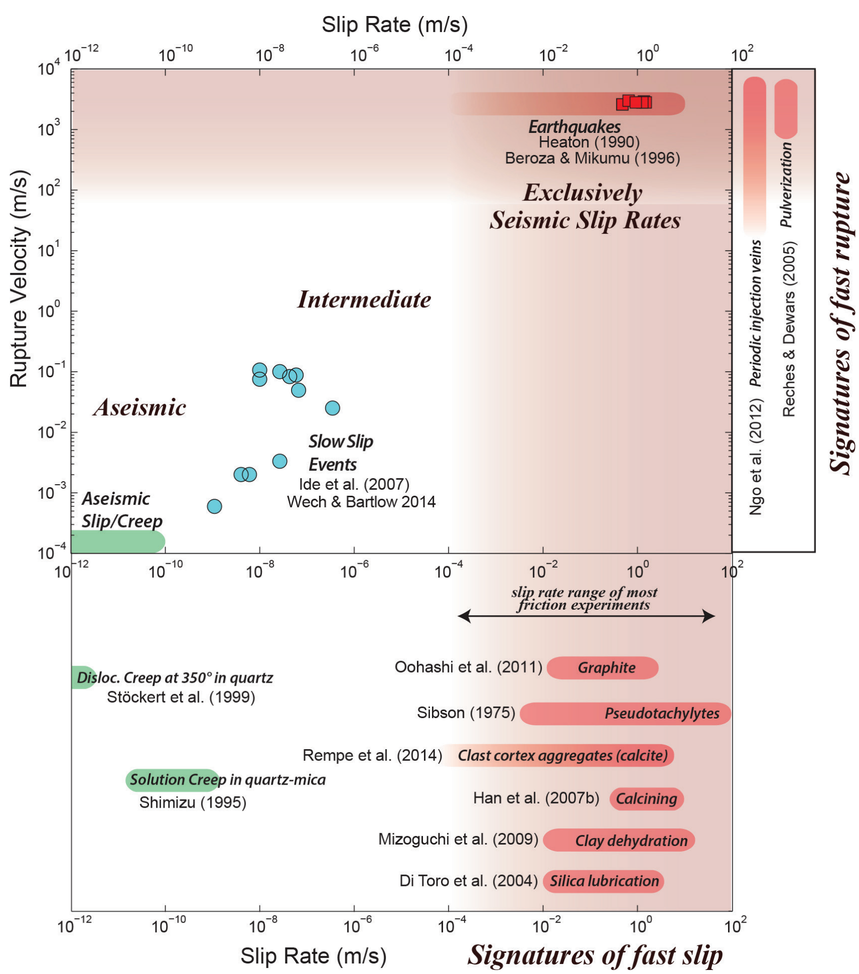

FIGURE 2-8 Slip rate and rupture propagation velocity for seismic (red), intermediate (blue), and aseismic (green) fault slip rates in active faults. The lower half of the plot shows experimentally reproduced deformation mechanisms and their textural signatures, with constraints in either slip rate or rupture velocity. SOURCE: Rowe and Griffith, 2015.

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tectonics and mantle convection would come to be seen as different manifestations of a single process, in which the Earth deforms in response to stress in predictable ways depending on material properties (Coltice et al., 2019).

This unified theory requires several key components: (1) seismic and geodetic observations that are integrated with fault zone geology to build a comprehensive understanding of deformational response to tectonic stress; (2) integrated field and geochronologic studies to determine slip histories and earthquake recurrence intervals on known faults; (3) field campaigns to determine how much motion is taken up by known and unmapped faults over the time scales relevant to fault systems (and by extension plate boundary) evolution; (4) experiments in rock mechanics and rheology that measure the material properties needed to describe deformation; and (5) the development of dynamical models that can reproduce the spectrum of observed deformations from rapid, slow, and steady slip to plate motions. Such a multi-pronged approach is compelling from a scientific point of view, but also important due to the human consequences of earthquakes.

The combination of fundamental science and societal relevance has been a theme of recent and proposed geoscience community plans (Williams et al., 2010; Davis et al., 2016; McGuire et al., 2017; Bebout et al., 2018; Huntington and Klepeis, 2018). These projects and proposals aim not only at imaging and measuring the Earth, but also at a predictive understanding of the underlying physical processes and their consequences, with obvious implications for earthquakes as natural hazards. They recognize that the variety of processes over the full range of time scales relevant to understanding deformation in the Earth, from earthquakes to plate motions, require synergistic interagency, national, and international partnerships. The breadth of processes also motivates a diversity of infrastructure—ranging from material characterization to seismometers, from instrument-based facilities to cyber- and personnel infrastructure—as well as controlled fluid injection experiments in which a fault is drilled and instrumented in advance of an induced earthquake.

5. What drives volcanism?

Volcanic eruptions are among the most spectacular and complex manifestations of the Earth system (see Figure 2-9a). How can their onset, duration, magnitude, and intensity be assessed and anticipated? Today, volcano science is poised to supply answers via physics-based models for all key processes driving eruptions, taking advantage of a wealth of data from eruption observations on fine temporal and spatial scales, and the emerging ability to process data extremely rapidly (NASEM, 2017). In addition, new time-sensitive geophysical imaging techniques and micro-scale geochemical clocks provide unmatched information about the speed of rising magma in the crust and mantle, and how the geometries of storage regions (reservoirs) and transport pathways (conduits) of volcanoes evolve and influence eruptions. Geoscientists are on the cusp of being able to use these approaches during eruptions to provide urgently needed advice to response agencies in near-real time.

Volcanoes are also a key connector within the Earth, unique in how they interact with other parts of the Earth system (NASEM, 2017). Eruption and emplacement of large igneous provinces, on a scale orders of magnitude larger than anything seen historically, are associated with global warming and ocean acidification from massive increases in atmospheric carbon dioxide, as well as global dimming and catastrophic volcanic winters. Such events are temporally linked with some of the most significant mass extinctions in the geological record (e.g., Burgess et al., 2017), highlighting the arguably outsized role of volcanoes and their associated intrusions in the history of life (Rampino and Self, 2015). Smaller but nevertheless catastrophic eruptions have occurred on active systems such as Yellowstone Caldera. Eruptions from caldera systems are about two orders of magnitude more common than large igneous provinces, and at least one or two orders of magnitude larger than historic eruptions. These catastrophic eruptions are very rare events but are critical to understand because their impacts were immense, and, in the modern world, would be horrific (see Figure 2-9b). Even smaller, historical eruptions profoundly change landscapes for decades or centuries and can have global impacts that affect society (see Figure 2-9b). For instance, aerosol cooling effects from eruptions such as Pinatubo in 1991 have had demonstrable global impact for weeks to years (Timmreck, 2012). An emerging challenge is to understand the feedbacks between volcanoes and climate change in the 21st century and beyond. Volcanologists look to understand the fundamental processes of magma generation, ascent, and eruption, and thereby establish how mechanisms and impacts of magmatism, and linked feedback cycles among the atmosphere, hydrosphere, biosphere, and geosphere, scale up by more

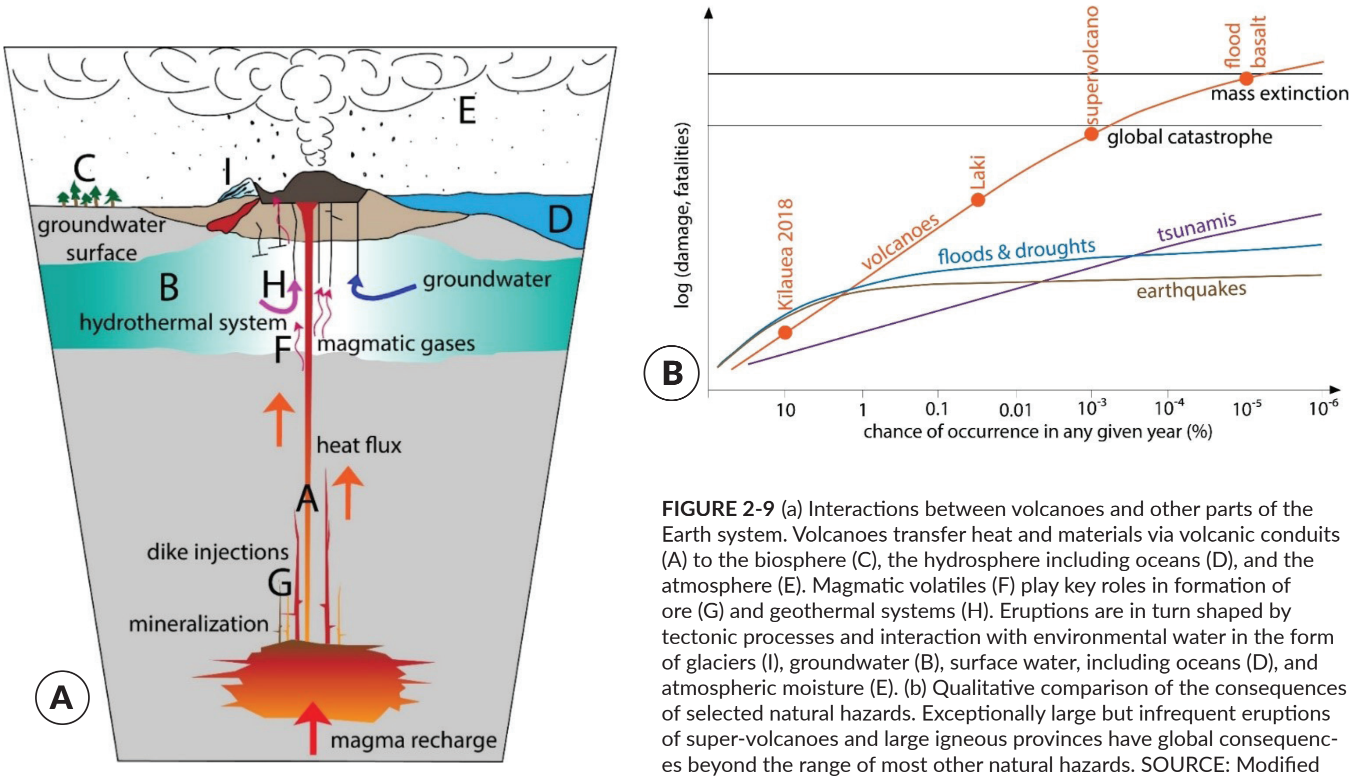

FIGURE 2-9 (a) Interactions between volcanoes and other parts of the Earth system. Volcanoes transfer heat and materials via volcanic conduits (A) to the biosphere (C), the hydrosphere including oceans (D), and the atmosphere (E). Magmatic volatiles (F) play key roles in formation of ore (G) and geothermal systems (H). Eruptions are in turn shaped by tectonic processes and interaction with environmental water in the form of glaciers (I), groundwater (B), surface water, including oceans (D), and atmospheric moisture (E). (b) Qualitative comparison of the consequences of selected natural hazards. Exceptionally large but infrequent eruptions of super-volcanoes and large igneous provinces have global consequences beyond the range of most other natural hazards. SOURCE: Modified from NASEM, 2017.

than three orders of magnitude to apply to these very large infrequent events.

The magnitude of maximum potential impacts from volcanoes can be global, compared to more localized hazards like extreme weather, landslides, and flooding (see Figure 2-9b). Yet, in understanding what drives volcanism, it is essential to recognize that eruptions do not simply modify their surroundings; they are also strongly influenced by them. Tectonics control the composition and amount of magma that is generated and transported through volcanoes. Large earthquakes are postulated to increase greatly the probability of eruptions at nearby volcanoes (Manga and Brodsky, 2006). There is clear evidence that changes in climate influence the behavior of volcanoes (e.g., Watt et al., 2013). Environmental water surrounding or overlying a volcano has profound effects on eruption processes on time scales that range from microseconds to hours, and spatial scales of submillimeters to kilometers (see Figure 2-9a). Volcanoes respond to deformation associated with seasonal and climatic cycles, including the behavior of glaciers (Rawson et al., 2016), as well as to orbitally paced changes in sea level that in turn affect eruptive rate (Conrad, 2015).

Major eruptions are rare among natural hazards in that they often offer weeks to months of warning in the form of seismicity, deformation, and outgassing that precede the onset of dangerous eruption. To turn these warnings into accurate forecasts, however, requires mapping the patterns of repose, unrest, precursors, and eruptions for the entire life span of many individual volcanoes. Currently, full histories are known for very few magmatic systems and individual volcanoes, so generalization is difficult. A goal for the next decade is to augment those histories—particularly for low-frequency but extremely high-impact events—using time series of volcanic products in sedimentary archives such as continuous cores and outcrops as well as ice cores. These contain volcanic relics of distal ashes, crypto-tephras, and chemical species, such as sulfate, chlorine, and mercury, that provide information about the frequency of eruptions beyond historical records. Scientific coring and drilling of volcanoes and their feeder systems support the understanding of the mechanisms of eruptions through real-time monitoring (e.g., Sakuma et al., 2008) and longer temporal records (e.g., Stolper et al., 2009).

The publication of *Volcanic Eruptions and Their Repose, Unrest, Precursors, and Timing* (NASEM, 2017) followed by the 2018 Kīlauea eruption have united volcanologists with a vision to create a coordinated community involving academia, USGS, and other

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government agencies. This diverse community includes geodesists, seismologists, gas and rock chemists, physical volcanologists, remote sensing specialists, numerical and analog modelers, sedimentologists, geochronologists, and experimental petrologists. An unprecedented increase in new technologies is now available to observe volcanic systems and transform the understanding of underpinning processes. New progress will require developing novel models leveraged by machine learning techniques, artificial intelligence, and collaboration with computer engineers, mathematicians, and statisticians. These developments bring with them the infrastructural and computational challenges of rapid acquisition, processing, and interpretation of large amounts of data on short time scales. Many key advances in understanding magmatic and volcanic processes will derive from data that can only be obtained during hazard events (a key component of the Community Network for Volcanic Eruption Response Research Coordination Network [CONVERSE], part of the SZ4D initiative); in turn, new advances in hazard forecasting will critically depend on better understanding of the physics of magmatic and volcanic processes.

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

Great progress over the past two decades has been made in linking climate, tectonics, and erosion processes to understand how they shape and are dynamically influenced by Earth's surface topography. This progress has brought into focus key scientific questions concerning the role of rock mechanical properties, short-term actors such as storms, and the rheology and dynamics of Earth's interior in landscape evolution and the co-evolution of landscapes with the atmosphere, cryosphere, sea level, and life. New technology for measuring topography over geologic to human time scales now makes it possible to address these key questions, and their implications for urgent societal challenges related to geologic hazards, resources, and climate change (NRC, 2015; Davis et al., 2016; McGuire et al., 2017; Barnhart et al., 2018; Huntington and Klepeis, 2018; NASEM, 2018).

Topography is sensitive to processes that operate above, on, and below Earth's surface at many scales. Mantle dynamics and plate boundary evolution drive the surface morphology of continents over time scales of millions to hundreds of millions of years and spatial scales of tens to thousands of kilometers as erosion actively removes mass. Actors like earthquakes, volcanic eruptions, storms, and glaciers affect regional to local (i.e., hillslope-scale) topography on time scales of minutes to millennia. Topography itself influences these processes and their interactions by affecting global and local climate, lithospheric stresses, and erosion processes. Topography is also the fundamental feature of the landscapes on which we live. Quantifying topographic change is therefore crucial to advance many areas of geoscience—from understanding Earth-system interactions over geologic time, to predicting landslides, ecosystem gradients, and the distribution of freshwater and soil resources in the coming decades.

Many newly recognized connections among different parts of the Earth system are expressed in topographic form and change. Such connections involve phenomena as diverse as the interactions of mantle dynamics, surface processes, ice-sheet changes, and sea level (e.g., Flament, 2014; Heller and Liu, 2016; Austermann et al., 2017; Whitehouse et al., 2019); and the co-evolution of landscapes and life (e.g., Badgley et al., 2017; Fremier et al., 2018). They are manifest in links between the geologic history of near-surface deformation and newly imaged deep lithosphere and mantle structures (Wu et al., 2016); and in feedbacks among rock strength, lithospheric stresses, biogeochemical cycles, climate, and physical and chemical erosion (e.g., Riebe et al., 2017). These are just a few examples of the many promising frontiers created by recent advances in our ability to measure and model topographic change on many time scales.

At the same time, the need to understand how topography and topographic change impact human society through geologic hazards and the creation or destruction of natural resources and habitats is more urgent than ever (Davis et al., 2016; NASEM, 2018). For instance, there is a critical need to quantify how topography will influence ecosystem and hydrologic change in a changing climate. In turn, we need to understand how land use, ecosystem, and water cycle changes alter topography. Topography and topographic change also affect the risk to lives and property posed by earthquakes, landslides, floods, mudflows, eruptions, and tsunamis. Observations and process-based understanding of topographic change have great potential to provide essential insight into the processes that underlie these hazards.

Technological advances set the stage for breakthroughs in understanding the causes and consequences of topographic change within the linked system encompassing the deep Earth, surface processes, climate, and the biosphere. For example, the rapid increase in lidar, photogrammetry, InSAR, and drone-based datasets has revolutionized our ability to quantify changes in modern topography (e.g., James and Robson, 2012; Roering et al., 2013; Deng et al., 2019; see Figure 2-10). In the next decade, a community goal is to reach submeter resolution in modern topography for much of the globe (Davis et al., 2016). Repeated measurements could capture responses to earthquakes, weather events, volcanic unrest, and human activity. Visualizations created from 34 years of Landsat imagery[3] are already transforming how we see the Earth, especially surface processes. River meandering, glacier dynamics, coastline changes, landslide events, and other large-scale surface processes can be observed in ways never before possible, providing new understanding and raising new questions (Schwenk et al., 2017; Dirscherl et al., 2020; Nienhuis et al., 2020).

Our ability to measure topographic change on geologic time scales has also seen recent advances and is poised to improve dramatically in the near future, creating unprecedented opportunity for progress. New thermochronology approaches (see Figure 2-11) provide opportunities to reconstruct the exhumation of rocks from the deep crust to the surface (Huntington and Klepeis, 2018), enabling estimates of the timing and rates of erosion and relief formation across the globe over thousand- to million-year time scales (e.g., Champagnac et al., 2014; Harrison et al., 2015). Refined paleoaltimetry methods, including use of hydrogen isotope archives in volcanic ash and carbonate clumped isotope thermometry, now provide data on topographic change at the scale of watersheds and mountain ranges over geologic time (e.g., Garzione et al., 2017), and are being integrated with climate models and geologic observations to provide 0.5-km-scale paleoelevation estimates (Cassel et al., 2018). Such approaches enable us to explore the significance of topographic change in deep time, for instance connections between plateau uplift,

[3] See https://earthengine.google.com/timelapse (accessed March 31, 2020).

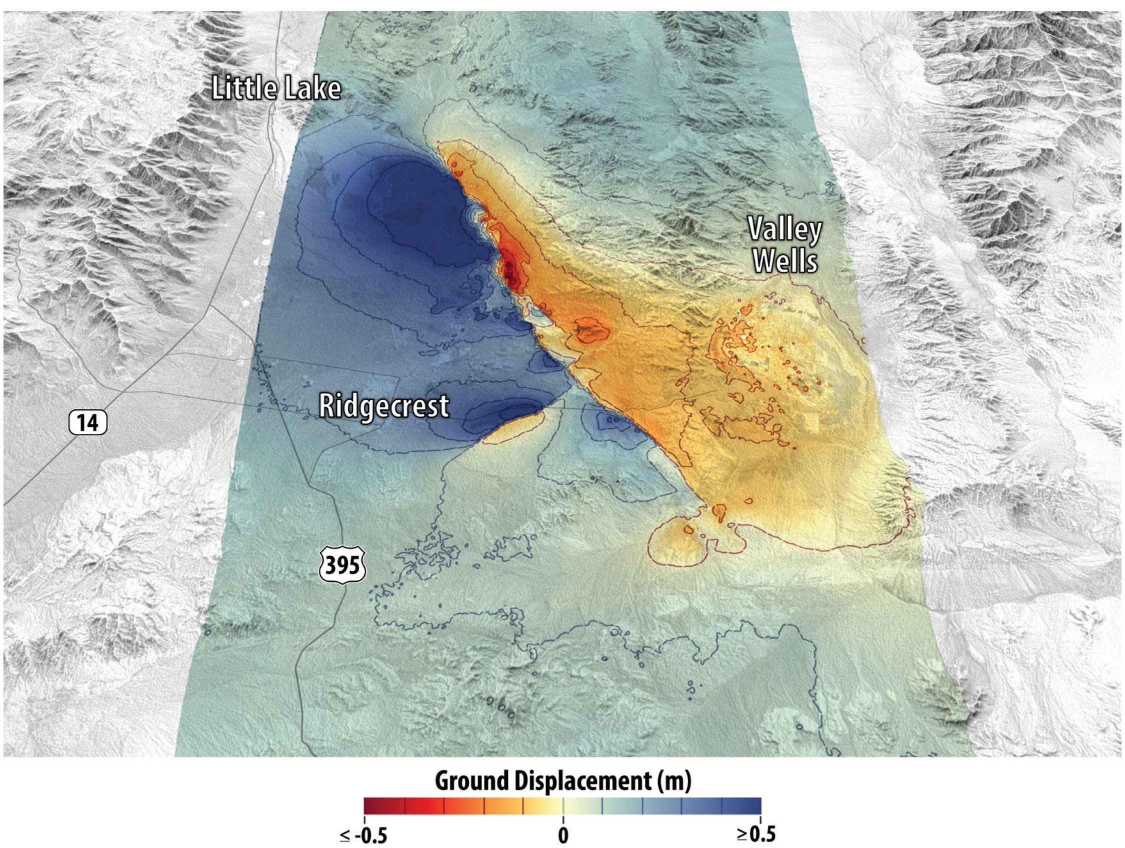

FIGURE 2-10 Topographic change associated with earthquakes in Ridgecrest, California, in July 2019 showed that unexpected slip occurred on many faults around the main rupture. The colors show the amount of ground displacement—land shifting vertically, horizontally, or both—in meters. Blue areas moved roughly northwest (horizontally) and up (vertically), while red and orange areas moved southeast and down. The map shows processed satellite-based SAR (synthetic aperture radar) data and a digital elevation model to show the contours of the land surface. SOURCE: NASA.

silicate and carbonate weathering, seawater chemistry, and atmospheric circulation and composition (e.g., Farnsworth et al., 2019), and potential links between the evolution of mountainous topography and species richness (Antonelli et al., 2018).

Several emerging challenges must be addressed to realize the opportunities that arise from recent conceptual and technological advances. Improved estimates of the timing and rates of surface uplift, subsidence, and erosion/deposition are needed to directly link near-surface deformation and resulting topographic change with the rheology and dynamics of Earth's interior. Illuminating rheology and dynamics through integration of seismological observations and dynamical models of mantle flow and lithospheric deformation will be critical for understanding the strength of such links—and the role of Earth's interior dynamics in present-day sea level and future sea-level predictions. Observations and theory are also needed to quantitatively define the role of chemical and mechanical properties of rocks, and the role of geologically short-term actors such as storms, earthquakes, and rapid glacial retreat in surface processes and landscape evolution. Coupling detailed landscape models to large-scale mantle models (e.g., Braun et al., 2013) remains a challenge owing to their differing spatial and temporal scales and uncertainties in Earth-material properties (e.g., rheology). The role of topography and topographic change in land–atmosphere feedbacks (see Figure 2-12), land–ice interactions, coastal and dryland processes, habitat creation, and ecosystem structure in a changing climate is just beginning to be explored, with important implications for Earth's habitability over geologic time and in the next century.

Focused attention on these challenges over the next decade promises new insights into the interactions of Earth's surface and deep interior, and into the co-evolution of Earth's solid, fluid, and living components. Progress will require high-resolution repeat measurements of modern surface topography and vegetation cover and cyberinfrastructure to support open access to, and rapid processing and analysis of, imagery and point cloud data; long-term observations of modern weather, hydrology, and geochemistry of surface waters, soils, and sediments; and new records of past climate, elevation, relief, deformation, weathering,

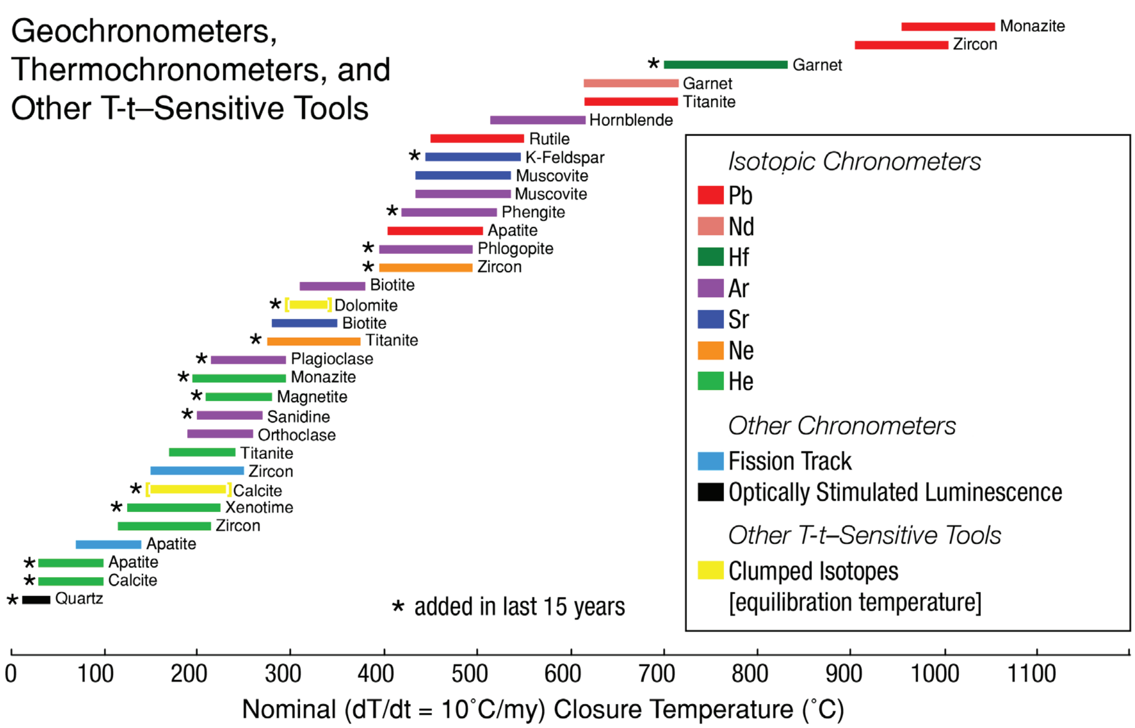

FIGURE 2-11 A broad range of geochronometers, thermochronometers, and other temperature-time-sensitive tools, highlighting advances in the past 15 years. Thermochronometer temperature ranges from Hodges (2014). Clumped isotope temperature ranges following Passey and Henkes (2012). SOURCE: Figure courtesy of Kip Hodges and Katharine Huntington.

FIGURE 2-12 Photograph showing landscape change due to landslides triggered by earthquakes and storms in Taiwan. Bridge and road infrastructure is also visible, highlighting societal relevance of the landslides. SOURCE: Image courtesy of Kristen L. Cook.

erosion, deposition, and ecosystem change through geologic time. Partnerships across GEO and with NASA, and new and refined geochronologic and stable isotopic approaches, will be central to developing these datasets and records. Geophysical methods (e.g., Aster et al., 2015) present exciting opportunities to quantify Earth's structure and rock mechanical properties (e.g., erodibility, rheology) at depths ranging from meters to thousands of kilometers. Integration of such diverse datasets with high-resolution computer models of landscape evolution, mantle dynamics, and climate is key to enabling process-based understanding of the causes and consequences of topographic change.

7. How does the critical zone influence climate?

The critical zone is the reactive skin of the terrestrial Earth, extending from the top of the vegetation through the soil and down to fresh bedrock and the bottom of actively cycling groundwater (NRC, 2001; Sullivan et al., 2017; see Figure 2-13). Critical zone properties are driven by the interactions of tectonics, climate, topography, weathering, erosion, and life that produce, over geologic time scales, a permeable, water-storing, chemically reactive environment out of dense bedrock (e.g., Riebe et al., 2017). This frontier area of investigation, which is so important to life and Earth's processes, has inspired research programs focused on the critical zone to be instituted in the United States and throughout the world (Richardson, 2017)—enabling pioneering studies of water, nutrient, and carbon cycles, and connections between vegetation and deep subsurface processes (e.g., Brantley et al., 2017). Scientific drilling and geophysical surveys have now revealed systematic variation in critical zone structure with hillslope topography (see Figure 2-13) and motivated development of quantitative models for these observed relationships (Riebe et al., 2017).

While it is widely understood that the structure and function of the critical zone is influenced by climate, only recently has the community begun to identify the ways and extent to which the critical zone also exerts influence on climate (Fan et al., 2019). Because the structure and reactivity of the critical zone influences moisture, groundwater, energy, and gas exchanges between the land and atmosphere, it exerts a key role in modulating atmospheric concentrations of greenhouse gases (particularly water vapor and carbon dioxide) and, therefore, temperature. This insight is particularly timely because it occurs synchronously with a growing realization in climate science that the land is not merely the bottom boundary condition for the atmosphere, but an integral part of the climate system. The critical zone stores water, providing moisture to vegetation, recharge to groundwater, and runoff to streams. While Earth system models include soil moisture exchange with the atmosphere via evaporation and transpiration, critical zone research reveals that moisture stored in weathered bedrock below the soil can be a significant source of transpired water—a missing reservoir in climate models (e.g., Fan et al., 2019). The critical zone is also where the terrestrial carbon storages exchange with the atmosphere, and growing evidence indicates that carbon dynamics extend deep into the critical zone. Process-based understanding and conceptual models of how critical zone structure and composition control coupled water, energy, carbon, and nutrient cycles are needed to quantify the role of the critical zone in Earth's climate system.

On longer time scales, critical zone development influences how physical erosion rates and chemical reactions that drive carbon dioxide drawdown are linked (e.g., Schachtman et al., 2019). Tectonism forces uplift and influences erosion rates, while channel incision drains landscapes—together, these actions strongly influence the physical and geochemical evolution of the critical zone. Throughout the geologic past, critical zone properties have likely changed with the emergence of life, land plants, and animals, and the physical and chemical consequences that followed. Exploring possible ancient critical zone properties and processes is important to understanding the evolution of Earth's climate and its biogeochemical and sedimentary record.

Looking toward our future in the Anthropocene, the critical zone is where all plants get water, where streamflow is sourced, and where our subsurface water supply is temporarily stored. It is where significant change will occur due to ongoing agricultural and other land-use activities, the warming of the Arctic, and the drying of semi-arid regions. The hydrologic and ecological consequences of these changes and the anticipated increased frequency and duration of extreme droughts and storms will be mediated by critical zone properties, and the deep, poorly known component of the critical zone may play an important role. Feedbacks between critical zone and atmospheric processes will drive regional to global climate conditions. For example, the progressive spatial shifting of vegetation and agricultural zones with warming will depend on moisture storage characteristics set by critical zone properties. Changes in vegetation and land use will in turn feed back on climate processes by altering albedo, transpiration rates, and atmospheric humidity and temperature.

Process studies of how the deep critical zone will influence the co-evolution of vegetation, water resources, and climate will be essential for quantifying feedbacks. These studies can take advantage of advances in field instrumentation for monitoring the water budget (including soil moisture, rock moisture, groundwater, transpiration, humidity, precipitation, and runoff) and gas dynamics (including CO_2 exchange). Repeat terrestrial and airborne lidar surveys enable documentation of vegetation structure, and hyperspectral surveys detect stress states. Natural isotopic tracers can be used to track water sources for vegetation and residence time of stored waters. Remote area studies now rely on solar power, rugged data loggers, and radio or cell phone connections for near-real-time observations. Sustained long-term observations to document changes at a site are essential. The field locations in the NSF-supported National Ecological Observatory Network program and the NSF Long Term Ecological Research Sites may provide settings for some critical zone studies. The NSF Critical Zone Observatories have created a benchmark dataset for the period 2007 to 2020. The Critical Zone Collaborative Network may lead to additional benchmark datasets for the period 2020 to 2025. Partnerships with various federal agencies ranging from DOE to the U.S. Forest Service are under way and can be expanded. The long-term satellite observations by Landsat will play an important role in tracking surface change, while large-scale moisture change at depth (GRACE mission) and in shallow soil (SMAP mission) are recorded globally.

A challenge to including the critical zone in Earth system models is the quantification of critical zone properties over regional, continental, and global scales. The properties (e.g., depth, porosity, and carbon content) of the critical zone below the soil are essentially unknown except for a few intensively studied sites. These few studies suggest that critical zone properties may vary systematically with topography (e.g., see Figure 2-13). Motivated by discoveries at the U.S. Critical Zone Observatories, several theories suggest predictable relationships between topography, lithology, climate, uplift and erosion rates, and the depth and degree

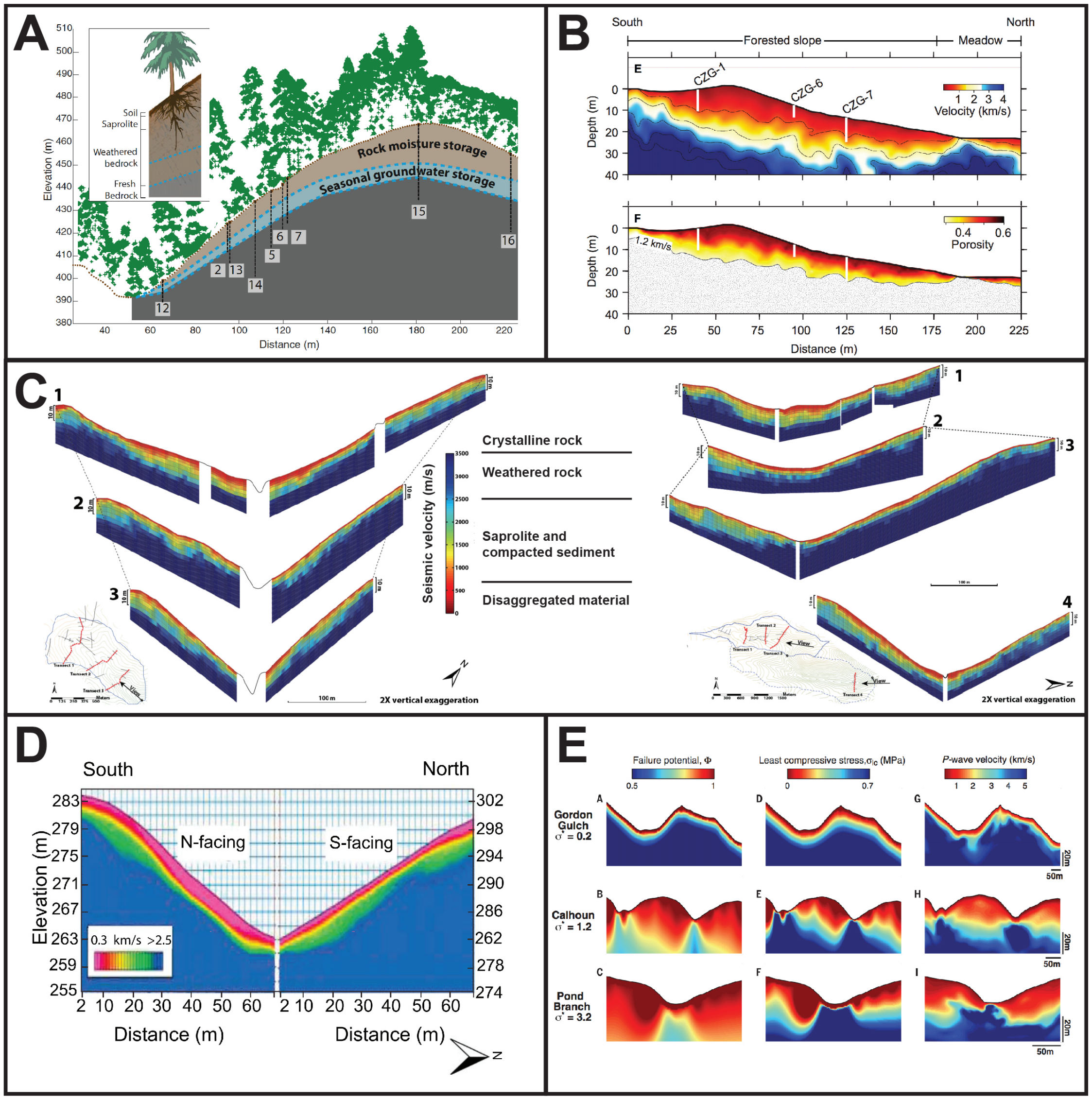

FIGURE 2-13 Hillslope cross-sections revealing measured or predicted critical zone properties at several U.S. Critical Zone Observatories (CZOs): (A) lidar-derived vegetation and surface topography and cross-section (based on wells), where rock moisture and seasonal water table in the weathered bedrock are monitored at the Eel River CZO, (B) seismic velocity (top) and interpreted porosity (φ) at the Southern Sierra CZO, (C) seismic velocity and inferred Earth materials across several transects at Boulder Creek CZO, (D) a north-south comparison in seismic velocity profiles at Shale Hills CZO, and (E) predicted failure potential (left), compressional stress (causing fracturing; middle), and observed seismic velocity (right) at Gordon Gulch in the Boulder Creek CZO (top), Calhoun CZO (middle), and Pond Branch, Maryland. SOURCES: A–Rempe and Dietrich, 2018; B–Hayes et al., 2019; C–images courtesy of Kevin Befus; D–image courtesy of Susan Brantley; E–St. Clair et al., 2015.

of weathering in the critical zone (e.g., Riebe et al., 2017; Anderson et al., 2019; Harman and Cosans, 2019). A long-term campaign to document for the first time the critical zone at the continental scale is needed. Aerial lidar surveys can rapidly generate high-resolution maps, and many areas have been flown already. Advances in ground and aerial geophysical technology and quantitative theory for predicting critical zone properties should accelerate data collection and map generation. Such a campaign could partner with USGS and state geological surveys. In addition, partnering with the National Center for Atmospheric Research to develop and refine global land models would benefit critical zone science.

Finally, to tackle the problem of the influence of the critical zone on climate, Earth scientists, biologists, climate scientists, and social scientists will need to work together, building collaborations across several NSF directorates, including Geosciences, Biological Sciences, and Social, Behavioral and Economic Sciences (SBE).

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

The more that is known about Earth's past, the better that future changes can be anticipated (NRC, 2011). We now live in the Anthropocene, where humans have become geologic agents (Crutzen, 2006). Changes that required thousands to millions of years to occur in the geologic past now occur on human time scales. Carbon that was buried and transformed over tens to hundreds of million years has been put back into the atmosphere over the time scale of a century. During the deglaciation from the last ice age, it took about 6,000 years to achieve a ~80 ppm rise in atmospheric carbon dioxide concentration. An equivalent magnitude of increase in atmospheric carbon dioxide has occurred over the past ~50 years, within the lifetime of a person born in the 1970s.

Earth scientists are integral to providing deep and compelling scientific context to the challenges faced by human society in the face of rapidly increasing rates and magnitudes of climate and environmental change. Evidence of both long-term and rapid environmental change in Earth's history—from the ancient past to the present—provides key baselines for comparison to modern change, helps to elucidate Earth system dynamics (climate forcings, feedbacks, responses, and thresholds), and plays a critical role in the calibration of physical models that are used to project future scenarios. While rapid, modern environmental changes have been observed from the top of the atmosphere to the depths of the oceans, longer records and observations outside of human experience are needed to accurately infer the impacts of ongoing change. At the same time, Earth science is a critical lens through which to study recent and ongoing changes, particularly in transdisciplinary partnerships to address issues such as geohealth, disaster risk, or urban regeneration and development (Harman et al., 2015; Klenk et al., 2015).

Society is already experiencing major impacts from climate and environmental changes, such as extreme temperatures and weather; sea-level rise; droughts and fires; effects on water quantity, quality, and availability; intensifying storms and inland flooding; and melting of permafrost and ice in polar regions (USGCRP, 2017, 2018; IPCC, 2019). Such impacts, including the intersection of coupled human and natural systems, will be defining issues for the 21st century, influencing everything from agriculture to defense and national security. To this end, continued and focused research on the interactions of Earth systems processes with climate and environmental change carries a particular urgency in the context of accelerating rates of change on human time scales.

There is still much to be learned about Earth's climate dynamics considering continuing progress in the accuracy and precision of paleoclimate proxies and associated geochronologic data. Here we highlight several areas in which Earth scientists are poised to make advances in the dynamics of climate and environmental change. One of those stems from the increasing capabilities of climate and Earth system modeling coupled with a greater potential for increased temporal and spatial resolution offered by paleoclimate proxies in the geologic record. These advances could enable research relevant to regions that are particularly vulnerable to rapid and/or sustained changes, for example coastal zones, where sea-level rise and subsidence contribute to more frequent flooding (Sweet et al., 2019).

As another example, high latitudes are undergoing rapid transformations as temperatures rise and as losses accumulate in the extent of land ice, sea ice, and permafrost (Plaza et al., 2019). While recent research has made great strides in accounting for the storage and transfer of carbon in this environment, there are still unresolved questions about the processes, such as permafrost melting and changes in microbial communities, that govern carbon storage and fluxes. Additionally, climate models tend to underestimate the magnitude of polar amplification (the higher rate of temperature rise in polar versus temperate and tropical regions). Paleoclimate archives and models are integral to addressing this deficiency and will be key to generating more confident projections in rates of environmental change at high latitudes. Likewise, targeted studies on past and present dynamics of polar ice sheet retreat and the global consequences on land and ocean of reduced sea ice and polar ice are critical to advancing our ability to project changes and adapt to them.

Emerging cyberinfrastructure that archives and analyzes paleoclimate datasets can now be leveraged to address fundamental questions about climate dynamics, thereby addressing long-standing discrepancies between paleoclimate data and models. Merging the knowledge base held in paleoclimate records collected on land and those from the ocean (currently not well integrated due to conceptual and institutional barriers) has the potential to advance the fundamental science on how the integrated climate system works.

Improved capacity to conduct continental scientific drilling projects or those that cross the land–sea interface could facilitate the development of targeted field programs to recover longer, continuous records of climate variability and/or to increase the spatial and temporal density of observations. Such undertakings will help to address key gaps in existing datasets and to address questions that require longer, more continuous records such as those showing how climate and environmental change connects to other Earth system processes such as tectonics, solid Earth, natural resources, and biotic and landscape evolution. Potential partners in the analysis of paleoclimate include AGS, OCE, NASA, and USGS. Additionally, partnerships with social science (such as research within SBE) can help effectively translate and communicate climate information to the public.

9. How is Earth's water cycle changing?

The water cycle is necessary for all terrestrial life, and now there is increased urgency to understand changes in the water cycle due to the influence of people and climate change. Terrestrial reservoirs of water throughout the world, particularly groundwater aquifers and the vadose zone, emerged under the influence of dynamics in climate and tectonics over thousands to millions of years. Human societies depend on these reservoirs for both water supply and disposal of wastewater (e.g., water co-produced through enhanced recovery of hydrocarbons). Earth science has a particularly critical role in advancing fundamental knowledge of the water cycle and how it integrates with other physical, biological, and chemical processes in the Earth system (NRC, 2012; NASEM, 2018).

Impacts of climate change on the water cycle and the associated ramifications for civilization motivate much of contemporary hydrology. Of particular interest are the ways in which climate change will affect the nature and frequency of extreme events like droughts, floods, and fires, and the concomitant impacts on human populations. Increased availability of open-source models and computing resources is enhancing applications at larger spatiotemporal scales (Wood et al., 2011; Bierkens et al., 2015). Specifically, the coming decade will see significant advances in integrated and more realistic modeling of hydrologic systems from aquifer to atmosphere (Fan et al., 2019). Because groundwater movement is an integral part of the water cycle, water fluxes across the land surface and between the shallow subsurface soils and deeper aquifers need better quantification. At the same time, there is a significant drive toward improved integration of hydrologic and reactive transport models for biogeochemical applications at watershed or larger scales (Dwivedi et al., 2018; Li, 2019). Methodological advances in data fusion and assimilation, including machine learning, will be key in jointly leveraging models and data.

There is also growing recognition of the inseparability of the water cycle and human activity (Sivapalan et al., 2014; Sarojini et al., 2016). The dynamic integration of hydrologic and human systems is therefore increasingly important in hydrologic modeling (NRC, 2012; Farhadi et al., 2016). Substantial water will be required for future food and energy production, but it is unclear whether water availability can meet the demand (D'Odorico et al., 2018). Key gaps in modeling capabilities need to be addressed for both scientific and societal benefit (Givens et al., 2018; Lesmes et al., 2019).

Few geographic frontiers challenge the hydrologic science enterprise like the rapidly changing high-latitude and high-altitude regions. Here there are compelling scientific and societal drivers for understanding the response of the water cycle to Earth's diminishing cryosphere (Williams et al., 2012; IPCC, 2019). Cryosphere loss, for example from melting glaciers, may increase water storage in other terrestrial reservoirs (Liljedahl et al., 2017; Somers et al., 2019). Thawing permafrost invigorates surface water and groundwater exchange (Walvoord and Kurylyk, 2016; Evans and Ge, 2017), but the long-term impact of cryosphere changes on the water cycle has only begun to be explored (see Figure 2-14). Little is known about how hydrologic properties of permafrost vary spatially and temporally and how water and biogeochemical fluxes change in thawing permafrost regions.

New technologies for measuring hydrologic storages and fluxes have proliferated during the past decade. New geophysical methods reveal the influence of precipitation and transpiration on subsurface water flow (Voytek et al., 2019). Geodetic measurements of snow water and soil moisture content are increasingly more finely resolved (Larson et al., 2008; McCreight et al., 2014; Koch et al., 2019). Advances in the technology of sensors, microcontrollers, and wireless communication will continue to drive innovation in observing hydrologic systems. Observations from space will be increasingly vital for quantifying volumetric and temporal changes of different parts of the water cycle. Improved remote characterization of subsurface hydrologic dynamics has aided the study of hydrologic systems at expanded spatial and depth scales. Insights

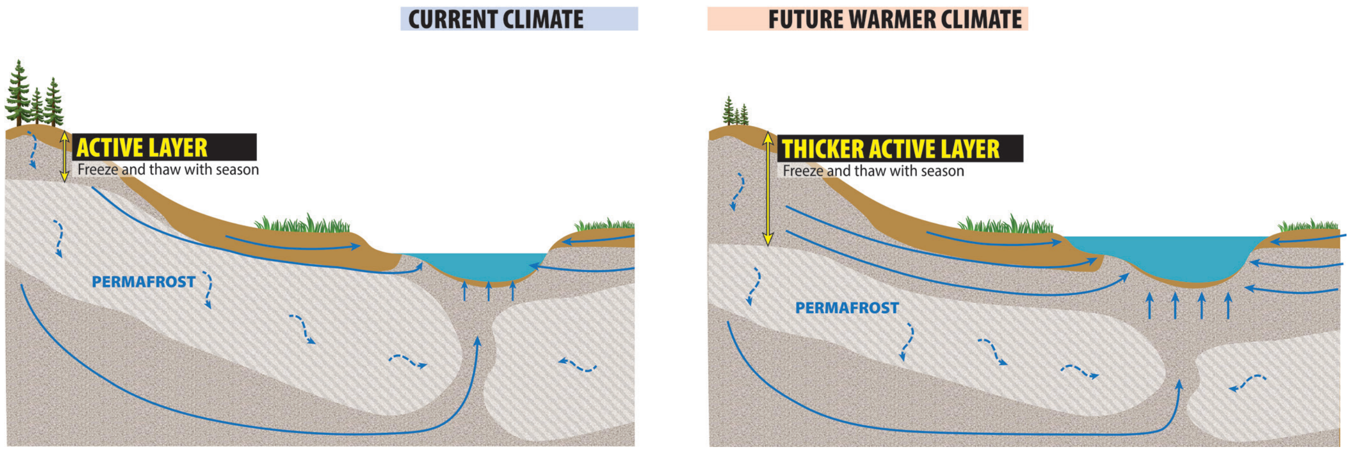

FIGURE 2-14 Schematic illustration of potential changes in the water cycle in permafrost regions under current (left) and future warmer climate scenarios (right). The seasonally freeze-thaw active layer below the land surface is expected to increase its thickness in response to a warmer climate. Thicker active layers enable transmitting more water from upland to streams and lakes downstream. When water sources from glaciers or snowpack in the upland dwindle, there will be insufficient water to sustain the water flow and the upland could become drier. SOURCE: Modified from USGS.

from NASA's GRACE satellite have helped the community identify discrepancies between model-derived and space-based observations of continental water storage trends, potentially pointing to shortcomings in model process representation and climate forcings (Scanlon et al., 2018). In the previous decade, various space agencies launched satellites focused on precipitation (GPM), soil moisture (SMAP), and groundwater (GRACE-FO). Forthcoming and potential satellites will capture surface water (SWOT), groundwater (GRACE2), and snow (Deeb et al., 2017).

Because of its complexity and importance, the water cycle is an area where partnerships can support NSF's mission to advance the fundamental state of knowledge. Of particular interest are decadal-scale processes integrating climate, shallow oceans, global water resources, and people. New observational data are being produced at an extraordinary pace by NASA's Earth-observing satellites, measuring changes in glaciers and snowpacks, land use and land cover, sea level, and soil moisture. EAR and NASA could consider a collaborative research initiative, with the possible inclusion of mission agencies focused on applications and societal needs, to quantify changes in freshwater storage and to understand the dynamics of water fluxes through the cryosphere and across the land surface. Additional natural partners of EAR are federal agencies such as DOE and USGS, as well as other directorates and programs within NSF that have interests in water cycle–related processes (e.g., SBE, Directorate for Engineering [ENG], Division of Environmental Biology in the Directorate for Biological Sciences, GEO's Office of Polar Programs, and the Intelligent Systems and other divisions within the NSF Directorate for Computer and Information Science and Engineering).

10. How do biogeochemical cycles evolve?

To date, the Earth is the only known planet with an active biosphere. This biosphere has evolved and interacted with the chemical makeup of Earth's surface for billions of years. Biological processes that cycle carbon, oxygen, nitrogen, sulfur, and other elements and influence the global chemistry and mineral diversity of Earth's surface include photosynthesis, microbially catalyzed weathering and mineral formation, and the production of biogenic greenhouse gases such as carbon dioxide and methane (see Figure 2-15). The next decade will bring advances in the mechanistic understanding of biological contributions to these biogeochemical cycles and the history of the Earth as a habitable planet. These advances will include the ability to identify genes, metabolic products, organismal groups, and interactions involved in different cycles (NRC, 2012); to track the evolution of relevant pathways using molecular methods; to quantify the influence of biology on the current climate; and to recognize the role of biological processes in the formation and weathering of rocks and minerals, the cycling of carbon, and the composition of the atmosphere (e.g., NRC, 2001; Derry et al., 2005; Azam and Malfatti, 2007; Quirk et al., 2012; Lyons et al., 2014).

Since the beginning of geobiology, reconstructions of the biogeochemical record have been grounded in environmental chemistry, mineralogy, geochronology, microbiology, stratigraphy, and sedimentology (e.g., Baas Becking, 1934; Cloud, 1965, 1968; see Figure 2-16). Major conceptual and methodological developments in the past two decades have mapped geological and geochemical processes onto the astounding and previously unappreciated microbial and metabolic diversity and activity in oceans, sediments, soils, and extreme environments (e.g., Karner et al., 2001; NRC, 2001, 2012; Nesme et al., 2016). These developments include data science, analysis of assemblages of genes and proteins of entire species and ecological communities, molecular microbiology, geochronology, geochemistry, and molecular clocks and molecular phylogenetics more broadly.

Because life can colonize a wide range of environments, the study of any aspect of Earth's surface chemistry, including critical elements, processes in the critical zone, the water cycle, and the sedimentary record, needs to account for microbial metabolisms that can produce or consume minerals (Hazen et al., 2019), greenhouse gases, and organic molecules. Currently, large uncertainties related to the nature and magnitude of biological feedbacks limit predictive capabilities of climate and geochemical models (NRC, 2012). Progress in cultivation and in molecular and genomic analysis has begun to reveal the metabolism and biogeochemical roles of environmentally common microbial groups (e.g., Boetius et al., 2000; Johnson et al., 2006; Sim et al., 2011). Challenges today and in the next decade will include relating the diversity of microbial communities,

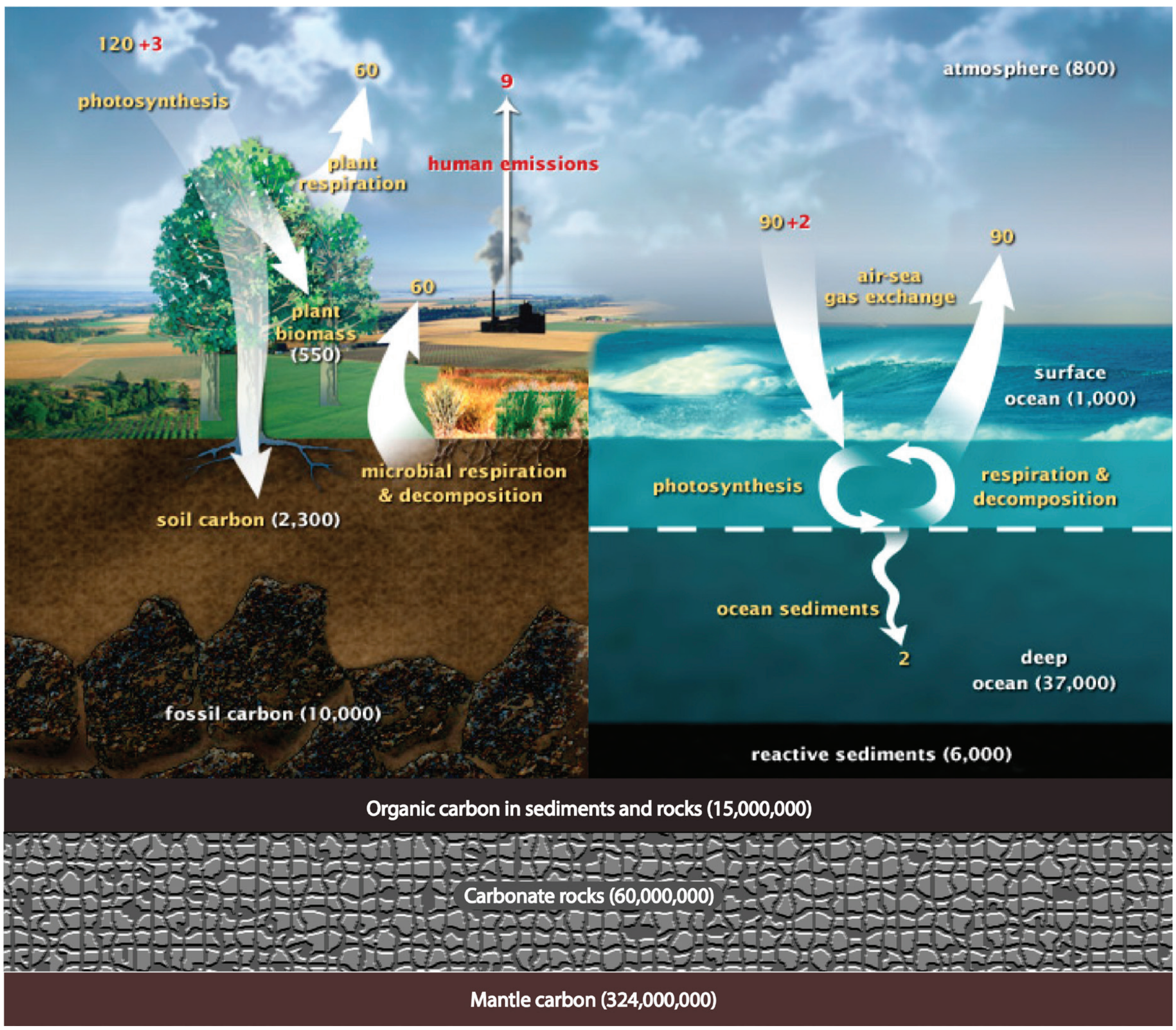

FIGURE 2-15 Example of a biogeochemical cycle (the carbon cycle). Reservoir sizes (white) in gigatons (Gt, 1012 kg); fluxes (yellow and red) in Gt per year. Fluxes from and to the largest reservoirs (sedimentary rocks, organic carbon in rocks, and sediments and the mantle carbon) are two to three orders of magnitude smaller than the fluxes that link the biosphere and surface ocean to the atmosphere. SOURCE: Modified from NASA.

genes, and enzymes, rather than species alone, to the community function, resilience, and geochemical rates of processes.

The convergence of geobiology with materials science, geochemistry, and environmental science is key to commercial applications (e.g., Ehrlich, 1997), bioremediation efforts, the formation of economically important minerals, the environmental stability of toxins or pollutants, and the production of antimicrobial compounds and nanomaterials (NRC, 2012; Boyd et al., 2019). A particularly pressing question concerns the potential impact of biota in all Earth surface habitats on global climate change. On short time scales, the question of geohealth is exemplified by the need to predict responses of modern microbial systems that emit greenhouse gases such as methane or nitrous oxide to human-induced changes such as the thawing of permafrost or agricultural practices (e.g., Richardson et al., 2009; Thomson et al., 2012; Drake et al., 2015; Johnston et al., 2019) and understand the transmission of pathogens in and across natural systems. Future agricultural and industrial developments will also need to consider the microbial cycling of nutrients in soils and marine sediments, transformations of economically important minerals, and the ability to concentrate critical elements.

Evidence of different redox, climatic, chemical, and biological regimes in Earth's sedimentary rocks invites questions about the drivers and feedbacks that influence the long-term evolution of Earth's habitability. Numerous major biogeochemical and climate transitions occurred over the past 4 billion years, such as the Great Oxidation Event, the Paleoproterozoic and Neoproterozoic Snowball Earth glaciations, ocean anoxic events and, possibly, metabolic innovations that led to mass extinctions (e.g., Luo et al., 2016; Gumsley et al., 2017; Rothman, 2019). The greatest of these transitions, the Great Oxidation Event, was predicated on the evolution of oxygenic photosynthesis (see Figure 2-16), a metabolism that produced molecular oxygen, stimulated subsequent biogeochemical evolution, and ushered complex life, including humans. Advances in isotope geochemistry tell us that Earth's atmosphere became oxygenated around 2.4 to 2.3 billion years ago (Farquhar et al., 2000), but when exactly this metabolism evolved and how and why Earth's surface and atmosphere became oxidized remains unresolved. The ever-increasing knowledge of gene functions and the availability of sequenced genomes, coupled with the microbial fossil record, contribute to the growing field of molecular clock analyses. These analyses are beginning to constrain the events in the early evolution of primary producers and other organisms, the delay between the evolution of oxygenic photosynthesis and the oxygenation of Earth's atmosphere, and the subsequent interactions among the cycles of oxygen, carbon, sulfur, and other elements (e.g., Sánchez-Baracaldo et al., 2017; Gibson et al., 2018; Magnabosco et al., 2018; Wolfe and Fournier, 2018).

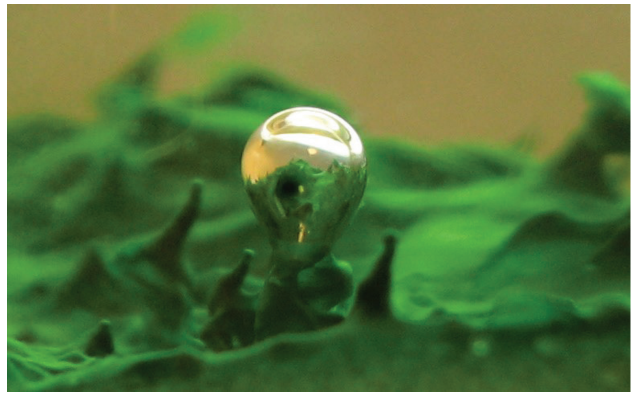

FIGURE 2-16 Oxygen bubble produced by cyanobacterial photosynthesis in a laboratory-grown microbial mat. The increase in Earth's atmospheric oxygen levels, documented with diverse data from the geological record, was triggered by the evolution of oxygenic photosynthesis in cyanobacteria. Field of view approximately 5 cm. SOURCE: Image courtesy of Tanja Bosak.

Research in geobiology requires well-sampled, resolved, and interpreted genomic and fossil records, robust and mechanistically understood proxies for microbial metabolisms and environmental conditions, and facilities for the collection and storage of biological samples from sediment cores. The analyses of processes at interfaces and at scales of microbial cells or communities and improved constraints on the rates of processes will benefit from the continuing development of high-precision geochronology (Harrison et al., 2015) and tools for high-precision and high-accuracy analysis of small samples, for example synchrotron X-ray spectroscopy, laser-ablation inductively coupled plasma mass spectrometry (LA-ICPMS), secondary ion mass spectrometry (SIMS), and NanoSIMS, as well as stable isotope and organic geochemistry (e.g., Orphan et al., 2001; Bobrovskiy et al., 2018). Some of these tools, like synchrotron X-ray spectroscopy, are available through partnerships between EAR and DOE; other tools relevant to materials science can be developed within EAR or through partnerships with ENG. Progress in characterizing modern biogeochemical cycles and reconstructing Earth's biogeochemical evolution will also require cyberinfrastructure that provides access to large and complex databases, and the tools by which to visualize and quantitatively analyze this information (in partnerships with National Institutes of Health's National Center for Biotechnology Information and DOE's Joint Genome Institute). All this progress will need the continuing ability to train a new generation of researchers who can generate, analyze, and synthesize information from many traditionally separate disciplines, while building and retaining strong disciplinary expertise.

11. How do geological processes influence biodiversity?

The diversity of life on the Earth is one of the most conspicuous and fundamental, but at the same time poorly understood, features of our planet. Earth scientists strive to deduce how this multifaceted property of the biosphere, which can be quantified as the number of species and their variation in function, form, metabolism, and physiology (see Figure 2-17), evolves over geological time (Bottjer and Erwin, 2010; Conservation Paleobiology Workshop, 2012). Biodiversity at any point in time and space reflects the net balance between the formation and loss of species and their biological traits through speciation, extinction, and change within species. The study of biodiversity is therefore inseparable from the study of evolutionary rates, as well as the timing and rate of geological processes that shape the environments in which evolution occurs.

The relationship between biodiversity and geological processes—which include large-scale human activities—is considered to be reciprocal (NRC, 2001, 2012), and understanding how and why diversity varies over time, environment, and geography is central to many Earth–life interactions and feedbacks. For example, novel metabolic pathways and other evolutionary innovations are hypothesized to have induced major changes in atmospheric and ocean chemistry, climate, and the nature of depositional systems and the sedimentary record (Boyle et al., 2014; Santos et al., 2016); the loss of diversity associated with major extinction events may perturb the basic ecological processes that influence geochemical cycles (D'Hondt, 2005); in ways that are not fully understood, tectonic processes and temporal changes in topography and bathymetry may affect the number and types of species across landscapes and within the oceans (Badgley, 2010; Zaffos et al., 2017); and there is evidence that the nature of terrestrial life in turn influences landscape stability and erosion (Davies and Gibling, 2010), thus influencing feedbacks between climate and tectonics. Some observational and experimental research also suggests that human-induced biodiversity loss may decrease the stability and productivity of ecosystems on which society depends for natural resources (Cardinale et al., 2012; Isbell et al., 2017).

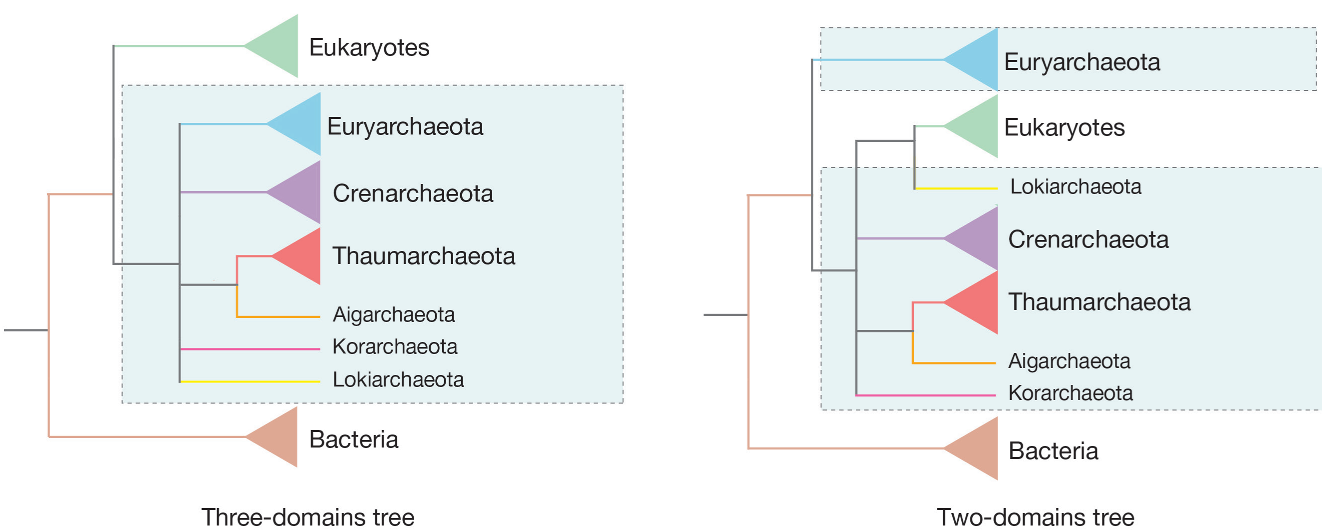

FIGURE 2-17 Two hypotheses regarding evolutionary relationships among the major groups of living organisms: the Eukaryota (plants, animals, fungi, and relatives) and the prokaryotic branches (archaeal groups [enclosed in boxes] and Bacteria). In the three-domain scheme (left), eukaryotes are distinct from Bacteria and Archaea. In the two-domain scheme (right), the eukaryotes are nested within a larger clade that includes the archaeal lineages. By either hypothesis of relationships, eukaryotes are quite diverse in their anatomy, whereas most of Earth's metabolic diversity lies within the prokaryotic groups. SOURCE: Modified from Williams et al., 2013.

Nearly all species that have ever lived are now extinct. Today's biosphere, as documented by centuries of biological surveys and reconstructions of evolutionary relationships, provides a broad and fairly representative sample of the small number of tips on the Tree of Life that are still living. At the same time, the stratigraphic record provides the deep-time perspective needed to interpret how life has been shaped by persistent geological and environmental processes like tectonics or climate variation (Johnson et al., 1996; Cohen et al., 2007; Crampton et al., 2018); rare but massive events such as the eruption of large igneous provinces (Clapham and Renne, 2019) and extraterrestrial impacts (Schaller and Fung, 2018; Gulick et al., 2019) and their associated geochemical changes; or singular evolutionary events such as the advent of oxygenic photosynthesis (Holland, 2002).

Recent developments make this an especially promising time to advance the study of biodiversity. Biologists and Earth scientists have recognized the need for a melding of data and methods from both fields to understand present-day biodiversity, its history, and prospects for the future, particularly in light of ongoing environmental change. For example, our view of the evolution of whales has recently been significantly advanced by inferring evolutionary relationships based on fossil and living species and by relating evolutionary trends to oceanographic changes (see Figure 2-18). At the time scales of macroevolution, mathematical models of diversification now allow explicit incorporation of extrinsic factors (e.g., geochemistry) and intrinsic traits of species (e.g., physiology) that combine to influence evolutionary rates and diversity, providing the capacity to rigorously test alternative hypotheses (Slater

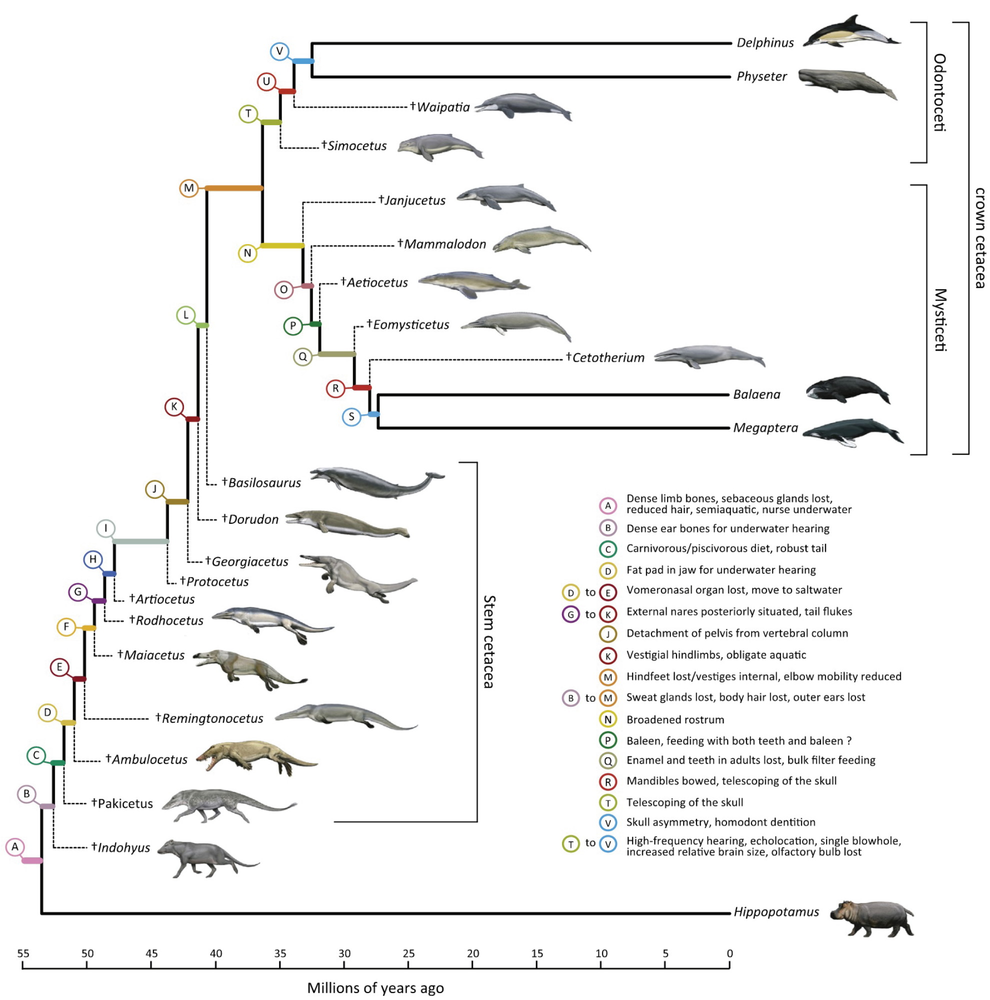

FIGURE 2-18 Evolutionary tree of whales and their relatives. Circled letters indicate specific evolutionary changes, for example, the freeing of the pelvis from the vertebral column (J). Combined analysis of fossil and living species has shown that whales began evolving extremely large body size during the Pliocene epoch, coincident with oceanographic changes that increased primary production in the plankton (Slater et al., 2017). SOURCE: McGowen et al., 2014.

et al., 2012). At shorter time scales, ecological models, which seek to explain species' spatial distributions as a function of observable environmental variables, are now being tested with Pleistocene data to establish the potential and limitations of such models to predict ecosystem responses to future climate change (Maguire et al., 2015). The rapid growth of community curated data platforms is empowering the macro-scale analytics of millions of individual biodiversity observations and their integration with other large data resources in biodiversity and paleoclimatology (Farley et al., 2018). In addition, data mining of both geological and biological systems has grown to provide an empirical foundation for evolutionary and ecological models and analyses (Peters et al., 2014), and efforts are under way to make diverse geological and biological databases interoperable.[4] On the experimental end, continued advances in the understanding of organismal physiology and the development of geochronology and environmental proxies, especially for crucial aspects of atmospheric chemistry (e.g., carbon dioxide concentration) and oceanic chemistry (e.g., redox state) enable tests of hypotheses regarding connections between environmental and biotic change.

Future progress in understanding the history of biodiversity will rest on continued development of these and other aspects of data acquisition (including field sampling of outcrops and cores), an improved geological time scale (Harrison et al., 2015), mathematical modeling, and cyberinfrastructure, as well as on the cultivation of a quantitatively and geologically trained workforce. In addition, EAR has strong potential to extend or initiate partnerships with NSF's Division of Environmental Biology (Systematics and Biodiversity, Dimensions of Biodiversity), OCE, NASA's Astrobiology Program, and, in the area of cyberinfrastructure, NSF's Directorate for Computer and Information Science and Engineering and the Defense Advanced Research Projects Agency (Automated Scientific Knowledge Extraction).

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

Geohazards (earthquakes, tsunamis, volcanic eruptions, landslides, and flooding) caused between $6.5 trillion and $14 trillion in damage and approximately 8 million fatalities between 1900 and 2015 (Daniell et al., 2016). The severity of impacts is increasing rapidly as risk mitigation fails to keep up with increasing exposure (Cutter et al., 2015). Improved collaboration with many other disciplines, including engineering, data science, disaster psychology, health sciences, land-use planning, and government policy is required to reduce risk; however, a predictive and quantitative understanding of geohazards by Earth scientists is foundational to all such efforts.

Recent analyses illustrate ongoing fundamental and consequential aspects of geohazards that need to be better understood through Earth science research. For example, the near-trench region of subduction zones was previously thought to inhibit rapid slip, yet in the 2011 M9 Tohoku-oki earthquake this area slipped rapidly, massively, and with deadly effect. High slip near the trench was responsible for the unexpectedly large tsunami that caused nearly all of the fatalities (Saito et al., 2011). This occurred even though Japan is the most tsunami-aware and tsunami-prepared country on the Earth. While it is difficult to predict research outcomes, the committee took the optimistic view that some of these areas are poised for breakthroughs in the next decade or two.

The recently observed hiatus in surface-rupturing earthquakes in California is not an expected outcome according to current earthquake forecast models (Biasi and Scharer, 2019), suggesting there are fundamental aspects of earthquakes that are not understood. It is unclear whether or not a flurry of large earthquakes should be anticipated in the near future. This uncertainty exists even though the San Andreas is the most thoroughly studied fault system on the Earth. The 2018 Kīlauea eruption was documented in unprecedented detail (Neal et al., 2019), yet important aspects of it were unanticipated, including the abrupt 20-km shift in the focus of activity; the role of older magma stored at very shallow depths; the dramatic collapse of the summit; and the abrupt end of the eruption. An inability to predict the exact form of behavior persists even though this is the most intensively studied volcano on the Earth. Profound uncertainty marks even these three exceptionally well-studied systems. Understanding hazards in less well-studied areas is yet more challenging. These examples indicate that fundamental science questions remain to be answered regarding natural hazards.

A goal in geohazards research is to develop warning systems to save lives and property. Landslides provide an informative example. They are local failures controlled by uncertain subsurface conditions; they are threshold

[4] See http://earthlifeconsortium.org (accessed January 25, 2020).

phenomena, which makes prediction highly sensitive to uncertainty in those conditions; they may initiate as a mass slump, then mobilize as a debris flow that travels kilometers and becomes highly destructive over a broad area; and debris flows may originate without a landslide, yet develop into large, boulder-charged flows (see Figure 2-19). To predict the onset of rainfall-induced landslides, current practice relies on empirical relationships involving rainfall intensity and duration (e.g., Chen et al., 2015). Satellite monitoring and rainfall prediction are used to estimate the location and timing of elevated risk (Kirschbaum and Stanley, 2018). More data on storm-driven landslides and higher-resolution topography would improve models and warning systems.

Geohazards present varied challenges. Global atmospheric cooling caused by aerosols from explosive volcanoes like Mt. Pinatubo, air travel disruptions caused by the Eyjafjallajökull eruption in Iceland, and ocean-wide tsunamis have global impact. At the other extreme, intensely localized destruction from natural disasters can also have devastating consequences. For example, expected annualized losses due to U.S. earthquakes are $6.1 billion per year, which is severe but manageable given the size of the U.S. economy. However, real losses are not annualized; rather, they occur in single powerful events that strike communities suddenly and without warning, causing concentrated damage from which full recovery may be impossible (Jaiswal et al., 2017).

Industrial activities such as fluid injection into the subsurface (in oil and gas production or enhanced geothermal systems) have induced earthquakes in the United States and elsewhere (Ellsworth, 2013; Grigoli et al., 2017). Earthquakes triggered by human activity are a concern, but also provide an opportunity to address major unanswered questions regarding possible earthquake precursors, and the controls on rupture nucleation, propagation, and arrest (e.g., Guglielmi et al., 2015; Savage et al., 2017; Huntington and Klepeis, 2018). A large-scale fluid injection and drilling experiment, such as the proposed Scientific Exploration of Induced Seismicity and Stress (SEISMS) project, could provide direct borehole measurements of key parameters such as stress, pore fluid pressure, and slip on faults. This may be an area of possible collaboration between EAR and DOE.

Rapid urbanization in susceptible areas and increasingly connected and fragile urban infrastructure are magnifying the risk to human life and property. As an example, losses from Hurricane Katrina in 2005 have been estimated between $160 billion and $200 billion (King, 2005; NOAA, 2018), while Hurricane Harvey in 2017 caused losses estimated at $125 billion (Smith, 2018). Flooding is compounded in many vulnerable areas due to natural and human-induced land subsidence, removal of natural ground cover, and dams and levees that restrict natural re-sedimentation. Climate change will increase the frequency and consequences of such events as the hydrologic cycle is modified and rainfall and hurricane events become more extreme. The accelerating financial losses from these events point to the urgent need to improve hazards forecasting and mitigation strategies.

FIGURE 2-19 Debris flows smashed and flooded 130 houses and killed 23 people in Montecito, California, in January 2018. The source area in the Santa Ynez Mountains had burned 3 weeks earlier, and up to 75 mm of water fell in an intense 15-minute rainfall. Runoff from the barren slopes entrained mud- and ash-enriched soils, producing mudflows in canyons where they swept up boulders and sent destructive debris flows into Montecito (Matinpour et al., 2019). This event emphasizes the need for basic research on the origin of debris flows and the development of warning systems that anticipate their travel paths. SOURCE: USGS.

While other agencies have operational responsibility for forecasting and communicating warnings for hazards, NSF plays a crucial role in supporting fundamental research that provides a foundation for current and future hazard forecasting. Improved forecasts require better quantification of the probability of hazards, capturing the full range of behavior, including extreme events whose frequency and magnitude may be evident only from the geologic record. Forecasting entails understanding the fundamental processes governing the complex interacting geosystems that cause geohazards. New technologies are available to observe and constrain processes at much higher temporal and spatial resolution than previously. For example, unmanned aerial system technology during the 2018 Kīlauea eruption demonstrated transformative capabilities, providing an example for future real-time, high-resolution airborne observations that can be transmitted directly to an Emergency Operations Center as disasters unfold. Such capabilities could enable timely forecasts of sudden changes in hazards. For landslides it may be possible to predict their transition from steady creep to catastrophic failure. Improved topographic resolution, prediction of local rainfall intensities, and landslide modeling can lead to narrowing the times when the hazard is considered elevated, thus minimizing the time needed for community response. For earthquakes too, slow deformation transients and patterns of accumulating strain or seismicity may provide clues to the timing of their occurrence. Computer simulations of geohazards increasingly approximate their full complexity. They suggest, for example, why exceptionally large tsunamis might be anticipated in certain subduction zones (Kozdon and Dunham, 2013). The wealth of information provided by observations, experiments, and simulations promises new insights—particularly into how small-scale processes can be represented in large-scale models. New approaches, such as machine learning, will be needed to take full advantage of these opportunities (Bergen et al., 2019).

Due to the unpredictable characteristics of many geohazards, permanent, observatory-style data collection will always play an important role in recording their behavior. In cases such as volcanoes, where eruptive precursors are frequent, and earthquakes, where the duration of hazards may persist after their initial onset, supplementary densification of instrumentation has an essential role. Progress in understanding geohazards has been, and will continue to be, both data and model driven. For data-driven approaches, new sensor technology and cyberinfrastructure in the form of scalable algorithms to extract meaning from large data volumes will be increasingly important. For model-driven approaches, high-performance computing that allows for increasingly realistic simulations will be required. Continued advancements in natural hazards research will depend on continuing collaborations with other agencies such as USGS, NASA, and DOE.

RESEARCH TO OUTREACH

Scientific advances do not automatically translate to the betterment of society unless they can be effectively communicated to the public. To this end, translating the research conducted by EAR-funded researchers into education and outreach is intrinsically linked to the ultimate impact of Earth science research. In 2018, more than 50% of Americans found their scientific information from the Internet, and only 40% had high confidence in scientific researchers (Besley and Muhlberger, 2018). It is clear that the Earth science community needs to continue to engage with the public to improve fundamental scientific literacy. In addition to contributing to broader inclusion and scientific literacy, outreach can spark reciprocal benefits wherein nonprofessionals contribute essential data and analysis to the scientific community. Some Earth science disciplines, such as paleontology, have a long and rich history of important contributions from avocational practitioners, and others, like seismology, are increasingly exploiting the rapid evolution of sensing technology and telecommunications, such as smart phones.

CONNECTING THE SCIENCE QUESTIONS TO INFRASTRUCTURE

The science priority questions exemplify the diverse and integrative array of scientific disciplines and methodological and analytical approaches spanned by the Earth sciences. Investment in instrument-based, cyber, and human infrastructure will be key to achieving the science priority questions, as well as other Earth science priorities, in the next decade. As outlined in the preceding narrative, critical instrument-based infrastructure includes experimental and analytical capabilities and field applications that will facilitate characterization of material properties under all relevant conditions throughout Earth's history. Improved geochronology will add the critical time component to understanding changes in the geology and biology of the planet through time. Acquisition and archiving of new and existing data will require continued development of cyberinfrastructure and data management approaches. The promise and hope of the next decade is that new computational developments will allow for the coupled modeling of physical processes at vastly different temporal and spatial scales, thereby driving a deep integration of data and models that can inform and guide each other. Fine-scale, rapid observations of dynamic processes and physical process modeling have paradigm-shifting potential to improve our understanding of a changing Earth. Such advances hinge on investments in human infrastructure, including highly skilled technical staff and a data-science and computer-science savvy workforce. Diversity within this workforce and the broader Earth science community is a fundamental feature of scientific excellence and integrity. Enhancing diversity and inclusion in Earth science has great potential both to drive the innovation needed to address the science priority questions, and to ensure that scientific discovery benefits all in society. These concepts will be discussed in Chapter 3.

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3
Infrastructure and Facilities

Earth scientists use instruments and facilities to collect data to observe the planet, relying on people's innovation and creativity to integrate this information and create leaps in fundamental understanding. Classic examples of this synthesis include the determination of the age and magnetic polarity of young basalts (Cox et al., 1963; McDougall and Tarling, 1964), which led to the emergence of plate tectonic theory, or the discovery of iridium-rich layers in sediments, which are now known as tracers of major extraterrestrial impacts (Alvarez et al., 1980) that in turn can drive evolutionary change/turnover. Today, the pace of technological development has never been faster, with an urgency to better understand Earth's systems on a growing range of spatial and temporal scales. Observing solid Earth deformation or surficial landscape changes, for example, will occur not at a single spatial or temporal scale, but rather as a continuum in both space and time from nano-scale to global distances, and from nearly instantaneous to billion-year time scales.

While data analysis continually moves toward automation, machine learning, and artificial intelligence, human infrastructure remains critical to interpreting and synthesizing data and designing and operating innovative facilities. Observations of the Earth and its constituent materials, and understanding of their governing physical and chemical processes, will rely more than ever on integrating emerging technology in instrument-based infrastructure and cyberinfrastructure with significant advancements in human infrastructure.

The committee's second task was to identify the infrastructure needed to advance the science priority questions, discuss research infrastructure currently supported by the National Science Foundation's (NSF's) Division of Earth Sciences (EAR) and other relevant areas of NSF, and analyze gaps between the two (see Chapter 1 for the complete Statement of Task). 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. Support for this infrastructure is built into nearly every EAR activity, from awards to individual investigators to direct support provided to operate national and international networks. The committee's second task is addressed as follows:

- **Task 2A** (identification of the infrastructure needed to advance the high-priority Earth science research questions): Chapter 2 briefly highlights infrastructure (e.g., instruments, cyberinfrastructure, and/or human expertise) that will be needed to address each of the priority science questions in support of Task 2A. While some infrastructure already exists and, in many cases, is supported by NSF, for many questions it is the development of new infrastructure that will allow scientists to make significant progress over the next decade. This chapter (Chapter 3) then maps existing EAR-supported facilities onto the priority science questions (in Table 3-2). This exercise demonstrates the essential connections among existing facilities and the questions of the future and identifies which facilities provide relevant information for the science priorities.

- **Task 2B** (a discussion of the current inventory of EAR and relevant NSF research infrastructure): This chapter begins with a description of all available infrastructure. The committee discusses infrastructure that is provided at various levels within NSF (e.g., within EAR, at the Directorate for Geosciences [GEO] level, and in other directorates) and from other federal agencies.
- **Task 2C** (an analysis of infrastructure capability gaps): The last section in this chapter is a set of recommendations regarding the infrastructure needed to advance EAR-supported Earth science in the next decade, based on the information gathered in support of Tasks 2A and 2B.

TYPES OF INFRASTRUCTURE DISCUSSED

Instrument-Based Infrastructure

Support for the development, acquisition, and deployment of larger-scale instruments is provided by the Instrumentation and Facilities and Major Research Instrumentation programs within EAR. Most proposals to these programs request support for acquisition of instruments that are used by numerous researchers for multiple research projects. Awards typically support acquisition of mass spectrometers, scanning electron microscopes, microprobes, X-ray powder diffraction/X-ray fluorescence instruments, GPS sensors, laser scanning devices, seismometers, magnetometers, organic geochemistry extractors and analyzers, and hydraulic sensors. EAR also supports large facilities that provide the infrastructure for entire disciplines in Earth science research (e.g., Seismological Facilities for the Advancement of Geoscience [SAGE], Geodetic Facility for the Advancement of Geoscience [GAGE], Consortium for Materials Properties Research in Earth Sciences [COMPRES], and GeoSoilEnviroCARS Synchrotron Radiation Beamlines at the Advanced Photon Source [GSECARS]).

Cyberinfrastructure

Cyberinfrastructure consists of the software tools that are needed to gather, analyze, integrate, model, and archive the information gathered from the instruments described above, as well as the contextual information from associated metadata. It also describes high-performance computation, independent of any data gathered by instruments. Development and maintenance of tools and computational approaches has been supported primarily by the Geoinformatics and Instrumentation and Facilities programs within EAR, the EarthCube Program (a joint program of GEO and the Division of Advanced Cyberinfrastructure), and the NSF-wide Cyberinfrastructure for Sustained Scientific Innovation Program. Awards have been provided to support development and maintenance of information systems that serve the broader Earth science community as well as specific disciplines.

Human Infrastructure

Essential for the effective use of hardware and software are the people who design, build, maintain, operate, and continually improve these tools. This technical expertise is supported in part by awards to individual investigators to conduct specific projects, with funding provided to faculty researchers, research scientists, post-doctoral scholars, technicians, and both graduate and undergraduate students. Most EAR-supported multi-user (community) facilities also provide training opportunities for researchers and students. This expertise is also supported more specifically in some cases by CAREER awards, post-doctoral scholar and graduate student support programs, laboratory technician funding from the Instrumentation and Facilities Program, and workshops funded by the GeoInformatics and EarthCube programs.

CURRENT INFRASTRUCTURE

The existing infrastructure used by EAR-supported researchers is provided at three levels, to individual investigators, by larger facilities supported by NSF or EAR, and by other federal agencies, including the U.S. Geological Survey (USGS), the National Aeronautics and Space Administration (NASA), and the U.S. Department of Energy (DOE). In response to Task 2B, the following sections describe the types of infrastructure provided at each of these different levels.

Infrastructure Provided to Individual Investigators

EAR commonly provides funding for individual investigators, or small teams of investigators, to acquire instruments, to build cyberinfrastructure, and/or to support people to provide technical assistance. Examination of recent awards from the Instrumentation and Facilities Program indicates that considerable funding is awarded to purchase or upgrade instruments, build databases or cyberinfrastructure, provide training opportunities (e.g., workshops), and support technical personnel. Infrastructure provided by individual investigators serves critical community needs for generating data (e.g., geochemical, geochronological, imaging, monitoring), training, and enabling technical advances and innovation. The committee chose not to further analyze infrastructure at the level of individual investigators or small laboratories, as instruments are widely dispersed in the research community, the conditions of individual instruments are not known, and it is not always known whether others in the community are using particular instruments.

Infrastructure Provided by Large Multi-User Facilities

EAR supports 30 large multi-user (community) facilities that provide infrastructure and expertise for the Earth science research community (see Appendix D for more detailed information). The larger facilities support researchers through a combination of instruments, cyberinfrastructure, and training, whereas most of the smaller facilities emphasize either instrument-based infrastructure or cyberinfrastructure. Following is a description of the four largest facilities supported by EAR: SAGE, GAGE, GSECARS, and COMPRES. Average annual budgets for these facilities are reported in Table 3-1 and Figure 3-1.

TABLE 3-1 Average Annual Budgets of the Instrument-Based Facilities Supported by EAR

EAR-Supported Facility	Acronym	Average Annual Budget
Geophysics		
Seismological Facilities for the Advancement of Geoscience	SAGE	$17,500,000
Geodetic Facility for the Advancement of Geoscience	GAGE	$11,400,000
Institute for Rock Magnetism	IRM	$387,000
International Seismological Centre	ISC	$250,000
Global Centroid-Moment-Tensor Project	CMT	$123,000
Materials Characterization		
GeoSoilEnviroCARS Synchrotron Radiation Beamlines at the Advanced Photon Source	GSECARS	$2,900,000
Consortium for Materials Properties Research in Earth Sciences	COMPRES	$2,400,000
Geochemistry/Geochronology		
Purdue Rare Isotope Measurement Laboratory	PRIME Lab	$708,000
University of California, Los Angeles, Ion Probe Lab	UCLA SIMS	$468,000
Arizona State University Ion Probe Lab	ASU SIMS	$402,000
Northeast National Ion Microprobe Facility	NENIMF	$339,000
University of Wisconsin SIMS Lab	Wisc SIMS	$330,000
Arizona LaserChron Center	ALC	$259,000
Support for Continental Scientific Drilling		
International Continental Scientific Drilling Program	ICDP	$1,000,000
Continental Scientific Drilling Coordination Office	CSDCO	$733,000
National Lacustrine Core Facility	LacCore	$358,000
Other Disciplines		
National Center for Airborne Laser Mapping	NCALM	$877,000
Center for Transformative Environmental Monitoring Programs	CTEMPS	$563,000
Virginia Tech National Center for Earth and Environmental Nanotechnology Infrastructure	NanoEarth	$500,000
University of Texas High-Resolution Computed X-Ray Tomography Facility	UTCT	$423,000

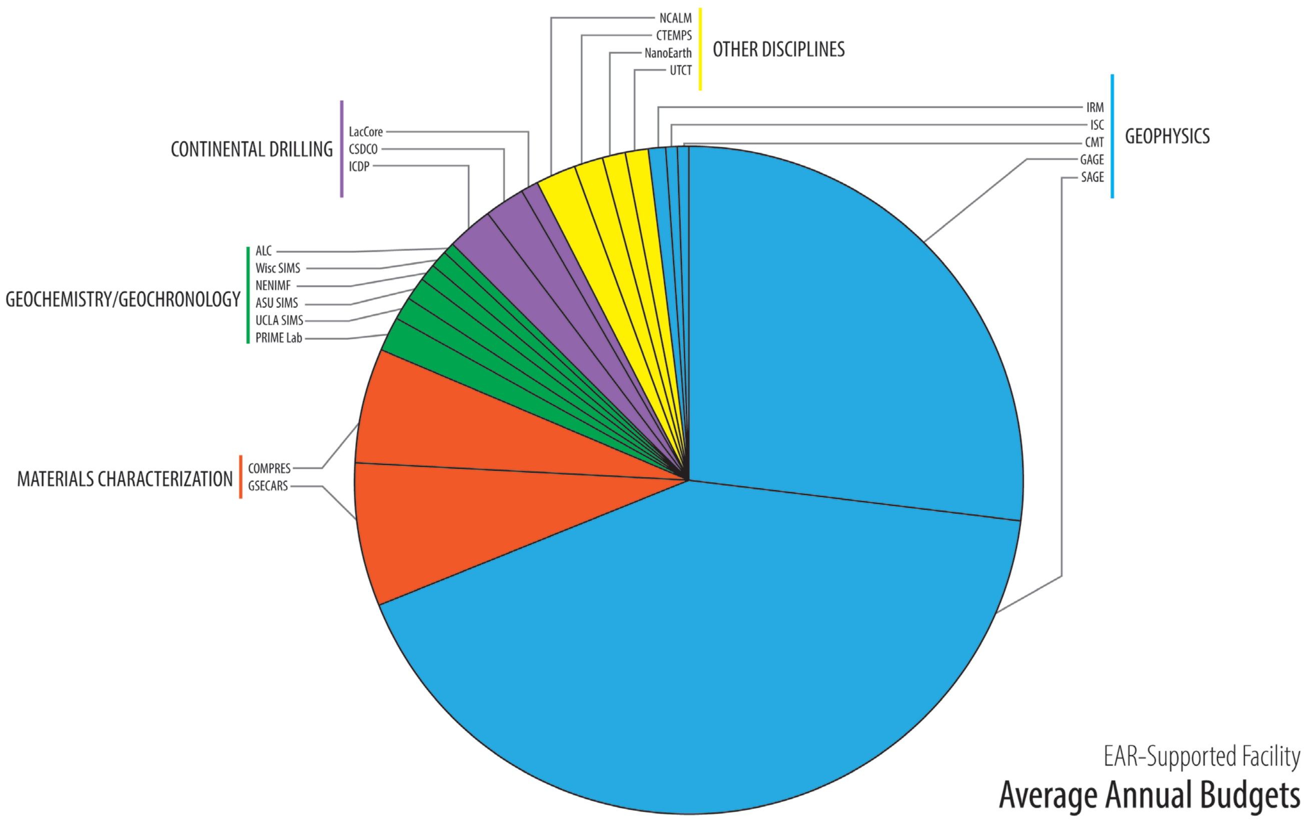

FIGURE 3-1 Pie chart showing the proportion of average annual budgets of EAR-supported, instrument-based facilities.
SOURCE: Data provided by NSF.

Seismological Facilities for the Advancement of Geoscience (SAGE)

SAGE provides instrumentation and data services in support of seismology, as well as education, workforce development, and community engagement activities. It is operated by the Incorporated Research Institutions for Seismology (IRIS) Consortium, which consists of more than 100 U.S. universities dedicated to operating science facilities to acquire, manage, and distribute seismological data. IRIS manages several instrument networks, including the Global Seismographic Network (an NSF partnership with USGS); Portable Array Seismic Studies of the Continental Lithosphere, a source of shared-use, portable seismic instruments; and a national magnetotelluric instrumentation facility. They also operate the IRIS Polar Support Facility (in coordination with UNAVCO Polar Facility), a Data Management Center, and an Education and Public Outreach program. In addition, IRIS operates the Transportable Array of EarthScope's USArray, currently deployed in Alaska. In addition to an average annual budget of \$17.5 million from EAR, SAGE receives ~\$900,000 per year from the Office of Polar Programs.

Geodetic Facility for the Advancement of Geoscience (GAGE)

GAGE supports instruments needed for geodetic research as well as education and workforce training. It is operated by UNAVCO, a nonprofit, university-governed consortium. Through GAGE, UNAVCO supports instruments, data, and engineering for terrestrial and satellite geodetic technologies; GPS networks for Earth, atmospheric, and polar science applications; and NASA's Global GNSS Network. Datasets and products provided or enabled by GAGE span the fields of seismology, hydrology, glaciology, geomorphology, geology, atmospheric sciences, data science, and others.

Scientific applications include the characterization of continental deformation and tectonic plate boundary processes; atmospheric, ice sheet, and glacier dynamics; and interactions among these components. GAGE receives an annual average budget of $11.4 million from EAR, with additional support of ~$840,000 per year from the Office of Polar Programs and ~$1 million per year from NASA.

NSF has been interested in understanding how management of seismological and geodetic facilities may change in the future and asked the committee to convene a workshop to discuss this topic (see Box 3-1).

BOX 3-1
WORKSHOP ON MANAGEMENT OF SEISMIC AND GEODETIC FACILITIES

The National Academies was asked by NSF to convene a workshop to explore possible management models for future seismologic and geodetic facility capabilities (see Box 1-1, Statement of Task). Currently, these facilities are run separately as SAGE and GAGE. Capabilities of these facilities are based on the scientific needs of their communities and have evolved as scientific needs and technological capabilities have evolved.

The workshop took place on May 13-14, 2019, and included a broad spectrum of participants. This included the workshop planning committee, members of the CORES committee, the presidents of UNAVCO and IRIS, representatives from the IRIS and UNAVCO boards of directors, members of the seismologic and geodetic user communities, management from other NSF-sponsored facilities, and representatives from international scientific facilities. EAR staff also attended, but primarily as observers.

Sessions on the first day reviewed current, emergent, and frontier capabilities of seismological and geodetic facilities; introduced management models for multiple scientific facilities; and focused on how different management models might be applied to seismological and geodetic facilities. The second day of the meeting explored the pros and cons of distributing seismological and geodetic capabilities across multiple facilities versus centralizing capabilities in a single facility. The workshop concluded with observations on the management of facility capabilities, particularly instrumentation, user support services, data management, education and outreach, and workforce development.

The workshop discussions were summarized in a rapporteur-authored proceedings released in September 2019 (NASEM, 2019). In October 2019, NSF announced that SAGE and GAGE would be merged and managed as a single facility after the current IRIS and UNAVCO awards end in 2023.[a] A new solicitation is likely to be released in Spring 2021.[b]

[a] See https://www.iris.edu/hq/news/story/nsf_issues_announcement_on_future_management_of_seismo_geodetic_facilities (accessed January 10, 2020).
[b] See https://www.nsf.gov/pubs/2020/nsf20037/nsf20037.jsp (accessed April 4, 2020).

GeoSoilEnviroCARS Synchrotron Radiation Beamlines at the Advanced Photon Source (GSECARS)

GSECARS is a national user facility for synchrotron radiation at the Advanced Photon Source (APS), Argonne National Laboratory. It supports research across several EAR core disciplinary programs. Since its inception in 1994, GSECARS has expanded to a current operating capacity of four simultaneous X-ray beamlines and hosts more than 500 visiting scientists per year. High-impact science projects are selected through an APS proposal process that awards DOE-supported beamtime, with instrumentation and personnel support managed by GSECARS and provided to users. Typically, EAR research awards cover travel and materials for visiting researchers. Techniques include high-pressure/high-temperature polycrystalline and single-crystal diffraction and spectroscopy using diamond anvil cells and the large-volume presses; deformation experiments; inelastic X-ray scattering; X-ray absorption fine structure spectroscopy; X-ray fluorescence microprobe analysis; and microtomography. Facilities at GSECARS support research in soil science, environmental geochemistry, porous media, cosmochemistry, rock and mineral physics, among others.

Consortium for Materials Properties Research in Earth Sciences (COMPRES)

COMPRES is a community-based consortium for high-pressure science and mineral physics that supports high-pressure facilities, including six different beamlines across all three U.S. synchrotrons (ALS, APS, and NSLS-II) and one university-housed facility that provides highly specialized, high-pressure assemblies to individual multi-anvil laboratories nationwide. COMPRES also seeds infrastructure development projects to foster new high-pressure technology, cyberinfrastructure, and education and outreach projects, as well as workshops on emerging methods. Since its inception in 2002, COMPRES has grown to include 70 active U.S. member institutions. Facilities supported by COMPRES harness new technology to determine the physical and mechanical properties of Earth materials under the wide range of conditions found on the Earth throughout geologic time. Experimental and computational studies of how rocks, minerals, and melts behave under wide-ranging conditions of pressure, temperature, stress, oxygen fugacity, etc., are applied to interpreting geophysical and geochemical observations of the crust, mantle and core, and feed more broadly into understanding Earth's dynamics and compositional heterogeneity. Although COMPRES is largely focused on high-pressure (mantle) mineral physics and rock deformation, crustal rock physics is a comparatively small part of COMPRES. New rock deformation initiatives, for example, those associated with SZ4D, have the potential to fill some of these gaps.

The COMPRES and GSECARS organizations have recently been asked to evaluate pros and cons of merging. See Box 3-2 for further discussion.

BOX 3-2
POTENTIAL COMPRES-GSECARS MERGER

GSECARS and COMPRES were asked by NSF to investigate the possibilities of merging the two organizations. They produced a white paper (Agee et al., 2020) that was reviewed by an ad hoc external review committee and disseminated to the community. The report outlined three merging scenarios—two "soft merger" scenarios (two institutions with formal coordination versus two institutions with common governance), as well as a fully unified scenario. Primary challenges to all three scenarios stem from core differences between the two facilities in terms of focus, management, and funding sources. COMPRES has a focus on high-pressure science and mineral physics, while GSECARS serves an interdisciplinary body of EAR scientists including soil science, environmental geochemistry, low-temperature geochemistry, biogeochemistry, and paleobiology, as well as high-pressure science. GSECARS is managed by the University of Chicago, while COMPRES is a community consortium supporting facilities at the three U.S. synchrotrons. While COMPRES is funded entirely by NSF, GSECARS also receives funding from NASA, DOE, and the University of Chicago Center for Advanced Radiation Sources.

Instrument-Based Infrastructure Provided by Smaller Multi-User Facilities

In addition to SAGE, GAGE, GSECARS, and COMPRES, the Instrumentation and Facilities Program supports 16 multi-user facilities that develop and provide community access to instrumentation. The annual average funding for these facilities is ~$7.7 million. Following is a list of these multi-user facilities and their annual funding, organized by application.

Geophysics

In addition to SAGE and GAGE, there are three smaller EAR-supported facilities related primarily to geophysics, with an average annual budget of $760,000. These are the Institute for Rock Magnetism (IRM), which operates instruments for study of the magnetic properties of natural materials; the International Seismological Centre (ISC), which provides a catalog of worldwide earthquakes; and the Global Centroid-Moment-Tensor Project (CMT), which provides a comprehensive record of global seismic strain release.

Geochemistry/Geochronology

There are six EAR-supported facilities that utilize specialized mass spectrometers to generate geochemical and/or geochronologic information, with an average annual budget of $2.5 million. The Purdue Rare Isotope Measurement Laboratory (PRIME Lab) is a research and user facility for accelerator mass spectrometry, which is an analytical technique for measuring long-lived radionuclides. The University of California, Los Angeles, Ion Probe Lab (UCLA SIMS) facility consists of instruments used for U-Pb geochronology and high-precision stable isotope ratio measurements, including those for cosmochemistry. Arizona State University Ion Probe Lab (ASU SIMS) facility contains instruments for precise isotope ratio measurements and trace element analyses. The Northeast National Ion Microprobe Facility (NENIMF) consists of instruments used for high-precision measurements of light elements such as hydrogen, lithium, boron, carbon, nitrogen, and oxygen for applications such as magmatic volatiles in silicate glasses and analysis of biogenic carbonates. The University of Wisconsin SIMS Lab (Wisc SIMS) utilizes a large-radius, multicollector ion microprobe for analysis of stable isotopes (including Li, C, N, O, Mg, Si, S, Ca, and Fe). The Arizona LaserChron Center (ALC) utilizes laser-ablation inductively coupled plasma mass spectrometry to generate U-Th-Pb ages, Hf isotope ratios, and trace element concentrations of geologic materials, with research focused on continent growth, mountain building, and sediment generation and dispersal, among others.

The facilities share a mission to provide measurements for their own and other universities, national laboratories, and federal agencies. Most focus on supporting EAR-funded research, and many provide reduced user fees for NSF research projects. They also share an interest in providing opportunities for research training and education, for improving quantitative standards, and for innovating new method development and measurement techniques.

Support for Continental Scientific Drilling

There are several facilities that provide instruments and analytical expertise for continental drilling. The International Continental Scientific Drilling Program (ICDP) is an international program to advance continental drilling. Projects are worldwide and are funded through international cost-sharing. The Continental Scientific Drilling Coordination Office (CSDCO) helps develop projects for drilling operations and supports project-specific logistics, sample and data management during drilling operations, and laboratories for core sample processing and curation. It also helps foster an engaged drilling community and broadens participation of underrepresented groups. The National Lacustrine Core Facility (LacCore), which is co-located with CSDCO, provides sedimentological analysis and archiving for lacustrine cores in support of projects related to paleoclimate, ecology, and biogeochemical cycles on the continents. LacCore operates open laboratories that provide field and laboratory equipment and staff expertise for core descriptions and analysis, as well as core storage and archival services. The average annual budget for these facilities is $2.1 million.

Other Disciplines

Other EAR-supported facilities include the National Center for Airborne Laser Mapping (NCALM), which provides research-quality airborne lidar observations to the scientific community; the Center for Transformative Environmental Monitoring Programs (CTEMPs), which offers community support for distributed fiber optic Raman backscatter distributed temperature sensing for observation of the spatial and temporal distribution of temperature; the Virginia Tech National Center for Earth and Environmental Nanotechnology Infrastructure (NanoEarth), which provides support to researchers who work with nanoscience- and nanotechnology-related aspects of the Earth and environmental sciences/engineering; and the University of Texas High-Resolution Computed X-Ray Tomography Facility (UTCT), which uses computed tomography to provide a nondestructive technique for visualizing the interior features of solid objects, and for obtaining digital information on their 3D geometries and properties. The average annual budget for these facilities is approximately $2.4 million.

Multi-User Facilities That Provide Cyberinfrastructure

EAR supports 10 multi-user facilities that develop and provide community access to cyberinfrastructure. These facilities are supported by Geoinformatics, EarthCube, Instrumentation and Facilities, and other programs, with an average of $10.7 million of funding provided per year (see Figure 3-2). The largest of the current multi-user facilities for cyberinfrastructure is the Interdisciplinary Earth Data Alliance (IEDA), which serves as a primary means for community data collection for global geochemistry and marine geoscience research and supports the preservation, discovery, retrieval, and analysis of a wide range of observational field and analytical data types.

For hydrology and surface processes, the Community Surface Dynamics Modeling System (CSDMS) provides human and cyberinfrastructure for advancing integrated modeling of Earth surface processes and promotes the development, use, and interoperability of software modules that predict the movement of fluids and the flux of sediment and solutes in landscapes. The Consortium of Universities for the Advancement of Hydrological Science, Inc. (CUAHSI) has a mission to develop infrastructure and services for advancing water science research and education. The OpenTopography High Resolution Data and Tools Facility (OpenTopo) provides web-based access to lidar-generated high-resolution topographic datasets and analysis tools in support of surface Earth process research and training.

Several of the cyberinfrastructure facilities support geophysics, petrology, and geochemistry. For example, the Computational Infrastructure for Geodynamics (CIG) builds and sustains cyberinfrastructure and computational capacity for geodynamics and seismology. Geo-Visualization and Data Analysis using the Magnetics Information Consortium (MagIC) develops and maintains an open community digital data archive for published rock and paleomagnetic data. Generic Mapping Tools (GMT) is an open-source collection of tools for manipulating geographic and Cartesian datasets and creating illustrations. Alpha-MELTS computational thermodynamics software includes models and algorithms for computational thermodynamics in geodynamics, geochemistry, and petrology.

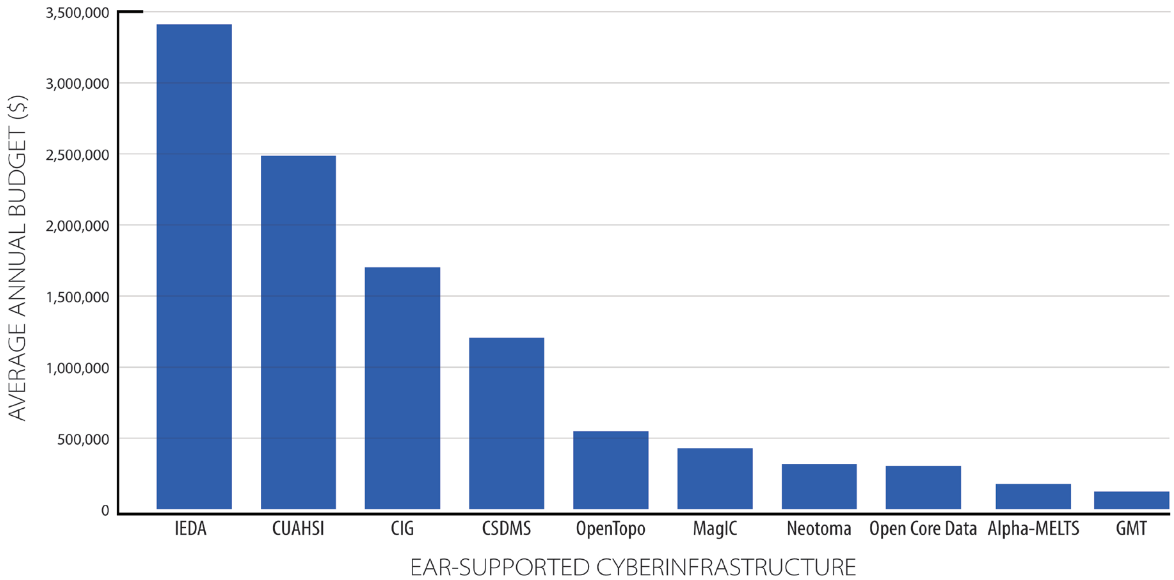

FIGURE 3-2 Bar chart of average annual budgets for cyberinfrastructure supported by EAR. SOURCE: Data provided by NSF.

In addition, the Neotoma Paleoecology Database and Community provides an online hub for paleoenvironmental data (from the past 5 Ma), as well as research and education, and Open Core Data provides the infrastructure that makes data from scientific continental and ocean drilling projects discoverable, persistent, citable, and accessible.

Additional Multi-User Facilities

There are other examples of infrastructure funded by EAR that do not easily fit into the categories above. This includes instrumentation support for Critical Zone Observatories (CZOs), which are place-based, watershed-scale environmental laboratories,[1] and support for the Southern California Earthquake Center[2] (SCEC).

The CZO program (initiated in 2007) developed a network of nine intensive field monitoring sites (from California to Puerto Rico, White et al., 2015) focused on investigating what controls critical zone properties and processes, the response of the critical zone structure to climate and land-use change, and improved understanding of the critical zone to enhance ecosystem resilience and sustainability and to restore ecosystem function. Each CZO site (and its associated monitoring scheme) was selected to address hypotheses about some component of one or more of these questions. Collectively, these field observatories brought researchers together from a wide range of disciplines and enabled them to make sustained measurements over 7-12 years that led to fundamental discoveries and new theories for critical zone processes and evolution (Brantley et al., 2017). Over their program life, CZOs were used by thousands of researchers and educators. They served as testing grounds for new observational technologies and a training site for early career scientists. The CZO program is ending in 2020. Contingent on funding, some CZOs may remain active as monitoring platforms and community resources. Sustained access to CZO program data is actively being developed. The average annual amount of EAR support has been $7.4 million.

SCEC is a research collaboratory funded by EAR and USGS to coordinate fundamental research on earthquake processes, using Southern California as a natural laboratory. SCEC includes 20 core institutions and more than 60 participating institutions, which operate as a virtual organization to coordinate interdisciplinary earthquake system science. The SCEC program supports research and education in seismology, earthquake geology, tectonic geodesy, and computational science. It accomplishes this by collecting data from seismic and geodetic sensors, geologic field observations, and laboratory experiments; using physics-based modeling to synthesize knowledge of earthquake phenomena; and communicating understanding of seismic hazards to reduce risk and increase community

[1] See http://criticalzone.org/national (accessed December 2, 2019).

[2] See https://www.scec.org (accessed December 20, 2019).

resilience. The average annual budget is $2.9 million from EAR, with another $1.3-1.6 million per year from USGS.

Infrastructure Provided by Other Parts of NSF

NSF operates many facilities across the organization that support a wide variety of science, including EAR research. Below are some examples of infrastructure and programs used by EAR researchers that are supported by other divisions within GEO or other NSF directorates. This is not a comprehensive list; rather, it highlights some of the major facilities relevant to Earth sciences.

EarthCube

EarthCube[3] aims to bring together the geoscience, geoinformatics, and data science communities to advance access to cyberinfrastructure and analysis of geoscience data. EarthCube has provided a pathway for community feedback from programs and divisions to be heard at the GEO level. EarthCube is a joint program of GEO and the Division of Advanced Cyberinfrastructure.

Academic Research Fleet and the *JOIDES Resolution*

The Division of Ocean Sciences (OCE) oversees the operation of the academic research fleet and the *JOIDES Resolution*. The academic research fleet has several ships that are essential for studying coastal zone and offshore processes. The *JOIDES Resolution*, a research vessel for scientific ocean drilling, contributes critical information for paleoclimate as well as petrologic, structural, and geochemical studies of the seafloor.

National Center for Atmospheric Research

The National Center for Atmospheric Research[4] (NCAR) was established in 1960. It provides supercomputing facilities, computer models, data, and research aircraft to the atmospheric research community and related scientific disciplines. In addition to computational time for EAR researchers, it supports both forward climate and paleoclimate modeling, paleoclimate proxies and validation, and hydrologic sciences and modeling. It is supported by the Division of Atmospheric and Geospace Sciences in GEO.

[3] See https://www.earthcube.org (accessed December 27, 2019).

[4] See https://ncar.ucar.edu (accessed December 20, 2019).

Long-Term Ecological Research Program

The Directorate for Biological Sciences (BIO) oversees the Long-Term Ecological Research Program[5] (LTER), which has been supported since 1980. The LTERs study ecosystems over long time periods at specific sites that range from Antarctica to the Alaskan Arctic. Currently, there are 28 sites in the LTER network. These sites are often multidisciplinary and have been of particular use for critical zone science. Some LTERs are co-located with EAR-funded CZOs to achieve complementary science objectives.

National Ecological Observatory Network

The National Ecological Observatory Network[6] (NEON) consists of 20 study sites in the continental United States, Hawaii, and Puerto Rico that were chosen to represent different ecological regimes. Automated data are continuously collected and include tower-based weather and climate data; measurements of chemical and physical soil properties; rainfall rates; and visual data collected with cameras. NEON became operational in 2019 and has a planned lifetime of 30 years. NEON operations are funded by BIO.

Collections

Collections in Support of Biological Research, a program run by BIO, helps improve curation and accessibility of scientifically significant collections, including data and management. It also allows for transferring ownership of important collections. Another BIO program, Advancing Digitization of Biodiversity Collections, supports efforts to digitize basic temporal and geographic information on species occurrences, as well as images and other kinds of data. Major institutions that have benefited from these programs include the Paleontological Research Institution, which houses one of the 10 largest invertebrate paleontology collections in the United States; the Yale Peabody Museum, which holds historically important American fossil collections; and the University of Colorado Boulder, whose fossil insect collections are being studied to assess the response of terrestrial communities to environmental change.

[5] See https://lternet.edu (accessed December 20, 2019).

[6] See https://www.neonscience.org/about (accessed December 20, 2019).

Supercomputing Resources

NSF supports supercomputing through the Extreme Science and Engineering Discovery Environment (XSEDE), which coordinates sharing of supercomputing resources and high-end data analysis and visualization with researchers across the nation. XSEDE is a virtual organization that provides supercomputers and data storage beyond what is typically available to individual researchers, as well as the support structures required for scientists to take full advantage of these resources. XSEDE has adapted to meet diverse needs in high-performance computing, high-throughput computing, as well as more specialized needs in memory-intensive problems, visualization, and data analytics.

Select Infrastructure Provided by Other Agencies

In addition to NSF, infrastructure provided by other agencies is critical for EAR-funded research. Examples of relevant infrastructure are presented here, with expanded discussion of current and potential partnerships in Chapter 4.

USGS

USGS operates regional earthquake monitoring networks as part of the Advanced National Seismic System, which issues notifications and warnings of their occurrence and hazard impact, including tsunami warnings. It funds cooperative agreements with academia in connection with the Alaskan Volcano Observatory, the Pacific Northwest Seismic Network, the Center for the Study of Active Volcanoes, and the Yellowstone Seismic Network. USGS coordinates with NSF and IRIS to run the Global Seismic Network, which monitors worldwide seismicity. Seismometers are combined with other instruments to form geophysical observatories. EAR partners with USGS's Powell Center for Data Synthesis and Analysis. In addition to monitoring seismic hazard, USGS operates the Volcano Hazards Program in close partnership with academia and is part of the EAR-supported Community Network for Volcanic Eruption Response (CONVERSE) Research Coordination Network. USGS also co-funds SCEC (discussed in a previous section) with EAR.

USGS also maintains the most comprehensive and consistent repository of water data in existence. This includes continuous observations of streamflow, groundwater elevation, water temperature, and sediment concentrations at thousands of monitoring locations throughout the United States and its territories. Additionally, USGS supports 29 Water Science Centers that produce important scientific datasets that are broadly disseminated to the community for scientific and management uses. USGS also develops and supports surface water, groundwater, and hydrogeochemistry/reactive-transport models that are broadly used by the EAR community. USGS laboratories also provide EAR-funded researchers with analytical capabilities in geochemistry and geochronology.

Through a partnership between USGS and NASA, land remote sensing products from the Landsat missions have been made broadly and freely available and are used extensively by EAR researchers. Additionally, USGS partners with universities to host eight Climate Adaptation Science Centers, which are devoted to co-producing actionable climate adaptation science that meets management needs of partners, particularly U.S. Department of the Interior agencies.

Jointly with the National Oceanic and Atmospheric Administration (NOAA), USGS operates the National Space Weather Prediction Network, which is critical for understanding the rate of change of Earth's magnetic field.

NASA

The NASA Earth Surface and Interior Focus Area, part of the Earth Sciences Division, provides funding to supplement NSF's support of GAGE. NASA's Earth-orbiting satellites provide key high-resolution datasets to study climate change, topography and bathymetry, and the gravity field. NASA's Earth Observing System Data and Information System is an essential resource for Earth data, which is accessed through several Distributed Active Archive Centers throughout the United States. The centers analyze, curate, and distribute data from NASA's Earth-observing satellite missions and field measurement programs. Available data include synthetic aperture radar (SAR), sea ice, snow and ice, geodesy, and gravity measurements for solid Earth, ecology, and hydrology applications. NASA also deploys aircraft and uninhabited aerial vehicles (UAVs) for Earth science remote sensing applications, such as land deformation measured by SAR sensors on UAVs.[7]

The Hydrologic Sciences Branch at the NASA Goddard Space Flight Center supports the development of important land modeling capabilities. The Land Infor-

[7] See https://uavsar.jpl.nasa.gov (accessed December 20, 2019).

mation System is an open-source framework for modeling land surface hydrology and assimilating a variety of remote sensing products. It is used by EAR-funded researchers to create synthetic spatio-temporal datasets of important land hydrology variables for which observations are otherwise unavailable.

DOE

Synchrotron radiation sources are large-scale user facilities[8] for highly-focused and intense X-rays that are operated by DOE (see Figure 3-3). GSECARS receives funding from EAR's Instrumentation and Facilities Program to support human and physical infrastructure at the APS for a wide range of EAR disciplines, and COMPRES receives funding to support human and physical infrastructure in the area of high-pressure mineral physics. Other national user facilities supported by DOE and NSF do not receive EAR funds but are also used by EAR researchers. These include many of DOE's National Laboratories (Argonne, Brookhaven, Lawrence Livermore, Los Alamos, Oakridge, Sandia, etc.). DOE infrastructure of growing interest to EAR researchers includes large-scale shockwave facilities to study dynamic processes such as collisions, Earth's formation and evolution, and materials equations of state along pressure–temperature paths relevant to Earth's interior.

DOE maintains field and experimental sites that provide data, models, and scientific partnerships for advancing understanding of the critical zone, water cycle, topography, and climate. These include the suite of Next Generation Ecosystem Experiment sites in the Arctic[9] and tropics,[10] the Spruce and Peatland Responses Under Changing Environments experiment,[11] and the East River Study Area (discussed in further detail in Chapter 4). DOE also develops and offers access to significant modeling capabilities, a key example of which is the Energy Exascale Earth System Model. DOE has significant high-performance computing resources that are used for Earth science research.

DOE also has longer-term applied research facilities that support Earth science objectives. These include the Frontier Observatory for Research in Geothermal Energy, a geothermal test site, and the Deep Underground Science and Engineering Laboratory (also supported by NSF).

[8] These include the Advanced Photon Source (APS, operated by UChicago Argonne LLC at Argonne National Laboratory), National Synchrotron Light Source-II (NSLS-II, operated by Brookhaven Science Associates at Brookhaven National Laboratory), and Advanced Light Source (ALS, operated by Lawrence Berkeley National Laboratory in Berkeley, California).

[9] See https://ngee-arctic.ornl.gov (accessed December 20, 2019).
[10] See https://ngee-tropics.lbl.gov (accessed December 20, 2019).
[11] See https://mnspruce.ornl.gov (accessed December 20, 2019).

FIGURE 3-3 DOE synchrotron radiation sources from left to right, the National Synchrotron Light Source-II (NSLS-II) at Brookhaven National Laboratory, the Advanced Light Source (ALS) at Lawrence Berkeley National Laboratory (LBNL), and the Advanced Photon Source (APS) at Argonne National Laboratory. SOURCES: NSLS-II, APS–DOE, and ALS–LBNL.

DOE/National Institutes of Health (NIH)

Biological information necessary to understand the evolution of biogeochemical cycles is provided largely by government agencies other than NSF. These include DOE's Joint Genome Institute and NIH's National Center for Biotechnology Information. In addition, the synchrotron sources described above are used to characterize chemical properties.

Smithsonian Institution and Museum Collections

The museums of the Smithsonian Institution hold the principal federally supported physical collections, whose millions of specimens provide a foundation for a diversity of scientific and cultural research. Of particular relevance to EAR are the Smithsonian's holdings in paleontology and stratigraphy, mineral sciences, and meteoritics. Numerous municipal and private museums play similar roles for EAR-supported scientists.

U.S. Department of Agriculture (USDA)

The Natural Resources Conservation Service operates the Soil Climate Analysis Network and Snow Telemetry networks, which provide quality-controlled measurements of soil moisture and snow water equivalent, respectively, to advance understanding of ecohydrologic processes and models. It also maintains, updates, and provides access to spatial soil datasets that inform models of surface and subsurface hydrology. The Agricultural Research Service operates watershed-scale experimental facilities throughout the United States. The U.S. Forest Service Forests and Ranges program also operates long-term, watershed-scale study sites, with a focus on forest landscapes and management practices. These facilities support research aligned with the water cycle, critical zone, and topography priority questions, and provide legacy datasets characterizing climate, hydrology, vegetation, and soils.

NOAA

The National Centers for Environmental Prediction produce and serve weather and climate forecast and historical datasets that are used as climate forcings for hydrologic and other land models. The National Centers for Environmental Information (NCEI) provides access to data such as historical climate records from across several observational networks, including archived precipitation datasets. Additionally, the NCEI paleoclimate database is extensively used by EAR researchers and others worldwide. NOAA's National Water Center recently implemented a National Water Model that provides fine-scale, near-historical, and forecast streamflow conditions at millions of stream segments throughout the continental United States. It was developed from modeling technology developed at NCAR and supported in part by EAR.

RELATIONSHIP BETWEEN CURRENT INFRASTRUCTURE AND THE SCIENCE PRIORITIES

There is a strong correlation between the existing infrastructure and facilities supported by EAR and the current needs determined for the science priorities discussed in Chapter 2. Table 3-2 shows how the science priorities and the existing facilities are connected. It is clear from this compilation that many of the current EAR facilities will continue to be needed to address the science priorities outlined in this report.

EVALUATION, ASSESSMENT, AND PRIORITIZATION OF FACILITIES AND INFRASTRUCTURE

To address Task 2B, the committee described research conducted in each of the EAR-supported facilities identified by NSF at the beginning of this study. It also attempted to evaluate the potential impact of the supported research on the priority science questions. Descriptions of each facility were assembled from information provided directly by facility operators, facility websites, and NSF award abstracts,[12] as well as the knowledge and direct experiences of committee members. It was difficult to access information that could be used to evaluate facility performance and impact. Project outcomes reports[13] were not available for all facility awards, and most of the available reports contained only limited information. However, several facilities provided comprehensive information to the committee, including annual reports, metrics used to assess success, and impacts. About half of the multi-user facility operators also responded to a committee question regarding primary criteria to consider when

[12] See https://www.nsf.gov/awardsearch (accessed March 23, 2020).

[13] See https://www.research.gov (accessed March 23, 2020).

TABLE 3-2 Connections Between the Science Priorities and Existing Infrastructure and Facilities

	Geomagnetism	Plate Tectonics	Critical Elements	Earthquakes	Volcanoes	Topography	Critical Zone	Climate	Water Cycle	Biogeochemistry	Biodiversity	Geohazards
Geophysics												
SAGE	■	■	●	■	■	■	●		●			■
GAGE	●	■	●	■	■	■			■			■
IRM	■	■	●	●	●							●
ISC	■	■		■	■							■
CMT	●	■		■	●							■
Material Characterization												
GSECARS	■	■	■	■	■		■	■	■	■	●	
COMPRES	■	■	■	●	■					●	●	
Biogeochemistry/Geochronology												
PRIME		●	●	■	■	■	■	■		■	■	●
Wisc SIMS	■	■	■	●	■	●		●		■	■	●
UCLA SIMS	■	■	■	●	■	■		●		■	■	●
ASU SIMS	■	■	■	●	■	●		●		■	■	●
NENIMF		■	■	●	■	■		●		■	■	●
ALC		■	■	●	■	■		●		■	■	●
Support for Continental Drilling												
CSDCO	●	■	●	●	●		●	■	●	■	■	●
LacCore	●	■	●	●	●			■	●	■	■	●
ICDP	●	■	●	●	●			■	●	■	■	●
Other Disciplines												
NCALM		●		■	■	■	■	●	■			■
CTEMPS							■	●	■			
UTCT	●	■	●	●	●			●		●	■	●
NanoEarth			●				■	■	■			
Cyberinfrastructure												
IEDA	●	■	●	●	●	●		●		●	●	●
CSDMS						■	■	■	■			●
CUAHSI						■	■	■	■			●
CIG	■	■	●	■		●						■
Open Topo		●		■	■	■	■					■
MagIC	■	■	●	●	●			●				●
Neotoma								●	●	■	■	
Open Core Data	■	■	●	●	●			●	●	■	■	●
Alpha-MELTS		■	■		■							
GMT	●	■	●	■	■							■

Abbreviations in first column:
SAGE: Seismological Facilities for the Advancement of Geoscience; GAGE: Geodetic Facility for the Advancement of Geoscience; IRM: Institute for Rock Magnetism; ISC: International Seismological Center; CMT: Global Centroid-Moment-Tensor Project; GSECARS: GeoSoilEnviroCARS Synchrotron Radiation Beamlines at the Advanced Photon Source; COMPRES: Consortium for Materials Properties Research in Earth Sciences; PRIME: Purdue Rare Isotope Measurement Laboratory; Wisc SIMS: University of Wisconsin SIMS Lab; UCLA SIMS: University of California, Los Angeles, Ion Probe Lab; ASU SIMS: Arizona State University Ion Probe Lab; NENIMF: Northeast National Ion Microprobe Facility; ALC: Arizona LaserChron Center; CSDCO: Continental Scientific Drilling Coordination Office; LacCore: National Lacustrine Core Facility; ICDP: International Continental Scientific Drilling Program; NCALM: National Center for Airborne Laser Mapping; CTEMPS: Center for Transformative Environmental Monitoring Programs; UTCT: University of Texas High-Resolution Computed X-Ray Tomography Facility; NanoEarth: Virginia Tech National Center for Earth and Environmental Nanotechnology Infrastructure; IEDA: Interdisciplinary Earth Data Alliance; CSDMS: Community Surface Dynamics Modeling System; CUAHSI: Consortium of Universities for the Advancement of Hydrological Science, Inc.; CIG: Computational Infrastructure for Geodynamics; OpenTopo: OpenTopography High Resolution Data and Tools Facility; MagIC: Geo-Visualization and Data Analysis using the Magnetics Information Consortium; Neotoma: Neotoma Paleoecology Database and Community; GMT: Generic Mapping Tools.

NOTES: Science priorities identified in the report are across the top and existing infrastructure and facilities are down the side. A fully colored box denotes a facility that provides essential capabilities needed to address a priority science question, while a colored circle denotes a facility that is relevant for a question. Determinations were made based on descriptions provided by the facilities, NSF award abstracts, and information taken from the community input questionnaire.

making decisions to establish new facilities or maintain (or sunset) existing facilities.

The committee asked EAR to provide information about the methods used to assess the effectiveness of the infrastructure it supports, with particular interest in understanding whether EAR has a process for evaluating the degree to which facilities are serving the goals of the Division. In response, the committee was informed that facilities are evaluated by EAR personnel, both annually and at the end of each funding cycle, and through the peer-review system with each proposal submitted for continued facility support. Based on committee members' individual experiences (e.g., serving on an NSF Committee of Visitors panel, prior experience as an NSF rotator, involvement with NSF-supported facilities), the evaluation systems that EAR has in place work well for individual facilities. However, because these evaluations are not publicly available, it was not possible for this committee to provide an informed evaluation of their effectiveness.

In an effort 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. For example, relevant metrics could include the number of publications that use data generated, analyzed, modeled, and/or archived by the facility, and the citations and awards garnered by these publications. Other criteria could include whether instruments, cyberinfrastructure, and personnel capabilities remain state of the art; the degree to which the facility takes advantage of new technologies and drives the development of new instruments, software tools, open-source protocols, data processing packages, models, analytical techniques, and science applications; and whether this opens new avenues of research for Earth science communities. Activity levels could also be tracked, such as size and breadth of user communities (in total and NSF supported) that conducted research in collaboration with the facility, those institutions served, the amount of NSF awards supported by facility activities, level of demand, partnerships built with other agencies, and database entries that contain facility information. Contributions to development of human infrastructure could be monitored through following the demographic and professional trends of scientists who work or conduct research at the facility, professional development of students and early career investigators who have been involved in facility activities, outreach activities that engage nonscientists in NSF-sponsored research, and accomplishments in improving Earth scientists' diversity, equity, and inclusion. The degree to which facilities provide community leadership and whether facility operators are leaders in their fields could also be considered. There may be a need for different facilities to be evaluated with slightly different ("tailored") sets of metrics, depending on the work done at the facility. Many of the examples listed above are already used in facility evaluation, but by explicitly stating the metrics considered in evaluations, the Earth science community would be better informed about the criteria used and valued.

A tailored set of metrics would also allow EAR and the Earth science community to periodically evaluate the performance and impact of the full portfolio of facilities and infrastructure. This would be especially helpful when evaluating the potential impact of proposed new facilities, deciding which facilities could be ramped down or sunsetted, and exploring whether changing science priorities require rebalancing infrastructure investments. Evaluation metrics and a synopsis of the assessment process could be made publicly available, perhaps on NSF's website. Additionally, relevant information about the entire portfolio of EAR-supported facilities could be compiled and available for easy public access, instead of only being available via the NSF awards database (as it is currently). Such information is essential to set priorities for infrastructure investments over the next decade, especially with the continued desire from EAR-supported investigators to incorporate novel and transformative technologies into their research.

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.

FUTURE INFRASTRUCTURE NEEDS

Future Needs Identified by Community Responses

The community input questionnaire[14] requested that participants "List up to 3 ideas for infrastructure

[14] See further discussion of the community input in Chapter 2. The form is reproduced in Appendix B.

(physical infrastructure, cyberinfrastructure, data management systems, etc.) that will be needed to address the above topics or issues over the next decade." Common themes regarding physical infrastructure and collections included the following:

- the need for centers or facilities that contain relevant instruments and expertise that are currently beyond the reach of a single investigator. These centers would ideally provide access to instruments and the expertise to operate them, train users in their operation, and help drive community initiatives.
- a need for facilities that archive geological samples and materials. Most individual investigators and their universities are not able to provide long-term archives, resulting in a real concern that critical (and in some cases irreplaceable) geological collections are being lost.
- the need to continue, and perhaps expand support for, traditional field-based geologic investigations.
- a need for geophysical, geochemical, biological, and bathymetric information from the oceans to address many problems in Earth science.

Regarding cyberinfrastructure, nearly half of the respondents noted that their research community is in critical need of improved data management systems. A common suggestion was that NSF build a system of databases that serves all disciplines in Earth sciences and provides capabilities for data access, analysis, and integration. It was apparent from the community that many respondents were either not aware of EarthCube or felt that EarthCube did not meet their current or anticipated cyberinfrastructure needs.

Many respondents also emphasized the need for enhanced training of researchers who can use sophisticated instruments and work with large and complex datasets, or who collaborate with scientists and engineers in complementary disciplines. There were also calls for improvements in access to high-performance computing, software and modeling, and for enhanced outreach to increase access to Earth science information and to grow diversity among Earth scientists.

Future Needs Identified by Facility Operators

EAR-supported multi-user facility operators (in sections above) were also asked about their top priorities if they had 10% more funding. Approximately half of them provided answers. Priorities for additional funding included hiring more technical staff and post-doctoral researchers, developing new instruments and/or capabilities, maintaining or modernizing instruments, initiating new projects, building community support (e.g., through development of new standards), and increasing outreach opportunities.

Future Needs Related to the Science Priority Questions

There are a range of instruments, facilities, and capabilities that will be needed to fully address the science priority questions over the next decade. As with the science questions themselves, the information below was compiled from literature review, community white papers, community responses, and input from facilities. These are discussed below, generally moving from Earth's interior to its surface.

Instrument-Based Capabilities

Geomagnetics, Plate Tectonics, Critical Elements, Earthquakes, Volcanoes

Studies of the core and magnetic field, plate tectonics, earthquakes, volcanoes and magmatic systems, and critical elements have need for enhanced capabilities to observe and monitor current geologic processes. Research in these areas would benefit from a subduction zone observatory, which could lead to new understanding of subduction-related phenomena and advance our ability to forecast earthquakes, tsunamis, and perhaps volcanic eruptions.

Instrumentation to observe earthquakes must be in place and ready to record at all times, and it must persist over time. Seismic and geodetic facilities for earthquake monitoring have done an excellent job of providing information to the research community, but the unpredictable nature of earthquakes means that instrumentation must be distributed efficiently, with reserve capacity to supplement them once an event has occurred. Alternative strategies include setting up observatories to catch earthquakes as they occur (Ben-Zion, 2019), temporary instrumentation followed by deliberately triggering an earthquake (Savage et al., 2017), and exploiting new sensor technologies, such as monitoring with dark fiber through distributed acoustic sensing (Marra et al., 2018). These developments will not only be important for deep Earth processes but will open the field of environmental seismology and increase knowledge of soils, water storage, and hillslope failure.

Studies of volcanic systems require a dedicated set of synchronized portable field instruments including a wide range of high-resolution video cameras across multiple wavebands, broadband seismometers, infrasound sensors, GPS receivers, gas cameras and spectrometers, and ash samplers. This hardware would be designed to be deployed during volcanic crises in a rapid-response fashion to observe eruption dynamics and sample the products of volcanic eruption cycles at volcanoes within the United States and contribute to international efforts worldwide.

The plate tectonics and geomagnetics questions need data with expanded global and temporal coverage to provide information about how plate tectonics (and predecessor processes) and the geodynamo have operated through geologic time. Particularly useful are collections of traditional types of outcrop-based geologic observations, as well as improved integration with a broader array of drill cores from continental and marine sedimentary sequences. An essential activity will be to sustain or even broaden access to samples and cores that have already been acquired but are at risk of being lost.

Plate tectonics, geomagnetics, volcanoes, and critical elements all need the following:

- laboratory facilities to carry out experiments under the full range of environmental conditions required to understand deformation processes;
- facilities with instrumentation for characterization of static and transport properties of Earth materials at Earth conditions (composition, temperature, pressure, stress) to build the appropriate constitutive laws, including new spectroscopic techniques; and
- development of capabilities to measure and model thermodynamic processes at time scales ranging from shock to plate movement, including kinetics and diffusion at extreme conditions and nonequilibrium processes.

The geomagnetics question also needs equipment that is tailored for measurements of magnetic signals in individual grains.

In addition, the critical elements and volcanoes questions require analytical instrumentation to obtain improved records of igneous/metamorphic/tectonic processes operating through Earth's history (e.g., analysis of different minerals and different geochemical/isotopic systems, on smaller spatial scale, with improved precision/accuracy and ability to determine oxidation state of minerals and melts) and new experimental methods in shockless compression by laser and pulsed power to allow the study of equations of state and physical properties of melts and minerals at conditions spanning the Earth and super-Earth interiors.

For these questions, finer spatial resolution of analyses will be a great strength. The volume of material needed for a geochemical or geochronologic analysis has been steadily decreasing, such that scanning electron microscopes and electron microprobes can be used to image and analyze materials at very fine scales, including light elements. In addition, transmission electron microscopes and atom probes are now capable of imaging and analyzing individual atoms. The next 10 years should see the application of this technology to a broad range of geologic materials, with new insights into the geochemistry of nano-scale inclusions and isotopic reservoirs.

Improved temporal resolution will also be essential. For much of geologic time, the uncertainty of geochronologic ages greatly exceeds the time scale of fundamental events and processes. New and anticipated technological developments (e.g., improved decay constants) provide opportunities to significantly improve the precision and accuracy of geochronologic rates and ages (Harrison et al., 2015). Advances that allow better linkage of processes and conditions to time are needed (e.g., improved calibration of the geologic time scale is important to reconstructing the carbon-oxygen-hydrogen-nitrogen system and its control on habitability).

Topography, Critical Zone, Climate, Water Cycle, Geohazards

There are shared threads through these five science questions that call on common instrumentation and facility needs. All five need:

- high-resolution data on topography and vegetation and repeat survey data for change detection;

- subsurface characterization of material properties that influence water storage and flux, pore pressure, mass strength, and solute and gas chemistry;
- long-term observatories and experimental watersheds to investigate processes;
- precipitation and runoff monitoring stations;
- satellite-based long-term observational data;
- ability to quantify long-term rates of erosion, exhumation, uplift, and subsidence; and
- proxy measurements of past environmental conditions.

The instrumentation and facilities for each of these categories are briefly summarized below.

Airborne lidar has been a breakthrough technology that enables thousands of square kilometers to be surveyed at resolutions of tens of centimeters in a single campaign. In contrast to photogrammetry, airborne lidar can penetrate dense forests to document the topography of the ground surface as well as the vegetation canopy structure. Research communities are increasingly comparing existing lidar data with new surveys for change detection or are working in new areas with the intent for repeat surveys.

Presently, satellite-based lidar has large footprints and limited coverage. Satellite-based photography, however, provides global coverage at sub-meter resolution, with the ability to do repeat observations. Currently, high-resolution topographic data are not available for most of the Earth. Although photogrammetry is limited by forest and brush cover, for much of the Earth vegetation density is low, and commonly where it is dense, the current topographic data is so coarse that satellite-derived topography, even with vegetation effects, will be a valuable improvement. The Polar Geospatial Center digital elevation surface models for the Arctic and Antarctica are two such data products. Sustained Landsat surveys are now enabling researchers to make movies of Earth surface dynamics that span more than 30 years. On the local scale, drone-based, photography-derived Structure from Motion digital surface topography will become increasingly used in field studies. Drone-based lidar surveys are likely to become progressively more widely used in intermediate-scale field studies.

While lidar has revolutionized understanding of Earth's surface, near-surface geophysics (from the ground surface to depths of tens to hundreds of meters [e.g., Kruse, 2013]) is revealing the structure of the subsurface domain. Advances in technology, and increasing access to and knowledge of geophysical tools, will play an important role in advancing these science priority questions. Drilling and borehole characterization is an important part of understanding the subsurface, as is subsequent instrumenting of the holes to characterize materials and subsurface dynamics.

Long-term field observatories and experimental watersheds play a unique role in Earth sciences, enabling researchers to test hypotheses that guide measurements to quantify and advance understanding of physical and biological processes (NRC, 2014). Observatories create a structure in which researchers can collaborate across a wide range of disciplines (such as Earth science, climate science, and biological science) to tackle major questions that lie beyond any single field. Observatory sites also serve as trackers of the rapidly changing Earth. The CZO program, which provided the first sustained intensive investigation of critical zone processes and evolution and inspired similar programs in the United States and other countries, sunsets in 2020. This will lead to losses of infrastructure that support the critical zone and water cycle questions.

The network of weather stations and streamflow monitoring stations operated by federal, state, and local agencies provides essential data on water inputs and outflows. Accessibility and quality control of such data has had a profound impact on scientific research and will continue to be essential, although budgetary limitations and changing priorities have led to loss of weather and gauging stations. It is important to advance efforts to preserve, generalize, and make available data relevant to climate monitoring, including the information coming from NOAA's Global Historical Climatology Network[15] and USDA's Parameter-elevation Regressions on Independent Slopes Model.[16]

Satellite-based Earth observations provide essential data for these science questions and several others. Such satellite systems include:

- the Global Precipitation Measurement constellation of satellites, which provide global coverage of precipitation from microwave sensors (Liu et al., 2017);
- Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On missions,

[15] See https://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/global-historical-climatology-network-ghcn (accessed December 27, 2019).
[16] See https://www.wcc.nrcs.usda.gov/climate/prism.html (accessed December 27, 2019).

which enable global tracking of underground storage for the amount of water held in soil moisture, lakes and rivers, ice sheets and glaciers, and sea-level changed caused by the addition of water to the ocean;

- Soil Moisture Active Passive (SMAP) provides information on soil moisture and freeze-thaw activity in the first 5 cm from the surface on a 2- to 3-day repeat at scales of about 40 km (Felfelani et al., 2018);
- Interferometric SAR (InSAR) enables monitoring of surface deformation, including faulting, landslides, groundwater storage change, ice sheet motion, permafrost change, and tracking of magma movement and volcanic deformation. A joint NASA and Indian satellite will launch in 2021, succeeding current European and Japanese missions; and
- Landsat and several commercial companies provide satellite photographic and spectral imagery at various repeat time and resolution. Landsat is particularly important in its sustained monitoring program and free access to high-quality data.

A thorough review of opportunities, applications, and future missions relative to Earth science can be found in *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space* (NASEM, 2018a).

Advances in noble gas geochemistry, thermochronometry, cosmogenic nuclide dating, and clumped isotope thermometry have revolutionized our ability to document Earth surface dynamics, such as long-term rates of erosion, exhumation, uplift, and subsidence. Water stable isotope reconstructions based on ice cores, fossil shells and plants, volcanic ash, and other geologic archives enable interpretation of past environmental conditions. Such proxy measurements provide necessary information to understand climate history and are an important component for all five science priority questions and others as well. Geochronological techniques, such as radiocarbon dating or optically stimulated luminescence dating, are essential to provide a temporal framework for proxy records of past environmental change. Improved precision and accuracy of these tools as well as further development of geochronological techniques that help to fill temporal gaps or access different archives will be vital to constraining both absolute time and rates of environmental change.

Biodiversity and Biogeochemical Cycles

For biodiversity and biogeochemical cycles, a range of instrument-based capabilities are needed to constrain what happened, where, when, and at what rate. These include:

- development of dedicated facilities for analysis of geological and biological samples and recovery and archiving of long-term geological records (paleontologic, stratigraphic, geochemical, climatic, etc.) from outcrops and continuous cores;
- upgrades of synchrotron sources and methods at individual beamlines; and
- development of dedicated geochronology facilities as well as new geochronologic tools to resolve evolutionary rates and processes and to constrain the timing and rates of biogeochemical transitions and perturbations.

Biodiversity also requires the support of existing facilities and creation of new ones for analysis of biological samples and sediments to yield paleoenvironmental proxy data for factors such as climate and atmospheric and oceanic chemistry.

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

Cyberinfrastructure-Based Capabilities

Cyberinfrastructure will be needed to support both model development and data analysis and integration. This will include the development or use of standardized data formats, storage of data and model results and the ability to access them, and data archiving (whether at commercially available or field-specific data repositories). There will be an increasing need for multi-scale, multi-physics models that use cutting-edge theory, numerical methods, and high-performance computing that incorporate knowledge from new and old measurements.

Geomagnetics, Plate Tectonics, Critical Elements, Earthquakes, Volcanoes

Addressing research about processes that operate within the Earth will need efficient access to geologic, geochemical, and geophysical information that has been generated from existing and new samples and records, which will require databases to store and provide this information. Although a daunting challenge, the alternative, which is that existing information may be lost, is unacceptable. The rapidly increasing size of geologic datasets adds considerable urgency to this challenge.

Once databases are available, advanced tools for analysis, visualization, and modeling of large volumes of data are needed. For example, while technological developments in X-ray detectors are making real-time chemical reactions observable, synchrotrons can generate terabytes of data in a single day, creating a cyberinfrastructure challenge for both users and facilities. This will only increase as new technologies such as distributed acoustic sensing using dark fiber become widely available. Other examples include:

- improved modeling capabilities to investigate key processes driving the rise of magma from storage to eruption;
- computational infrastructure for geodynamic modeling of Earth's interior; and
- modeling capabilities with open-source tools, software optimization, and high-performance computing to represent geometrically and dynamically complex fault systems over a range of relevant scales.

In addition, there will be a need for high-performance computing with state-of-the-art techniques for data assimilation. These can be used for numerical simulations that incorporate newly determined constitutive laws for the deformation of Earth materials, applicable to a range of plate boundary processes from faulting to long-term plate motion. For brittle deformation, such laws will be important on intermediate scales—larger than typical laboratory samples but smaller than the spatial discretization in typical simulations.

Modeling collaboratories provide exemplars of the integration of data and modeling and can coordinate and support the distributed development of a diverse set of numerical codes, training, scientific exchange, and access to large-scale computations. They can provide an incubator for the new generation of models that incorporate theory and data, and are capable of informing and guiding new data acquisition to fill gaps in physical understanding.

Topography, Critical Zone, Climate, Water Cycle, Geohazards

Data access for processes that operate on Earth's surface has been improved by providing lidar data through OpenTopography and various hydrologic and critical zone datasets through the CUAHSI Hydroshare program. However, surface processes data lack the organization and ease by which seismic data worldwide are made available. Because of a lack of shared observational data storage at the individual, state, and federal level, it is quite difficult to quickly discover and use previous and ongoing surface process data collections (e.g., erosion rates, soil moisture dynamics, results of drilling bore holes, groundwater levels, climatic measurements). In addition, there are no centralized and approved data centers for the diverse data types these communities produce. Some databases are available for the geochronologic, geochemical, and petrologic data needed to study Earth surface processes and their interactions with other components of the Earth system through geologic time (e.g., EarthChem), but data standards and access are limited and heterogeneous. The ability to generate data far outstrips the funding currently available to store and access in open databases expected to have a sustained presence into the future.

A common goal of these questions is to build models that can exploit the progressively increasing resolution of spatial and temporal data to predict event-based Earth surface dynamics. High-performance computing will play a central role in enabling the creation of a first-generation high-resolution global digital surface model from satellite imagery (e.g., the Polar Geospatial Center, see Chapter 4). Among many other objectives, enhanced high-performance computing access will enable large-scale, high-resolution water resources models to address the coupling of natural processes and management strategies; improved prediction of the timing and location of landslides in storm events; event-based models of landscape evolution over large scales; improved earthquake prediction through the ability to do large-scale computations and include the complex built environment of urban areas; and inclusion of spatially varying critical zone properties in the prediction of land surface interaction with climate. High-performance computing will also enable coupling of landscape evolution models that capture the complexity of these interactions with continent- to global-scale geodynamic models.

Cyberinfrastructure that supports the integration of paleoclimate records with each other and with other archives of Earth's history and evolution, including paleoclimate models, is at varying stages of development within different subdisciplines and will require continued support to better leverage existing and new data collected by EAR scientists. High-performance computing is required for climate and Earth systems models spanning simulations of past to future, helping to build a critical bridge between studies of deep time and the anticipated emergence of near-future climates with few counterparts in human experience (Burke et al., 2018; Haywood et al., 2019).

For geohazards, there will be continued need for access to high-performance computing coupled with a community-modeling ecosystem to simulate geohazards; scalable algorithms to extract meaning for large data volumes; and for model-driven approaches, capability computing that allows for increasingly realistic simulations. There will be increasing need for cyberinfrastructure to process massive datasets that contain information on wide ranges of spatial and temporal scales, and across a broad range of topics (seismology, geodesy, lidar, InSAR, heat flow, topography, geochronology, mineral physics, geochemistry, hydrology, weather, etc.) and for information to be rapidly accessible for prediction and response.

Biodiversity and Biogeochemical Cycles

Addressing these questions involves the development of databases that unify high-quality, curated, stratigraphic, lithological, biological, and geochemical information, and the tools to search, access, visualize, and analyze the diverse datasets and conduct appropriate statistical analyses. There will be increasing need to access and integrate model data and data from different fields—stratigraphy, geochronology, geochemistry, paleontology, molecular evolution, microbial diversity, and molecular microbiology, for example. Essential sequence information is accessible from non–NSF-funded databases such as the GenBank (NIH sequence database). Bioinformatic tools to analyze these types of data are developed largely outside of GEO.

Future research will require enhanced cyberinfrastructure given the large size, diverse nature, and temporal scope of the relevant data. It is important to bear in mind that an enormous amount of relevant data resides in a century or more of published literature that has not been digitized. Improvements could include extension of a Neotoma database–like approach to deep-time records; automated mining of published literature; curation of new and legacy data; development of community standards for curating new data as they are produced; the ability to seamlessly integrate data from diverse geologic and biologic disciplines; recovery and archiving of long-term geological records (paleontologic, stratigraphic, geochemical, climatic, etc.) from outcrops and continuous cores obtained by oceanic and continental drilling; and automated access to an improved global Geologic Time Scale. In addition, increasing model complexity requires high-performance computing on a large scale. Phylogenetic, biogeochemical, and other models not only assimilate massive amounts of data; modeling results can in turn direct future data-gathering efforts. Advances in machine learning may help to harness the power of these data.

Personnel-Based Capabilities

Progress on the science priority questions and other innovative Earth science research will be made by researchers who generate critical new observations and interpretations, as well as experts who create new methods to integrate, analyze, and model this information. The Earth science community needs to develop a workforce that has high levels of expertise with the instruments and data used in each discipline, as well as the ability to work with information from other Earth science fields and an increasingly broad range of other fields. There will continue to be a need for training of field geologists, as field geology is an essential aspect of many Earth science research areas. The trend away from field camps and the tradition of field geology was a concern raised by many of the respondents in the community input. However, careers beyond field geology need to be emphasized in order to attract a more diverse workforce (I. Casellas-Connors, Texas A&M University, presentation to the committee, March 14, 2019). A more diverse workforce will drive exciting research and increase the connections between Earth scientists and society as a whole (see Chapter 2 and the discussion of Human Infrastructure below for additional discussion).

Because much of the novel research in Earth science increasingly involves integration of information from different methods and disciplines, addressing important science questions will require researchers who can generate new information utilizing field skills and increasingly complex and specialized instruments, integrate the diverse types of information, and develop new methods for interrogating and modeling the large and complex datasets. For example, the next decade of Earth science will require personnel able to design, build, and use increasingly complex and sophisticated instruments, and to access, integrate, and analyze large datasets that have diverse formats and a broad range of spatial and temporal scales. We are already seeing emergence of a new field of Earth data science as a specific discipline.

Personnel infrastructure will also be needed to support acquisition and analysis of geochronologic, geochemical, and geophysical data, and the development of new analytical techniques and modeling approaches. Dedicated software engineers and computer scientists will be needed to handle the expanding role of computational research in Earth science, both in terms of data analysis and physical processes modeling, as well as the increasing sophistication of software. The lack of dedicated software engineers for Earth science applications is often an issue in cyberinfrastructure, data analysis software, and database development.

Because of the significant need for disciplinary excellence and expertise, this type of training is currently provided largely by individual investigators or by small training programs for analytical, experimental, field, and computational methods (e.g., the Cooperative Institute for Dynamic Earth Research, CIG, the Paleobiology Short Course). Funding for small collaborative, multi- or interdisciplinary projects and post-doctoral projects that train post-doctoral researchers in new disciplines can also provide the necessary disciplinary and topical breadth to trainees. Continued emphasis on the proven success of NSF graduate research fellowships, post-doctoral fellowships, and faculty early-career development programs can ensure the training and continued development of a strong, vibrant community of experts who can address future challenges in the field.

RECOMMENDATIONS FOR POSSIBLE NEW INITIATIVES

In the next section, the committee offers suggestions of possible new initiatives that EAR and the Earth sciences community may wish to consider. All these initiatives originate from EAR research communities and are based on community input responses, community white papers or reports, and/or presentations in public sessions.

While the committee feels that significant progress can be made on the science priorities within the context of the present EAR budget, it is worth noting that EAR's infrastructure support has been flat for the past decade and that some of these proposed initiatives would demand significant infrastructure investment. For example, full implementation of SZ4D or the continental critical zone campaign would likely be too costly to incorporate into the current EAR budget. Due to their scale, in most cases funding these initiatives will require either a source of new funds (e.g., NSF's Mid-Scale Research Infrastructure or Major Research Equipment and Facilities Construction) and/or sunsetting of current programs. In all cases, the committee strongly believes that these initiatives (or others) should not be developed at the expense of the core disciplinary research programs.

These initiatives were chosen because they provide potentially transformative capabilities to address and support the science priorities discussed in Chapter 2 and the infrastructure needs discussed previously in this chapter. Three of these initiatives—creating a national consortium for geochronology, funding a U.S.-based very large multi-anvil press user facility, and establishing a near-surface geophysics center—are well developed, with years of community involvement and support, including white papers, endorsement in previous community reports, and/or proposals to NSF. Another initiative, SZ4D, has had strong community support in recent years, including a large NSF-supported workshop and three funded research coordination networks (RCNs), but is still developing its program plan. Other possible initiatives discussed below—continental drilling, Earth archives, and the continental critical zone—have various levels of community engagement and program development. Further exploration of these possible initiatives would need broad involvement of the Earth science community via workshops, white papers, and coordinating mechanisms such as RCNs. The committee's recommendations are based on both the potential scientific impact and the developmental stage of the proposed initiatives.

National Consortium for Geochronology

Given that nearly all the high-priority science questions require improved constraints on the ages and rates of geologic processes, it will be important for EAR to build enhanced geochronologic capabilities. Questions concerning the origin and dynamics of Earth's interior will require the ability to determine the timing and rates of geologic events and processes significantly better than is possible with current instruments and methods. Understanding how geologic, hydrologic, atmospheric, and biologic processes shape the surface of the Earth, and control our existence, requires much better temporal coverage than is currently available. All applications will benefit from enhanced abilities to acquire complementary geochemical and structural information and will require improved cyberinfrastructure to integrate geochronologic/geochemical/crystallographic data with information from other disciplines.

As highlighted in *New Research Opportunities in the Earth Sciences* (NRC, 2012) and *It's About Time: Opportunities & Challenges for U.S. Geochronology* (Harrison et al., 2015), significant issues exist with respect to providing the geochronologic information that is essential for current and future research in Earth science. Issues arise principally from the current funding model, in which most geochronology laboratories are supported mainly by awards to address specific science questions, with little or no funding awarded to support laboratory infrastructure, technique development, or educational/outreach activities. Currently, nongeochronologists are frustrated by the high cost and long delays of acquiring the geochronologic information needed for their projects, and laboratory operators struggle to cover the costs of their operations. This has inhibited development of new instruments, techniques, and applications that will be needed to address future Earth science questions.

The U.S. geochronology community is ready to develop a consortium of geochronology laboratories that will be equipped to accomplish the following goals:

1. Acquisition of the geochronologic information required for EAR-funded projects in a timely and cost-effective manner. A reasonable target would be to generate most types of geochronologic data in 3-6 months, at a cost that covers only the personnel and consumables needed to conduct the analyses.
2. Support for geochronology laboratories to provide the information described above and to drive the development of new geochronologic instruments, methods, and applications. Examples of new capabilities needed for the future are as follows:
    - increased mass spectrometer ionization efficiency to generate more precise ages, with greater efficiency, and on smaller volumes of material;
    - improved determination of decay constants, which will improve the age accuracy;
    - standards development for improved interlaboratory and intermethod calibration;
    - enhanced capabilities to acquire geochemical and/or crystallographic data simultaneously with geochronologic information; and
    - development of emerging and new chronometers, especially those that record processes operating on short time scales near Earth's surface or those that fill gaps in existing capabilities.
3. Commitment to FAIR data policies for all chronometers, as well as development of computational tools that allow for more sophisticated methods of data analysis, visualization, integration with other types of data, and modeling.
4. Improved education and training of geochronologic theory and practice in order to produce a new generation of highly diverse, cyber-savvy geochronologists; researchers who can effectively use geochronologic information; and better public understanding of why geochronology is important for societal applications.

Following Harrison et al. (2015), the committee endorses the creation of a consortium that consists of larger laboratories, for example, EAR-supported multi-user facilities, as well as single-investigator labotatories. Participating laboratories would commit to addressing the above goals, follow community-established protocols, and monitor outcomes through quantitative measures of success. The cost of developing and maintaining this consortium is estimated to be $8-10 million per year, some portion of which could be offset by lower sample analysis costs in future science proposals.

Recommendation: EAR should fund a National Consortium for Geochronology.

Very Large Multi-Anvil Press User Facility

Determining the physical and mechanical properties of rocks, minerals, and melts under various conditions found in the Earth through geologic time is a fundamental area of EAR research, with direct application to interpreting geophysical and geochemical observations. Laboratory experiments are also critical to replicate reactions and processes occurring beyond the reach of direct sampling, especially under variable conditions of pressure, temperature, composition, stress, strain, and oxygen and water fugacity. Advances in experimental rock and mineral physics are driven by the priority science questions, as well as by new technology.

An overarching theme across multiple science questions in Chapter 2 is to improve our fundamental understanding of how Earth's interior, surface, and atmosphere have co-evolved through time. Because pressure is force over area, the deeper into Earth's interior geoscientists need to explore to answer these questions, the higher are the forces and/or smaller are the samples available for study. These limitations create a challenge to generate high-pressure samples that are large enough for certain measurements, such as dynamic compression experiments or high-pressure deformation experiments on samples with large grains, or to work at conditions deep in the lower mantle with multi-millimeter-sized samples. Expanding the pressure range and sample size simultaneously will facilitate the development of new types of physical properties measurements at variable length, frequency, and time scales that cannot be achieved with existing multi-anvil technology.

The rock and mineral physics community is poised to create a user facility with pressure and sample-size capabilities beyond what is currently available in the United States. A multipurpose, very large multi-anvil press in the 5,000-10,000-ton range would greatly expand the community ability to synthesize novel samples and to conduct physical properties and deformation experiments in new regimes. In July 2015, ahead of the 2016 COMPRES renewal proposal, the high-pressure community held a workshop titled *U.S. Large Multi-Anvil Press Facility* to explore community needs and opportunities.[17] Although COMPRES was renewed, the very large multi-anvil press and its startup costs of $2-3 million were beyond the financial scope of the current cooperative agreement.

Recurring costs for this press could be as low as one full-time staff position, if the selected site already runs large-volume, high-pressure facilities. Therefore, this facility could be achieved with a modest one-time instrument investment, while the recurring staff costs could potentially fall within the financial and science scope of an existing facility such as COMPRES or GSECARS. There is opportunity for partnerships across agencies (e.g., NASA and DOE) as well as within NSF (e.g., such as the Division of Materials Research, where discovery and design strategies for materials in extreme environments is identified among top science priorities for the next decade [Faber et al., 2017]). The high-pressure community is poised to accomplish these goals within existing community organization and access models.

Recommendation: EAR should fund a Very Large Multi-Anvil Press User Facility.

Near-Surface Geophysics Center

Geophysical surveys have become an essential tool for investigation of the near-surface region of the Earth, which is generally considered to extend from the ground surface to depths of tens to hundreds of meters (e.g., Kruse, 2013). This region profoundly influences how the Earth works. Most of the science priority questions posed here are either centered in this near-surface region or have a component that is involved. Investigation of Earth deformation, as expressed through surface rupture and near-surface structure of fault zones, provides insight about the mechanisms of earthquakes. Gravity, seismic, and magnetic surveys on volcanoes reveal deformation, flow patterns, and underlying stratigraphy. The critical zone is rooted in this near-surface environment, and it is through the critical zone that the subsurface interacts with the atmosphere. Geophysical surveys can document porosity, moisture

[17] See https://compres.unm.edu/workshop/us-large-multi-anvil-workshop (accessed January 9, 2020).

retention, and structure of the subsurface materials that controls moisture availability to plants, groundwater storage, runoff, and thus streamflow in channels, and the pathways and fate of solutes and contaminants. Such surveys have already strongly influenced our understanding of critical zone structure and processes (see Figure 2-13) and will be essential to mapping the critical zone at the continental scale. The water cycle operates mostly in this near-surface domain. Subsurface material properties also influence strength and pore pressure evolution, which control susceptibility to landsliding, ultimately influencing the slope and height of hillslopes and mountains. Permafrost develops in this near-surface region and the advancing thaw that is now occurring threatens to release significant quantities of methane to the atmosphere, change rates of landsliding, reduce coastal bluff stability, and lead to increased stream bank erosion.

Over the past two decades there has been a progressive growth of near-surface geophysics as a discipline. There have been significant advances in technology, of instrument integration into many fields of research, and of the formation of research groups in several universities. In 2008, Robinson et al. summarized opportunities for research advances in watershed hydrology using near-surface geophysics and called for a shared facility that would provide access to equipment and would be a center of research and equipment development. They specifically included airborne methods as a means to survey larger areas. In 2010, the NRC report *Landscapes on the Edge: New Horizons for Research on Earth's Surface* summarized the many applications of near-surface geophysics to Earth surface process research and noted that the IRIS model of instrumentation support could possibly be used for shallow geophysics applications. In a community workshop report on future geophysical facilities needed to address grand challenges in the Earth sciences, Aster et al. (2015) noted that the surface processes community currently did not have access to the wide range of geophysical tools, nor the technical support or user training, to take advantage of the considerable capabilities of near-surface geophysics. Their list included ground-penetrating radar, seismic refraction and reflection, nuclear magnetic resonance, magnetotellurics, electrical resistivity, magnetic gradiometry, microgravity, and time and frequency domain electromagnetic systems. They also suggested the need for downhole logging instrumentation capabilities that would include fluid temperature/conductivity, resistivity, natural gamma, flowmeters, caliper, sonic, and acoustic and optical borehole tele-viewers. In both 2016 and 2019, IRIS included funding for a near-surface geophysics center in its larger geophysics instrumentation proposals but did not receive funding.

A Near-Surface Geophysics Center is needed to meet EAR community research needs across a broad range of disciplines and to address most of the science priority questions posed here. Community support for this is well established. Because of the evolving landscape of new technological applications in the near-surface domain, it is impractical for distributed research groups at various universities both to support the research needs of this broad community and to stay abreast of changing technology. Furthermore, such a center can provide training in both data acquisition and analysis for new and established researchers. Such a center would not only enable answers to fundamental questions, it will also lead to new questions and insights.

The cost for a Near-Surface Geophysics Facility would depend on the range of equipment to be supported, number of instruments, and staffing needs. An estimate could be approximately $6 million over 4 years. There would likely be cost efficiencies if it were incorporated into other, existing instrumentation centers.

Recommendation: EAR should fund a Near-Surface Geophysics Center.

The SZ4D Initiative

The SZ4D initiative emerged from a 2016 NSF-sponsored workshop on subduction zone observatories. The workshop attendees developed a vision document for infrastructure and physical process modeling to enable a deeper understanding of the four-dimensional evolution of processes at subduction zones that create geohazards and drive the evolution of the solid Earth (McGuire et al., 2017). The initiative seeks to capture and model key subduction-related phenomena as they evolve both in real time and geological time. SZ4D would enable activities that are currently difficult or impossible.

The initiative has four science questions that dovetail with several of the science priority questions discussed in Chapter 2: (1) When and where do large earthquakes happen?; (2) How is mantle magma production connected through the crust to volcanoes?; (3) How do spatial variations in subduction affect seismicity and magmatism?; and (4) How do surface processes link to subduction? SZ4D seeks to quantify mass, stress, and fluid fluxes between the plate boundary and shallow crustal faults that threaten coastal cities. New multidisciplinary datasets are needed for this, both in the United States and globally. Possible activities within this initiative could be to instrument offshore seismic gaps to capture large ruptures sufficiently well to derive the frictional, hydrologic, and thermal behavior before and during slip and in the excitation of a tsunami, or the ability to track subsurface motion and storage of magma on time scales of hours to months and relate it to the events leading to eruptions.

SZ4D is currently in the planning stage. NSF has funded ~$1.2 million over the past few years to support three research coordination networks: CONVERSE, the Modeling Collaboratory for Subduction, and the SZ4D RCN. The steering committee anticipates having a community-drafted implementation plan in place by the end of 2021. The initiative's 10-year goal is a deeper understanding of subduction phenomena that advances the ability to forecast earthquakes, tsunamis, and potentially volcanic eruptions. There are strong possible collaborative links with other federal agencies, including USGS, NASA, and NOAA, as well as the opportunity for synergy with international partners. There is also opportunity to partner with OCE on the aspects of SZ4D that cross the shoreline, including seafloor observations and instrumentation.

The modeling collaboratory is conceived as an interdisciplinary center geared toward model building and testing with the goal of advancing the understanding of subduction zones in the context of a multi-scale, multi-physics Earth. The center would coordinate and support the distributed development of a diverse set of numerical codes, training, scientific exchange, and access to large-scale computations. A key objective would be to provide new physical models for time-dependent hazard assessment (e.g., to complement probabilistic approaches in the evaluation of possible tectonic precursors in global seafloor observatories). This RCN held a kickoff workshop and has planned or held three science workshops—on fluid transport (May 2019), megathrusts (August 2019), and volcano modeling (planned for July 2020). These workshops have been accompanied by a series of cyberinfrastructure webinars, and the organizers have planned another series (January-May 2020) focused on collaborations between observationalists and modelers.

In 2020, the volcanological community is moving to build CONVERSE into a permanent consortium of academic and federal institutions with expertise in volcano science that use geological, geophysical, and geochemical hardware and infrastructure to respond rapidly to developing volcanic crises and to facilitate volcano science in the United States. The consortium of academic and USGS scientists would facilitate investigations of cycles of volcanic unrest and eruption, principally at U.S. volcanoes, by acquiring and maintaining a suite of dedicated communal hardware; archiving and promoting free and unrestricted access to volcanological data and samples from documented eruptions; facilitating volcanological research and education via workshops and symposia; and coordinating promotion of volcano sciences, including outreach to the public. A series of nine planning workshops have been held and a white paper will be released in 2020. The initial hardware investment is likely to be approximately $3-5 million, with recurring materials and human resources costs estimated at $300,000 per year.

Recommendation: EAR should support continued community development of the SZ4D initiative, including the Community Network for Volcanic Eruption Response.

Continental Critical Zone

Five of the science priority questions proposed in Chapter 2—those associated with paleoclimate, topographic change, the water cycle, geohazards, and the critical zone itself—highlight processes that occur within the critical zone. While satellite mapping and aerial surveys can provide data to characterize vegetation and surface topography (and their dynamics), the subsurface critical zone below the soil is largely uncharted, invisible, and difficult to access. Without a systematic and focused effort to generate maps of subsurface properties over large areas, progress on these questions will be limited. There is a need to incorporate the critical zone in the water, carbon, and nutrient cycles, in landscape evolution and hazards prediction, and in climate interactions. Early, coarse efforts to create global maps (Pelletier et al., 2016; Xu and Liu, 2017) have pointed to the value of such integrated maps, as well as the need for field data. Local, intensive process studies and critical zone mapping have great value in discovering and quantifying key processes, but extending that understanding to watershed or continental scales is inhibited by the guesswork of characterizing the subsurface critical zone. Quantification of the subsurface structure of the critical zone is a frontier research area and challenge for our times, the results of which will inform both basic research and practical applications. Without a planned long-term campaign to achieve this goal, this vital part of our planet will remain unknown but for the equivalent of point measurements.

Soil scientists have created regional, continental, and global maps through a system of field sampling intended to test (for a given climatic zone) hypotheses about the relationship of soil properties to surface features (e.g., topography, vegetation, lithology) (U.S. Natural Resources Conservation Service Soil Science Division, 2017). Field-defined point associations then use these readily mapped surface features to create soil maps over large areas. This effort has led to global soil maps that are used to predict soil moisture storage potential and surface runoff climate models. Similar information derived from mapping is needed to the full depth of the critical zone. While soil depth can be readily drilled by hand or exposed by digging, the critical zone is mostly inaccessible by such means.

The challenge will be how to construct and deploy a major mapping campaign to characterize the subsurface critical zone over large areas. A Continental Critical Zone Initiative would create an opportunity for such a program to be developed. This will require collaboration across the geosciences: climate scientists, geologists, geomorphologists, hydrologists, geophysicists, geochemists, and soil scientists would need to bring their collective expertise to conceive of ways to address this challenge. Theory, modeling, and field knowledge and experience will all be needed to design an efficient mapping program that provides data of sufficient resolution for the wide range of science questions involving subsurface critical zone processes. Theory that predicts critical zone properties across landscapes (e.g., Riebe et al., 2017) would be used to create stratified sampling programs. Climate, hydrologic, and landscape evolution models would define what critical zone properties are essential to quantify and illustrate over what spatial resolution these properties need to be defined. Field knowledge of particular regions will play an essential role in hypothesizing critical zone patterns that need to be mapped. All of this must come together to design field campaigns to illuminate the subsurface critical zone.

The specific methods used in such an ambitious mapping effort would only emerge after development from a working group of community members. The field campaign would likely rely on a mixture of ground and possibly aerial geophysical surveys, combined with borehole geophysics and local monitoring. The continental scope and decadal-scale duration of such a campaign could encourage technology innovation in both aerial and ground surveys, which could increase vertical resolution and operation speed, respectively. Seismic refraction lines, possibly combined with ground-penetrating radar and electrical resistivity for ground surveys, would be primary ground survey tools (e.g., Holbrook et al., 2014; Parsekian et al., 2015; Carey et al., 2019). Aerial electromagnetic surveys may play an important role in estimating critical zone structure, especially in difficult-to-access areas. Moisture detection tools (e.g., ground- and space-based gravity, GPS, cosmic ray neutron probes, and ambient noise seismology) could give both information on water storage dynamics and inference about critical zone structure. Boreholes can characterize the vertical structure of the critical zone and relate geophysical indirect measures to observed properties, and could also be used for downhole moisture dynamics monitoring (using nuclear magnetic resonance and neutron probes) and groundwater level tracking.

Development of this field mapping program could start with trial locations, where methods, equipment, and theory application can be explored. Significant progress could be accomplished in 10 years if several field teams were to work simultaneously across the continent. Just as topographic maps have continually improved with advances in technology, so too would mapping of the subsurface critical zone. This initiative would interact strongly with the proposed Near-Surface Geophysics Center, becoming an essential training program.

The Continental Critical Zone initiative would enable the investigation of many questions and improve considerably our understanding of how Earth's surface works and interacts with the atmosphere. For example, it is needed to predict how vegetation, water resources, and climate will co-evolve. This campaign will also reveal the degree to which subsurface critical zone properties co-evolve with surface topography and provide data to test theories for co-evolution. Hydrologic modeling at watershed to continental scale will for the first time have field characterization of subsurface critical zone properties over large areas, rather than relying simply on inference from limited data. Large-scale mapping of the subsurface critical zone will also enhance landslide risk prediction.

It will take inspired and sustained leadership from the community to meet these ambitious goals. Because of the scope of this potential program, it may eventually take decades to complete and cost more than $100 million. A smaller Continental Critical Zone pilot could be initiated at a cost of ~$5 million over 5 years. However, such an effort would be best pursued in collaboration with the many state and federal agencies with expertise and information on water resources, geology, soils, and other natural resources of the critical zone. In particular, USGS would play an essential role due to its expertise in mapping natural resources; DOE national laboratories could provide considerable experience based on the Watershed Function Scientific Focus Area study of the East River in the upper Colorado River basin (e.g., Wan et al., 2019); and NASA could contribute spectral and gravity data from satellite-based observing platforms, which provide global scale information on surface properties and water storage, the spatial pattern of which may covary with subsurface critical zone conditions.

Recommendation: EAR should encourage the community to explore a Continental Critical Zone initiative.

Continental Scientific Drilling

A theme that intersects many of the science priority questions is the need to acquire continuous cores from continental scientific drilling, an endeavor that has up to now received only modest investment from NSF. Continental scientific drilling has shown it can (1) provide a high-resolution geological time scale via geochronology, orbital astrochronology, and paleomagnetic polarity stratigraphy; (2) obtain climate and other environmental records; (3) sample zones of active processes that involve magma, geothermal fluids, mineral alteration, faults, and crustal deformation; and (4) sample and monitor the deep biosphere. Drilling and coring are essential because outcrop is often discontinuous, missing, or weathered. Continuous records from continents are important to access geologic histories beyond the age of the oldest ocean floor and recover records of continental and marine climates, environments, and biota. Advances in rapid core chemical analysis (X-ray fluorescence, laser induced breakdown spectroscopy), geochronological techniques, and core imaging make the time right for NSF to encourage community planning for a U.S. continental scientific drilling program.

Scientific continental drilling can access sedimentary archives and samples of subsurface materials and can monitor deep active processes that cannot be reached from the surface. It provides a mechanism of accessing long records of the deep history of the Earth. Records of tectonic processes involving sedimentary basins, plate motions, and heat flow in active continental basins can be accessed via continental drilling, as well as records of past variability and phenomena with characteristic time scales beyond the duration of instrumental and written history. Relationships between potential drivers and pacers of change can be explored through continental scientific drilling, and pristine proxy records of biogeochemical changes can be recovered.

Community interest[18] supports an invigorated effort toward a U.S. continental scientific drilling program to address interdisciplinary Earth system questions, including several priority questions in this report. While planning and core processing support (CSDCO and LacCore, respectively) are available as EAR facilities, a lack of funding through a dedicated U.S. continental scientific drilling program is a major impediment to progress. Currently, funding for U.S. researchers in continental drilling requires separate proposals for science (to NSF) and drilling support (ICDP, which is worldwide). This structure ends up with project lead times from 5 to 10 years, making scientific drilling projects outside the scope of early-career investigators and increasing the burden on investigators to get commitments of funding for laboratories and graduate students at their home institutions. The community needs a more directed mechanism for support of scientific drilling.

Recommendation: EAR should encourage the community to explore a Continental Scientific Drilling initiative.

Earth Archives

This report emphasizes the need to procure, curate, and archive digital data on geological materials and records in a way that will continue to make physical, chemical, and biological information accessible and useful to Earth scientists. No less important is the need

[18] See the GSA Continental Scientific Drilling section (1,700 members) (https://community.geosociety.org/continentaldrilling/home [accessed December 27, 2019]) and the EarthRates white papers (https://earthrates.org/2018/02/06/ninewhitepapers [accessed December 27, 2019] and https://drive.google.com/file/d/1CJDJHi1KxC8jOd87lAVj-gkp-0-p5W5I/view [accessed December 27, 2019]).

to archive the very materials—those that already exist and those yet to be acquired—from which the data are extracted. This need reflects both the basic standards of reproducibility and the recognition that new questions and analytical methods are continually being introduced to Earth science, thus making physical archives invaluable to scientists many years after the relevant materials were collected. Even if one were willing to invest the time and money needed to replicate a physical collection, that would often not be possible because materials are unique or ephemeral or found only at localities that are no longer accessible. The importance of archiving materials has been previously addressed (e.g., *Geoscience Data and Collections: National Resources in Peril* [NRC, 2002]), but remains a critical issue for many Earth science disciplines.

As is clear in the science priority questions, the geomaterials needed for future scientific utility span an enormous range. Important Earth materials include cores from oceanic, lacustrine, and continental drilling; rock samples from outcrops; unconsolidated sediments; soils; air, gas, and water samples; minerals; fossils; preserved parts of living organisms, including DNA and other biomolecules; hydrocarbons; and experimentally produced materials such as high-pressure and high-temperature mineral phases.

Although some selective archiving efforts exist (e.g., museum collections of minerals, rocks, and fossils; and cores obtained through scientific ocean drilling), such efforts fall short of satisfying an urgent need to halt the ongoing loss of Earth science collections through neglect, lack of curation, lack of funds and space, and other factors. Community input received by the committee pointed to a widely recognized priority for preserving physical archives relevant to Earth science, many of which have been and will be enabled by NSF funding. Moreover, for such archives to be useful, they must be linked with adequate metadata and with derived measurements and products in digital archives, according to community standards, so that researchers know of their existence and can access them. This community input echoes views that have been expressed for years (e.g., NRC, 2002) but that have not been adequately addressed. That report made a compelling case for why long-term storage of materials that have no immediate obvious further use can benefit society and researchers in unanticipated ways. Additionally, new data mining methods could enable discoveries in legacy seismic data that are currently in precarious storage settings on paper and other physical media.[19] Conversion to machine-readable formats would preserve and extend seismological observations of the Earth back many decades.

Unfortunately, space and funding at universities are generally insufficient to allow long-term storage of physical samples, with the effect that important scientific collections commonly languish or vanish after a student graduates or a career scientist retires. Moreover, even the museums whose central mission includes indefinite curation must make difficult choices about which materials to accept into their often-crowded facilities. A further challenge relates to the question of whether materials are archived in regional or national facilities or in the numerous institutional homes of individual researchers.

At least two alternative general approaches could facilitate archiving and curation. An all-purpose, centralized repository presents financial and logistical challenges that would argue for a distributed network of archives that reflect specific community interests, as proposed in *Geoscience Data and Collections* (NRC, 2002). However, even a network of highly localized collections, some as small as the career acquisitions of an individual researcher, requires predictable resources to sustain curation and ensure accessibility after key scientists retire. Archiving of geomaterials would benefit enormously from collaboration with a diverse set of partners, including universities, state geological surveys, USGS, the Smithsonian Institution, and other national, state, private, and municipal museums.

In the face of finite resources, it is unrealistic to propose that every physical sample should be preserved. At the same time, it is essential to bear in mind that instances of future use may well be unanticipated. This topic is crucial to address, as there are numerous examples of novel and significant studies that have been possible thanks to careful curation of geomaterials. These include the evidence for an early Earth with an active hydrologic cycle, neutral rather than strongly reducing atmosphere, and silica-rich crust potentially indicative of plate tectonics, provided by geochemical analyses of Hadean zircons that were initially collected for geochronology (Mojzsis et al., 2001; Watson and Harrison, 2005; Trail et al., 2011; Boehnke et al., 2018). Another example is the discovery of gradients in sediment characteristics with distance from the end-Cretaceous Chicxulub impact site (Schulte et al., 2010), based on analysis of the global distribution of ejecta from continental and marine drill cores generated over more than two decades.

[19] See https://geodynamics.org/cig/events/calendar/2019-seismic-legacy (accessed November 1, 2019).

Recommendation: EAR should facilitate a community working group to develop mechanisms for archiving and curation of currently existing and future physical samples and for funding such efforts.

CONCLUSIONS AND RECOMMENDATIONS FOR CYBERINFRASTRUCTURE AND HUMAN INFRASTRUCTURE

In the following sections, the committee presents conclusions and recommendations on cyberinfrastructure and human infrastructure, which are critical to a robust future for Earth science. Implementing the recommendations for cyberinfrastructure and human infrastructure will require not just a commitment of funding, but significant changes to "business as usual" for the Earth science community. This could include the flexibility to adapt the core disciplinary research programs as new technologies, questions, and opportunities appear and as research becomes more interdisciplinary.

Cyberinfrastructure

Earth science is experiencing an explosion of data acquisition capability and rapidly increasing computational demands, as models advance to exploit these data and ever-increasing hardware capabilities. The computational environment, especially modeling capabilities, is and will continue to rapidly evolve. In addition, massive amounts of legacy data have been acquired that are at risk of being lost. Following are several significant challenges for Earth science cyberinfrastructure, as well as recommendations that EAR may wish to consider.

Data Management and Archiving

The Earth science communities collectively generate enormous quantities of data that are scientifically valuable but heterogeneous in format. Experience also indicates that it is often difficult and frustrating to locate and retrieve archived data even if they have been well curated. Moreover, much of our important legacy data (e.g., paper seismograms or publications describing fossil collections) have not even been digitized. Essential needs include (1) making legacy data digitally available along with the metadata that are crucial to their utility, an endeavor that may well involve development of machine learning approaches; (2) development of community standards for data and metadata fields; (3) development of methods for archiving, curating, analyzing, and visualizing data as they are being produced; and (4) reliable, sustained support for databases so that they do not become obsolete or unavailable after a single funding cycle.

The needs for data archiving and access will continue to grow in the coming decade, and the great diversity of data types is likely to make the development of a single, centralized database infeasible. Support is needed for community groups, most likely working collaboratively with computer and data scientists, to develop/establish long-term data storage systems. Because the creation of such databases explicitly falls outside most of the EAR-supported cyberinfrastructure funding opportunities, such proposals must currently compete with other research proposals within the core disciplinary programs. The cost likely exceeds the capability of any single NSF division. However, if EAR-supported data and analyses are not easily available to other members of the scientific community or the general public, the benefit is lost.

FAIR Standards

The scientific community at large is increasingly recognizing the benefits of open science principles (e.g., NASEM, 2018b) and of adopting FAIR data criteria (findable, accessible, interoperable, reusable; Wilkinson et al., 2016). FAIR data standards will improve the longevity, utility, and impact of EAR-funded data, especially when compared with current data plans on individual grants. Additionally, many journals[20] already require that published data meet FAIR data standards independent of existing data management policies at NSF. The adoption of FAIR standards by journals in effect represents an unfunded mandate for researchers. Although EarthCube promotes FAIR practices in spirit,[21] the committee is not aware of any GEO-wide implementation strategy.[22]

The committee sees a community desire for funding to support FAIR data practices, but it also recognizes that the financial cost makes general EAR support for long-term, compliant data storage difficult in times of

[20] See https://publications.agu.org/author-resource-center/publication-policies/data-policy (accessed December 27, 2019).
[21] See https://www.earthcube.org/FAIR (accessed December 27, 2019).
[22] See https://www.nsf.gov/geo/geo-data-policies/index.jsp (accessed December 27, 2019).

level budgets. Beyond financial limitations, there is the challenge of meeting FAIR data standards in a way that is attentive to the benefit and effort to achieve compliance. Existing examples of EAR-funded data resources, such as IEDA and Neotoma, can be used as models of best practice for other communities.

Recommendation: EAR should develop and implement a strategy to provide support for FAIR practices within community-based data efforts.

Evolving Computation Needs

EAR faces a challenge in its attempts to keep pace with the rapidly evolving computational landscape (including cloud, graphics processing unit, edge, and possibly quantum computing). At the current time, the potential for these new technologies may currently be outpacing our understanding of how it will be applied in practice, but over the next decade, the integration of Earth science and cutting-edge computational tools will be needed to advance the field. EAR researchers will need access to state-of-the-art hardware, including not only NSF-wide facilities but private sector and other government facilities, such as DOE and national laboratories; scalable software and computer engineering expertise to help develop it, including strategies to extract information from large data volumes or simulations; and increased development of a computationally savvy Earth science workforce (described below). This may be achieved quickly by partnering with other computationally oriented divisions within NSF and in other federal agencies. NSF's Big Idea on Harnessing the Data Revolution may also provide an opportunity for EAR researchers to take advantage of new modes of computational Earth science.

EAR faces a challenge in keeping pace with the rapidly evolving computational landscape.

Guidance for EAR

In order to make optimal investments of resources in the coming decade, EAR needs regular guidance about the needs of its researchers, opportunities in cyberinfrastructure, and changing computational and modeling capabilities. This need takes on greater relevance because funding for EarthCube is not currently planned beyond 2021 (E. Zanzerkia, NSF, personal communication). A standing committee to provide this type of guidance, composed of representatives from academia, industry, and federal agencies, could report on emerging hardware, software, and data storage capabilities and help identify opportunities to effectively exploit this dynamic cyberinfrastructure environment.

Recommendation: EAR should initiate a community-based standing committee to advise EAR regarding cyberinfrastructure needs and advances.

Human Infrastructure

In order to attain the scientific and infrastructure goals put forward in this report, a robust and innovative workforce is needed. Yet, Earth science as a community still faces many challenges in developing and sustaining sufficient capacity, expertise, and diversity. In the following sections, several aspects of human infrastructure that will be central to advancing Earth science in the coming decade are highlighted.

Technical Staff

Highly trained individuals in science, technology, engineering, and mathematics (STEM) are an essential part of Earth science infrastructure and are central to future breakthroughs and the continued relevance of geoscience to societal issues. There are challenges to recruit and retain a highly competent and inclusive STEM workforce with expertise in Earth, data, and computational sciences because of increasing competition from other fields of science and engineering, as well as from high-paying industry jobs, especially in the computational sector.

As Earth data science and analytical technology become more sophisticated, the expertise of technical staff becomes one of the limiting factors for data collection, curation, visualization, analysis, and dissemination—all aspects that contribute to rigorous and meaningful results. The availability of competitive, long-term funding is critical for the development and continuity of technical knowledge, expertise, and experience. Enabling a high-quality technical staff as part of EAR infrastructure promotes cross-disciplinary collaboration and education and supports the long-term success of EAR investigators. The collaborations made possible by stable technical staff lead to technical and conceptual innovation, contribute to the future STEM workforce, and ultimately lead to solutions to the most pressing challenges in Earth science. As computationally intensive research expands across Earth science, software engineers and people with computational and numerical training will become more prevalent among Earth science technical staff. To drive innovation in instrument design and development, technical staff with expertise in electrical engineering, mechanical engineering, and materials science will be needed.

Preparing the next generation of Earth scientists for an increasingly technological field will be enhanced by strengthening financial support for technical staff in a way that is competitive with other disciplines and fields. Trained and highly skilled staff are needed to tackle the science priority questions about the complex Earth system at analytical, computational, sequencing, and instrument development facilities. However, these needs come at a time when many U.S. geoscience departments are struggling to maintain support for technical staff because institutional support has decreased.[23] In addition, long-term support of technical staff becomes progressively harder as early-career scientists move into tenured positions, promotions that commonly do not come with additional research funds. These trends put staff members in a financially precarious position and potentially interrupt the transfer of knowledge.

Recommendation: EAR should commit to long-term funding that develops and sustains technical staff capacity, stability, and competitiveness.

Training Earth Data and Computational Scientists

Heavy computational work and an understanding of machine learning algorithms are required to integrate modeling with field observations or analytical data. Future Earth scientists will need to be trained in an increasingly quantitative educational framework, both for data analysis and reduction as well as high-performance computing. Balanced training in geoscience with high-performance computing would train Earth scientists with computational skills, as opposed to computer scientists with some knowledge of geoscience. This type of training will need targeted strategies that lead to the development of more expertise in terms of both cyber-savvy Earth scientists and Earth science–savvy computer scientists and software engineers, and will increase the potential workforce pool of future Earth data scientists.

Diversity, Equity, and Inclusion

Enhancing innovation through the diverse perspectives of scientists with a wide range of expertise, experiences, and identities is critical to addressing the science priority questions described in Chapter 2. Diversity leads to wide-ranging benefits, including improved problem solving, effectiveness of teams, and public Earth and environmental science literacy (e.g., NASEM, 2011; NRC, 2012; Atchison and Gilley, 2015; Nielsen et al., 2017). Diverse groups also publish more and get cited more often (Freeman and Huang, 2014; Powell, 2018). In addition to arguments about advancing the science itself, there is an ethical argument against having scientific knowledge and associated power invested only in limited portions of the population. The inclusion of diversity in all aspects of research and collaborations, from study design to dissemination, also garners better participation from and improves the relevance of science to marginalized communities (e.g., Stewart and Valian, 2018).

Despite these benefits, Earth science remains one of the least diverse STEM fields with respect to underrepresented minorities (American Indian or Alaska Native, Black or African American, Pacific Islander, and Hispanic or Latino groups) (Gonzales, 2010; NCSES, 2019; see Figure 3-4). Recent analyses show that long-term efforts have not broadened representation of historically underrepresented groups in the Earth sciences and that gains in diversity lag other STEM disciplines (McDaris et al., 2018). Over the past 40 years, racial diversity in geoscience Ph.D. programs has not significantly improved and as recently as 2012, underrepresented minorities held less than 4% of the tenure-track or tenured faculty positions in the top 100 U.S. Earth science departments (Nelson, 2017; Bernard and Cooperdock, 2018). With respect to gender diversity, as of 2017, women still held only 20% of all geoscience faculty positions at 4-year institutions in the United States, despite being awarded nearly half of the Ph.D. degrees in the field (Wilson, 2019). Going forward, diversity and inclusion must be thought of in the broadest terms to address systematic barriers to opportunity across the full range of "personal attributes, cultural affiliations, and professional or socioeconom-

[23] For example, see https://www.cbpp.org/research/state-budget-and-tax/unkept-promises-state-cuts-to-higher-education-threaten-access-and (accessed December 6, 2019).

ic status" (AGU, 2018). In addition to race and gender, protected characteristics include gender identity, gender expression, sexual orientation, parental status, age, ability, citizenship status, and veteran status, among others that constitute all people of society.

Part of the challenge in changing trends in diversity lies in changing the pervasive culture of harassment (verbal, physical, or visual), bullying, and discrimination (NASEM, 2018c). In response to the persistent problem of sexual harassment in professional settings, several professional societies have adopted codes of conduct and ethics standards to clarify expectations regarding appropriate behavior and to enforce those expectations with sanctions when necessary (e.g., American Geophysical Union [AGU] Scientific Integrity and Professional Ethics [AGU, 2017]; Geological Society of America [GSA] Code of Ethics and Personal Conduct [GSA, 2019]). While awareness of these issues is on the rise, existing data paint an incomplete picture of the varied ways in which underrepresented and marginalized groups are affected. Nonetheless, the representation and inclusion of diversity in our discipline continues to impede scientific progress and education (Nielsen et al., 2017).

There have been a variety of initiatives to address this problem at the division (EAR), directorate (GEO) and agency-wide (NSF) levels, including the Enhancing Diversity in the Geosciences program (NSF, 2001) through which GEO awarded more than $50 million in grant funding for research on broadening participation strategies from 2001 to 2013. More recent investments include GEO Opportunities for Leadership in Diversity (GOLD) and GOLD-Expanding Networks pilot projects, which bring together Earth and social scientists to develop effective professional development strategies to improve diversity, equity, and inclusion. EAR also contributes to other initiatives such as the Research Experience for Undergraduate programs, CAREER awards, and broader impacts activities in individual science programs. Lessons learned from two decades of intense NSF focus and investment in research on strategies to enhance diversity and inclusion can be used to inform best practices and drive future progress (e.g., NASEM, 2018c; Karsten, 2019; Posselt et al., 2019).

While individual communities, institutions, professional organizations, and partnerships among these groups (e.g., Earth Science Women's Network, GeoLatinas, Association for Women Geoscientists, AGU Bridge Program, ADVANCE GEO, National Association of Black Geoscientists) have made progress through their own initiatives, EAR could participate more directly in partnerships with institutions and professional or-

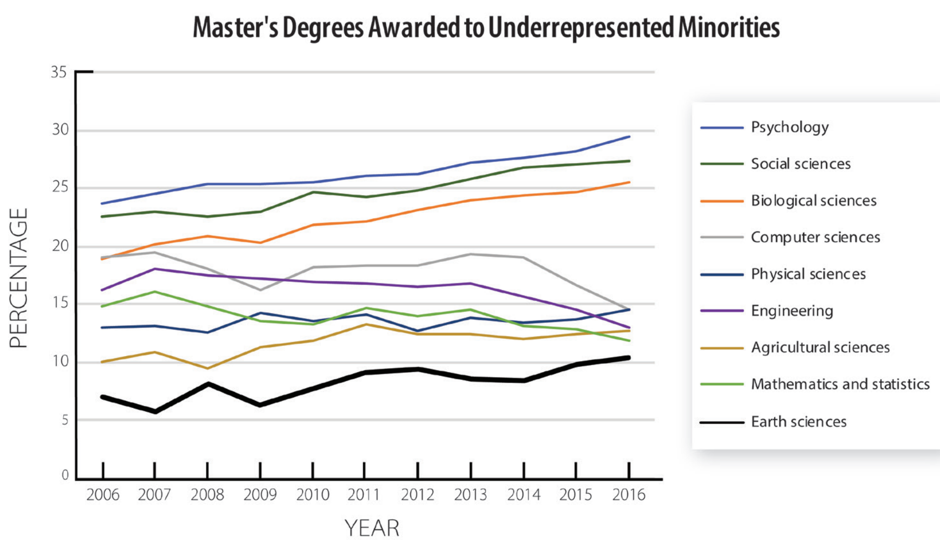

FIGURE 3-4 Master's degrees awarded to underrepresented minorities. The percentages represent the total number of reported nonwhite recipients of master's degrees who are U.S. citizens or permanent residents where nonwhite refers to the total from the following categories: Hispanic or Latino, American Indian or Alaska Native, Asian or Pacific Islander, Black or African American, Native Hawaiian or Other Pacific Islander. Equivalent data for bachelor's and doctoral degrees show a similar pattern, with Earth sciences ranking consistently below all the other scientific disciplines shown here, but with totals of 6% in 2006 and in 2016 for both degrees, showing no net change over the decade. SOURCES: Data from the National Science Foundation, National Center for Science and Engineering Statistics, special tabulations of the U.S. Department of Education, National Center for Education Statistics, Integrated Postsecondary Education Data System, Completions Survey, unrevised provisional release data. See https://ncses.nsf.gov/pubs/nsf19304/data (accessed March 27, 2020).

ganizations. Furthermore, the EAR community would benefit from centralized resource sharing, including access to guidance on best practices and emerging research on effective and scalable strategies. This centralized guidance could also highlight key best practices of education (e.g., Teach the Earth On-Ramps quick-start guides)[24] and outreach, many of which intersect with issues related to diversity, equity, and inclusion. The present demographics of the Earth science community hinders our collective ability to communicate and bring Earth science expertise to diverse communities (McDaris et al., 2018). One approach to address this includes community-engaged partnerships that involve individuals who are not Earth scientists to address local issues such as land use, water quality, and local effects of climate change.

While it is beyond the scope of this report to prescribe specific strategies to improve the diversity of the Earth science community, it is clear that the goal of improving diversity needs to rise higher as a priority in order to achieve a cultural shift where the burden of doing so does not rest disproportionately on those within underrepresented groups. Instead, it needs to be recognized as a core value within the Earth science community and driven in part by increased and wider community participation in this effort (Karsten, 2019; Dutt, 2020).

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.

[24] See https://serc.carleton.edu/onramps/index.html (accessed March 27, 2020).

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4
Partnerships

The complex, interdisciplinary nature of Earth science provides outstanding opportunities to increase the impact of Division of Earth Sciences (EAR)-sponsored research through partnerships, both within the National Science Foundation (NSF) and with other agencies. Effective scientific partnerships are essential for creating productive collaborations, leveraging usage of facilities, and ensuring prudent use of research dollars. The potential of such interactions is central to the third task of the committee's study charge, which is a discussion of how EAR can leverage and complement the capabilities, expertise, and strategic plans of its partners to encourage greater collaboration and maximize shared use of research assets and data.

Over the course of this study, the committee spoke with representatives throughout NSF, including the Directorate for Geosciences (GEO); the Divisions of Earth Sciences (EAR), Ocean Sciences (OCE), and Atmospheric and Geospace Sciences (AGS), and the Office of Polar Programs (OPP); the Office of International Science and Engineering (OISE); and the Directorates for Computer and Information Science and Engineering (CISE), Engineering (ENG), and Biological Sciences (BIO). In addition, the committee also spoke with a number of other federal agencies, including the U.S. Geological Survey (USGS), the National Aeronautics and Space Administration (NASA), the U.S. Department of Agriculture (USDA), and the U.S. Department of Energy (DOE). Box 4-1 provides the acronyms used throughout this chapter.

The committee was also informed by the community input responses to the questionnaire, which asked participants, "How might NSF best leverage this research and infrastructure through collaboration with other NSF divisions and directorates, federal agencies, and domestic and international partners?" These discussions and inputs form the basis of the committee's response to its task.

BOX 4-1
ACRONYMS FOR NSF DIRECTORATES AND OTHER FEDERAL AGENCIES

NSF Directorates

BIO: Directorate for Biological Sciences
CISE: Directorate for Computer and Information Science and Engineering
ENG: Directorate for Engineering
GEO: Directorate for Geosciences

Geosciences Divisions

AGS: Division of Atmospheric and Geospace Sciences
EAR: Division of Earth Sciences
OCE: Division of Ocean Sciences
OPP: Office of Polar Programs

OISE: Office of International Science and Engineering

Other Federal Agencies

DOE: U.S. Department of Energy
NASA: National Aeronautics and Space Administration
NIH: National Institutes of Health
USACE: U.S. Army Corps of Engineers
USDA: U.S. Department of Agriculture
USGS: U.S. Geological Survey

PARTNERSHIPS WITHIN NSF

Division Level

EAR is one of four divisions within GEO. The others are OCE, AGS, and OPP. EAR has established strong relationships across these divisions and GEO in order to meet the needs of advancing research across the Earth system, not just within Earth science.

EAR

The committee invited EAR leadership and program directors to its first meeting and asked them for their thoughts on partnerships that EAR had within GEO, with other units of NSF, and with other federal agencies. The division director, section heads, and program directors noted a number of partnerships that exist at the division, directorate, and agency levels within NSF, as well as collaborations with other agencies such as NASA, USGS, DOE, and USDA. Discussants included Lina Patino, EAR Division Director; Stephen Harlan and Sonia Esperanca, Section Heads; and program directors throughout the division (listed in Appendix C).

Ongoing and new partnership opportunities such as Coastlines and People (CoPe), Signals in the Soil, Innovations at the Nexus of Food, Energy and Water Systems (INFEWS), and ideas stemming from NSF's 10 Big Ideas[1] were mentioned. CoPe[2] is a partnership of many NSF directorates—GEO, BIO, ENG, the Directorates for Social, Behavioral and Economic Sciences (SBE) and Education and Human Resources, and the Office of Integrative Activities (OIA). Projects will focus on capacity building and research related to impacts of natural processes and geohazards on coastal areas. This program also has direct applicability to national security; for example, some coastal military installations are facing threats to infrastructure and concerns about salinity and contaminants.

Signals in the Soil[3] partners programs within GEO, BIO, ENG, and CISE with USDA and several agencies in the United Kingdom to fund transformative research on soil processes through modeling and advanced sensors. INFEWS[4] partners GEO, ENG, SBE, and OIA with USDA to fund research that supports better understanding of the food–energy–water nexus as an integrated system. Built on the success of the Science, Engineering and Education for Sustainability-Water Sustainability and Climate program with similar participating partners, INFEWS fosters new and continuing collaborations among researchers from diverse disciplines to advance fundamental questions in this nexus. Each of these is an example of Growing Convergence Research, one of NSF's 10 Big Ideas. The Convergence initiative is encouraging NSF programs to bring together ideas from a wide variety of fields in order to inspire transdisciplinary research.

Program directors have fostered excellent international partnerships within EAR, including with China (National Natural Science Foundation of China), Israel (U.S.-Israel Binational Science Foundation), Taiwan, and the United Kingdom (National Environment Research Council). Section heads expressed a desire to strengthen these partnerships and have encouraged program directors to develop additional international collaborations. EAR is actively engaged in the Belmont Forum,[5] an international partnership for funding of research on environmental change. An important aspect of international partnerships is how essential they are to developing and strengthening the global scientific workforce and networks of international contacts. These contacts are increasingly important as science becomes more global. The community input supported increasing international collaboration and noted possible opportunities with Canada, China, the European Union, Germany, Japan, Mexico, the United Kingdom, and the United Nations Educational, Scientific and Cultural Organization's International Geoscience Programme.

However, respondents also recognized the challenges to international collaboration. International programs can work on a longer time scale than typical NSF programs, and there was some feeling among EAR program directors that some partnership programs were terminated just as they were becoming fully established, sometimes due to changes in division leadership. The budgeting, fiscal management, and project oversight environments can be significantly different. Rotation of program directors within NSF and in external agencies can also make it difficult to sustain new partnerships. Another issue raised was that international partnerships can increase program directors' workloads, especially when NSF leads the responsibility for review. Access to data remains a challenge to international partnerships, as not all countries share the same data policies as NSF.

Compared to other GEO programs (e.g., OCE, OPP), EAR has a larger number of research programs (seven), each covering a disciplinary area. This organizational scheme enhances a strong interaction of program personnel with researchers in specific core disciplines and is an important mechanism for supporting

[1] See https://www.nsf.gov/news/special_reports/big_ideas (accessed December 20, 2019).
[2] See https://www.nsf.gov/pubs/2019/nsf19059/nsf19059.jsp (accessed December 20, 2019).
[3] See https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505577 (accessed December 20, 2019).
[4] See https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=505241 (accessed December 20, 2019).
[5] See http://www.belmontforum.org (accessed December 20, 2019).

individual and small-group collaborations. EAR maintains this positive aspect of disciplinary research programs while also encouraging and supporting interdisciplinary research (e.g., through its Frontier Research in Earth Sciences [FRES][6] program). This is an important mechanism for supporting interdisciplinary research within EAR. However, given the vast scope of the Earth system in time and space, EAR may wish to consider other ways to increase funding flexibility to support interdisciplinary research across GEO divisions.

A nimble EAR can quickly take advantage of the shifting frontiers in basic science and interdisciplinary research.

Because Earth science is increasingly global, EAR-funded researchers benefit from international collaboration.

OCE

The committee spoke with Terry Quinn, OCE Division Director, and Candace Major, Marine Geosciences Section Head, to better understand the relationships between EAR and OCE. There is a record of successful collaborations in regions such as coastal environments and subduction zones, covering disciplines such as seismology, geodesy, tectonics, geochemistry, volcanism, and paleoclimatology. The two divisions have worked together on Geodynamic Processes at Rifting and Subducting Margins (GeoPRISMS)[7] and Paleo Perspectives on Climate Change (P2C2).[8] Subduction zone science is funded by both EAR and OCE, and EAR supports Seismological Facilities for the Advancement of Geoscience (SAGE) and Geodetic Facility for the Advancement of Geoscience (GAGE) awards for research cruise–related experiments. In addition, a working group of program directors is considering how EAR and OCE can better cooperate regarding coastal oceanography.

Research that recognizes connections between terrestrial and ocean environments ("crossing the shorelines") has the potential to advance many of the key research questions, from dynamics of Earth's interior, to water and biogeochemical cycles, biodiversity, and climate (both paleoclimate and future climate questions), to reducing risks from earthquakes, eruptions, and tsunamis. Partnerships with OCE and international partners (such as those involved in the International Ocean Discovery Program) are needed to access sedimentary archives of continental tectonic and surface processes that are archived in the ocean basins. Characterizing change in topography and bathymetry could be another area of partnership, as are shallow ocean chemistry and coastal terrestrial water quality from seawater intrusion and storm surge. The intricate connections among precipitation, changes in ocean salinity, and moisture transport from ocean to land provide opportunities with both OCE and AGS.

AGS

The committee spoke with Anjuli Bamzai, AGS Division Director, to learn more about partnerships between EAR and AGS. EAR and AGS collaborate on funding paleoclimate (through P2C2), climate and large-scale dynamics, and meteorology. However, EAR appears to make limited use of the National Center for Atmospheric Research (NCAR) and its research opportunities. While EAR and AGS do not currently have many collaborations in the areas of atmospheric chemistry, aeronomy, and magnetophysics, they work together on disciplines such as hydrometeorology and hydroclimate and topics such as flooding, land-surface coupling, and trace gas emissions related to seismic activity. Because of NCAR's mission to develop and maintain community-supported Earth System Models, it invests significantly in advancing land modeling. Areas of active development in land modeling intersect directly with a number of EAR disciplinary and cross-cutting programs, particularly Hydrologic Sciences, Geomorphology and Land-use Dynamics, and the Critical Zone Collaborative Networks. Land models are increasingly key for understanding the response of terrestrial systems to climate and land-use change, and they benefit

[6] "The FRES program will support research in Earth systems from the core through the critical zone. The project may focus on all or part of the surface, continental lithospheric, and deeper Earth systems over the entire range of temporal and spatial scales. FRES projects should have a larger scientific scope and budget than those considered for funding by disciplinary programs in the Division of Earth Sciences (EAR). FRES projects may be interdisciplinary studies that do not fit well within EAR's disciplinary programs or cannot be routinely managed by sharing between disciplinary programs." From https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504833 (accessed March 30, 2020).
[7] See http://geoprisms.org (accessed December 20, 2019).
[8] See https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=5750 (accessed December 20, 2019).

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significantly from data collected with EAR funding. EAR and AGS could partner to uncover fundamental aspects of Earth's internal magnetic field and how it affects space weather and could strengthen interdisciplinary research on paleoclimate and the water cycle. Other potential partnerships between EAR and AGS include calibration of cosmogenic isotope production, to enable accurate estimates of exposure ages and radiocarbon dates, and of magnetic field strength, which influences astronomical cycles and orbital forcing.

OPP

The committee interviewed Alex Isern, OPP Antarctic Sciences Section Head, to understand collaborations between EAR and OPP. There have been no formal partnerships between the two divisions for at least a decade, but OPP is interested in taking advantage of any collaborative efforts that arise. OPP contributes support to the Portable Array Seismic Studies of the Continental Lithosphere Instrument Center and to GAGE, which are co-funded by EAR. OPP also participates in P2C2 with other GEO divisions. Due to the logistical difficulties of working in polar regions, Earth science projects in the Arctic and Antarctic are funded by OPP rather than EAR. The two divisions could jointly encourage proposals if there was an interesting science question where an EAR-OPP partnership seemed natural (such as in Greenland or Arctic Canada, for example). Another possibility for collaboration is to continue having EAR program directors detail with OPP, as has been done previously. Partnerships dealing with cryosphere water flow, a new research frontier, reflect closely related interests within OPP and EAR. Potential collaboration may integrate cryosphere observations to study subglacial water flow, glacial and snowmelt runoff to streams, hydrologic changes in permafrost and frozen grounds, polar region ecohydrology (which also intersects with BIO), snow and ice physics, and remote sensing of polar regions (see Box 4-2). Understanding how polar regions will change due to climate change is increasingly important and an area where EAR-supported research is a critical knowledge base. NSF's Navigating the New Arctic Big Idea, which seeks to leverage knowledge from outside the Arctic, could support better partnering between OPP and EAR scientists.

GEO

William Easterling, GEO Assistant Director, provided an overview of GEO's current and future partnerships. He noted that the coasts, climate, water, energy, and geohazards will continue to be major research directions within GEO. He highlighted CoPe as well as GeoPRISMS, INFEWS, Signals in the Soil, and several of NSF's 10 Big Ideas (Growing Convergence Research, Navigating the New Arctic, Harnessing the Data Revolution), as well as GEO's success with international partnerships. Dr. Easterling also mentioned the Geosciences Opportunities for Leadership in Diversity and Improving Undergraduate STEM Education Pathways into Geoscience programs. Finally, he stressed the need for EAR to better articulate and publicize the important benefits of its research to policy makers and the public.

Across GEO Divisions

As mentioned previously, EAR has strong partnerships across the GEO Directorate. However, as research becomes more inter- and transdisciplinary, there will be continued opportunity to strengthen and expand both formal and informal collaborations. Because Earth science processes cross the boundaries set up by NSF's organizational structure, and significant progress on the science priority questions will need collaboration with other disciplines, EAR might consider how to lower barriers to support interdisciplinary research across GEO divisions.

An important consideration is that cross-divisional programs are assessed in terms of achieving scientific goals or benefiting core disciplinary research programs. As an example, there were concerns among the committee that some interdisciplinary programs end just as they are demonstrating tangible success. Dr. Easterling mentioned that by redirecting research back into the disciplinary programs, research in some cross-divisional programs could continue after the specific program ends.

Components of the Earth system do not adhere to the administrative boundaries of GEO.

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.

BOX 4-2
LEVERAGING REMOTE-SENSING RESOURCES: POSSIBLE OPP-EAR CONNECTIONS

The Office of Polar Programs supports the Polar Geospatial Center (PGC) at the University of Minnesota. The PGC and The Ohio State University have been working with the National Geospatial-Intelligence Agency to produce 2-m posting Digital Surface Models (DSMs) of Earth's polar regions and have now imaged both the Arctic and Antarctic an average of 10 times. The same team is now producing DSMs of the entire Earth using imagery licensed by the National Geospatial Intelligence Agency, open-source photogrammetry software, and high-performance computing provided by NSF's Office of Advanced Cyberinfrastructure.

Although PGC-provided DSMs are not as high in resolution as lidar images, they have the advantages of being significantly less expensive and faster to acquire globally. Furthermore, repeat images can easily be obtained over time, providing the opportunity to view changes in geologic features and landscapes, including before-and-after images of natural disasters (e.g., earthquakes, volcanic eruptions, landslides, floods) or slower changes that affect a particular environment. The PGC is an agile and innovative research center that takes advantage of changes in technology and can respond rapidly in the event of a natural disaster. These data would be of immense value to EAR-supported researchers.

In 2017, a workshop was held in response to community requests for EAR–OPP cooperation (Hodges et al., 2020). Currently, EAR researchers do not have access to the high-resolution (sub-2-m) satellite images and associated products provided by the PGC, although the PGC receives numerous requests from EAR researchers for imagery and high-resolution satellite imagery is highly relevant to the science priority questions on topography, geohazards, the critical zone, and climate and environmental change. At present, there is no mechanism for EAR researchers to request imagery for nonpolar regions, although the PGC is in the process of acquiring such imagery globally, including imagery of dynamic areas such as coastlines, volcanoes, plate boundaries, Long Term Ecological Research sites, Critical Zone Observatory sites, and other facilities of great relevance to EAR research.

Cross-Directorate Relationships

The committee also heard from Brandi Schottel, Associate Program Director, ENG Division of Chemical, Bioengineering, Environmental, and Transport Systems (CBET); Kendra Mclauchlan, Program Director, BIO Division of Environmental Biology; Amy Walton, Program Director, CISE Office of Advanced Cyberinfrastructure; and Jessica Robin, Cluster Lead, OISE. Throughout the discussion, two repeated themes were the successful relationships that EAR has built with other directorates and EAR's involvement in productive cross-directorate, cross-agency, and international partnerships. Several of these are discussed below. INFEWS was brought up by several representatives as a flagship EAR-led partnership program that is successful in leveraging budgetary resources from various programs to attempt to solve scientific and societal research questions of shared interests. Signals in the Soil was also mentioned as a successful cross-directorate partnership.

EAR has also entered into program partnerships with the Division of Chemistry and the Division of Materials Research within the Directorate for Mathematical and Physical Sciences through the Critical Aspects of Sustainability program. Proposals can address overarching issues of sustainability, such as increasing needs for raw materials used in sustainable energy infrastructure from minerals that are limited in abundance. Other areas of interest are identifying new sources of critical minerals on Earth's surface, understanding pathways that lead to concentration of critical elements by metasomatic and geobiological processes, and the development of methods for sustainable extraction of critical minerals.

Future partnership opportunities for EAR exist. For example, an initiative in CBET with Earth science application is Urban Systems and Communities in the 21st Century,[9] which seeks to understand the changes associated with urbanization. Paleoclimate research is an inherently collaborative discipline that integrates across programs within and outside of EAR. Earth scientists exploring climate and environmental change from deep time to the present day can provide valuable partnerships with a wide swath of federal agencies that are tasked with responding to climate change. There are many connections to different programs within GEO, given that climate records can be recovered from land, ocean, and ice archives. Additionally, there are natural connections to cross-cutting programs such as CoPe, P2C2, and Dynamics of Integrated Socio-Environmental Systems. The other directorates also described the importance of international collaborations.

Many of the challenges outlined in this report need high-performance computing capabilities that

[9] See https://www.nsf.gov/ere/ereweb/urbansystems (accessed December 20, 2019).

include state-of-the-art hardware, software engineering, and computational science to represent the effects of small-scale processes on large-scale phenomena and to use diverse observations to constrain multi-scale and multi-physics models of the Earth. EAR has partnered with CISE on some efforts, but there remain ample opportunities to realize the full potential of computational geoscience. These efforts will entail deep collaboration with computational scientists and engineers and new approaches to data management and processing. Strengthening computational competencies for Earth science students could also be a partnering opportunity for EAR and the Divisions of Undergraduate and Graduate Education in the Education and Human Resources Directorate.

Co-funding interdisciplinary programs and partnerships poses challenges. There is a demand on program director time for planning and managing these programs. Some directorates have a program director devoted to cross-directorate and international programs (Brandi Schottel from CBET is one). The process of co-reviewing proposals across divisions is often a concern for scientists. A widely held belief in the geoscience community (and one mentioned several times in the community input) is that the process of having proposals reviewed by more than one panel reduces the chance of success, and that there were significant barriers to obtaining support when proposals need to be reviewed by more than one GEO division. However, NSF representatives stated that this is not supported by their data. There is a disconnect between NSF and the researchers in this regard, and therefore a need for improved communications to correct the perception that co-reviewed proposals have a lower success rate.

PARTNERSHIPS WITH OTHER FEDERAL AGENCIES

Cross-agency partnerships work best when there is strong common interest and robust community input and involvement. Determining which areas of research might be valuable for collaboration between NSF and other agencies can be challenging, because mission agencies generally have less flexibility in funding research topics than does NSF. However, there are important advantages when it is possible to converge on a research partnership. Cost-sharing is an obvious benefit, as well as the ability to meet NSF's broader impacts criteria by demonstrating that NSF-funded investigator research supports agencies' mission objectives. One of the major obstacles to partnerships is the administrative workload. Because the agencies have different missions, separate components of a collaborative project could be supported by different agencies.

Several other federal agencies fund and advance basic and applied Earth science research. USGS supports geologic mapping, the study of volcanoes, earthquakes, landslides, and other geohazards, water resources, coastal and marine geology, and space weather. NASA supports satellite missions and ground-based instruments for terrestrial research, including the cryosphere, surface processes, hydrology, and ecosystems. It also has robust programs in geobiology, low-temperature geochemistry, astrobiology, and planetary geology. DOE provides access to synchrotron-radiation facilities at national laboratories and supports significant field programs in Earth surface processes. USDA supports research related to agriculture, forest, and water management, including soils and sediment, land cover change, and the carbon and water cycles. Federal funding in basic and applied Earth science is shown in Figure 4-1.

The committee met with David Applegate, Associate Director, USGS Natural Hazards Mission Area; Gerald Bawden, Program Scientist, NASA Earth Surface and Interior; Mary Voytek, Senior Scientist, NASA Astrobiology; and Nancy Cavallaro, National Program Leader, USDA National Institute of Food and Agriculture. In addition, committee members interviewed Jim Rustad, Geosciences Program Manager, Chemical Sciences, Geosciences, and Biosciences Division, Basic Energy Sciences, DOE Office of Science, and Paula Bontempi, NASA Acting Deputy Director, Earth Science Division.

USGS

Within USGS, many opportunities exist for partnerships with EAR, including making use of multiple datasets related to seismic and volcanic monitoring networks, stream gauges, hazard research, subduction zone science initiatives, and linking with the Volcano Hazards Program. USGS has an external research program on earthquake processes and effects and co-funds the Southern California Earthquake Center[10] with EAR. It also operates regional earthquake monitoring

[10] See https://www.scec.org for more information (accessed January 28, 2020).

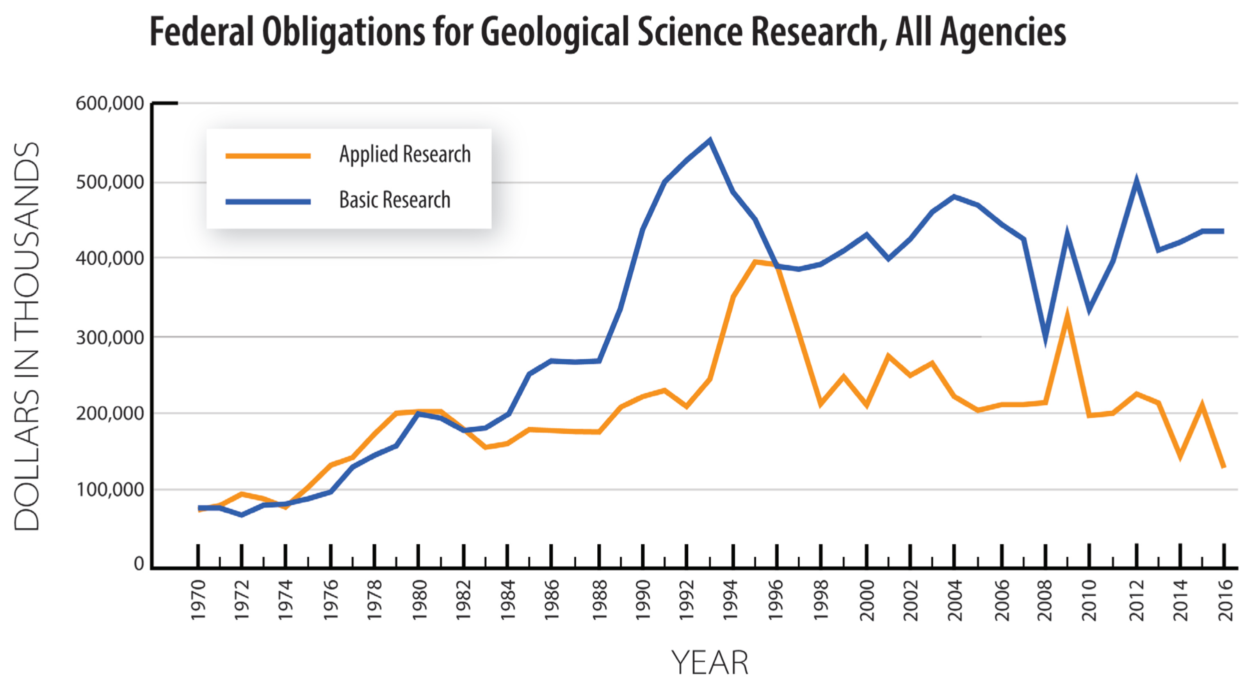

FIGURE 4-1 Federal obligations for geological science research at all agencies. NOTE: Blue denotes basic research; orange is applied research. SOURCES: Data from National Science Foundation, National Center for Science and Engineering Statistics, Survey of Federal Funds for Research and Development, Fiscal Years 2016-17. See http://www.nsf.gov/statistics/fedfunds (accessed April 16, 2019).

networks across the United States as part of the Advanced National Seismic System, which is a cooperative effort that analyzes seismic and geodetic data, provides dependable notifications of earthquake occurrences, and collects data for earthquake research and hazard and risk assessments (USGS, 2017). USGS also partners with NSF and the Incorporated Research Institutions for Seismology to run the Global Seismic Network, which provides worldwide monitoring of earthquake activity, with more than 150 seismic stations distributed globally. In many cases, seismometers are combined with other sensors, such as microbarographs, anemometers, magnetometers, and Global Navigation Satellite System receivers, to form geophysical observatories.

A key relationship is between the USGS Volcano Hazards Program and academic volcanologists, with many USGS volcanologists participating in the NSF-funded Community Network for Volcanic Eruption Response (CONVERSE) Research Coordination Network (part of SZ4D). The Volcanic Hazards Program currently funds cooperative agreements in research and monitoring and operates volcano observatories and seismic networks throughout the United States. The USGS National Volcano Early Warning System (Ewert et al., 2005, 2018) aims to double the federal commitment to volcano science and includes provisions for expanding the program of cooperative agreements and funding grants for volcanic research by academic partners.

USGS's Powell Center for Data Synthesis and Analysis has a partnership with NSF, including EAR. The Center offers research opportunities for working groups to utilize existing data to advance science in areas related to USGS's missions. Several of the areas are closely related to EAR core disciplinary programs, including natural hazards, water and land resources, and energy and minerals.

There are also partnership opportunities between USGS and EAR on topics such as geomagnetic hazards and space weather. USGS has a long commitment to hydrogeophysics and would be a logical partner in critical zone and near-surface research, particularly related to the Near-Surface Geophysics facility and Continental Critical Zone initiative discussed in Chapter 3.

NASA

The report *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space* (NASEM, 2018) develops the rationale for NASA Earth Science Division research. Among the highest science priorities are quantifying water storage in aquifers and reservoirs; processes affecting sea-level rise; land deformation processes including eruptions, earthquakes, and landslides and the implications for the risks for human life and property; and changes to the state of terrestrial vegetation and the effects on biodiversity, as well as the effects on biogeochemical processes, including sources and sinks of methane and carbon dioxide and their future changes. The synergy between the science priorities outlined above and those of this report suggests the possibility of new research partnerships between EAR and NASA Earth Science Division's Earth Science and Interior (ESI) Focus Area that would combine the large-scale observations from aircraft and spacecraft with ground-based measurements. This powerful combination could elucidate key Earth processes more completely than is possible if each research agency supported just their own investigators and studies.

In addition to providing funding to supplement NSF's support of GAGE, NASA ESI has strong research interests in understanding subduction zone processes. NASA researchers participate in and have co-funded pilot projects with the Southern California Earthquake Center and are involved in the NSF-funded Research Coordination Network CONVERSE. They are also promoting connections between the NSF-supported Modelling Collaboratory for Subduction Research Coordination Network (part of SZ4D) and NASA High-End Computing resources and expertise.

Although the main focus of the NASA Astrobiology Program is planetary bodies beyond the Earth, the research begins with understanding the Earth through diverse studies ranging from the origin of life to the evolution of advanced life, as well as extraterrestrial impacts and studies with implications for solar system formation and evolution. NASA's Astrobiology Program has research interests (NASA, 2015) that align well with the critical elements, biogeochemical cycles, and biodiversity questions, including the evolution of life and Earth's habitability. Major themes in their strategy include abiotic sources of organic compounds, macromolecule function in the origin of life, increasing complexity of early life, and co-evolution of life and the environment. The research related to these four themes includes many study sites on the Earth[11] and experiments with Earth materials. The complementary objectives with the Astrobiology Program also suggest opportunities for collaboration.

NASA also sees potential collaboration in the data space. For instance, NSF-funded investigators could take advantage of the large amount of data coming from Earth-observing satellites. Very large high-resolution datasets from NASA missions represent an under-tapped resource in the study of volcanic processes. Partnerships with NASA are needed to provide repeat measurements of topography of the continents, continental shelf bathymetry, and soil moisture and vegetation cover. Collaboration could be forged between EAR and NASA on satellite mapping of the geomagnetic field to monitor short-term changes such as geomagnetic jerks, and magnetization of meteorites and lunar samples. One of the barriers to direct participation of NASA researchers in NSF programs is that NSF does not accept proposals from federal employees or from federally funded research and development centers (such as the Jet Propulsion Laboratory).

DOE

DOE's Office of Science Basic Energy Sciences Program invests significantly in infrastructure to support Earth science research at synchrotron radiation facilities. There are three DOE synchrotrons operating as user facilities: the Advanced Light Source at Lawrence Berkeley National Laboratory (LBNL), the National Synchrotron Light Source-II, which was recently completed in 2015 at Brookhaven National Laboratory, and the Advanced Photon Source (APS) at Argonne National Laboratory.

DOE provides synchrotron beamtime to users free of charge through user proposals. Research performed at APS's GeoSoilEnviroCARS (GSECARS) facility by individual principal investigator groups is typically supported by NSF research grants spanning most or all of the disciplinary programs, especially Petrology and Geochemistry, Geobiology and Low-Temperature Geochemistry, and Geophysics. NSF's Consortium for Materials Properties Research in Earth Sciences (COMPRES) targets research on Earth's interior, especially rock and mineral physics. COMPRES supports user facilities at all three DOE synchrotrons, including human infrastructure and small-scale infrastructure development projects.

DOE's National Nuclear Security Administration builds and operates facilities for dynamic compression of materials, needed for understanding the interior of the Earth. This includes the National Ignition Facility

[11] See https://astrobiology.nasa.gov/research-locations (accessed December 20, 2019).

and the OMEGA Laboratory for Laser Energetics. At Sandia National Laboratory, the Z Machine and newly developed THOR are pulsed-power, dynamic compression systems, and at APS a newly built dynamic compression sector is now operational. While access to these facilities is considerably more limited than the DOE Basic Energy Science user facilities, there is tremendous opportunity for EAR researchers to access new regimes of pressure and temperature relevant to the Earth and exoplanet interiors, especially through ramp compression.

DOE's Climate and Environmental Science Division has an interest in watershed function and runs a study site that is available to NSF researchers (see Box 4-3). Its Biological and Environmental Research mission is supporting the Next-Generation Ecosystem Experiments (from 2012 to 2022) to improve understanding of carbon-rich Arctic system processes and feedback to climates. Earth surface processes studies are central to this effort. DOE's Office of Energy Efficiency and Renewable Energy runs the FORGE geothermal test site, a multiyear experiment in creating enhanced geothermal systems. Partnering with DOE on this site could provide NSF with data and site access for instrumentation and subsurface samples. DOE also has several subsurface research sites in abandoned mines, such as the LBNL Deep Underground Science and Engineering Laboratory site at the former Homestake Mine in South Dakota, which is also supported by NSF. These sites could host new research pathways in rock mechanics, fluid flow, and mineral systems. Partnerships with DOE could be developed related to energy development such as critical mineral resources, geothermal processes, and induced seismicity related to energy development.

DOE provides high-performance computing resources through its Innovative and Novel Computational Impact on Theory and Experiment program, which gives researchers computer time and support at its Argonne Leadership Computing Facility and the Oak Ridge Leadership Computing Facility.

DOE's National Energy and Technology Lab supports research in a number of areas of potential interest to EAR researchers, including surface deformation and induced seismicity associated with fluid injection and extraction, reservoir characterization, and technology development. It maintains extensive contacts with industry and can help to facilitate academic–industry partnerships in these and related areas.

NASA, DOE, and USGS provide important capabilities supporting EAR research.

BOX 4-3
MULTI-AGENCY PARTNERSHIPS TO CREATE COMMUNITY PLATFORMS THAT ADVANCE UNDERSTANDING OF WATERSHED FUNCTION AND THE CRITICAL ZONE

In 2016, DOE's Climate and Environmental Sciences Division organized a Scientific Focus Area (SFA) aimed at advancing fundamental understanding of how watersheds retain, store, and release water and how physical, chemical, and biological processes and properties give rise to emergent hydrologic and biogeochemical properties of watershed systems, like concentration–discharge relationships. SFAs were patterned after the NSF Critical Zone Observatory program, ending in 2020, which brought together multidisciplinary investigations to focus on a single location. Led by the Earth & Environmental Sciences Area at LBNL, the Watershed Function SFA has resulted in significant infrastructure investments at its study site in the East River watershed upstream of Crested Butte, Colorado.[a] The East River is an approximately 300 km^2 headwater watershed in the Colorado Rockies that drains to the Gunnison River. Key investments in infrastructure made by the Watershed Function SFA include installation of surface weather-observing stations, stream gaging stations, groundwater wells and pressure sensors, water quality probes, and continuous stream water isotope measurements. In addition to monitoring infrastructure, the Watershed Function SFA has supported a large effort to perform near-surface geophysical surveys throughout the East River, acquisition of airborne remote sensing data including lidar data from NASA's Airborne Snow Observatory and hyperspectral imagery from the National Ecological Observatory Network's Airborne Observing Platform. From its inception, the Watershed Function SFA has advocated a model of a community watershed, where university investigators and researchers from other agencies can both benefit from the significant investments in data collection infrastructure and contribute to fundamental discoveries made as part of the broader SFA effort. It has enabled this model by making data collected at the site immediately available through an online portal and providing letters of support to investigators submitting proposals to funding agencies including NSF, DOE, and NASA. DOE and NSF have supported awards to university investigators for work at the East River. This community watershed approach holds up the study site as a type of field-based user facility that is complementary to the Critical Zone Observatory network. The Watershed Function SFA provides an example of an opportunity for interagency partnership that could mutually benefit partnering agencies and the broader scientific community, other facilities of great relevance to EAR research.

[a] See https://doesbr.org/research/sfa/sfa_lbl.shtml (accessed December 20, 2019).

USDA

Partnerships currently exist between EAR and USDA, mostly with the National Institute of Food and Agriculture (NIFA) (e.g., Signals in the Soil and INFEWS). EAR and NIFA have had past collaborations that link food, water, and energy issues. There are opportunities to partner on pressing global challenges related to food security, water, land use, biodiversity, and sustainability. EAR also has had the opportunity to collaborate with NIFA on the Global Soil Partnership, the soils database interface, and on critical zone studies. Because NIFA funds some projects for 5-10 years, there are also opportunities for long-term research partnerships.

The Agricultural Research Service (ARS) supports a wide range of research in water management, sedimentation, and soils. ARS's experimental watersheds provide sites where EAR-supported researchers—in cooperation with ARS managers—install new observational instrumentation, and conduct field campaigns that can include destructive sampling of soils and vegetation, as well as experiments. A prime example of an EAR–ARS partnership is the co-location of the Reynolds Creek Critical Zone Observatory with the Reynolds Creek Experimental Watershed. In addition, ARS's National Sedimentation Laboratory maintains a research program in watershed physical processes, with an emphasis on soil erosion mechanics and channel sediment transport.

Research at the U.S. Forest Service network of Experimental Forests and Ranges has played a central role in developing an understanding of ecologic, hydrologic, and geomorphic processes and how forest and range management interact with these processes (Hayes et al., 2014). On these sites, large-scale experiments such as harvesting of all trees in a watershed and monitoring the consequences have revealed key linkages among surface processes and ecosystems, as well as provided guidelines for land management. Sustained monitoring at several of the 84 sites across the United States provides unique multidecadal observations. Six of the nine Critical Zone Observatories are located on U.S. Forest Service land.

Bureau of Land Management

The Bureau of Land Management provides access to important field areas for EAR researchers. The National Conservation Lands program of ~34 million acres specifically invites research in areas that are managed as wilderness, national monuments, conservation lands, and wild and scenic rivers. Ranging across diverse climate and ecosystems, mostly in the West, these contain valuable field settings for research. As an example, both the Reynolds Creek and Eel River Critical Zone Observatories are located on Bureau of Land Management lands.

Smithsonian Institution

The collections of the Smithsonian Institution, especially those of the Departments of Paleobiology and Mineral Sciences, provide a major resource for Earth scientists. Access is available regardless of funding source. In addition, the Smithsonian provides internships and fellowships for undergraduate and graduate students and for post-doctoral researchers. The Smithsonian Institution also runs the Global Volcanism Program, whose mission to "document, understand, and disseminate information about global volcanic activity" is strongly aligned with the volcanism question.

New Possibilities for Partnerships

There are a number of federal agencies that could be fruitful partners for EAR in the future. The U.S. Department of Defense has interests in climate change, food security, and coastal resiliency that fit well with EAR's research programs. For example, the National Geospatial Intelligence Agency's use of satellite imagery to evaluate Earth surface characteristics complements the work of many EAR researchers. As EAR scientists increase their use of drones for research activities, EAR may wish to partner with the Federal Aviation Administration to come up with appropriate policies for drone operations. In the emerging field of geohealth, EAR could collaborate with the National Institutes of Health to help transition NSF basic research in areas such as biochemical and water cycles or contaminant and sediment transport to human health applications. The U.S. Army Corps of Engineers (USACE) has interests in hydrology research and applications that are complementary to those of EAR, and EAR's strong expertise in geohazard research is a natural fit for USACE's role in flood mitigation and levee maintenance and with the Federal Emergency Management Agency's need for information, training, and response capabilities. In addition, there are potential partnerships with the National Oceanic and Atmospheric Administration in areas such as the water cycle and tsunami processes and hazards. Office of Science and Technology Policy committees and subcommittees (such as those related to water quality, critical minerals, and disasters) may be appropriate places to develop and strengthen these relationships. Responses from the community input also encouraged more cooperation with the U.S. Department of Education on a range of topics, from expanding the geoscience curriculum in K-12 education and establishing national Earth science education standards to more graduate and post-doctoral programs.

Recommendation: EAR should proactively partner with other NSF divisions and other federal agencies to advance novel societally relevant research.

CONCLUDING THOUGHTS

There are multiple federal agencies that conduct basic and applied research that directly intersect with EAR. These points of intersection present opportunities to partner across agencies to better leverage facilities, optimize expenditure of budgetary resources, promote workforce development, and extend the application of data for scientific research. At the same time, they also present challenges due to contrasts in the individual agencies' goals and missions. While it is important to navigate these areas carefully, partnerships with other federal agencies represent opportunities to expand the research enterprise for the benefit of the community, especially in a resource-constrained environment.

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5
A Decadal Vision for Earth Sciences

Research in Earth science is central to revealing how our planet works, from the core to the clouds. The mission of the Division of Earth Sciences (EAR) is more urgent and important than ever before, as rapid changes bring immense consequences and continued progress in understanding will make society better prepared to meet the challenges of a changing Earth. For example, one can consider the impact of remote imaging on earthquake and volcano science or landscape evolution, the consequences of deeper understanding of the properties of Earth materials, and new perspectives on the complex interactions of terrestrial, hydrologic, biological, and atmospheric systems.

In order to facilitate significant discoveries in the next decade, EAR can enhance support for research that investigates the planet as an integrated system. In this "all hands on deck" moment we need a diverse and inclusive group of Earth scientists, working both individually and in collaborative networks, to create and deploy cutting-edge analytical, computational, and field-based research methods, in an open environment where success builds expeditiously on success. An expanded and agile workforce of innovative Earth scientists will further understanding of how human activities are driving fundamental changes to the Earth, including impacts on public health, and will utilize new technologies and approaches to reduce the natural and societal impact of these activities.

A Vision for NSF Earth Sciences 2020-2030: Earth in Time outlines some emerging initiatives and research directions in the Earth sciences, while also recognizing that this rapidly changing discipline will also evolve in directions not yet anticipated. Future advances in diversity and inclusion have the potential to transform what we study—and how we do it—by unlocking new perspectives and creating new ways of framing research questions, such as by building opportunities for citizen science and making information more accessible to decision makers and the public. The committee envisions a bright future, where students and scientists in academia, industry, government, and nongovernmental organizations more accurately reflect the demographics of the United States, with improved gender equality, increased participation by underrepresented minorities, and higher representation across the full spectrum of personal, cultural, and socioeconomic statuses and identities that make up our vibrant society. With substantive inclusion in academia, Earth scientists will be able to more deeply engage with affected communities to solve issues of critical societal importance, such as communicating seismic hazard along the West Coast or mitigating sea-level rise for Gulf Coast communities. The field of Earth sciences will benefit from increasingly diverse perspectives just as substantially as it will from advances in computational geoscience and higher-precision instruments.

Earth science is on a frontier with respect to data access, management, and use. Combined with new analytical and computational techniques, this new wealth of data will allow discovery and advances that were previously unattainable. New technology will help EAR investigators cross disciplinary, organizational, and political boundaries that currently inhibit the research enterprise, as will strengthening collaborations with other parts of the National Science Foundation (NSF), federal agencies, and international partners. Facilitating, embracing, and expanding development and access to data, technology, approaches, and perspectives are at the core of the vision for the next decade.

The priority questions outlined in this report illustrate the significance, breadth, and magnitude of the challenges and opportunities for Earth science research in the next decade. These questions are actionable, varied, and distinct; they pertain to deep-Earth processes, geohazards, and complex surface and near-surface systems that are increasingly recognized as being intertwined. The priority questions encompass surficial topographic evolution and the connection to deep and shallow water systems, highlighting the value of understanding critical zone, climate, and other surface and near-surface system interactions. These science questions are pertinent to the persistence of life and recognize humans as geologic agents, and thus require a multidisciplinary approach.

The committee envisions a future in which EAR-supported research leads to routine, accurate forecasting of formerly unpredictable, devastating natural hazard events on time scales that permit mitigation of risk. EAR will help enable this by strengthening partnerships with other federal agencies and organizations to more rapidly put new NSF-supported research into use. More accurate forecasting may be accomplished if geoscientists investigate and quantify the full range of geohazards, from the nearly undetectable to the most extreme events, and develop a new understanding of the fundamental factors governing the behavior of the complex, interacting geosystems that cause them.

Over the next decade, scientists will increase understanding of deep-Earth processes and plate tectonics. If coupled with research into rock–water–atmosphere interactions, this will further illuminate the fate of carbon dioxide and other drivers of climate change over short (human) and long (geologic) time scales, improving understanding of critical element budgets in different Earth reservoirs. Furthermore, a better understanding of the processes that control the distribution of critical elements in geologic systems has the potential to put the United States on a pathway to less reliance on other countries for materials that are foundational to a clean energy future.

Researchers need to build collaborations across physical boundaries such as the shoreline and the interface of Earth's surface and the atmosphere, especially to investigate Earth's response to anthropogenically driven climate change and shifts in land use. Latitudinal shifts in the water cycle, vegetation dynamics, agriculture, and habitability require researchers to work across disciplinary boundaries, supported by flexible administrative and governance structures that support this approach. The questions and initiatives proposed here will increase our ability to understand the changing planet and devise sustainable responses. Earth science needs to connect and integrate well beyond traditional boundaries.

Although this report was finalized during a global pandemic that has profoundly disrupted the world in which we live, the overarching perspective of this report is one of optimism. EAR is already well on the way to leading the investigation of the Earth as an interconnected system and is therefore poised to launch the next decade of innovative research. This vision for an influential role of Earth scientists will be successful if there is increased development of and access to cutting-edge analytical, computational, and other facilities, leading to scientific breakthroughs that will transform our understanding of geological processes from nano-scale to global scale and from deep time to the present, with profound implications for the future of life on the Earth.

Appendix A
Biographical Sketches of Committee Members and Staff

COMMITTEE MEMBERS

James A. Yoder (*Chair*) is the dean emeritus of Woods Hole Oceanographic Institution (WHOI) and a professor emeritus of the Graduate School of Oceanography (GSO) at the University of Rhode Island (URI). He served as the dean at WHOI from 2005 to 2017. Dr. Yoder was a professor of oceanography at GSO from 1989 to 2005, where he conducted research involving satellite and aircraft measurements to study ocean processes, taught graduate courses, and advised M.S. and Ph.D. students. He also served for five years as the associate dean in charge of the graduate program in oceanography. Dr. Yoder started his career in 1978 at the Skidaway Institution of Oceanography. He held temporary positions in the federal government, including as the director of the National Science Foundation's (NSF's) Division of Ocean Sciences (2001-2004) and as a program officer at the National Aeronautics and Space Administration (NASA) (1986-1988 and 1996-1997). During his time at NSF, Dr. Yoder chaired the National Ocean Partnership Program's Interagency Working Group. He has served on many national and international committees and panels. He was a member of the National Research Council's (NRC's) Decadal Survey of Ocean Sciences (2013-2015) and chaired the NRC's Committee on Assessing Requirements for Sustained Ocean Color Research and Operations (2011-2012). He co-chaired the National Academies of Sciences, Engineering, and Medicine's (the National Academies') Ecosystem Panel for the Decadal Survey for Earth Science and Applications from Space (2016-2017) and was a member (2009-2013) of the National Academies' Ocean Studies Board. He is a former member and former chair of the International Ocean Colour Coordinating Group, which seeks cooperation among the international space agencies for satellite measurements of ocean color radiometry. Dr. Yoder was a recipient of a URI Distinguished Achievement Award in 2008 and was elected a fellow of The Oceanography Society in 2012 and a fellow of the American Association for the Advancement of Science in 2018. Dr. Yoder received his B.A. in botany from DePauw University and his M.S. and Ph.D. in oceanography from URI.

Gregory C. Beroza is the Wayne Loel Professor of Earth, Energy, and Environmental Sciences in the Department of Geophysics at Stanford University. His research concerns earthquake science broadly, with a focus on developing techniques for analyzing seismograms to understand how earthquakes work and to help quantify the hazards they pose. Since 2007 he has been first deputy director then co-director of the Southern California Earthquake Center (SCEC). His principal responsibility in that role is to chair the planning committee, which guides and coordinates the core research program of the SCEC collaboration. Since 2013 he has also been co-director of the Stanford Center for Induced and Triggered Seismicity. His current research includes using ambient field measurements for ground motion prediction, developing data-mining and machine learning methods for earthquake detection and characterization, and understanding the systematics of induced, slow, and intermediate-depth earthquakes. He has authored more than 150 peer-reviewed scientific journal articles. Dr. Beroza was a National Science Foundation Presidential Young Investigator, has been a fellow of the American Geophysical Union since 2008, was the Incorporated Research Institutions for Seismology/Seismological Society of America Distinguished Lecturer in 2012, and was awarded the Beno Gutenberg Medal of the European Geosciences Union in 2014 for outstanding contributions to seismology. He holds a B.S. in Earth sciences from the University of California, Santa Cruz, and a Ph.D. from the Massachusetts Institute of Technology.

Tanja Bosak is a professor of geobiology in the Department of Earth, Atmospheric, and Planetary Sciences at the Massachusetts Institute of Technology (MIT). She is the author of more than 50 papers and book chapters that focus on the parallel evolution of life and microbial metabolisms, microbial fossils, biogeochemical patterns, and other biosignatures that can be expected on the early Earth or Mars. Her laboratory explores these questions using experimental geobiology, which integrates microbiology, sedimentology, and geochemistry. For this work and her work with graduate students and undergraduates, Dr. Bosak received the Subaru Outstanding Woman in Science award by the Geological Society of America (GSA), the Macelwane Medal from the American Geophysical Union (AGU), the Edgerton Award for young faculty at MIT, the Undergraduate Research Opportunities for Undergraduates Mentor of the Year award by MIT, and the Award for Outstanding Contributions and Dedication to Geobiology and Geomicrobiology from the Geobiology and Geomicrobiology Division of GSA. Dr. Bosak is a fellow of AGU and a member of the Simons Foundation Collaboration on the Origins of Life and its steering committee. She chaired the Gordon Research Conference in Geobiology and was a member of the organizing committee for the National Academies of Sciences, Engineering, and Medicine workshop Searching for Life Across Space and Time. Dr. Bosak was born in Croatia and graduated from the Zagreb University with a degree in geophysics. She earned a Ph.D. in geobiology from the California Institute of Technology and spent two years at Harvard as a Microbial Initiative Postdoctoral Fellow before joining the faculty at MIT.

William E. Dietrich (NAS) is a professor of earth and planetary science at the University of California, Berkeley. Dr. Dietrich's research focuses on the processes that underlie the evolution of landscapes. His research group and collaborators have developed geomorphic transport laws for soil production, weathering and transport, and for river and debris flow incision into bedrock. They have explored the processes that control the sorting of sediment in river bends, rates of river migration, the transport of sediment in steep, coarse bedded channels, the routing of sediment through river networks, the influence of sediment supply on river morphodynamics, and the dispersion and deposition of sediment across floodplains. He has led intensive investigations of hydrologic processes at the hillslope scale at sites along the Pacific Coast Ranges. He is part of the Mars Science Laboratory Mission (Curiosity Rover). Dr. Dietrich is the director of the Eel River Critical Zone Observatory, and co-founder (in 2003) and co-director of the National Center for Airborne Laser Mapping. He earned his Ph.D. in geology from the University of Washington. His most recent National Academies of Sciences, Engineering, and Medicine service is a member of the steering committee of the 2017-2027 Decadal Survey for Earth Science and Applications from Space.

Timothy H. Dixon is a professor in the School of Geosciences at the University of South Florida. His research uses satellite geodesy and remote sensing data to investigate changes in Earth's land and water surfaces. These geodetic data allow study of a variety of natural and anthropogenic processes, including strain accumulation on faults, volcano deformation, mountain building, coastal subsidence, groundwater extraction, and glacier motion. He has conducted geological field investigations on several continents, participated in sea-going campaigns, organized GPS field programs, conducted glacier studies in Iceland and Greenland, and conducted volcano deformation studies in Central and South America. He is a fellow of the American Geophysical Union, the Geological Society of America (GSA), and the American Association for the Advancement of Science. He is the 2010 recipient of GSA's Woollard Award for excellence in geophysics. He previously worked at National Aeronautics and Space Administration's (NASA's) Jet Propulsion Laboratory and at NASA Headquarters. Dr. Dixon received a B.Sc. with honors in geology from the University of Western Ontario and a Ph.D. from the Scripps Institution of Oceanography.

Andrea Dutton is a professor at the University of Wisconsin–Madison. Dr. Dutton is an international expert in the study of past climate and sea-level change using carbonate sedimentology and isotope geochemistry. Her research program focuses on understanding the rates, magnitudes, sources, and drivers of past sea-level change to facilitate improved understanding of the climate system and of projections for the future. Dr. Dutton has served in leadership positions for several disciplinary working groups and has an active role in science communication on climate change and sea-level rise. She is a MacArthur fellow, a Fulbright scholar, and a fellow of the Geological Society of America. Dr. Dutton received her M.S. and Ph.D. from the University of Michigan in Ann Arbor and was a post-doctoral fellow and research fellow at the Australian National University.

Diana F. Elder[1] is the associate dean for academic affairs in the College of the Environment, Forestry and Natu-

[1] Resigned from the committee.

ral Sciences and an associate professor in the School of Earth and Sustainability at Northern Arizona University. Her research is aimed at understanding the long-term variability of sediment flux and landscape change in arid lands as a response to low-amplitude climate change. She has received funding from the state of Arizona for an interdisciplinary project in riparian restoration and has conducted research on the paleoclimate, paleohydrology, and geomorphology of the Death Valley region. Dr. Elder has also worked in the Four Corners region of the Colorado Plateau to assess alluvial system response to past fire events. Dr. Elder has been the lead on projects to broaden participation in science, technology, engineering, and mathematics (STEM) fields and has served as a program director in the Division of Biological Infrastructure at the National Science Foundation. She has been actively involved in mentoring students from groups traditionally underrepresented in STEM, including Native American students from the Navajo Nation. Dr. Elder holds a B.S in geology, a B.S. in physical sciences, and an M.S. in Quaternary studies from Northern Arizona University. Dr. Elder received her Ph.D. in geological sciences from the University of California, Riverside.

Alejandro N. Flores is an associate professor in the Department of Geosciences at Boise State University. His research focuses on understanding mountain watersheds as regional Earth systems where large-scale patterns emerge as a product of interactions between and among biophysical processes and human action. His research synthesizes numerical models of and data characterizing regional climate, ecohydrology, and human, land, and water management activities in order to assess how perturbations propagate across scales and through component systems. At Boise State, Dr. Flores is the principal investigator and director of the LEAF group, which researches the intersection of water, energy, nutrients, policy, and human activity. His work has been published in journals such as *Water Resources Research*, *Geophysical Research Letters*, and *Remote Sensing*. He is a recipient of a National Science Foundation (NSF) CAREER award and an Army Research Office Young Investigator Program award. He is a co-principal investigator on NSF's Reynolds Creek Critical Zone Observatory. Dr. Flores holds a B.S. and an M.S. in civil and environmental engineering from Colorado State University. He received his Ph.D. in hydrology from the Massachusetts Institute of Technology in 2009.

Michael Foote is a professor in the Department of the Geophysical Sciences, the Committee on Evolutionary Biology, and the College at the University of Chicago. He is also a fellow of the Paleontological Society. He studies the geological history of biological diversity and evolutionary rates, mainly in marine animals. His research has focused on documenting major evolutionary trends and on developing methods for analyzing diversity and rates in the face of an incomplete fossil record. Principal areas of research have included the evolution of morphological diversity, rates of taxonomic origination and extinction, dynamics of diversification, mathematical modeling of evolution, and determinants of extinction risk. He contributed to the early development of the Paleobiology Database, served on its steering committee, and taught in its summer course. Dr. Foote teaches Earth history for undergraduates and multi-variate data analysis for graduate students. He has served as master of the Physical Sciences Collegiate Division, chair of the Department of the Geophysical Sciences, and deputy dean for academic affairs in the Physical Sciences Division. He taught at Wake Forest University and the University of Michigan before joining the faculty at Chicago. Dr. Foote received his A.B. in geological sciences from Harvard University and his Ph.D. in evolutionary biology from the University of Chicago.

Shemin Ge is a professor in the Department of Geological Sciences at the University of Colorado Boulder. Her research involves studying groundwater in Earth's crust with a focus on the interaction of groundwater flow with other geologic processes and how these interactions advance science and offer insights on societally relevant issues. She studies earthquake-induced groundwater flow as natural experiments to reveal the hydrologic properties of geologic systems and explores the mechanisms of seismicity induced by reservoir operation and wastewater injection. Another thread of Dr. Ge's research relates to groundwater resources and surface–groundwater interactions under a changing climate, with a focus on headwater regions. She was the chair of the Hydrogeology Program Planning Group for the Ocean Drilling Program from 1999 to 2002. She has also served as the editor and the associate editor for publications such as *Hydrogeology Journal*, *Geofluids*, and *Journal of Ground Water*. From 2012 to 2014, Dr. Ge served as a program director for the Hydrologic Sciences Program at the National Science Foundation. In recognition of her pioneering research and leadership in the field, the Hydrogeology Division of the Geological Society of America awarded Dr. Ge the 2018 Meinzer Award and named her as the 2016 Birdsall-Dreiss Lecturer, an honor awarded based on a scientist's outstanding reputation, excellence in research, and ability to communicate effectively. Dr. Ge received her Ph.D. in hydrogeology from Johns Hopkins University in 1990. She holds an M.S. from the University of British Columbia and a B.S. from the Wuhan University of Technology.

George E. Gehrels is a professor of geosciences at the University of Arizona. His primary area of expertise is in the application of U-Th-Pb geochronology to study the origin of mountain belts and sedimentary basins, as well as the resources found in these areas. Dr. Gehrels also oversees the Arizona LaserChron Center, a National Science Foundation–supported facility that provides research assistance for U-Th-Pb geochronology/thermochronology, Hf isotope geochemistry, and scanning electron microscope imaging and chemical analysis. Dr. Gehrels has recently served the geochronology community through co-authorship of "It's About Time," a white paper with recommendations concerning geochronologic infrastructure in the United States, and as one of the leaders in establishing a new Geochronology Division within the Geological Society of America (GSA). Each year, Dr. Gehrels teaches university courses with roughly 1,000 students; these courses emphasize science literacy and responsibility and also encourage the involvement of underrepresented populations in science and technology fields. He is a fellow of the American Geophysical Union and was awarded the GSA Arthur L. Day Medal. Dr. Gehrels received his B.S., M.S., and Ph.D. in geology from the University of Arizona, the University of Southern California, and the California Institute of Technology, respectively.

Douglas Hollett is the president of Melroy & Hollett Technology Partners, which focuses on advanced technology and policy solutions in the aerospace and energy sectors, and is the senior energy advisor at Nova Systems, an Australia systems engineering provider in the energy, aerospace, and defense sectors. Additional engagements include advisor with SmartUQ, a Wisconsin uncertainty quantification company; advisor to FERVO, a California geothermal company; and member of the Sandia National Laboratory Energy and Homeland Security Board and the Commonwealth Scientific and Industrial Research Organisation Energy Advisory Committee (Australia). Mr. Hollett is the former acting assistant secretary and the principal deputy assistant secretary in the Office of Fossil Energy at the U.S. Department of Energy (DOE, 2016-2017). Previously, he served as the deputy assistant secretary for renewable power in the Office of Energy Efficiency and Renewable Energy, where he oversaw research and development in solar, wind, geothermal, hydro, marine hydrokinetics, and grid modernization. At DOE, Mr. Hollett also conceived and implemented the Frontier Observatory for Research in Geothermal Energy enhanced geothermal system test project, and he was co-chair of the Subsurface Technology and Engineering Research, Development, and Demonstration geologic research initiative. Prior to government service, he had more than 29 years in the oil and gas sector, including as the director, Unconventional New Ventures; the manager, International Exploration; and the general manager and vice president, Atlantic Canada with Marathon Oil. He holds a B.A. in geology from Williams College and an M.S. in geology from the University of Utah.

Bruce Houghton is the Gordon A. MacDonald Professor of Volcanology at the University of Hawaii at Manoa and the state volcanologist of Hawaii. He is also the science director for the Federal Emergency Management Agency–funded National Disaster Preparedness Training Center at the University of Hawaii. Dr. Houghton's research focuses on understanding the mechanisms of explosive eruptions by constraining the nature of the eruptions and their products in near real time. His natural hazards research examines knowledge, perceptions, and preparedness for volcanic eruptions, tsunamis, and flooding. Dr. Houghton has served on numerous committees focused on different aspects of volcanism, and he is currently an executive member of the IAVCEI (International Association of Volcanology and Chemistry of the Earth's Interior) Commission on Tephra Hazard Modeling and Commission on Cities on Volcanoes. He was awarded the 2017 Thorarinsson Medal by IAVCEI. He is a fellow of the American Geophysical Union and the Geological Society of America, and a former president of the Geological Society of New Zealand. He is a fellow of the Royal Society of New Zealand. He received a B.Sc. in geology from the University of Auckland and a Ph.D. in volcanology from the University of Otago, New Zealand.

Katharine W. Huntington is a professor in the Department of Earth and Space Sciences at the University of Washington, where she holds the Endowed Professorship for the College of the Environment in Earth Systems. Her research focuses on the interactions of tectonics, erosion, and climate in shaping Earth's surface and crust over million-years to human time scales. Dr. Huntington's work has made contributions to understanding the dynamic interactions of surface and deep-Earth processes; paleoclimate and paleotopography; soil processes and geochemistry; and the role of extreme floods in landscape evolution. She has also developed new approaches using geochronology and isotope geochemistry to quantify erosion patterns, basin thermal histories, and fluid movement through fault zones. Dr. Huntington serves as a mentor in the Sparks for Change National Science Foundation Leadership in Diversity program. Recently she was lead author and co-coordinator of the "2018 Tectonics Community Vision Document" prepared for the National Science Foundation (NSF). Dr. Huntington is a fellow of the Geological Society of America (GSA). She is the recipient of the NSF CAREER Award and the GSA Donath Medal. Dr. Huntington earned her B.S. in geology and economics from the University of North Carolina at Chapel Hill and completed her Ph.D. in geology at the Massachusetts Institute of Technology.

Steven D. Jacobsen is a professor of Earth and planetary sciences at Northwestern University specializing in mineral and rock physics. He studies the role of volatiles, especially water and carbon, controlling geophysical processes driving the evolution of Earth's crust, mantle, and atmosphere. Dr. Jacobsen developed ultrasonic methods to measure acoustic velocities in materials at deep-mantle conditions, and by examining the influence of water on the structure and properties of minerals and melts he is working to map the distribution of water in the mantle from dense, regional seismic data. His research has broader implications for global geochemical budgets and the origin of Earth's water. Dr. Jacobsen is active in high-pressure science and technology development at large-scale U.S. Department of Energy facilities including the Advanced Photon Source at Argonne National Laboratory and pulsed-power facilities at Sandia National Laboratories. His awards include a Presidential Early Career Award for Science and Engineering, a David and Lucile Packard Fellowship, and a Distinguished Teaching Award from Northwestern University. He previously served on the Executive Committee of the Consortium for Materials Properties Research in Earth Sciences and is currently the editor of *Geophysical Research Letters*. Dr. Jacobsen received his B.A. in geology and Ph.D. in geophysics from the University of Colorado Boulder and was the Barbara McClintock Postdoctoral Fellow at the Geophysical Laboratory, Carnegie Institution for Science in Washington, DC.

Dennis V. Kent (NAS) is the Board of Governors Distinguished Professor at Rutgers University and an adjunct senior research scientist at Lamont-Doherty Earth Observatory. He is an author of more than 300 journal and book articles dealing with paleogeography and paleoclimate, the tempo of geomagnetic polarity reversals, and other aspects and applications of Earth magnetism, and he is listed as an Institute for Scientific Information Highly Cited Researcher. He is a member of the National Academy of Sciences and is a fellow of the Geological Society of America (GSA), American Geophysical Union (AGU), American Association for the Advancement of Science (AAAS), and the American Academy of Arts & Sciences. Dr. Kent was awarded the GSA Arthur L. Day Medal, the Vening Meinesz Medal from Delft University in Holland, the Petrus Peregrinus Medal from the European Geophysical Union, and the AGU William Gilbert Award, and received an honorary doctorate from the Institut de Physique du Globe de Paris-Sorbonne. He has served on the governing boards of the Joint Oceanographic Institutions and Integrated Ocean Drilling Program Management International; as president of the Geomagnetism, Paleomagnetism, and Electromagnetism Section of AGU; as elected member-at-large of the section on Geology and Geography of AAAS; and on the advisory board of the Elsevier journal *Earth and Planetary Science Letters*. He received his B.Sc. in geology from the City College of New York and his Ph.D. in marine geology and geophysics from Columbia University.

Carolina Lithgow-Bertelloni is the Louis B. and Martha B. Slichter Chair in the Geosciences in the Department of Earth, Planetary and Space Sciences at the University of California, Los Angeles (UCLA), which she joined in 2018. Prior to joining the UCLA faculty she was a professor at the University College London and an assistant and an associate professor of geophysics at the University of Michigan. She was the recipient of the Alfred P. Sloan and the David and Lucile Packard Fellowships and was selected as the 2018 Birch Lecturer of the American Geophysical Union. Dr. Lithgow-Bertelloni's research has focused on understanding how the motions in Earth's interior deform, shape, and move Earth's surface, from the large-scale motions of plates to smaller scale topography both today and through Earth's history. Her current efforts are geared toward understanding how Earth's material properties affect the internal dynamics of the mantle, its thermal evolution, and especially how those are reflected on Earth's surface record. Dr. Lithgow-Bertelloni's group employs observational, numerical, and experimental techniques to study the fluid dynamics of Earth's mantle and lithospheric deformation. Together with her group they have developed state-of-the-art visualization and analysis techniques for understanding the dynamics, entrainment, and evolution of mantle plumes in the laboratory and in the real Earth. She received her B.Sc. in geology at the University of Puerto Rico at Mayagüez and her Ph.D. at the University of California, Berkeley.

Paul E. Olsen (NAS) is a professor at Columbia University and holds the Arthur D. Storke Chair in the Department of Earth and Environmental Sciences. Dr. Olsen is a broadly trained geologist and paleobiologist who has authored more than 190 papers on projects examining patterns of evolution and extinction as a response to and cause of climate change, especially in early Mesozoic continental ecosystems, as well as mapping the chaotic history of the solar system using climate archives. His research methods include sedimentology, paleontology, geochemistry, geophysics, and time series analysis, frequently employing scientific drilling. He is an internationally known expert on early Mesozoic continental ecosystems, stratigraphy, paleoclimate, and environments with experience spanning more than 40 years. He has organized and hosted five international workshops and served on two National Research Council committees that published *New Research Opportunities in the Earth Sciences* and *Scientific Ocean Drilling: Accomplishments and Challenges*. He pioneered the use of scientific drilling to recover very long (more than 10 million years) continental paleoclimate records in Triassic and Jurassic strata. Furthermore, he has successfully demonstrated how those records reflect major events in Earth and life history, and how they precisely and accurately map the chaotic evolution of planetary orbits. His applied research has been on hydrocarbon exploration in eastern North American rift basins and carbon sequestration in the same area. He was awarded the Thomas Jefferson Medal for Outstanding Contributions to Natural Science in 2015 and has been a member of the National Academy of Sciences since 2008. Dr. Olsen received a B.A. in geology and an M.Phil. and a Ph.D. in biology (ecology and evolution) from Yale University with a thesis on the evolution of lake ecosystems.

Donald L. Sparks is the Unidel S. Hallock du Pont Chair, Francis Alison Professor, and the director of the Delaware Environmental Institute at the University of Delaware. He is internationally recognized for his research in the areas of kinetics of biogeochemical processes and surface chemistry of natural materials. His research has focused on fate and transport of trace metals in soil and water, soil remediation, water quality, and carbon sequestration in soils. Dr. Sparks is fellow of five scientific societies, and he has been the recipient of major awards and lectureships, including the Geochemistry Medal from the American Chemical Society, the Liebig Medal from the International Union of Soil Sciences, and an Einstein Professorship from the Chinese Academy of Sciences. Dr. Sparks served as the president of the Soil Science Society of America and the International Union of Soil Sciences, has served on advisory committees for several national laboratories and national and international centers and institutes, and served as the chair of the U.S. National Committee for Soil Sciences. Dr. Sparks received his B.S. and M.S. from the University of Kentucky and his Ph.D. from Virginia Tech.

Donna L. Whitney is a Distinguished McKnight University Professor and the head of the N.H. Winchell School of Earth Sciences at the University of Minnesota. Her research focuses on the chemical and physical processes of metamorphism in the deep crust using observations from the scale of mineral grains to mountain systems. A particular interest is the role of the metamorphosing crust in mantle-to-surface dynamics, such as when the deep crust rapidly ascends to the near-surface, influencing topography and heat flow. Dr. Whitney has made contributions to understanding the flow of the deep crust, including trajectory, magnitude and rate, driving mechanisms, and the thermal, chemical, and mechanical consequences for continental evolution. She has also worked on metamorphic processes in subduction zones, with a focus on the interaction of deformation, fluid flow, and metamorphic reactions. She recently led a large, interdisciplinary and international team of geoscientists in a National Science Foundation (NSF) Continental Dynamics project (CD-CAT) that investigated the dynamics of a subduction to collision to tectonic escape system. Dr. Whitney teaches courses in mineralogy, petrology, and introductory geology, including a freshman course on the interaction of geology and humans from prehistory to the present. She is a fellow of the Mineralogical Society of America and the Geological Society of America and she was a recipient of an NSF CAREER Award. She has been an editor of the *Journal of Metamorphic Geology* since 2005. Dr. Whitney received an A.B. in geology at Smith College and a Ph.D. in geological sciences at the University of Washington.

NATIONAL ACADEMIES OF SCIENCES, ENGINEERING, AND MEDICINE STAFF

Deborah Glickson (*Study Director*) is a senior program officer with the Board on Earth Sciences and Resources at the National Academies of Sciences, Engineering, and Medicine. She received an M.S. in geology from Vanderbilt University and a Ph.D. in oceanography from the University of Washington. Her doctoral research focused on magmatic and tectonic contributions to mid-ocean ridge evolution and hydrothermal activity at the Endeavour Segment of the Juan de Fuca Ridge. After finishing her Ph.D., Dr. Glickson participated in the Dean John A. Knauss Marine Policy Fellowship and worked on coastal and ocean policy and legislation in the U.S. Senate. Prior to her Ph.D. work, she was a research associate in physical oceanography at Woods Hole Oceanographic Institution. Since joining the National Academies staff in 2008, she has worked on several ocean and Earth science studies, including such topics as scientific ocean drilling, critical ocean science research needs and infrastructure, the academic research fleet, marine hydrokinetic energy, methane hydrates, coal mining and human health, and geoscience education.

Elizabeth Eide is the senior director of the Board on Earth Sciences and Resources and the Water Science and Technology Board at the National Academies of Sciences, Engineering, and Medicine. The boards oversee a range of activities at the National Academies, including geospatial, geographical, and mapping science; energy and mineral resources; natural hazards; deep- through surface-Earth processes; geological and geotechnical engineering; and all things related to water. A geologist by training, she has overseen 11 National Academies studies on topics including critical minerals, disaster resilience, induced seismicity, coalbed methane, and floodplain mapping. Prior to joining the National Academies in 2005, Dr. Eide served as a research geologist, team leader, and geochronology laboratory manager for 12 years at the Geological Survey of Norway in Trondheim. Among her publications are more than 50 peer-reviewed journal articles and book chapters. She received a Fulbright Scholarship to Norway and was elected to membership in the Royal Norwegian Society of Sciences and Letters. She enjoys mentoring middle school students in Washington, DC, with the Higher Achievement Program. She completed a Ph.D. in geology at Stanford University and received a B.A. in geology from Franklin and Marshall College.

Eric J. Edkin is a program coordinator for the National Academies' Board on Earth Sciences where he coordinates logistical and administrative aspects of committees, meetings, and a variety of other promotional and summary related products. Mr. Edkin started at the National Academies in 2009 and has contributed to projects in the earth sciences, water sciences, disaster resilience, and communication fields. Mr. Edkin earned career diplomas in desktop publishing and computer graphics from the Penn Foster Career School. He is a recipient of the internal 2019 Asteroid Award given to a person who has had a huge impact in the division; the 2017 Group Distinguished Service Award for his role in an Earth Science Decadal project; and the 2017 Trailblazer Award given annually to an outstanding innovative staff member within the Division on Life and Earth Studies.

Raymond M. Chappetta was a research assistant and senior program assistant with the Board on Earth Sciences and Resources and the Water Science and Technology Board. He joined the National Academies staff in 2016 and until April 2020 supported Earth and water studies projects on a variety of topics. Mr. Chappetta graduated with honors and high distinction from The Pennsylvania State University with a B.S. in community, environment, and development and dual minors in international agriculture and environmental soil science.

Appendix B
Community Input Questionnaire

The following questionnaire was distributed through many networks, including the National Science Foundation's (NSF's) Division of Earth Science (EAR); the National Academies of Sciences, Engineering, and Medicine; professional societies; and disciplinary listservs, with a goal of obtaining input to this report from a broad range of the Earth science community. The committee received almost 350 responses to this form.

The Catalyzing Opportunities for Research in the Earth Sciences (CORES) committee is seeking guidance from the Earth sciences community on research priorities for the coming decade, and asks for your input. **The deadline to submit input is March 1, 2019,** and the success of this effort depends upon vigorous community engagement. The CORES committee thanks you for your participation.

The information you provide in response to this questionnaire will inform the CORES committee in its consideration of its study charge. In accordance with Section 15 of the Federal Advisory Committee Act, any information you provide to the committee will be placed in and available through the project's public access record. Responses will be anonymized but will otherwise appear as they are submitted.

1. Your Name*
2. Your Email*
3. Your Affiliation *
4. Your Discipline*
5. Which best describes your current career stage?*
    a. Early Career
    b. Not Early Career

You are welcome to comment on the charge to the committee, but we specifically seek your input on the following:

6. **Across all disciplines,** list 3 important scientific topics or issues that you believe should drive future research in Earth science and intersecting fields.
7. **Within your own discipline,** list 3 important scientific topics or issues that you believe should drive future research in Earth science and intersecting fields.
8. List up to 3 ideas for infrastructure (physical infrastructure, cyberinfrastructure, data management systems, etc.) that will be needed to address the above topics or issues over the next decade.
9. How might NSF best leverage this research and infrastructure through collaboration with other NSF divisions and directorates, federal agencies, and domestic and international partners?
10. How might NSF contribute to training a workforce prepared to lead innovation and discovery in Earth science and intersecting fields over the next decade?
11. Other comments pertinent to the committee's charge.

Appendix C
Open Session Agendas

COMMITTEE MEETING 1

November 19, 2018

National Academy of Sciences Building
2101 Constitution Avenue, NW
Washington, DC

1:00 p.m.
Welcome and Introductions
Jim Yoder, Committee Chair

1:15 p.m.
Discussions with the National Science Foundation

- **Feedback from Directorate for Geosciences on Other Decadal Surveys**
  William Easterling, GEO Assistant Director; Scott Borg, GEO Deputy Assistant Director

- **Discussion with Division of Earth Sciences Management**
  Lina Patino, Acting EAR Division Director; Sonia Esperanca and Steve Harlan, Acting Section Heads

- **Discussion with EAR Program Directors**
  Luciana Astiz, Holly Barnard, Enriqueta Barrera, Phil Bennett, Maggie Benoit, Neysa Call, Sonia Esperanca, Margaret Frasier, David Fountain, Dennis Geist, Steve Harlan, Kevin Johnson, Russell Kelz, Venkat Lakshmi, David Lambert, Justin Lawrence, Aisha Morris, Lina Patino, Paul Raterron, Robin Reichlin, Judy Skog, Dena Smith, Tom Torgersen, Maggie Toscano, Jennifer Wade, Steve Whitmeyer, Jonathan Wynn, Richard Yuretich, Eva Zanzerkia

5:15 p.m.
Concluding Remarks
Jim Yoder, Committee Chair

5:30 p.m.
Open Session Adjourns

COMMITTEE MEETING 2

January 14, 2019

Beckman Center
100 Academy Way
Irvine, CA 92617

10:30 a.m.
Welcome and Introductions
Jim Yoder, Committee Chair

- Committee and participant introductions
- Brief overview of the National Academies, CORES study, and committee process
- Expectations for today's meeting and how information might be used

11:00 a.m.
Lightning Talks on Research Topics

- In-depth introduction to each participants' interests, to set the stage for further discussions
- Each participant spends 3-5 minutes discussing their research area
- 1-3 PowerPoint slides (slides will be available publicly, so please credit any images and do not put in proprietary information)
- Q&A with committee

Participants:

- Maryjo Brounce, University of California, Riverside
- Joern Callies, Caltech
- Joe Carlin, California State University, Fullerton
- Parveen Chhetri, California State University, Dominguez Hills
- Jennifer Cotton, California State University, Northridge
- Roby Douilly, University of California, Riverside
- Heather Ford, University of California, Riverside
- Naomi Levine, University of Southern California
- Vali Memeti, California State University, Fullerton
- Nikki Moore, Pomona College
- Mathieu Morlighem, University of California, Irvine
- Kingsley Odigie, University of California, Riverside
- Matt Weingarten, San Diego State University

12:15 p.m.
Small Group Discussion 1 – Research

- Discussion over lunch, provided in the dining room
- Committee and participants will be assigned groups to sit with based on research interests
- Rapporteurs capture overarching themes and highlights
- Select 1-2 participants to present in plenary

Guiding questions:

1. What are the most exciting or highest-priority questions for the next decade, in your field or across Earth sciences?
2. What infrastructure, facilities, or instrumentation will be needed to answer these questions?
3. How do you see your field evolving?

1:30 p.m.
Small Group Discussion 2 – Challenges and Opportunities

- Committee and participants will be assigned to different groups
- Rapporteurs capture overarching themes and highlights
- Select 1-2 participants to present in plenary

Guiding questions:

1. What is your experience submitting proposals to NSF's Division of Earth Sciences (EAR) or other divisions?
2. Besides research funding, what opportunities could EAR provide to help advance your career (e.g., support staff, training)?
3. What are the greatest barriers or challenges to the development of your research program? Which of these could EAR address in definitive ways?

2:15 p.m.
Break

2:30 p.m.
Plenary

- Presentations from each small group about overarching themes and highlights
- Discussion with entire group

3:15 p.m.
Concluding Remarks
Jim Yoder, Committee Chair

3:30 p.m.
Open Session Adjourns

COMMITTEE MEETING 3

March 14, 2019

Houston Marriott North
255 N Sam Houston Pkwy E
Houston, TX 77060

8:15 a.m.
Welcome and Introductions

8:30 a.m.
Panel on Increasing and Sustaining Diversity in the Geosciences

- Sharon Mosher, Dean, Jackson School of Geosciences, The University of Texas at Austin
- Ishara Casellas Connors, Assistant Dean for Diversity and Climate, College of Geosciences, Texas A&M University

9:30 a.m.
Panel on Decadal Scientific and Technology Directions for the Energy Sector

- Scott Tinker, Bureau of Economic Geology and State Geologist of Texas

- Lauren Birgenheier, University of Utah (representing the American Association of Petroleum Geologists)
- Michael Braun, University of Texas Energy Initiative, ExxonMobil Upstream Research Company
- Eugene Szymanski, Basin Framework Team, Chevron Energy Technology Company

11:00 a.m.
Open Session Adjourns

COMMITTEE MEETING 4

May 14, 2019

Hyatt Regency Chicago
151 E Wacker Dr.
Chicago, IL 60601

3:30-4:00 p.m.
Mark Rivers: Overview of GSECARS, Discussion of COMPRES, and Planned Updates to DOE Advanced Photon Source

4:00 p.m.
Open Session Adjourns

COMMITTEE MEETING 5

July 22-24, 2019

National Academies Keck Center
500 Fifth Street, NW
Washington, DC 20001

Monday, July 22

1:00 p.m.
Panel 1: NSF Cyberinfrastructure and Data Science

- Geoinformatics – Steve Whitmeyer, EAR, and Kevin Johnson, EAR
- EarthCube – Eva Zanzerkia, EAR, and Ken Rubin, University of Hawaii
- Cyberinfrastructure for Sustained Scientific Innovation (CSSI)/Harnessing the Data Revolution – Amy Walton, CISE Office of Advanced Cyberinfrastructure

2:30 p.m.
Open Session Adjourns

Tuesday, July 23

10:30 a.m.
Panel 2: Partnerships Within NSF

- GEO Division of Ocean Sciences – Terry Quinn and Candace Major
- GEO Division of Atmospheric and Geospace Sciences – Anjuli Bamzai
- Office of International Science and Engineering – Jessica Robin
- ENG Division of Chemical, Bioengineering, Environmental, and Transport Systems – Brandi Schottel
- BIO Division of Environmental Biology – Kendra McLauchlan

12:00 p.m.
Working Lunch with Guests and Attendees

1:00 p.m.
Panel 3: Partnerships with Other Federal Agencies

- USGS Natural Hazards Mission Area – David Applegate
- NASA Earth Surface and Interior – Gerald Bawden
- NASA Exo/Astrobiology – Mary Voytek
- DOE Basic Energy Sciences – Jim Rustad
- USDA National Institute of Food and Agriculture – Nancy Cavallaro

3:00 p.m.
Open Session Adjourns

Wednesday, July 24

9:00 a.m.
Discussion with Bill Easterling, GEO Director

10:00 a.m.
Open Session Adjourns

Appendix D
Current Research Infrastructure Provided by Multi-User Facilities

The Division of Earth Sciences (EAR) of the National Science Foundation (NSF) supports 30 multi-user facilities that provide infrastructure for EAR-supported research communities. The larger facilities support researchers with a combination of instruments, cyberinfrastructure, and expertise/training, while most other facilities emphasize either instrument-based infrastructure or cyberinfrastructure.

Budget amounts were determined based on the total amounts awarded to date (as of February 2019; information provided by EAR), divided by the number of years for which funds have been awarded. In some cases, these values differ somewhat from the average amounts awarded for the entire award period. If principal investigators provided updated award amounts, these were used instead. Most of the facilities described above are supported primarily by EAR. Some facilities also receive funding from other NSF divisions or directorates—these funds are included as additional support.

Following sections are divided into multi-user facilities that provide instrumentation and those that provide cyberinfrastructure.

INSTRUMENTATION

The Instrumentation and Facilities Program supports 20 multi-user facilities that develop and provide community access to instrumentation. The annual average of funding for these facilities is $41.6 million per year.

Seismology and Geodesy

Seismological Facilities for the Advancement of Geoscience (SAGE)

SAGE provides instrumentation services, data services, as well as education, workforce development, and community engagement activities in support of seismology. It is operated by the Incorporated Research Institutions for Seismology (IRIS) Consortium, which consists of more than 100 U.S. universities dedicated to the operation of science facilities for the acquisition, management, and distribution of seismological data. The mission of the IRIS Consortium is to:

1. Facilitate investigations of seismic sources and Earth properties using seismic and other geophysical methods.
2. Promote exchange of seismic and other geophysical data and knowledge through the use of standards for network operations and data formats, and through pursuing policies of free and unrestricted data access.
3. Foster cooperation among IRIS members, affiliates, and other organizations in order to advance seismological research and education, expand the diversity of the geoscience workforce, and improve Earth science literacy in the general public.

Website: https://www.iris.edu/hq

Average annual budget: $17,500,000 from EAR, with an additional ~$900,000 from the Office of Polar Programs

Geodetic Facility for the Advancement of Geoscience (GAGE)

GAGE supports the NSF investigator community for geodesy, Earth sciences research, education, and workforce development with broad societal benefits. It is operated by UNAVCO, a nonprofit, university-governed consortium. Supporting services include:

1. Operation of the Network of the Americas, an integrated set of geodetic systems including continuous Global Navigation Satellite System (cGNSS), real-time GNSS, borehole strainmeters, tiltmeters and seismometers, and metpacks;
2. Engineering, instrumentation, and data services to NSF-funded investigators who use terrestrial and satellite geodetic technologies (e.g., Terrestrial Laser Scanning, GNSS, and Interferometric Synthetic Aperture Radar [InSAR]) in Earth science research as well as geosciences more broadly;
3. Operations to support NSF-funded community GNSS networks for Earth, atmospheric, and polar science applications, and the National Aeronautics and Space Administration's (NASA's) Global GNSS Network; and
4. Planning support for principal investigators and core programs to advance geoscience education resources and geodesy community engagement.

Website: https://www.unavco.org

Average annual budget: $11,400,000, with an additional ~$840,000 from the Office of Polar Programs and ~$1,000,000 from NASA

Materials Characterization

GeoSoilEnviroCARS Synchrotron Radiation Beamlines at the Advanced Photon Source (GSECARS)

GSECARS is a national user facility for frontier research in the Earth sciences using synchrotron radiation at the Advanced Photon Source, Argonne National Laboratory. GSECARS provides Earth scientists with access to the high-brilliance hard X-rays from this third-generation synchrotron light source. Primary applications include:

1. High-pressure/high-temperature crystallography and spectroscopy using the diamond anvil cell
2. High-pressure/high-temperature crystallography and imaging using the large-volume press
3. Powder, single crystal and interface diffraction
4. Inelastic X-ray scattering
5. X-ray absorption fine structure spectroscopy
6. X-ray fluorescence microprobe analysis
7. Microtomography

Website: http://gsecars.uchicago.edu

Average annual budget: $2,900,000

Consortium for Materials Properties Research in Earth Sciences (COMPRES)

COMPRES is a community-based consortium whose goal is to enable Earth science researchers to conduct the next generation of high-pressure science on world-class equipment and facilities. It facilitates the operation of beamlines, the development of new technologies for high-pressure research, and advocates for science and educational programs to the various funding agencies.

Website: https://compres.unm.edu

Average annual budget: $2,400,000

Geochemistry/Geochronology

Purdue Rare Isotope Measurement Laboratory (PRIME Lab)

The PRIME Lab is a dedicated research and user facility for accelerator mass spectrometry (AMS). AMS is an ultra-sensitive analytical technique for measuring long-lived radionuclides. Their mission is to provide measurements of long-lived radionuclides for researchers at Purdue University, at other universities, at national laboratories, and at agencies providing measurements of environmental levels of long-lived radionuclides in the United States and throughout the world. PRIME Lab facilities include the AMS system, based on a tandem electrostatic accelerator, and those laboratories needed for physical preparation of samples and the chemical separation and purification of long-lived radionuclides. Isotopes analyzed include ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, ^{41}Ca, and ^{129}I.

Website: http://www.physics.purdue.edu/primelab

Average annual budget: $708,000

University of California, Los Angeles, Ion Probe Lab (UCLA SIMS)

The UCLA SIMS facility consists of a CAMECA IMS 1270 which is used primarily for U-Pb geochronology and a CAMECA IMS 1290 with a Hyperion-2 ion source that focuses on high-precision stable isotope ratio measurements. Priorities include providing (1) access to these instruments for U.S. geochemists, cosmochemists, and geochronologists; (2) UCLA scientists the resources required to continue to develop and refine existing and new methods for research in geochemistry, geobiology, cosmochemistry, and geochronology; and (3) opportunities for research training at a variety of levels.

Website: http://sims.epss.ucla.edu

Average annual budget: $468,000

Arizona State University Ion Probe Lab (ASU SIMS)

The ASU SIMS facility contains a CAMECA IMS 6f and a CAMECA NanoSIMS 50L. The IMS 6f is well suited for precise isotope ratio measurements and trace element analyses in small (several micrometer) areas and for in-depth profiling of trace element distributions with few-nanometer resolution. The NanoSIMS has extremely high lateral resolution coupled with high secondary ion transmission at high mass resolving power. It is a good match for a wide range of NSF EAR-supported research and is the only NanoSIMS in the United States that acts as an open facility. Priorities include (1) helping a diverse group of visitors obtain the best possible trace element and isotopic microanalyses, (2) developing new analytical techniques and instrumentation, (3) improving quantification and infrastructure (standards), and (4) enhancing educational approaches for new visitors.

Website: http://sims.asu.edu

Average annual budget: $402,000

Northeast National Ion Microprobe Facility (NENIMF)

The NENIMF consists of a CAMECA IMS 1280 and a CAMECA IMS 3f which are used for high-precision measurements of light elements such as hydrogen, lithium, boron, carbon, nitrogen, and oxygen. Primary applications include determination of magmatic volatiles in silicate glasses and analysis of biogenic carbonates as records of climate change and its impacts on marine organisms. Additional applications include studies of B isotopes in MORB glasses and subduction zone minerals, Zr in rutile geospeedometry, Ti diffusion in quartz, and U-Th-Pb dating of monazite and zircon.

Website:https://www2.whoi.edu/site/nenimf

Average annual budget: $339,000

University of Wisconsin SIMS Lab (Wisc SIMS)

Wisc SIMS utilizes an IMS-1280 large-radius, multicollector ion microprobe (SIMS) for analysis of stable isotopes (including Li, C, N, O, Mg, Si, S, Ca, and Fe). The three most common areas of research that are enabled by Wisc SIMS are Igneous and Metamorphic Petrology and Geochemistry; Cosmochemistry and Astrobiology; and Low-Temperature Geochemistry and Paleoclimatology. More than 50% of instrument beamtime has been devoted to Earth science and NSF-supported projects. NSF-funded projects receive the highest priority and a reduced-fee schedule.

Website: http://www.geology.wisc.edu/%7Ewiscsims

Average annual budget: $330,000

Arizona LaserChron Center (ALC)

The ALC utilizes laser-ablation inductively coupled plasma mass spectrometry to generate U-Th-Pb ages, Hf isotope ratios, and trace element concentrations of geologic materials. Instruments include dedicated single-collector (Thermo Element2) and multicollector (NU Plasma) mass spectrometers, two excimer lasers, and an SEM with SE, BSE, EDS, EBSD, and color CL capabilities. Priorities are to (1) provide opportunities for researchers from around the world (and especially NSF-supported scientists) to use our instruments and expertise to address geologic problems; (2) drive the development of new instruments, techniques, and applications of geochronology, thermochronology, and petrochronology; (3) build new cyberinfrastructure for data acquisition, analysis, and archiving; and (4) use every aspect of facility operation as an opportunity to enhance expertise and diversity in geochronology. Research focuses on the growth of continents, processes of mountain building, generation and dispersal of sediment, formation of mineral and hydrocarbon resources, history of evolutionary changes, and genetic linkages between climate and tectonics.

Website: http://www.laserchron.org

Average annual budget: $259,000

Support for Continental Scientific Drilling

International Continental Scientific Drilling Program (ICDP)

ICDP performs the critical function of providing a working infrastructure that facilitates scientific drilling through access to a multisensor core logger, core scanner, and deep lake drilling system, among other equipment and services. ICDP endeavors to benefit stakeholders through (1) focusing scientific efforts on drilling sites of global significance, (2) offering affordability and cost-effectiveness through sharing, (3) attracting high-quality researchers to topics of high national and international priority, (4) providing intellectual benefits to all participants arising from international cooperation, and (5) monitoring the socioeconomic benefits linked to water quality, climate change, sustainable resource development, and natural hazard vulnerability. The organizational structure of ICDP aims to be simple, transparent, and flexible in balancing project logistics and scientific rigor.

Website: https://www.icdp-online.org/home

Average annual budget: $1,000,000

Continental Scientific Drilling Coordination Office (CSDCO)

The CSDCO performs several critical functions for scientific communities requiring drilling and coring on Earth's continents: (1) develop project-specific technical, logistical, budgetary, and funding plans, engineer optimal drilling solutions, solicit bids, and secure and manage contracts for field operations; (2) manage domestic and international logistics and field operations; (3) procure, stock, and provide specialized equipment and consumables; (4) provide expertise for training and supervision of operations including drilling-science interface, sample and data management, and outreach activities; (5) manage laboratory services for processing, scanning, and subsampling all types of core samples and derivative data; (6) develop software and data systems for visualization, workflow support, and data management; (7) develop infrastructure for support of project and community goals; (8) facilitate curation of cores and data/metadata in repositories; and (9) foster the development of an engaged, active, and technologically advanced community and coordinate the development of long-range community science plans.

Website: https://csdco.umn.edu

Average annual budget: $733,000

National Lacustrine Core Facility (LacCore)

The LacCore Facility supports the limnological community for studies that contribute to our understanding of past climates, ecological systems, Earth processes, and biogeochemical dynamics on the continents though collection, scanning, analysis, and archival services for lacustrine sediment core samples. LacCore operates open facilities for community access to specialized field coring equipment, laboratory instrumentation, curatorial services, and staff expertise for core collection; core splitting; lithologic description; core scans and automated logging; SEM imaging and EDS; optical petrography/smear slide analysis; preparation and analysis of subsamples for palynology; grain size; loss on ignition; X-ray diffraction; thin sections; and several other analyses. LacCore also provides refrigerated, frozen, and ambient core storage, and repository and data services. Since 2012, LacCore has extended its services to additional geoscience communities for analysis and curation of other types of continental core samples.

Website: http://lrc.geo.umn.edu/laccore

Average annual budget: $358,000

Other Disciplines

National Center for Airborne Laser Mapping (NCALM)

The primary function of NCALM is to provide research-quality airborne light detection and ranging (lidar) observations to the scientific community. LiDAR measures surface topographic features with very high accuracies and spatial resolution, resulting in very detailed digital elevation models (DEMs) that offer an unprecedented high-resolution representation of topographic features and illuminate the processes that shape them. Examples include fault scarps, hill slopes, river channels, barrier beaches and sand dunes, mountain and continental glaciers, volcanic edifices and the structure of the forest canopy. Secondary objectives are to advance the state of the art in airborne laser mapping and to train and educate graduate students with knowledge of airborne mapping to meet the needs of academic institutions, government agencies, and private industry.

Website: http://ncalm.cive.uh.edu

Average annual budget: $877,000

Center for Transformative Environmental Monitoring Programs (CTEMPs)

CTEMPs offers community support for planning, training, equipment loan, and field implementation using distributed fiber optic Raman backscatter Distributed Temperature Sensing (DTS) for observation of the spatial and temporal distribution of temperature. Applications include snow, groundwater, and watershed hydrology; aquatic and terrestrial ecology; karst geology; soil science (including permafrost studies); physical limnology and oceanography; micrometeorology; and glaciology. New initiatives include developing the use of actively heated optical fiber sensing for the measurement of soil moisture and fluid flux and incorporating unmanned aircraft systems technology to hydrologic and earth surface monitoring. CTEMPs added in 2019 the OPEnS lab (Open-Sensing.org), where CTEMPs clients learn to apply micro-sensors and wireless communication to Earth science measurement projects. Services of OPEnS include sensor-to-web data systems, 3D printing, consulting on selection of sensors, power sources for remote sensing systems, and wireless communication (including satellite- and cell phone–based solutions). CTEMPs runs three to five workshops annually.

Website: https://ctemps.org

Average annual budget: $563,000

Virginia Tech National Center for Earth and Environmental Nanotechnology Infrastructure (NanoEarth)

VT NanoEarth provides a National Nanotechnology Coordinated Infrastructure site to support researchers who work with nanoscience- and nanotechnology-related aspects of the Earth and environmental sciences/engineering. VT NanoEarth has a close partnership with the Environmental Molecular Sciences Laboratory (EMSL) at Pacific Northwest National Laboratory (PNNL). NNCI geo- and environmental science/engineering users have access to both the Virginia Tech and EMSL/PNNL sites depending on specific technical needs and geographic considerations. NanoEarth facilities at Virginia Tech house a broad array of electron-, ion-, and X-ray-based characterization tools as well as facilities for sample preparation and nanomaterials synthesis.

Website: https://www.nanoearth.ictas.vt.edu

Average annual budget: $500,000

University of Texas High-Resolution Computed X-Ray Tomography Facility (UTCT)

UTCT utilizes X-ray computed tomography (CT) to provide researchers across the Earth, biological and engineering sciences access to a completely nondestructive technique for visualizing features in the interior of opaque solid objects, and for obtaining digital information on their 3D geometries and properties. UTCT serves both as a source of high-quality data for investigators without access to CT instrumentation, and as a repository of experience and expertise in all aspects of CT data acquisition and analysis.

Website: http://www.ctlab.geo.utexas.edu

Average annual budget: $423,000

Institute for Rock Magnetism (IRM)

The IRM provides advanced instrumentation, expertise, and training to the Earth Science research community for studies of magnetic properties of natural materials and their synthetic analogs. Research focuses on the characterization of magnetic minerals in natural systems and understanding the origin, evolution and significance of magnetic minerals and natural remanent records of ancient magnetic field behavior on Earth and other planetary bodies. Natural-material magnetic research has important applications over a broad range of Earth science, including (paleo) environmental research, history of geomagnetic field variations, evolution of the deep interior, plate tectonic reconstructions, quantification of flow and deformation fabrics in sedimentary, igneous and metamorphic rocks, biomagnetism, and planetary and meteorite magnetism. The IRM also hosts a Summer School for Rock Magnetism for graduate students and early-career scientists and organizes biennial interdisciplinary conferences.

Website: http://www.irm.umn.edu/IRM/index.html

Average annual budget: $387,000

International Seismological Centre (ISC)

The ISC data provide the most comprehensive and complete account of earthquakes worldwide for the entire instrumental period from 1904 to present. This is the principal data source for several hundred research papers each year. The types of studies for which the ISC data are virtually indispensable include research of tectonics and inner-Earth structure, seismic hazard and mitigation of earthquake disasters, earthquake source physics, earthquake forecasting, and monitoring the Comprehensive Nuclear Test Ban Treaty. The ISC products also serve as unique and valuable tools for education and scientific publishing. With the current tendency of other agencies such as the U.S. Geological Survey (USGS) to focus their efforts on rapid determinations, the value of the most comprehensive and accurate ISC data is further enhanced.

Website: http://www.isc.ac.uk

Average annual budget: $250,000

Global Centroid-Moment-Tensor Project (CMT)

The objective of the Global CMT Project is to provide the best and most comprehensive record of global seismic strain release available. The project involves (1) systematic determination of moment tensors for earthquakes with M>5 globally, and accumulation of the results in the CMT catalog; (2) rapid determination of moment tensors for earthquakes with M>5.5 globally and quick dissemination of results; (3) curation of the CMT catalog; and (4) development and implementation of improved methods for the quantification of earthquake source characteristics on a global scale.

Website: https://www.globalcmt.org

Average annual budget: $123,000

Cyberinfrastructure

EAR supports 10 multi-user facilities that develop and provide community access to cyberinfrastructure. The annual average of funding for these facilities is $10.7 million.

Interdisciplinary Earth Data Alliance (IEDA)

IEDA systems serve as primary community data collections for global geochemistry and marine geoscience research and support the preservation, discovery, retrieval, and analysis of a wide range of observational field and analytical data types. Our tools and services are designed to facilitate data discovery and reuse for focused disciplinary research and to support interdisciplinary research and data integration. IEDA hosts and serves data that include marine seismic data and bathymetry; rock and seafloor sediment and hydrothermal vent fluid geochemistry; geochronology; Antarctic research; information about physical samples; and other marine and Earth science data. It also has developed and deployed map-based data discovery tools and compiled data products that enable quick identification of data and/or datasets of interest.

Website: https://www.iedadata.org/about/ieda-overview

Average annual budget: $3,410,000

Consortium of Universities for the Advancement of Hydrological Science, Inc. (CUAHSI)

CUAHSI is a 501(c)(3) research organization representing more than 130 U.S. universities and international water science-related organizations. CUAHSI's mission is to develop infrastructure and services for the advancement of water science by (1) strengthening interdisciplinary collaboration in the water science community, (2) empowering the community by providing critical infrastructure, and (3) promoting education in the water sciences at all levels.

Website: https://www.cuahsi.org

Average annual budget: $2,485,000

Computational Infrastructure for Geodynamics (CIG)

CIG is a community-driven organization that advances Earth science by supporting and sustaining the cyberinfrastructure and computational capacity for geophysics and related fields. During the past decade, CIG has supported the development of open source software communities and widely used numerical modeling codes as well as their dissemination for research and education in computational seismology, mantle convection, magma dynamics, short- and long-term lithospheric and crustal deformation, and dynamo modeling.

Website: https://geodynamics.org

Average annual budget: $1,700,000

Community Surface Dynamics Modeling System (CSDMS)

CSDMS is a diverse community of experts that promotes the modeling of Earth surface processes by developing, supporting, and disseminating integrated software modules which predict the movement of fluids and the flux (production, erosion, transport, and deposition) of sediment and solutes in landscapes and their sedimentary basins. Specific processes that are studied include soil erosion, glaciation, river sedimentation, coastal change, seafloor processes, and many natural phenomena that can impact human life and infrastructure. CSDMS focuses on the development and applications of computer models that help researchers and other professionals understand these processes and their potential impacts on human activity. The organization provides support in community, computing, and education.

Website: https://csdms.colorado.edu/wiki/Main_Page

Average annual budget: $1,206,000

OpenTopography High Resolution Data and Tools Facility (OpenTopo)

OpenTopo provides web-based access to high-resolution topographic data from technologies such as lidar and photogrammetry, co-located with processing and analysis tools in support of Earth science research, research training, and education. Earth science fields, including geomorphology, hydrology, glaciology, volcanology, and neotectonics, have benefited and will continue to benefit from OpenTopo data and tools. Current activities focus on development of strengthened interoperability, a broadened suite of processing and data services, improved scalability via cloud and high-performance computing, and provision of outreach and user support through short courses and workforce development.

Website: https://opentopography.org

Average annual budget: $546,000

Geo-Visualization and Data Analysis using the Magnetics Information Consortium (MagIC)

MagIC is designed to develop and maintain an open community digital data archive for published rock and paleomagnetic data. This allows researchers and other users continued free access to archive, search, visualize, manipulate, and download data that are used to study (1) past climate changes and their relation to Earth's magnetic field; (2) the timing of the appearance and growth of Earth's solid inner core and the associated influences on the geomagnetic field; (3) the geodynamics of Earth's mantle; (4) biogeomagnetism; and (5) magnetism at high pressures and in extraterrestrial bodies.

Website: https://www2.earthref.org/MagIC

Average annual budget: $429,000

Neotoma Paleoecology Database and Community

The Neotoma Paleoecology Database is an online hub for community data curation, research, and education about paleoenvironments that existed during the past 5 Ma. Data currently include pollen (NAPD, EPD, LAPD, APD, IndoPac), fossil mammals (FAUNMAP), diatoms, ostracodes, insects, charcoal, isotopes, radiocarbon dates, etc. with global coverage for pollen and North American coverage for other proxies. Multiple national to international research campaigns are under way to add or refine data in Neotoma and use them in regional to global reconstructions of past environments (e.g., ACCEDE, CLIMATE12K, HOPE, LANDCOVER6K, PALEON, SKOPE). Information provided by Neotoma is of benefit primarily to the paleobiology, paleoclimatology, geochronology, archaeology, global change, biogeography, and Earth surface processes communities.

Website: https://www.neotomadb.org

Average annual budget: $319,000

Open Core Data

Open Core Data provides the infrastructure that makes data from scientific continental and ocean drilling projects findable, accessible, interoperable, and reusable (FAIR), according to community best practices for data stewardship. Drilling data are used to study the nature of the deep biosphere and oceanic sub-seafloor, understand environmental change and evolution of the Earth and Earth-life systems, species evolution, fault zone dynamics, magmatism, tectonics, and geothermal energy, among many other topics. Open Core Data benefits from partnerships with a wide range of U.S. and international cyberinfrastructure and technology projects and communities.

Website: https://csdco.umn.edu/resources/software/open-core-data

Average annual budget: $305,000

Alpha-MELTS

Alpha-MELTS develops software that includes models and algorithms for computational thermodynamics in petrology, geochemistry, and geodynamics. It enables earth scientists to execute forward models of complex petrogenetic scenarios with internal thermodynamic consistency and integrated volatile and trace element calculations. All software is released free of charge for use by the scientific community.

Website: https://magmasource.caltech.edu/alphamelts

Average annual budget: $176,000

Generic Mapping Tools (GMT)

The GMT software package is an open-source collection of about 90 command-line tools for manipulating geographic and Cartesian datasets (including filtering, trend fitting, gridding, projecting, etc.) and producing illustrations ranging from simple x–y plots via contour maps to artificially illuminated surfaces and 3D perspective views to animations. GMT supports more than 30 map projections and transformations and requires support data such as Global Self-consistent, Hierarchical, High-resolution Geography Database coastlines, rivers, and political boundaries and optionally Digital Chart of the World country polygons. GMT source code is distributed, free of charge, under the GNU Lesser General Public License. The GMT website has more than 20,000 visits per month and roughly 2,000 downloads per month.

Website: https://www.generic-mapping-tools.org

Average annual budget: $123,000