The National Academies of
SCIENCES · ENGINEERING · MEDICINE

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

Jim Yoder, Greg Beroza, Andrea Dutton, Michael Foote,
George Gehrels, Kate Huntington, Donna Whitney, and the Committee
on Catalyzing Opportunities for Research in the Earth Sciences

May 19, 2020

NSF Organization

- **Directorate for Geosciences (GEO)**
  - **Earth Sciences (EAR)**
  - Division of Ocean Sciences (OCE)
  - Division of Atmospheric and Geospace Sciences (AGS)
  - Office of Polar Programs (OPP)

DISCIPLINARY PROGRAMS

Geobiology and Low-Temperature Geochemistry

Geomorphology and Land Use Dynamics

Geophysics

Hydrologic Sciences

Petrology and Geochemistry

Sedimentary Geology and Paleobiology

Tectonics

DIVISION-WIDE PROGRAMS

Frontier Research in Earth Sciences

Critical Zone Collaborative Network

INFRASTRUCTURE

Instrumentation

Facilities

Geoinformatics

Education and Human Resources

Postdoctoral Fellows Program

Statement of Task

NASEM will help provide advice that EAR can use to set priorities and strategies for its investments on research, infrastructure, and training in the coming decade. The report will include:

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.

2. (A) **Identification of the infrastructure 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.

Statement of Task, cont.

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.

In addition, the National Academies convened **a workshop to address different management models for future seismological and geodetic facility capabilities**, providing additional information for Task 2 of the CORES study.

Committee Roster

Jim Yoder (Chair), Woods Hole Oceanographic Institution

Greg Beroza, Stanford University

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Kate Huntington, University of Washington

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Dennis Kent, Rutgers University

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Paul Olsen, Columbia University

Don Sparks, University of Delaware

Donna Whitney, University of Minnesota

Outline

- Vision
- Science priority questions
- Infrastructure & initiatives
- Partnerships

Vision

- EAR can enhance support for Earth research as an integrated system

- This is an “all hands on deck” moment; we need
  - Diverse, inclusive groups
  - Individuals, teams, and collaborative networks
  - Cutting-edge analytical, computational, and field-based methods

Science Priorities – Approach

Field gear.

Information-gathering

- Literature review
- Community input questionnaire
- Listening sessions/town halls
- Workshops held previously by community groups
- Interviews with colleagues
- Invited discussions during committee meetings

Developing priorities

- Generating “long list”
- Merging similar questions
- Examining the scientific importance and likelihood of transformative impact
- Framing the questions

Identify specific questions that are **poised for major advances** in next 10 years

Some questions have long been of great interest

Science Priorities

Integrating Themes

- Earth system components interact over time and space
- Connections between Earth spheres increasingly important
- Technological advances enable new observations and modeling
- Societal relevance of fundamental Earth science research

Person conducting fieldwork.

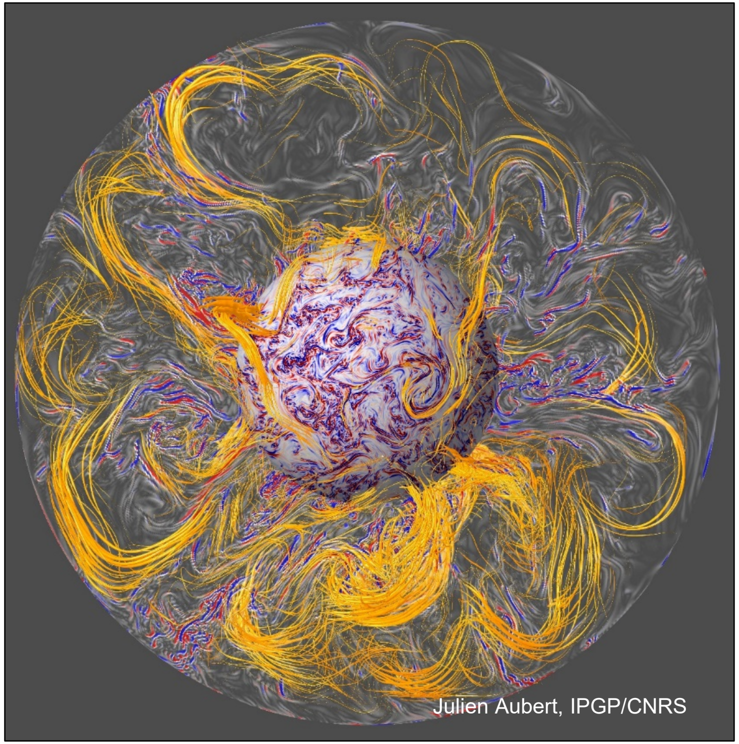
- Key insights come from a strong disciplinary research program
- There will be unanticipated discoveries with profound effects

Science Priority Questions

- How is Earth's internal magnetic field generated?
- When, why, and how did plate tectonics start?
- How are critical elements distributed and cycled in the Earth?
- What is an earthquake?
- What drives volcanism?
- What are the causes and consequences of topographic change?
- How does the critical zone influence climate?
- What does Earth's past reveal about the dynamics of the climate system?
- How is Earth's water cycle changing?
- How do biogeochemical cycles evolve?
- How do geological processes influence biodiversity?
- How can Earth science research reduce the risk and toll of geohazards?

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.

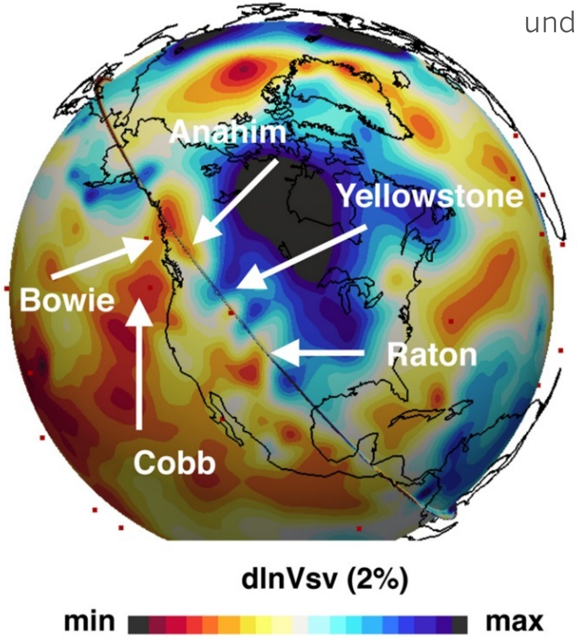


Magnetic field lines stretched by turbulent core flow

When, why, and how did plate tectonics start?

Plate tectonics produce and modify continents, oceans, and atmosphere, but we don't yet understand *when* it developed, *why* Earth has plate tectonics, and *how* it developed.

Tomographic modeling shows the map view underneath North America

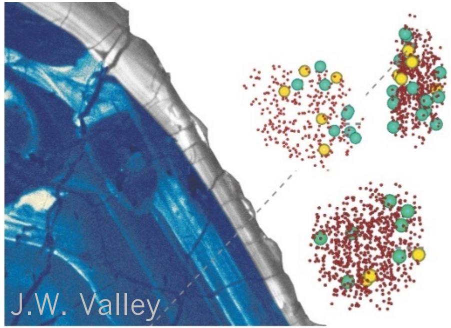


Bozdağ et al., 2016

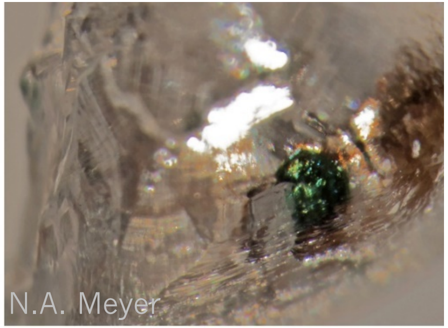
How are critical elements distributed and cycled in the Earth?

Element cycling creates suitable conditions for life and ingredients for materials needed for modern civilization, yet questions remain about how elements are transported within the Earth, across many spatial & temporal scales.

Atomic scale

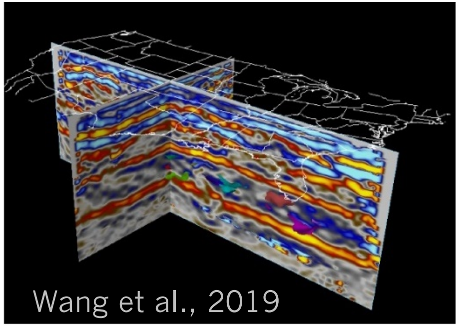


Mineral scale



Rock scale

Mantle scale



The redistribution and cycling of critical elements occurs from atomic to global scales over geologic time.

What is an earthquake?

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

Surface rupture from the Ridgecrest earthquake

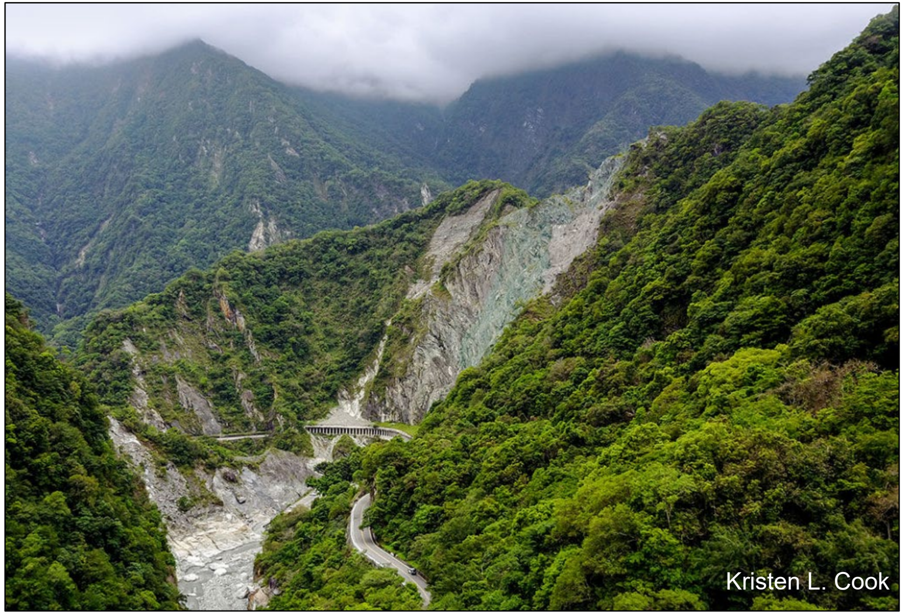
What drives volcanism?

Volcanic eruptions affect people, the atmosphere, the hydrosphere, and Earth, creating an urgent need for research on how magma forms, rises, and erupts.

Halemaumau lava lake

What are the causes and consequences of topographic change?

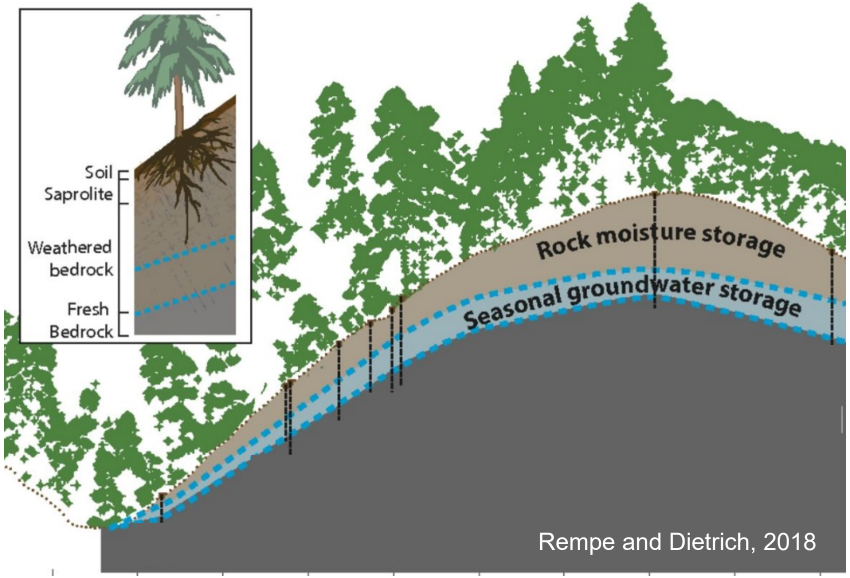
New technology for measuring topography over geologic to human timescales makes it possible to address Earth system interactions & urgent societal challenges.



Landscape change due to landslides triggered by earthquakes and storms in Taiwan

How does the critical zone influence climate?

The critical zone influences moisture, groundwater, and energy & gas exchanges between the land and atmosphere, and its influence on climate is vital to understanding how the Earth system has responded and will respond to global change.



Lidar-derived vegetation and surface topography at Eel River CZO.

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

Evidence of long-term and rapid environmental change in Earth's history helps us understand Earth system dynamics and provides magnitudes and rates of change, which are crucial for prediction.

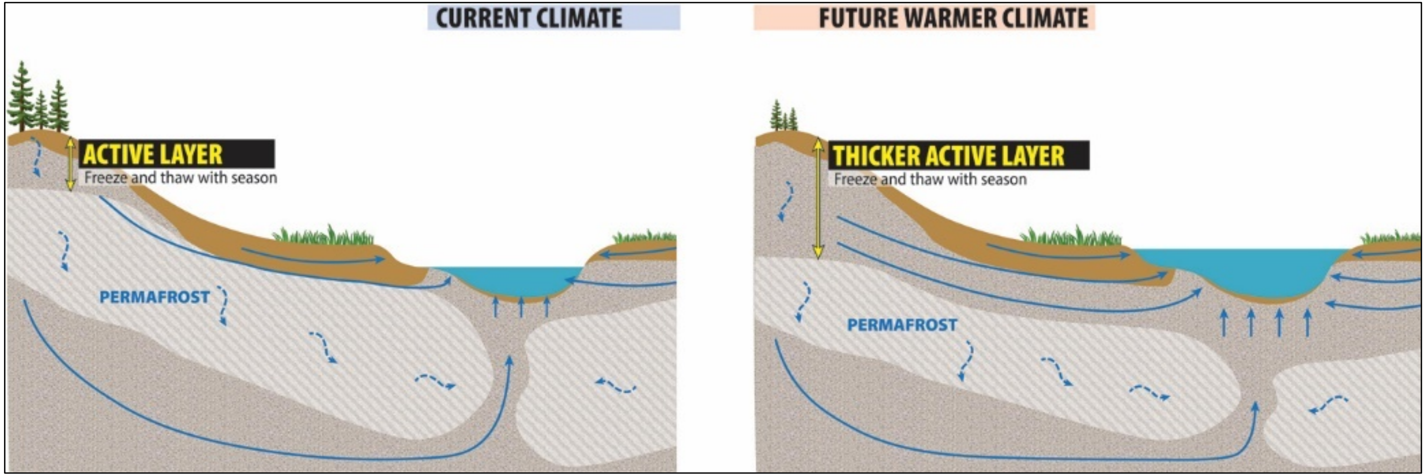
Speleothem

Tree ring

Sediment core

How is Earth's water cycle changing?

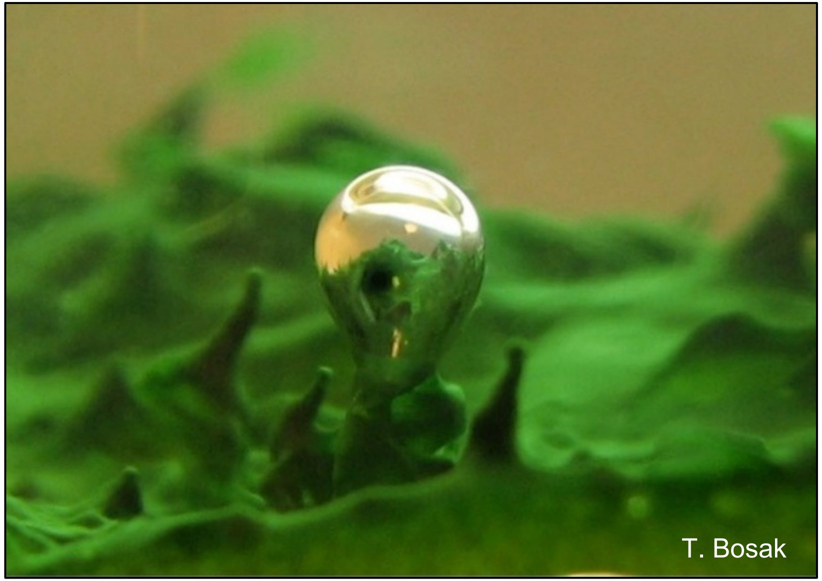
Understanding current and future changes to the water cycle requires fundamental knowledge of the hydro-terrestrial system and how the water cycle interacts with other physical, biological, and chemical processes.



Potential water cycles changes in permafrost regions under current and future warmer climate scenarios.

How do biogeochemical cycles evolve?

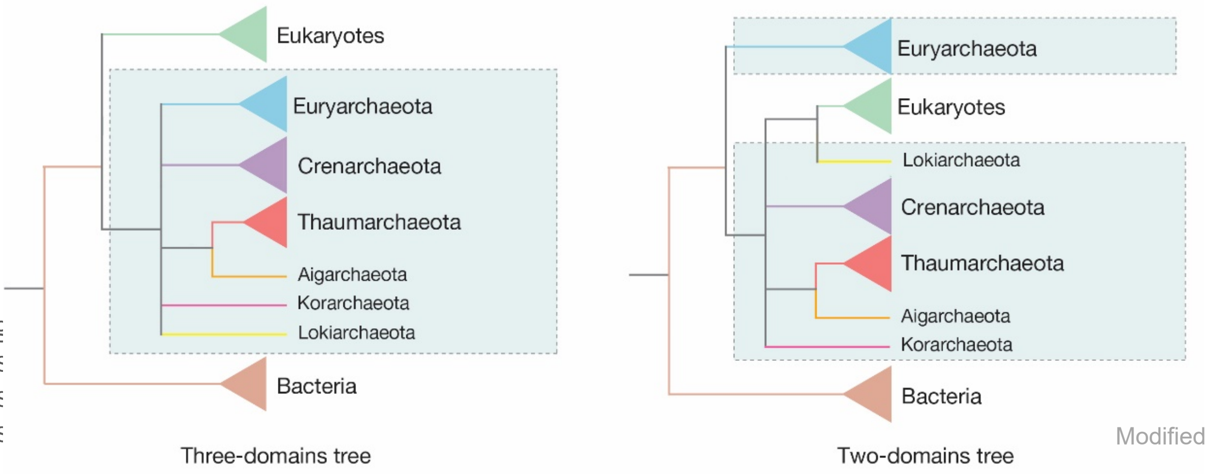
To quantify biology's role through time in mineral formation and weathering, carbon cycling, and the composition of the air we breathe requires a new understanding of biogeochemical cycles.



Oxygen bubble produced by cyanobacterial photosynthesis in a laboratory-grown microbial mat

How do geological processes influence biodiversity?

Biodiversity varies over time, environment, and geography, including major extinctions, and we are poised to address how and why to advance understanding of Earth-life interactions and feedbacks.



Two hypotheses regarding evolutionary relationships among the major groups of living organisms

Modified from Williams et al., 2013

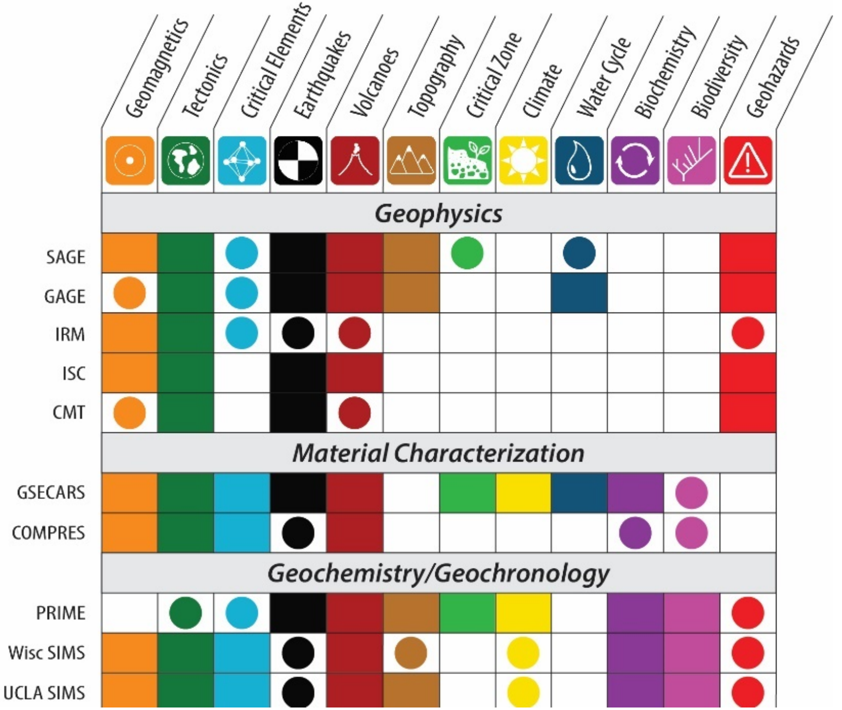
How can Earth science research reduce the risk and toll of geohazards?

Fundamental science questions must be addressed to have a predictive and quantitative understanding of geohazards, to provide the essential foundation needed to reduce risks and to save lives and infrastructure.

Debris flows smashed houses and killed people in Montecito, California, in January 2018.

Facilities & Infrastructure Approach

- Task 2A: Describe future infrastructure needed to address science questions
- Task 2B: Describe current infrastructure and show connections to science questions
- Task 2C: Capability gaps



Portion of a table showing connections between existing infrastructure and questions

Facilities & Infrastructure Approach

- Describe available infrastructure (EAR, GEO, NSF, NASA, USGS, DOE, etc.)
- Establish connections between infrastructure and science questions
- Challenging to evaluate how well the needs of EAR research communities are met
  - *information needed to perform this type of assessment was not available*

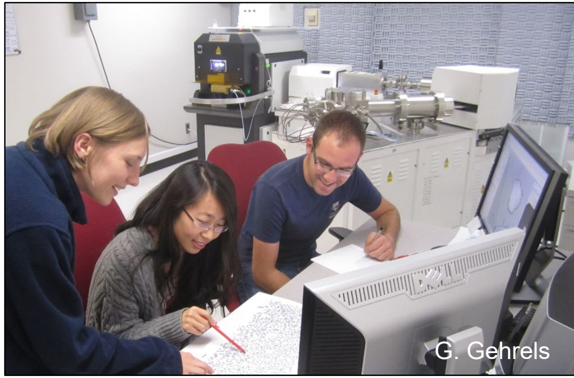
Recommendation: EAR-supported facilities and the entire portfolio of EAR-supported infrastructure should be regularly evaluated using stated criteria in order to prioritize future infrastructure investments, sunset facilities as needed, and adapt to changing science priorities.

Facilities & Infrastructure Approach

Analyzed three components of infrastructure:

- **Instruments**
- **Cyberinfrastructure**
- **Humans**

(NSF 10 Big Ideas)



Synchrotron and people in lab working.

Possible New Initiatives

- Originate from EAR research communities - based on questionnaire responses, community white papers, presentations in public sessions

- Funding will require either a source of new funds and/or sunsetting some current programs

Recommendations for New Initiatives

- EAR should fund
  - a National Consortium for Geochronology
  - a Very Large Multi-Anvil Press User Facility
  - a Near-Surface Geophysics Center

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

Recommendations for New Initiatives

- EAR should encourage the community to explore
  - a Continental Critical Zone initiative
  - a Continental Scientific Drilling initiative

- 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.

Cyberinfrastructure Recommendations

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

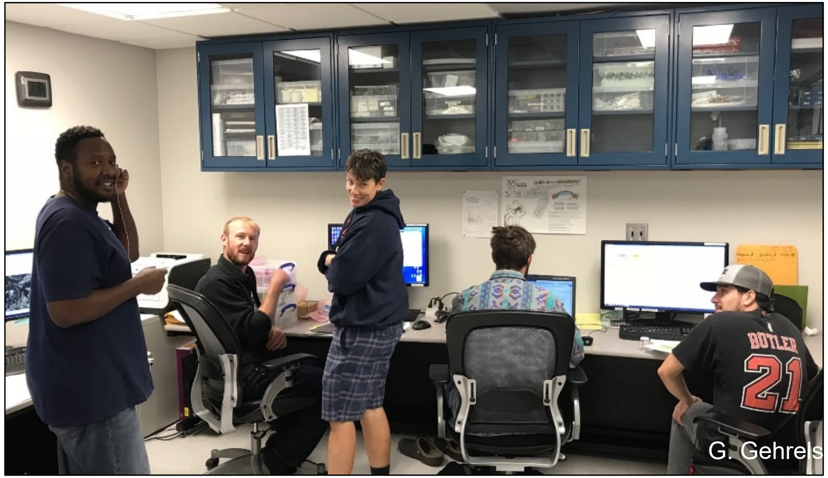
- EAR should develop and implement a strategy to provide support for FAIR practices within community-based data efforts.

Hand with computer code.

Human Infrastructure Recommendations

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

- EAR should enhance its existing efforts to provide leadership, investment, and centralized guidance to improve diversity, equity, and inclusion within the Earth science community.



Lab team at the Arizona Laserchron Center.

Partnerships Conclusions

- 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.
- Components of the Earth system do not adhere to the administrative boundaries of GEO.
- NASA, DOE, and USGS provide important capabilities supporting EAR research.

Partnerships Recommendations

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.

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

Final Thoughts

- EAR's mission is more important and urgent than ever
- Science priority questions illustrate the significance, breadth, and magnitude of the challenges and opportunities for Earth science research in the next decade
- Implementing cyber and human infrastructure recommendations will require not just a commitment of funding, but significant changes to "business as usual" for the community
- EAR already leads investigation of Earth as an interconnected system and is poised to launch the next decade of innovative research

Thank You