Implications of the Recent NSF Earth Sciences Decadal Report for the Mineral Sciences

The Earth is constantly changing and has done so throughout geologic time by a combination of processes both slow-and-steady and sudden, including catastrophes. Humans are relatively recent agents of geologic change, but have, nonetheless, profoundly altered (and continue to alter) the planet, with consequences for the linked fates of the natural world and civilization. With new urgency, geoscientists have the important task of investigating the Earth’s systems, from the core to the clouds. We must invent and utilize methods to probe the unseen parts of the Earth; to measure the chemical and physical properties of materials over vast spatial scales; and to understand complex process interactions in the context of their ages, durations, and rates.

The geosciences have existed as a set of interrelated disciplines for centuries and have changed in some significant ways over the generations. But they have not changed as much as they need to in order to advance science in creative ways that will most benefit humanity. At this moment, as the world is gripped by a pandemic and there are worldwide protests against racial injustice, it is particularly important to recognize the power of diverse perspectives and ideas and to take real and effective action to increase diversity, equity, and inclusivity in the Earth sciences. The world needs highly skilled Earth scientists – including those with expertise in mineralogy, petrology, and geochemistry: this is an “all hands on deck” moment.

One way that funding agencies plan for the future is to survey the recent work of the broad community of Earth sciences. This information can be used to identify priority research questions; identify the infrastructure needed to advance them; and to explore new ideas for partnerships and collaborations, including those that cross geological and geographical boundaries. In May 2020, the most recent decadal survey of the Division of Earth Sciences (EAR) of the US National Science Foundation (NSF) was published by the National Academies of Sciences, Engineering, and Medicine (NASEM). Titled “A Vision for NSF Earth Sciences 2020–2030: Earth in Time”, the report represents nearly 18 months’ work by a diverse committee of geoscientists who were asked to produce a document that included the following:

1. A “concise set of high-priority scientific questions that will be central to the advancement of Earth sciences over the coming decade” and that “could help to transform our scientific understanding of the Earth”;
2. Identification of infrastructure required to address key science questions, both existing resources and any “capability gaps”;
3. Partnerships that could be formed with other NSF units or with other US or international agencies, the aim being to maximize resources and expertise and foster collaboration.

The NASEM report contains twelve high-priority science questions that were developed based on community input via white papers, the scientific literature, an online survey, town hall meetings at conferences, interviews, and other mechanisms. These questions are not meant to limit what the Division of Earth Sciences will fund: creative ideas of investigators are always at the core of innovation. Nevertheless, outlining some potentially transformative research questions that are poised for significant advancement in the next decade is one way to reflect the ideas of the community and to highlight research that appears poised for major advances. The twelve questions, in approximate order from “core to clouds” are as follows:

- 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?

There are aspects of the mineral sciences (broadly defined) in all of these questions, as well as opportunities for international partnerships and collaborations. For example, progress in understanding processes in the planet’s inner and outer core requires a wide range of experimental and theoretical mineral physics investigations, as well as field-based studies of rocks and minerals to examine the historical record of geomagnetism. Understanding why the Earth has plate tectonics and when and how the tectonic system started, while recognized as a longstanding problem, is poised for revolutionary progress through a broad range of approaches, including experimental and computational methods, data assimilation into physical models, and high-resolution geochronology in novel isotopic systems which will allow other chemical and structural observations from rocks and minerals to be placed in a temporal context.

Questions surrounding the distribution and mobility of elements that are critical to life, that govern redox conditions and/or track recycling processes, and that are essential to modern society and its low-carbon energy future, are inherently rooted in mineralogy, petrology, and geochemistry. Significant advances in understanding element cycling and the distribution of elements will require interdisciplinary efforts to unravel the global plumbing system: this will impact fundamental aspects of our society, including energy generation/storage, climate change, global trade, and national security.

At the crust–atmosphere interface, also known as the critical zone, interactions between hydrological, biogeochemical, and geothermal systems require sophisticated multi-component transport models to understand how climate affects this highly reactive region, as well as how the critical zone affects climate. Topographic change, crustal deformation and aseismic slip, and ascent of magma through the crust will all require an understanding of the behavior of Earth materials, including fluids and melts, across many spatial and frequency scales. These processes have a direct impact on society, given their connection to natural disasters such as volcanic eruptions, earthquakes, and tsunamis.

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A large portion of NSF’s EAR annual budget supports infrastructure and facilities, which includes physical, cyber, and human infrastructure. As an example, human and physical infrastructure at US synchrotrons, utilized by mineral scientists worldwide, is supported in part by NSF EAR (e.g., via COMPRES). The report summarizes the current array of multi-user facilities and discusses how these relate to the science questions. Recommended new facilities include a National Consortium for Geochronology, a Very-Large Multi-Anvil Press Facility, and a Near-Surface Geophysics Center. The report also recommends support for continued community development of other initiatives, such as S2AD (subduction science and hazards); for a continental-scale effort to characterize the subsurface critical zone (to understand water, carbon, and nutrient cycles, among other goals); and for renewed attention to issues such as stable archival storage of physical samples of Earth materials.

Other infrastructure topics relate to cyberinfrastructure and human infrastructure. The former emphasizes the need for the Earth-science community to develop an open-data policy as we move into the new world of big data. Recommendations regarding human infrastructure relate to improving diversity, equity, and inclusivity within the Earth sciences, and to providing stable funding for the highly skilled technical staff who are essential to many aspects of research, including driving the technical innovation necessary by which to advance the research questions.

Mineral-science research, education, and engagement with communities outside of our discipline is more urgent than ever. This has the potential to help societies be more resilient in the face of a changing planet. This requires an “all hands on deck” approach to be successful. By “all hands” we mean, 1) scientists who are domain experts and who are capable of interdisciplinary research, 2) the highly diverse group of researchers who represent every facet of our society, 3) members of the public who utilize Earth-science information in their daily lives.

The Earth in Time report, which can be downloaded for free in pdf format from the NASEM website (http://nap.edu/25761), presents ideas for potentially transformative research directions and emerging initiatives in the Earth sciences, while emphasizing that our field will also change in ways not yet known or anticipated. For example, technology may enable citizen science to operate at scales previously unimaginable. Increased diversity will require careful attention to inclusivity and will drive innovation by bringing in new perspectives, which might lead to the major changes necessary to advance our scientific, technical, and educational priorities and to contribute solutions to the major environmental challenges that now face our world.

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unfamiliar topics within the Earth sciences. Other than the published articles, none of the other uses result in measurable citations, yet all have a significant impact on the reader.

Fortunately, there are metrics (“alternative metrics”, popularly known as “altmetrics”) that can capture the impact of our work beyond citation counts in journals (Priem et al. 2010). Altmetrics have been shown to circumvent several weaknesses that citation counts possess as indicators of scientific attention (e.g., Altmetric https://www.altmetric.com/, PlumX Metrics https://plumanalytics.com/). They can do this in three main ways. (1) They can be collected for articles, books, book chapters, presentations, figures, and so on. (2) They are available much faster than citation counts (Thelwall et al. 2013). (3) They can reflect the resonance of our work among nonscientific or nontraditional audiences, such as the mainstream media. In addition to altmetrics, there are other tentative alternatives to the JIF, such as the TOP Factor, which is based on the Transparency and Openness Promotion (TOP) Guidelines set out in Nosek et al. (2015).

Metrics are needed. But metrics are numerous, and we have to be careful of using a single metric to measure the impact of our work. Both bibliometrics and altmetrics come with their shortcomings and yet-unsolved challenges (Lemke et al. 2019). We need to work together to find more appropriate measures of quality for authors and research. For a start, research excellence should be remodeled around transparent workflows and accessible research results (Hicks et al. 2015).

Science must go on! So, where will you publish your work, and how will you measure its “value to the community”? A system based on bibliometric parameters favors an approach to “quantity over quality” and undervalues achievements such as societal impact. The best decisions are taken by combining robust statistics with sensitivity to the purpose and nature of the assessed research. There is a need for both quantitative and qualitative evidence; each is objective in its own way. Ultimately, we need to find a way for researchers and their work to be assessed in a way that is fair and accurate, but not to be over-reliant on publication metrics.

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