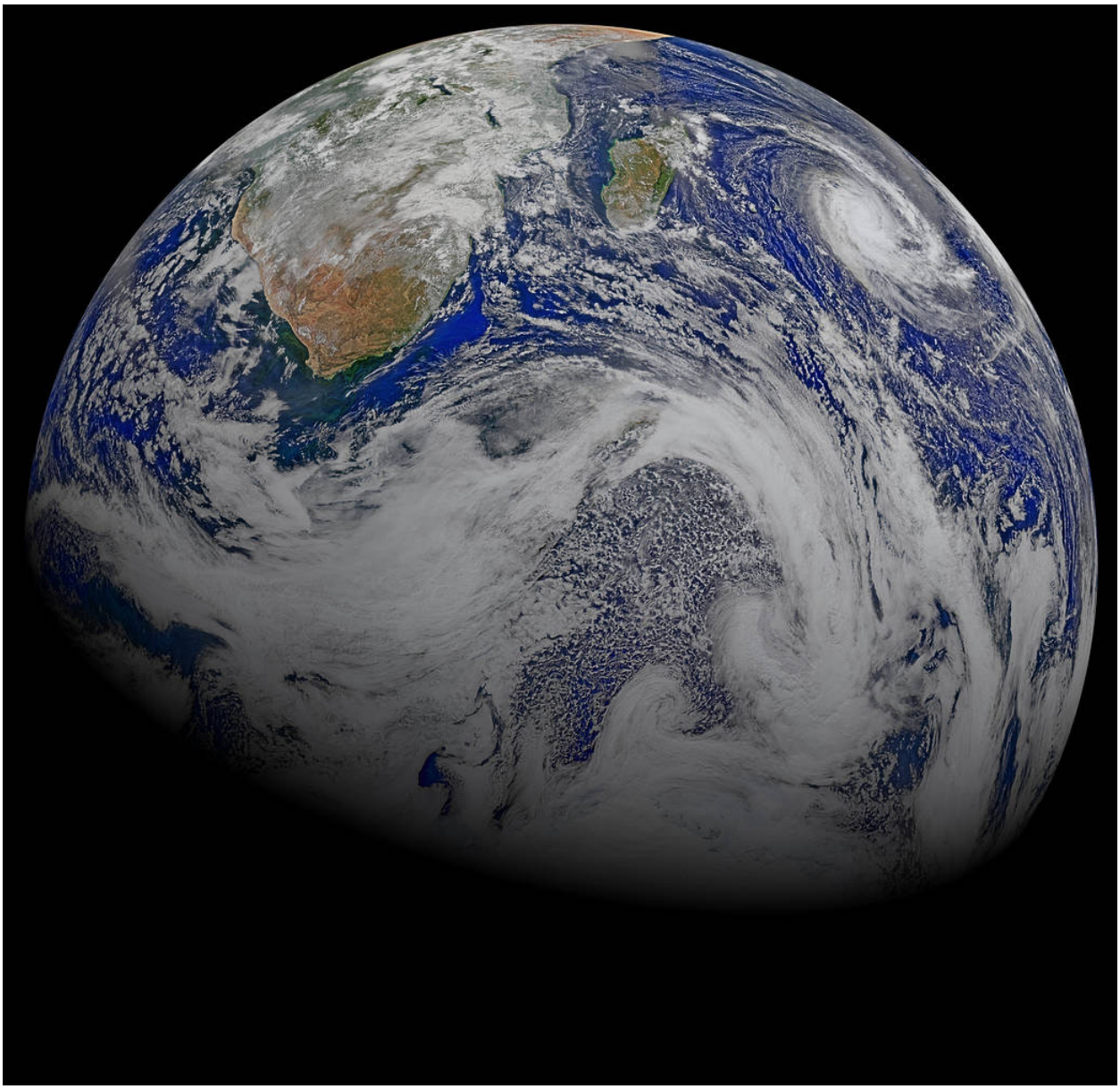
Imperative Science for the 21st Century

Why a Vibrant Geoscience Research and Educational Enterprise Is Essential to American Society and How the National Science Foundation Can Ensure Its Vitality

A Report of the National Science Foundation Advisory Committee for Geosciences

September 2021



Southern Africa and environs from the NASA/NOAA Suomi National Polar-orbiting Partnership spacecraft. April 9, 2015. Credit: Ocean Biology Processing Group, NASA Goddard Space Flight Center.

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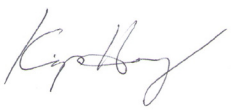
Foreword

Having served as Chair of the Advisory Committee for the National Science Foundation's Directorate of Geosciences (GEO) from 2017 to 2021, I am pleased to share *Imperative Science for the 21st Century*. This report builds on an earlier report completed by the Advisory Committee (*Dynamic Earth: GEO Imperatives & Frontiers 2015-2020*) which aimed to identify and articulate research pathways in the geosciences that deserved funding prioritization by GEO over the following five years. In 2017, the Advisory Committee (hereafter referred to as AC-GEO) was asked to review and adjust the priorities as articulated in Dynamic Earth by revising or replacing it with an entirely new report that might help GEO better fulfill its mandate to strengthen and financially support the geosciences research and educational enterprise in the United States.

In 2017, we began gathering information from the United States geoscience community to inform the new or revised report. Members of the committee attended open forums at major professional meetings (annual meetings of the American Geophysical Union and Geological Society of America, for example), sought written commentary from the broader community, and deliberated during numerous formal AC-GEO meetings. We found broad agreement within the community that the list of priorities in Dynamic Earth was incomplete, and encountered some community skepticism about several of the recommended priorities. However, one of the most resounding messages we received was concern that any small group of American geoscientists (e.g., AC-GEO) may not have sufficient breadth of perspectives to identify the highest priorities for all research domains represented by the Directorate. Upon reflection, we agreed. Rather than a new or revised set of recommended priorities, we instead decided to encourage GEO to primarily use the results of NSF-sponsored surveys and studies conducted under the auspices of the National Academies to establish funding priorities. These reports are typically produced by experts in the selected focus area and are organized to seek broad community input. Recent examples include *A Vision for NSF Earth Sciences 2020-2030: Earth in Time* (2020), *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences* (2015), *Attribution of Extreme Weather Events in the context of Climate Change* (2016); *Reflecting Sunlight: Solar Geoengineering Research and Research Governance* (2021), *Negative Emissions Technologies and Reliable Sequestration* (2019), and *Advancing a Systems Approach to Studying the Earth: A Strategy for the National Science Foundation* (2021). Documents of this kind should be commissioned for all Divisions and Offices in GEO on a periodic basis. Along with more discipline-specific reports, community-led plans for interagency collaborations, and international calls for scientific cooperation, such resources should inform GEO's plans to support community priorities.

Rather than update *Dynamic Earth*, we elected instead to write *Imperative Science for the 21st Century*. Here our principal focus is on articulating the value of the geoscience enterprise to American society and explaining why geoscience should be a very high priority for federal investment. Having built that foundation, we explore important obstacles that hold back progress in United States geoscience research: issues of equity and inclusion, as well as current procedural issues within GEO. It will not be easy to overcome these obstacles, and we offer no simple solutions. Instead, we suggest steps that GEO might take in the short term to accelerate progress on these fronts.

Kip Hodges



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The Importance of Geoscience Research in the United States

Geoscience research comprises myriad scientific studies of planet Earth, spanning the atmosphere, solid earth, oceans, and cryosphere. Offering fundamental insights about our planetary environment, geoscience provides the intellectual foundations necessary for humanity to thrive on Earth.

Nurturing a strong geoscience research effort is essential for American interests. Geoscience research focuses on processes that influence the health of America's citizens and productivity of American industry. An investment in geoscience is an investment in the current and future economic and social well-being of the United States. Furthermore, understanding how natural systems change, in the past and the future, is central to the development of sound public policy that will enable our society and economy to continue to rely for decades to come on these systems and the resources they provide.

For over a century, some sectors of the geoscience research enterprise have played central roles in the search for and extraction of the fossil fuel resources that helped build the U.S. economy. In recent decades, other kinds of geoscience research have identified the causes and consequences of anthropogenic global warming, demonstrating how our exploitation of fossil fuel resources is taking a devastating toll on our global environment. For example, modern cryosphere research has revealed how such global warming accelerates the melting of polar ice sheets, which in turn accelerates sea-level rise. These sorts of interconnected changes do not solely affect the natural Earth system; economic analyses project significant adverse results for the U.S. economy in the absence of climate change mitigation.

The United States must transition away from its dependence on fossil fuels, no matter how disruptive that might be, in order to protect the health of the planet and its inhabitants. In order to be successful, that evolution must be guided by geoscience research. Geoscience research underpinned the United States' economic growth when our nation was almost exclusively dependent on fossil fuels, and ongoing research furthers the continued, limited use of fossil fuel reserves as we seek a better, more sustainable path forward. Similarly, geoscience research must support and enable the rapidly evolving alternative energy economy through both basic research and partnerships with the private sector. Geoscience plays a fundamental role in the identification, assessment, and development of unconventional energy resources, and it is also foundational for the successful development of wind and solar energy resources. The lessons learned through geoscience research inform strategies for carbon capture and sequestration and will guide our search for and responsible extraction of the critical mineral commodities that will be necessary to build and sustain the necessary infrastructure for a society run on renewable energy. Priorities for the current Administration involve significant financial investments in clean energy and green infrastructure, which can be made more efficient and effective through investments in geoscience research. Since justice and inequality issues will also arise in this energy transition (*e.g.*, Carley and Konisky, 2020), they should be considered as NSF research opportunities.

Americans depend on the results of geoscience research every day. The weather forecasts that help us plan our daily routines are built upon, sustained, and improved through geoscience research. Weather and climate related disasters can have detrimental economic impacts, such as $100 billion in damage from a single major hurricane (Weinkle *et al.,* 2018). Roughly 30% of the gross domestic product (GDP) is influenced by variations in weather and climate (Allianz, 2013). Research on space weather prediction provides benefits that include an understanding of risk to the power grid and telecommunications. Food, water, and energy accessibility help shape the US and global economies, and our current understanding of all three are critically dependent on geoscience research. Such resources, as well as human population, are not uniformly distributed on our planet and the world's population is becoming increasingly concentrated into

urban centers with need for just-in-time geoscience information for small spatial areas. Natural disasters take a disproportionate toll on lives in the low-income nations with, for example, natural disasters causing a $520 billion reduction in economic activity and driving an additional roughly 26 million people into poverty each year (Hallegatte *et al.,* 2017). This inequity is a primary cause of social and political instability around the world. Thus, geoscience research contributes to U.S. national security. Coastal regions are important for the national defense and as an economic resource (*e.g.*, recreation, fisheries, and energy). Unfortunately, they are under increasing pressure as populations grow, sea levels rise, and shoreline development continues. The economic activity from our nation's seaports account for nearly 26% of our gross domestic product (NOAA, 2021), and globally roughly 40% of the world's population lives within 100 km of the coast (UN, 2017). Research on the role of the oceans and cryosphere towards sustaining our marine resources, as well as mitigating climate change by disproportionately absorbing both heat and CO_2, are critical components of geoscience research. Globally, the ocean economy is valued at $3-6 trillion (UN, 2017). The state of the oceans is critical to life and commerce on the planet, but the oceans are increasing threatened by the behaviors of our societies, including our role in climate change. Threats include ocean acidification, coral bleaching, the extinction of species, ocean pollution, sea level rise, and sea ice loss.

Poor air quality results in over 10 million premature deaths annually (*e.g.*, Vohra et al., 2021) and costs the global economy of over $5 trillion each year (WB-IHME, 2016). The impact of air quality on health spans a wide variety of diseases including, but not limited to respiratory problems, such as chronic obstructive pulmonary disease (COPD), asthma, and bronchiolitis, cancer, cardiovascular events, reproductive and central nervous system dysfunctions, and cutaneous diseases. Early indications suggest that air pollution may also have played a role in increasing COVID-19 mortality (Petroni et al., 2020; Wu et al., 2020; Jackson and Hodges, 2020). People and communities are differentially exposed to greater air quality and climate-related health risks. The most affected populations include low-income communities and many communities of color, a fact that is a persistent environmental justice challenge (Marshall et al., 2014; USGCRP, 2018). Greenhouse gases and aerosols commonly associated with climate change also play significant roles in the formation of smog and air pollution. Sustainable solutions to address the threats of climate change and poor air quality will require a multidisciplinary, national and international scientific effort (*e.g.*, Manisalidis et al., 2020). Geoscience research has a strong role to play in studies at the critical intersection of atmospheric composition, climate, health disparities, economy, and justice.

Geoscience research underpins efforts to ensure food and water security in the United States, as well as the maintenance of the nation's land and water resources. It informs the responsible and sustainable development of these resources and the infrastructure that interfaces with them. Successful strategies for land-use development require a detailed understanding of soils and ecosystems. Similarly, hydrological research supports the maintenance of water resources and the engineering of waterways and dams. Studies of atmospheric chemistry and atmospheric dynamics reveal the causes and consequences of air pollution and provide insight into the lifetimes and reaction histories of greenhouse gases. Such research is essential to building a sustainable future for American society.

Finally, geoscience research protects American prosperity and national security by providing key information to assess and predict the hazards to life, property, and economic activity posed by natural disasters. It improves forecasting of meteorological events such as hurricanes, tornadoes, floods, periods of high air pollution, and severe weather. Such research bolsters impact assessment and planning efforts in response to other natural phenomena such as earthquakes, wildfires, tsunamis, volcanic eruptions, and space weather. It improves our understanding of the causes and consequences of the anthropogenic climate change, offering an opportunity to avoid the worst of its effects on human and natural systems: more persistent heat waves, more intense storms and droughts, accelerated melting of the polar ice caps, sea level

rise, increasing wildfires, and progressive acidification of the oceans. Ensuring that the infrastructure of our cities, transportation, communications, public health, and energy systems are adequately designed to withstand these events and trends requires a strong foundation of geoscientific knowledge.

With such essential roles to play, a strong government investment in geoscience research is essential for American economic prosperity and quality of life. Geoscience research supports the development of sound public policy in the energy, agricultural, water resource, land use, air quality, and infrastructure sectors. While some of this support can – and does – come from the private sector, many facets of geoscience research fall outside the scope of industrial activity and interest. In its support of U.S. scientists to participate in international collaborations, NSF Geoscience also accelerates *global* scientific research; the growth in scientific productivity over the past two decades in many developed nations is almost entirely accounted for by international collaborations (*e.g.*, Wagner et al., 2015).

The Necessity of a Systems Approach

Earth is a complex and highly adaptive system that includes the solid Earth, the hydrosphere, the atmosphere, the cryosphere, the biosphere, the anthroposphere, and even nearby regions of space. Understanding how this system came to be and how it evolves demands coordinated study that challenges traditionally disparate scientific fields (NASEM, 2021b). For example, a "systems approach" to the geosciences requires the study of the connections among biological, chemical, physical, and societal processes, not just narrowly focused, largely independent study of each class of processes. While disciplinary advances enable us to recognize the complexity of the Earth system and provide the tools to interrogate that system, geoscience is now trending more and more toward transdisciplinary modes of analysis to gain improved perspectives. Researchers must strive to achieve a fluid perception of the time scales of Earth processes that range from seconds to billions of years, and spatial scales that range from nanometers to global. At the same time, these researchers must navigate the cultural differences and standards of traditional geoscience disciplines. The increasing impact of human activity on the earth system increases the need for geoscientists to work with researchers focusing on the human dimension. The responsibility of geoscience to inform policy decisions on issues of human well-being and economic activity – and the closely related issues of environmental health and justice – requires geoscientists to interface with social sciences, the health fields, and other disciplines. The computational nature of many aspects of geoscience requires collaboration with researchers in the computer sciences, from the designers of high-performance computational systems to researchers at the frontiers of deep learning. Already the most integrative of the sciences, geoscience is only becoming more so.

Sustaining this intellectual evolution will present substantial challenges for the geoscience community. It will necessitate changes in how we reward and facilitate transdisciplinary research, and how we educate the next generation of geoscience researchers. We must redesign graduate and undergraduate course materials, and reconsider how geoscience programs in academic institutions are organized. We must support programs aimed at educating geoscience researchers across disciplines and beyond what might be possible within a single institution. Interdisciplinary advances in geoscience have led to an increase in geoscience efforts in the private sector. In turn, this shift is changing employment opportunities for our post-graduates and redefines the educational needs of our students in order to become part of an expanded workforce.

Importantly from the perspective of our committee, the imperative to do both excellent disciplinary and transdisciplinary geoscience challenges not only NSF's Geosciences Directorate but the Foundation as a whole, which continues to have a basic operational structure devised in the last century to support largely disciplinary science. GEO should anticipate an increasing need to coordinate and collaborate with other directorates within NSF and with other national and international funding agencies. GEO also should

anticipate that changes in its internal operations will be required to effectively support earth system science, and we recommend better coordination – and increased procedural consistency – across divisions as well as the programs within them. Depending on how the budget for GEO evolves over the next few years, it may prove necessary to redistribute resources among divisions and programs. It will be especially challenging to continue to support both disciplinary and transdisciplinary research, but we regard that duality as essential. As GEO addresses these challenges, administrators and managers within GEO must seek and act upon a broad spectrum of community input. Ultimately, the evolution of geoscience in the twenty-first century will require enhanced funding within NSF commensurate with the increasingly critical importance of geoscience to the nation and the world. Achieving these goals would be facilitated by concerted efforts in the geoscience community to communicate the societal impacts of their science to leaders in government and industry as well as the general public.

Acknowledging the Elephant in the Room: The Limited Diversity of Geoscientists

Although low diversity is a systemic issue across all STEM fields, the problem is especially acute in geoscience. Recent findings indicate very little change in the number of people of color who have earned doctoral degrees in geoscience over the last four decades (Bernard and Cooperdock, 2018). Fewer than 25% of all employed geoscientists identify as female (AGI, 2019). The academic geoscience workforce is even less diverse at higher levels of seniority. We applaud GEO's efforts to address issues of diversity through its *Opportunities for Leadership in Diversity* (GOLD) program, which has yielded some encouraging results. Still, we have far to go to build a richly diverse geoscience workforce, and success will require profound cultural change that can be accelerated through broader efforts within GEO.

Recent discussions within the geoscience community have resulted in general calls to action (*e.g.*, https://notimeforsilence.org/), as well as suggestions for specific ways in which we can support a more diverse geoscience community (Cartier, 2020; Cooperdock *et al.*, 2020). Barriers to diversity are numerous but are sometimes not well defined. Recent research indicates that while diversity can lead to an increase in innovation, the contributions of underrepresented scientists are less likely to be recognized by the majority population (Hofstra *et al.*, 2020). Geoscience sometimes discourages women and people of color because of its traditional emphasis on field research; many such individuals report negative field experiences which have deterred them from pursuing or persisting in geoscience degree programs (Marín-Spiotta *et al.*, 2020). For example, in one study, 64% of all respondents (more than 660) reported they had personally experienced sexual harassment during their time in the field (Clancy *et al.*, 2014). Collaborative field work can wear down traditional professional barriers, sometimes increasing the likelihood of implicit bias and hostile behavior (Marín-Spiotta *et al.*, 2020). To ensure that geoscience is well-positioned to build innovative and creative approaches to the significant problems addressed through geoscience research, we must act boldly to ensure that diverse perspectives are represented within the geoscience community. As Jill Karsten wrote in her commentary on GEO's now-concluded *Opportunities for Enhancing Diversity in the Geosciences* (OEDG) program: "Significant and sustainable change will only be realized, however, when the levers that drive behavior in the educational and professional systems of the geosciences are tuned so that diversity is recognized as a core value and fundamental feature of scientific excellence and integrity."

Toward a More Diverse Community

We urge GEO to consider the following high-level efforts to support the geoscience community as it

addresses persistent issues of diversity. In pursuing these efforts, GEO must pay careful attention to more than just the *recruitment* of minoritized individuals to geoscience (Morris, 2020). It is equally important to address issues of *inclusion* and *retention*.

Identify, Understand, and Overcome Barriers

Low diversity in geoscience has many causes, but we cannot hope to address them effectively without identifying barriers to entering geoscience, staying in geoscience, and applying successfully for funding. Some potential barriers have already been identified. Deserving students might be overlooked for fellowship awards because of exclusive definitions of "academic talent". Unintentional biases may arise when "non-traditional" students are evaluated alongside their younger, more traditional counterparts. Some barriers are more prevalent in geoscience than in many other STEM fields and deserve special attention. One example is field research, an activity that might easily result in the isolation of minoritized individuals. Some barriers stem from policies within many of our academic institutions. One example is an excessive emphasis on standardized tests and grade point averages for graduate admissions, a practice that may prevent faculty from factoring in a variety of arguably more important indicators of research capability: direct research experience that result in authorships on publications and public presentations. Additional factors that should influence admissions decisions require closer contextual scrutiny of an individual's record. Did the student need to work while in school? Did the student have family obligations? Even if the student's grades were mixed, does their transcript demonstrate significant improvement over time? High standardized test and application fees are a major obstacle for many students who come from low-income families or who have been racially minoritized. Although some academic institutions grant waivers or reduction of application fees, others do not. Barriers to successful graduate experiences include reimbursement policies that require students to pay up front for out-of-pocket student research or travel expenses, and then be reimbursed later. Large and small, overt and subtle, these issues combine to discourage many minoritized individuals from geoscience careers. GEO should play a leadership role in more fully identifying such barriers in order to inform strategies for removing them. Importantly, GEO must listen carefully to the voices of the minoritized in this process.

Define Success (And Failure)

Once the barriers that hold back diversity are clear, we must set and measure progress toward diversity goals. GEO should carefully examine how they define the success of funded researchers with regard to issues of diversity. If the Broader Impacts of their proposals include efforts to address issues of diversity, GEO must have a clear definition of success against which to measure specific outcomes. Principal investigators also must be held accountable when, in the course of their research, members of the research team are subjected to a hostile or threatening work environment.

Learn from Successful Efforts

GEO should take the lead on (or at least support community efforts to) collect information from faculty, researchers, and administrators who have participated in successful diversity-enhancing programs whether funded by NSF or not. What are they doing differently? What procedures and activities contributed to the success of these programs, and how can they be adopted or adapted to increase the likelihood of success in future programs? Such information can be used to evaluate proposals and provide constructive feedback to proposal writers. Most importantly such information can help modify existing programs and help design effective programs that support a diversity of approaches.

Lead in Community Education

GEO should provide substantial funding for and endorsement of programs designed to educate the

geoscience community about the lack of diversity, the benefits of a more diverse community, and sound mentoring practices. The directorate should provide direct funding for programs and materials designed to increase awareness of harassment in field and laboratory settings. Moreover, for those researchers who would like to include activities aimed at addressing issues of diversity, GEO should support programs that provide training and guidance.

Encourage New Educational Modalities

As noted earlier, changes in the employment opportunities of matriculated geoscience majors is forcing geoscience departments to change their educational strategies, and GEO should both monitor and encourage these changes. Funded research could help departments design new educational pathways for such students – including, for example, technical degrees with geoscience associations.

Build Effective Partnerships

Issues of diversity are generating widespread interest and action in the STEM community, and GEO would do well to explore a range of partnerships with other interested parties. For example, GEO should build more effective bridges to other NSF directorates (*e.g.*, EHR) and other government agencies (*e.g.*, the NIH and NASA) so that GEO initiatives would have broader reach without reducing its support of scientific research. In line with the most recent OCE Committee on Visitors report, we encourage all GEO divisions to make more concerted efforts to partner with historically black colleges and universities, other major minority-serving institutions, and tribal colleges.

Establish and Clearly Articulate Behavioral Protocols

GEO can play an important role in the evolution of a more inclusive geoscience culture by assuming a leadership role in defining acceptable behaviors for all principal investigators, mail reviewers, panelists, and participants in GEO-sponsored research. GEO should caution them all to abide by these standards or risk the loss of NSF support. GEO should develop consistent standards across all divisions for research conduct and should establish and enforce the consequences of non-compliance to both the principal investigator and that investigator's home institution. NSF should also consider developing financial support mechanisms for junior members of research teams whose careers may be imperiled by reporting issues of harassment.

Support the Building and Nurturing of Diverse Research Teams

While educational activities are vital to success, so are activities aimed at improving the diversity of research teams and reducing bias, whether intentional or unintentional. It may be appropriate for GEO (or NSF more broadly) to require all proposals to include a brief diversity statement. If such a policy is adopted, the quality of the diversity statement should be a factor in proposal ratings. GEO should provide assistance to and targeted funding for investigators in their efforts to build diverse research teams and evaluate the success of their efforts throughout the duration of research projects.

Lead by Example

GEO should actively promote diversity and inclusion – and, more broadly, the elimination of implicit bias in all forms – throughout the proposal evaluation and funding process at the program level. Faculty and administrators from institutions serving more diverse student cohorts should be invited to review proposals in all programs on a routine basis. This goal may be served best by the development in each program of a pre-identified group of willing reviewers so as not to systematically overburden the relatively small numbers of underrepresented scholars in the geosciences. GEO should uniformly require implicit bias training for panelists, program officers, and mail reviewers. The chairs of review panels and program officers should have intervention training to ensure that issues of bias that do occur during the review process are addressed

immediately, before funding decisions are made. These training efforts could be layered on top of implicit bias training efforts that may be required by the home institutions of those who apply for grants through GEO.

Optimizing the Support Structure at NSF for Geoscience Research

Our committee recognizes the dedication and hard work of GEO personnel as they strive to support the geoscience research enterprise in the United States. However, there is room for improvement. Our conversations in the broader geoscience community have unearthed some common frustrations that GEO might alleviate (or at least diminish) through procedural adjustments. Knowing that GEO is always in search of ways to serve the community better, we suggest below some ideas that have arisen in committee discussions. Some of these ideas are straightforward and would have an immediate positive impact if adopted. Others may or may not work and should not be widely adopted without some indication of their impact on geoscience research enterprise. We especially appreciate that NSF has a willingness to test new process ideas via piloting, without immediate and permanent changes. If such a pilot indicates that an idea has merit (both from the perspective of GEO and the community), then GEO could move on to a wider adoption of it. This approach worked well recently for testing the idea of removing proposal deadlines in GEO programs.

Routinely Collect and Report Information on Funding Trends

Over the past few years, AC-GEO and Committees of Visitors have been frustrated by an inability to get reliable and objective information about awards at the program level. This information gap appears to the broader community as a lack of transparency, and that is bad for the morale of researchers. The community should be able to quickly assess information at the program level on proposal success rates, and how success rates differ for early-career, mid-career, and late-career proponents. GEO should make public the fraction of proposals, awards, and funding in each program that goes to men, women, and minoritized individuals, and the success rates of proposals from researchers in all these categories. The community should be able to find out the ratio of how many new research proposals are being funded each year to how many continuing awards are being funded. Researchers should be able to find out how much of each program's portfolio goes to disciplinary *vs.* transdisciplinary research, how much goes to community building efforts such as sponsored workshops, and how much goes to high-risk research. Without such data being publicly available, the community is left to speculate about whether or not there are inappropriate biases within the proposal selection process. We know that GEO is committed to eliminating such biases, but greater transparency would assuage persistent concerns within the community.

Strive for Better Procedural Consistency Across Programs

During its deliberations, AC-GEO has noticed considerable variation among programs and across divisions in the mechanisms through which proposals are evaluated, the time required for those evaluations, how mail reviews are incorporated, how panels are constituted and how panel meetings are conducted for those programs that use them, how both the Intellectual Merit and Broader Impacts components of proposals are evaluated. For those programs that use panels, there are also variations in how program officers weigh the perspectives of the panel and the mail reviews which provide advice in deciding on the relative merits of proposals. Over time, more seasoned proposers learn to tune their proposals to the idiosyncrasies of the specific programs to which they submit, but early career scientists struggle as they face these idiosyncrasies. Although this situation has evolved over decades, it is not optimal for GEO in an era of increasing transdisciplinarity. For example, we will see more and more individual geoscientists working

across traditional geoscience disciplines and who may submit proposals to multiple programs, sometimes in multiple divisions. Such researchers deserve the security of knowing that each program in GEO follows the same basic evaluation criteria and makes funding decisions using these criteria regardless of how the proposal evaluation process is conducted.

Insist on a Shared Perspective on Broader Impacts Among Proposers, Reviewers, Panelists, and Program Officers

The Broader Impacts criterion for proposal evaluation, introduced upon the recommendation of the National Science board, is well-intentioned. However, practical application of this criterion can be highly subjective. Different interpretations regarding what does – and does not – represent a good broader impact section in a proposal often causes consternation among those who write proposals and those who review them. In its most recent form (NSB, 2011), the criterion is envisioned as a way to encourage American scientists to articulate how their proposed efforts would contribute to the achievement of "desired societal outcomes." However, both the National Science Board and the National Science Foundation have taken pains not to specify what those outcomes might be, intentionally leaving it up to the proposers to come up with their own ideas about how to define them and how to propose activities to contribute to their achievement.

In evaluating the Broader Impacts component of a proposal, it falls to the reviewers, panelists, and program officers to determine whether or not they think the proposed efforts are well conceived and may legitimately benefit society. However, a fair and in-depth evaluation of the Broader Impacts component of a proposal is made unnecessarily challenging as many (perhaps most!) proposers, reviewers, and panelists do not fully appreciate the breadth of Broader Impacts as envisioned by the National Science Board. For example, more than a few researchers seem to think that a Broader Impacts section is not meritorious if it does not include a formal or informal educational component. This narrow perspective is inconsistent with all NSF public documents about how Broader Impacts should be evaluated during review, including the current Proposal & Award Policies & Procedures Guide (PAPPG). In their 2011 report (NSB, 2011), the National Science Board made it clear that Broader Impacts "may be accomplished through the research itself, through activities that are directly related to specific research projects, or through activities that are supported by, but are complementary to, the project." While educational activities certainly meet these criteria, so do many other activities.

At the urging of the broader scientific community, NSF has articulated many examples of what might be considered meritorious activities, but the Foundation has always taken pains to make it clear that such lists are provided to inspire creative thinking by proposers and not to be used as checklists for proposal evaluation. We recommend that GEO enforce this expectation through a concerted effort to educate mail reviewers and panelists as to how they should evaluate Broader Impacts. Reviewers should base their scoring only on whether or not the defined Broader Impacts are consistent with NSF guidelines, and whether or not the Broader Impacts are well-conceived and likely to produce positive results. If panelists or mail reviewers base their ratings instead on their personal and subjective interpretations of what a Broader Impact section should include, it is the responsibility of the program officers to ignore their assessments of the Broader Impacts in making final funding decisions. We recommend that a uniform set of rubrics be established at the Directorate level for how Broader Impacts will be evaluated across all divisions and programs, including a directive for how Intellectual Merit and Broader Impacts should be weighted in final proposal rankings. These rubrics should be announced publicly to the broader U.S. geoscience community. Ideally, these guidelines should be on the review forms for both mail reviewers and panels so they are easily accessible during review.

Ensure the Diversity of Review Panels

Many programs in GEO rely heavily on the opinions of review panels for proposal evaluations and award decisions. The criteria used by program officers to invite geoscientists to serve on review committees are largely opaque to the geoscience community, and the identities of those who serve are not made public. While understandable, this lack of transparency leads to concerns in at least some quarters that panels in GEO might not always be appropriately diverse. Diversity and equitable representation in review panels at the Program level should be a requirement that is monitored at the Division level and reported for transparency to the larger community. Whenever possible, each panel should have balanced representation of active researchers representing the entire range of professional career levels and the complete range of subfields funded by the program. In addition, the panel should reflect a diverse population with regards to race and ethnicity, gender spectrum, and institution type. When asking individuals to review, part of the request should include a recommendation for other names who share common expertise, which would help to identify a field of allies so as not to overburden the service of the underrepresented scholars.

Redouble Efforts to Eliminate Bias in the Review Process

The committee stands with NSF in its strong desire to eliminate biases in the proposal review process. We are thus as disappointed as our colleagues at NSF when principal investigators continue to report perceived biases against certain groups of proposers. In addition to perceived bias against minoritized groups, there are also stories of biases against either early-career or late-career researchers. We have heard stories of purported bias by review panels and mail reviewers against specific investigators, often in the form of destructive or gratuitously harsh reviews. Such behavior in review panels should not be tolerated by program officers and should be dealt with immediately. We also recommend giving program officers broad discretion to eliminate biased and/or excessively harsh mail reviews from consideration in the decision process before these reviews are passed along to the panels. We recommend that GEO undertake a focused study of how proposals from minority-serving institutions are currently being reviewed and evaluated to ensure that they are being treated fairly.

We note that many international funding agencies, as well as NASA, are exploring or adopting the use of double-blind (or dual-anonymous) review procedures for proposals in order to reduce unconscious biases. Early pilots suggest that this approach – which preserves the anonymity of both the proposer and reviewers – shows promise. The committee does not have a consensus opinion regarding whether or not GEO should try such pilots in the near-term, but we recommend that the directorate carefully monitor on-going pilots in other agencies to gage the merits of trying such experiments in the future.

Encourage Grass-Roots Efforts in Transdisciplinary Science

The committee supports the continued development of targeted interdisciplinary programs in GEO and other Directorates. The current *Coastlines and People* (CoPe) program stands as an excellent example. However, major programs of this kind do not fully accommodate the growing trend in geoscience toward interdisciplinarity and transdisciplinarity. GEO is likely to receive an increasing number of such proposals that involve no more than a few investigators and cut across the research portfolios of existing programs. We support current efforts by some program officers to find colleagues in other NSF programs, other US government agencies, and international partners who are willing to collaborate in funding meritorious proposals of this kind, and we would like to see such collaborations become more routine. However, reviewers with a highly discipline-specific perspective are frequently biased against transdisciplinary proposals, and good proposals may go unfunded as a consequence. We recommend that program officers craft an addendum to the standard instructions to reviewers of such proposals, reminding them that the proposed work crosses disciplines and should be reviewed (in terms of disciplinary content) in that

light. We also encourage program officers to include information in their reviewer data bases to identify researchers with experience in interdisciplinary research (*e.g.*, current and former leaders of and participants in interdisciplinary research efforts). Finally, to explicitly encourage interdisciplinary proposals, we recommend formally designating a small fraction of GEO funding to specifically attract and support project proposals involving at least two programs.

Encourage an Appropriate Balance of Disciplinary and Interdisciplinary Funding

While our committee recognizes the trend toward and importance of interdisciplinary and transdisciplinary research, such work is built upon the foundation of constantly advancing knowledge provided by disciplinary research. Despite modestly growing budgets in GEO, the Directorate must rise to the challenge of sustaining strong disciplinary research while simultaneously encouraging more interdisciplinary and transdisciplinary research. It is too much to ask either the Directorate or the community to establish a specific balance *a priori*. Instead, we encourage GEO to decide based on the volume of meritorious proposals it receives in the two categories. If, in any single cycle, two-thirds of all proposals are disciplinary and only one-third are interdisciplinary or transdisciplinary, funding portfolios should be adjusted appropriately. If, in the next funding cycle, the opposite is true, the portfolios should be adjusted again. In this way, GEO could be optimally responsive to community perspectives.

Encourage the Submission and Fair Review of High-Risk Proposals

There is a perception by some in the community that reviewers and program officers may be biased against "high-risk" proposals. Reviewers are notoriously risk averse, but we contend that there is risk in funding any research. The question – for which there may be no consensus – is how high the risk is in any proposal and how we should balance that risk against potential rewards. All proposals should be evaluated considering two criteria: one that examines the likelihood of success, and another that considers the potential for the science to be transformative. Both should be considered in the evaluation (although the weight of the criteria might change) and perhaps both criteria deserve specific comment by reviewers and the panel. Typically, a high-risk proposal may have great potential for being transformative if successful, but it is funded only if it is deemed likely to have a successful research outcome. Instead, GEO should work to develop a strategy for funding meritorious high-risk proposals without bias. We recognize that GEO already has the EAGER (*Early-Concept Grants for Exploratory Research*) funding mechanism, though that is targeted at supporting exploratory research for untested new approaches and does not include all forms of high-risk research. Just as one might do in constructing an investment portfolio, perhaps all program officers should be encouraged to designate a small fraction of their research portfolios for high-risk research. This approach would have to be done in the full expectation that "high risk" really means what it says, so that there is genuine tolerance for failure in some of these projects as long as the failure did not result from project mismanagement.

Ensure That Funding Decisions Are Based on Sound Advice

Proposers who have had their proposals rejected are always disappointed, but some have legitimate complaints about the outcome. In some cases, factually incorrect statements in mail reviews or panel summaries appear to have heavily influenced the final decision. Some proposers are convinced that panels are biased against certain types of research despite community consensus that those types of research actually have great potential. When such problems arise, proposal writers typically contact program officers to complain of unfair treatment, but those program officers, while they may be sympathetic, often have no way to reverse their decision. (By the time a proposer gets the reviews, all of the available funds in a program may have been promised elsewhere.) The only recourse these frustrated proposers have is to resubmit the proposal, but current rules within some GEO programs only permit that after an entire year has passed.

The current pace of research in U.S. geoscience, not to mention the timescales of university promotion and tenure decisions, make such artificial delays extremely problematic. The committee discussed ways to address these issues but did not reach universal consensus on specific recommendations. We recommend nonetheless that GEO give two ideas careful consideration.

First, GEO programs that require investigators to wait a full year to resubmit a failed proposal should be urged to discontinue that practice. Instead, they could simply require that the proposals be revised on the basis of reviewer, panel, and program officer comments before resubmission. (One idea is for program officers to require such resubmissions to include an explicit statement about what has been revised.)

Second, GEO should consider a process by which proposers have an opportunity to address a negative mail review before a final funding decision is made. For programs that use review panels, the opportunity to rebut should take place before the proposal goes to the review panel. This sort of policy would ensure that the rebuttal is considered along with each negative review as part of the final evaluation process. This step is common practice in some NASA panels and is reported to have improved investigators' perspectives about the fairness of the evaluation process. In order to make this approach tractable, the NASA Program Officers limit permitted rebuttals to a few, short sentences and require that rebuttals only address specific, demonstrable errors and do not include arguments based on reviewer opinions.

Final Remarks

Geoscience research is at an evolutionary crossroads. While historically dominated by individual investigator projects and focused within subdisciplines, geoscience research is now increasingly interdisciplinary and striving to be transdisciplinary. Much of the most exciting research in the geosciences today involves large and small groups of researchers which include not just traditionally educated geoscientists but colleagues from biology, chemistry, physics, public health, and the social sciences. This holistic approach to research has emerged from a growing awareness of the complexity of Earth system science and the importance of that science to the nation and the world community. As we build a stronger and more diverse geosciences effort in the United States, GEO must adapt in ways to support it most effectively.

The geosciences are too important to the United States to tolerate policies, structures, and attitudes that limit the diversity of the geoscience workforce. All in the U.S. geoscience community must engage by working to change what has been a depressing lack of diversity thus far, but GEO must assume a leadership role in this effort. GEO should support proactive efforts to identify barriers to greater diversity, should censure non-inclusive behaviors, and should eliminate any internal procedures that might undermine the effort.

Although it is obvious that GEO should continue to encourage and support traditional, disciplinary research, we feel that developing procedural and financial strategies for adequately supporting a growing portfolio of interdisciplinary, transdisciplinary, and high-risk proposals should be a fundamental goal of GEO moving into the future.

Since its establishment, the National Science Foundation has provided essential support to fundamental geoscience research through its Directorate for Geosciences. Now more than ever, that effort is essential to the long-term sustainability of American prosperity and security. In partnership with GEO, the geoscience community eagerly embraces this responsibility.

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