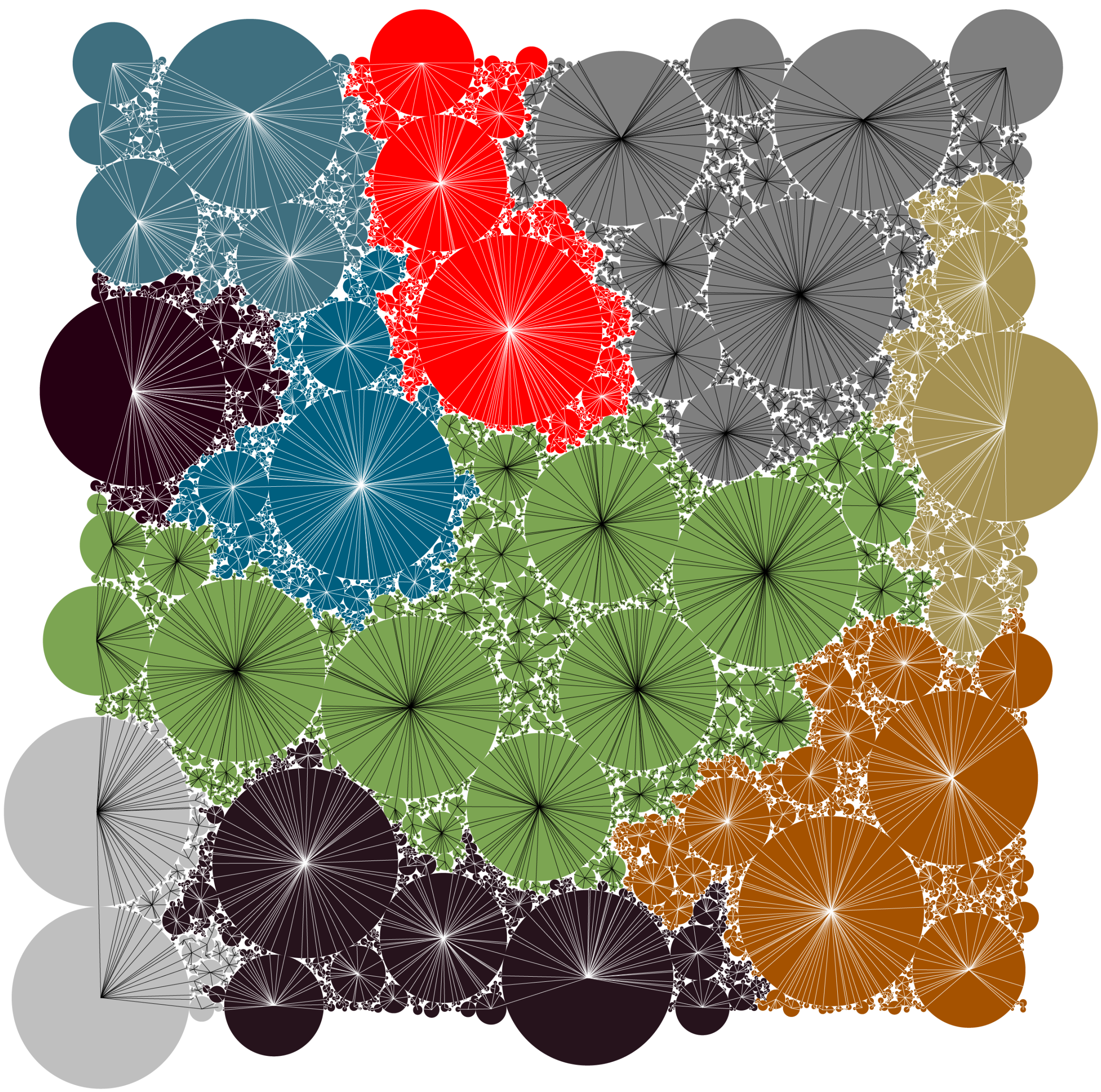
A Community Framework for Geoscience Education Research

1 Framework - 48 Authors - 10 Research Themes
2 to 5 Grand Challenges per Theme



Edited by Kristen St. John

Authorship and Acknowledgements

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The Project Leadership team included Kristen St. John (PI; James Madison University), Kim Kastens (Lamont-Doherty Earth Observatory), Heather Macdonald (College of William and Mary), Karen S. McNeal (Auburn University), and John R. McDaris (SERC at Carleton College). Working Group leaders included Kelsey Bitting (Northeastern University), Cinzia Cervato (Iowa State University), Kim Kastens (Lamont-Doherty Earth Observatory); Heather Macdonald (College of William and Mary); Karen S. McNeal (Auburn University); Heather L. Petcovic (Western Michigan University); Eric J. Pyle (James Madison University), Eric M. Riggs, (Texas A&M University); Katherine Ryker (University of South Carolina), Steven Semken (Arizona State University), and Rachel Teasdale (California State University-Chico). Chapters on Project Development and Synthesis were written by Kristen St. John, with contributions from Project and Theme Group Leaders.

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Cover Image: The cover image is Constellations no.5, a drawing designed by architects Andrew Kudless and Laura Rushfeldt, 2006 (https://www.matsys.design/constellations) and is used with their permission. The drawing is an abstract representation of a community framework for geoscience education research (GER). In it we see thematic grand challenges illuminating interconnected paths for future geoscience education research. Collectively this creates a guiding framework to harness the power of GER to improve undergraduate teaching and learning about the Earth.

Conversion of the online content for print-ready pdfs was completed by Greg Johnson.

Recommendation for Citations

Cite the full framework as: St. John, K (Ed.) (2018). A Community Framework for Geoscience Education Research. National Association of Geoscience Teachers. Retrieved from http://commons.lib.jmu.edu/ger_framework/15

Cite individual chapters using the following format: Chapter authors. Chapter title. In St. John, K. (Ed.) (2018). A Community Framework for Geoscience Education Research. National Association of Geoscience Teachers. Retrieved from DOI weblink; such as in the following example:
Pyle, Eric J.; Darling, Andy; Kreager, Zo; and Conrad, Susan Howes. "Research on Students' Conceptual Understanding of Geology/Solid Earth Science Content". In St. John, K (Ed.) (2018). Community Framework for Geoscience Education Research. National Association of Geoscience Teachers. Retrieved from DOI https://doi.org/10.25885/ger_framework/2

A Community Framework for Geoscience Education Research

Table of Contents

Framework Development

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Summary

Fourteen years ago the Wingspread Report (Manduca, Mogk, & Stillings, 2003) helped establish geoscience education research (GER) as an important research field and highlighted major research questions for GER at the time. More recently, the growth and interest in GER is evident from the increase in geoscience education research articles in a peer-reviewed journals, the establishment of the NAGT GER Division, the creation of the GER Toolbox, an increase in GER graduate programs, and the growth of tenure-eligible GER faculty positions. As an emerging DBER field (NRC, 2012), the GER community is examining the current state of their research and considering the best course forward so that it can have the greatest collective impact on advancing undergraduate teaching and learning in the geosciences.

	Research on:
1	Students' Conceptual Understanding of Geology/Solid Earth Science Content
2	Students' Conceptual Understanding of Environmental, Oceanic, Atmospheric, and Climate Science Content
3	Elementary, Middle, and Secondary Earth and Space Sciences Teacher Education
4	Teaching about Earth in the Context of Societal Problems
5	Access and Success of Under-represented Groups in the Geosciences
6	Cognitive Domain in Geoscience Learning: Spatial and Temporal Reasoning
7	Cognitive Domain in Geoscience Learning: Quantitative Reasoning, Problem Solving, and Use of Models
8	Instructional Strategies to Improve Geoscience Learning in Different Settings and with Different Technologies
9	Geoscience Students' Self-Regulated Learning, Metacognition, and Affect
10	Institutional Change and Professional Development

Table 1. Themes that span the spectrum in which GER operates and have the potential to impact **undergraduate geoscience teaching and learning.**

Building on a prior NSF-funded workshop, this NSF-funded GER Framework project engaged ~200 geoscience educators and researchers through a sequenced series of virtual and face-to-face events to share ideas, gain feedback, and create and revise priority research questions, or "Grand Challenges", that span 10 geoscience education research themes (Table 1). For each theme, several Grand Challenges and recommended strategies have been proposed by the community.

Goal and Objectives

The project goal is to improve teaching and learning about the Earth, by focusing the power of Geoscience Education Research (GER) on a set of ambitious, high-priority, community-endorsed grand challenges.

To achieve this goal, we sought to:

- Engage the community, where "community" involves discipline-based education researchers, scholars on geoscience teaching and learning, geoscience educators from a range of institution types and career levels, and cognition scientists.
- Focus on challenges that can be achieved within 10 years.

- Focus on strategies that impact undergraduate teaching and learning.
- Produce, and widely disseminate, a report on the Community Framework for GER.

Vision

It is our vision that the final outcome of this community-grounded process is a published **guiding framework** to:

- Focus future GER on questions of high interest to the geoscience education researcher and practitioner community,
- Provide funding agencies with a strong rationale for including GER in future funding priorities,
- Increase the strength of evidence of GER community claims, and
- Elevate the visibility, stature, and collaborative potential of GER in the geosciences and in STEM education research.

Process Used to Develop the GER Framework

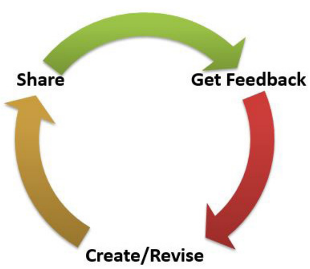

Figure 1. A community-engaged iterative process was used to develop the GER Framework.

Figure 2. Major steps in the process toward defining GER grand challenges and strategies.

The project was a community-engaged iterative process that involved multiple steps of creating, sharing, getting feedback, and revising (Figures 1 and 2).

Themes Defined by Literature Review and Community Input

An initial step in the process was to identify themes that have the potential to impact *undergraduate* teaching and learning.

The GER themes were informed by a range of reports, discussions, and surveys including: focus group discussions at the 2015 GER workshop, results from the 2017 GER Survey, the DBER Report (NRC, 2012), the Wingspread workshop Report (Manduca, Mogk, & Stillings, 2003), the Earth and Mind II Synthesis report (Kastens & Manduca, 2012), and Lewis & Baker (2010). The Wingspread and Earth and Mind II reports emphasized

Alignment of GER Framework Themes with Topical Areas Addressed in Relevant Prior Discussions, Surveys, Reports						
GER Framework Themes	Wingspread Report (Manduca et al., 2003)	Editorial (Lewis and Baker, 2010)	Earth in Mind II synthesis Report (Kastens and Manduca, 2012)	DBER Report (Singer et al., 2012)	2015 GER workshop	2017 GER Community Survey
WG1: Students' Conceptual Understanding of Geology/Solid Earth Science Content	√		√	√	√	√
WG2: Students' Conceptual Understanding of Environmental, Ocean, Atmosphere, and Climate Science Content	√		√	√	√	√
WG3: Elementary, Middle, and Secondary Earth and Space Sciences Teacher Education		√				√
WG4: Teaching about the Earth in the Context of Societal Problems						√
WG5: Access and Success of Under-represented Groups in the Geosciences		√			√	√
WG6: Cognitive Domain in Geoscience Learning: Temporal and Spatial Reasoning	√		√	√	√	√
WG7: Cognitive Domain in Geoscience Learning: Quantitative Reasoning, Problem Solving, and Use of Models	√		√	√	√	√
WG8: Instructional Strategies to Improve Geoscience Learning in Different Settings with Different Technologies	√		√	√	√	√
WG9: Self-Regulated Learning, Metacognition, and Affect		√		√	√	√
WG10: Institutional Change and Professional Development		√		√	√	√

Table 2. Alignment of GER Framework Themes with topical areas addressed in relevant prior discussions, surveys, and reports. Note that distinctions between students conceptual understanding in different sub-areas of geoscience (e.g., WG1 and WG2) and the full range of geocognition sub-themes (WG6 and WG7) did not emerge until the 2017 GER Survey.

themes of research on conceptual learning, geocognition, and instructional design, all largely under the umbrella of research on the development of geoscience expertise. In contrast, Lewis and Baker's "Call for a New Geoscience Education Research Agenda" emphasized research on K-12 teacher preparation, pipeline issues of attraction of under-represented groups to the geosciences, and on motivation and institutional support factors that affect these populations (Table 2). The DBER Report was more broad in scope, identifying several education research themes that cross STEM disciplinary fields, but not addressing either of these special populations. The 2015 GER workshop was a preliminary exploration of the comprehensive set of themes that emerged out of the earlier resources. Outcomes from the 2015 GER workshop highlighted the potential value of an additional theme on geoscience teaching in the context of societal problems, which was included along with K-12 teacher education as a themes for the community to give feedback on in the 2017 online GER survey.

Iterative Process of Community-Engaged Project Activities

Initial Community Survey and Webinar

The 2017 online GER survey was the first of a series of community-engaged activities in this project. The purpose of the survey was to share tentatively defined themes, and develop an initial database of important developments, recommended resources, and important research questions for each of the themes. Survey respondents (n=66, Figure 3) recommended ~100 resources related to the themes. Their comments highlighted the varying scale and scope of prior work done in different theme areas, the need for greater awareness and collaboration between GER and other STEM Education research fields, the need for better grounding of research in theories, and the need for stronger research design and assessment. Results demonstrated interest in all themes, with the greatest interest in cognition topics, instructional strategies, conceptual understanding, and teaching the Earth in the context of societal problems (confirming the decision to create this new research theme area). While prior reports (Table 2) emphasized research on conceptual understanding and on cognition research, the 2017 GER survey results suggest it would be valuable to make thematic distinctions between different sub-areas of conceptual understanding (Table 2, WG1 and WG2) and different sub-areas of cognition (Table 2, WG6 and WG7). In particular, although there is widespread interest in teaching with an Earth system science perspective, much of the published research in students' conceptual understanding lies in geology/solid Earth concepts. Creating a theme for the other Earth system "spheres" highlights their importance as areas of future geoscience education research. Survey results were reported to the community in a webinar and informed the program development of the 2017 GER workshop.

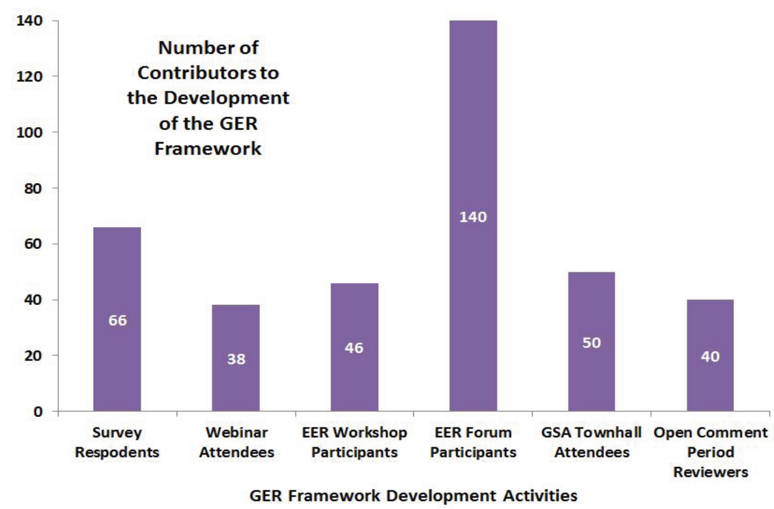

Figure 3. Community participation in the activities towards developing the GER Framework.

EER Grand Challenges and Strategies Workshop

A critical step to facilitate action towards the project goal was a multi-day workshop of 46 geoscience education researchers at the 2017 Earth Educators Rendezvous. Prior to the face-to-face workshop, 10 working groups were defined, one for each GER themes (Table 1). Applicants were matched to the thematic working groups, and working group leaders were nominated and selected based on experience and expertise for that theme. Working groups had 3 to 5 members. Participants included geoscience education researchers at different stages in their career and different types of institutions.

Figure 4. Draft grand challenges and strategies were presented and critiqued by the other workshop participants and feedback was used to revise their work. Sharing and feedback also occurred in a preliminary community online survey, in a webinar, at the EER Geoscience Educator and Researcher Forum, at the GSA Townhall, in posters at the GSA, AGU, and AMS meetings, and during the online Open Comment Period.

The expectations of the workshop were high, and working groups were tasked with defining an initial set of 3-5 grand challenges for their theme, a rationale for those challenges, and preliminary strategies to address those challenges. The grand challenges were to be in the form of well-justified, large-scale research questions that could, and should, guide future research for the GER community, and the recommended strategies were to be ideas on how the GER community could make significant progress on those important research questions, given their knowledge of the GER landscape.

To support this effort, the workshop was structured to include focused working group time, opportunities for working groups to share and get feedback from other participants, and two whole-group cross theme sessions, the topics of which emerged out of the earlier survey (Table 3 and Figure 4). Working groups had access to recommended resources submitted from survey respondents, as well as resources recommended by project leaders and submitted pre-workshop by working group members.

Workshop Overview				
	Sunday	**Monday**	**Tuesday**	**Wednesday**
Working Group Time	Grand Challenges Part 1: Discuss	Grand Challenges Part 2: Add & Refine	Grand Challenges Part 3: Finalize & Present. Strategies Part 1: Discuss	Strategies Parts 2 and 3: Finalize & Present
	→ Record in Online Workspace → Share and Get Feedback →			
Whole Group Sessions	Lessons Learned from the Wingspread Workshop/Report	Role of Models and Theories in Research Design		Thinking Strategically about Assessment
Special Connected Session		*Geoscience Education Research and Practice Forum*		

Table 3. Workshop structure to support thematic working groups in defining GER grand challenges, their rationale, and preliminary strategies to address the challenges.

Engaging with the Broader Community: Opportunities to Share and Get Feedback

In order to ensure broad community input, there were opportunities for sharing with and getting feedback from outside the working groups at different stages in the GER Framework development process. The largest of these was the EER Geoscience Education Research and Practice Forum, which attracted ~140 geoscience educators and researchers. The purpose of the Forum was for researchers to listen to educators' ideas on what questions they would most like geoscience education researchers to address on their behalf. Educators divided into small discussion groups organized around the GER theme areas, with one or more working group researchers present in each small group. Discussions were rich; this provided an opportunity to identify promising practices and puzzling questions that are important and suitable for research, as well as a means of gauging

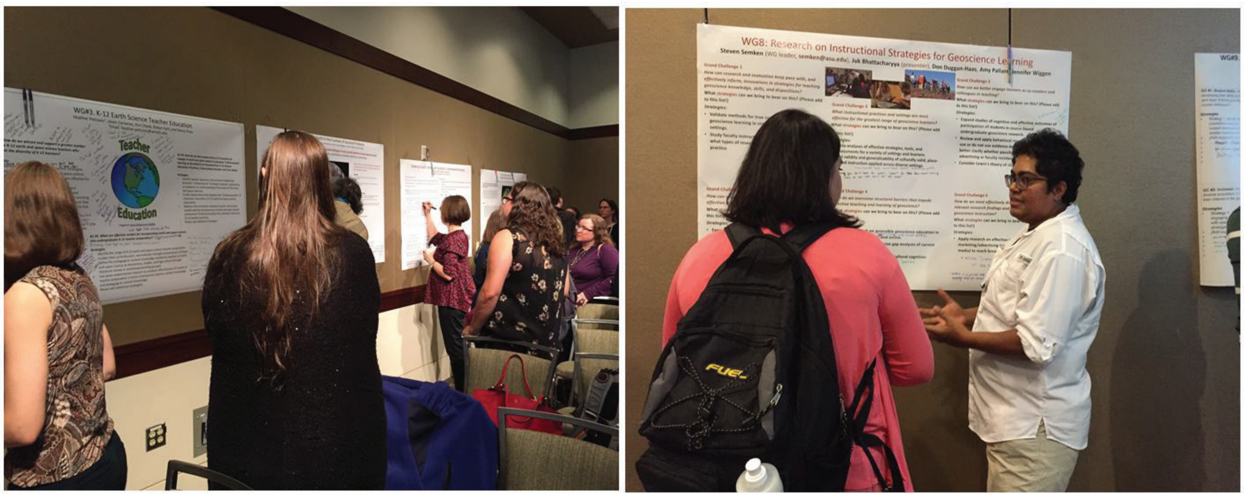

Figure 5. Working group representatives shared their theme's draft Grand Challenges and preliminary strategies at a GSA Townhall for review and discussion. Attendees could write comments and suggestions on the posters, which later working groups would use to revise their work.

alignment of ideas on what educators think is important to address with ideas that GER working group members were already generating on grand challenges. Feedback from the Forum influenced the evolution of the draft grand challenges and raised the awareness among GER working group members of educators' interests, concerns, and priorities.

By the close of the EER GER workshop, a preliminary set of theme-based GER grand challenges and supporting strategies was produced. A GSA Townhall meeting was organized as the first opportunity to publicly share and vet these draft Framework materials. It was attended by ~50 people. Representatives from each working group gave a "lightning" 1-2 slide presentation on their GER theme, and then attendees had the opportunity to visit and write notes on theme posters (Figure 5) which listed all of their grand challenges and had space for adding critiques, ideas on prioritization, and suggested strategies. In addition, more traditional outlets of conference presentations were also used as ways to share ideas and get feedback; these included posters at GSA (poster accessible online) and AGU meetings, and an oral presentation at the AMS meeting (recorded presentation accessible online).

Following the GSA Townhall, working group leaders and contributors from their teams revised the grand challenges, and expanded upon the rationales and strategies so that by the start of the AGU meeting each theme had a full draft ready for critical review by the broader community. This was facilitated through a 2-month Open Comment Period. Draft GER Framework materials (at this point referred to as theme "chapters") were hosted on a SERC website; comments could be entered in 'Discussion' boxes directly on the webpages for each of the 10 theme chapters. Efforts to alert and encourage community members to contribute their comments included distribution of flier (with a QR code to the webpage) at the AGU NAGT booth and at the project poster, notices in the NAGT newsletter, the NAGT GER Division newsletter, the GSA Geoscience education listserv, direct emails to attendees of the 2015-2017 EER GER workshop attendees, authors that published articles in the JGE theme issue on *Synthesizing Results and Defining Future Directions of GER*, and other members of the GER and geoscience education community. In sum, comments from 40 people were submitted; 67% of these were from geoscience educators and researchers external to the project, and the remaining comments were from those internal to the project but from other working groups than the themes they critiqued. Each theme chapter received comments from 3 to 5 reviewers. Reviewers provided substantial feedback, on par with the thoughtful constructive comments expected on manuscripts submitted for peer-review. These comments helped chapter authors recognize and address gaps, refine the ideas communicated, and better situate the grand challenges and recommended strategies in a meaningful context.

Framework Scope and Audience

Intended Scope of the GER Framework

This project embraces a broad definition of GER that reflects the geoscience education community's values and the evolution of STEM education research. The geosciences have a long and rich history on the scholarship of teaching and learning (SoTL), which involves the development, application, and evaluation of new geoscience teaching innovations and curricula. More recently, in the geosciences and in other STEM fields, there has been rapid growth in interest and activity in discipline-based education research (DBER), which develops and tests discipline-specific (i.e., geoscience) education research questions and hypotheses. Both SoTL and DBER are important for improving teaching and learning in the geosciences, and therefore both are included in the scope of GER for this project (Figure 6). Contributors to this project were asked to situate their thinking about GER to include both SoTL and DBER as they considered GER themes, grand challenges, and strategies to meet those challenges.

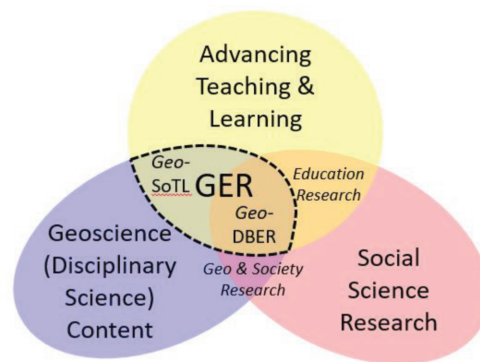

Figure 6. Geoscience education research Venn diagram. Figure by Kristen St. John, modified from one by Lukes et al., (2015).

In addition, this project focuses on GER that informs future teaching and learning at the undergraduate level. We recognize that GER itself is broader than this; there are researchers that focus on pre-college, graduate level, and informal geoscience education, as well as those whose work is purely for the advancement of knowledge (non-applied) research. The project emphasis on undergraduate-related GER was made for two reasons: (1) the majority of GER activities as reflected in meeting abstracts, publications, and geoscience education workshops are largely undergraduate-focused, and (2) the NSF-IUSE program, which funded this project, targets improvement in undergraduate STEM education.

Organization of the GER Framework Chapters: Communicating to Multiple Audiences

In organizing the GER Framework chapters, we recognized the need to effectively reach multiple audiences: geoscience education researchers, geoscience educators, colleagues, administrators, program officers in funding agencies, as well as education researchers in other STEM disciplines. Therefore, theme chapters have two tiers of information: (1) an introductory page and (2) expanded pages for each grand challenge (Table 4). The aim of the introductory page is to help those outside of GER understand what we do, what we want to do, and why it is important. It includes a brief overview of that theme, and lists the grand challenges with brief descriptions; citations are kept at a bare minimum on that page and jargon is avoided. In contrast, the expanded pages on each grand challenge are for those who want to dive deeper. Each of these grand challenge pages can be accessed from the theme introductory page, and contain a more thorough rationale for why research to address that grand challenge is needed, and makes recommendations for immediate strategies to be used to address it. It includes a set of key references to support the rationale and strategies, however it is not intended to be a full literature review of all the work done thus far that inform that theme. Both the introductory page and the expanded grand challenge pages include one or more diagrams, tables or photos that help illustrate that challenge and/or strategies to address it.

GER Framework Organization	
Want just a short overview of the Theme and its Grand Challenges?	Go to the Introductory page for each Theme Chapter
Want to dive deeper and get a more detailed perspective along with recommended strategies and key citations?	Go to the expanded pages on each Grand Challenge
Want to see how it all connects together?	Go to the Synthesis Chapter

Table 4. The GER Framework is designed for multiple audiences. It includes introductory, detailed, and synthesis levels of information.

In addition to the theme chapters, the GER Framework includes a synthesis chapter, which highlights strands that connect multiple themes (in some cases, all themes), which may serve as high impact pathways to achieve transformative research. It also describes the potential for using the GER Toolbox as a means to support a range of recommended strategies. The synthesis chapter compares the outcomes of this effort to that of earlier community efforts (e.g., Wingspread report) to give a longitudinal perspective on the evolution of GER. It looks outside of GER as well, to describe potential synergies between the outcomes of this project and that of other relevant and timely large-scale efforts, including the Summit on the Future of Undergraduate Geoscience Education and cross-DBER efforts; and it situates the outcomes of this project within the recent NSF report on big ideas for the future funding investment.

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Figures and Tables

Figure 1.
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Figure 5.
Provenance: Heather Macdonald, College of William and Mary

Figure 6.
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Table 1.
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Table 2.
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Table 3.
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Table 4.
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Research on Students' Conceptual Understanding of Geology/Solid Earth Science Content

Eric J. Pyle, James Madison University; Andy Darling, Colorado State University; Zo Kreager, Northern Illinois University; and Susan Howes Conrad, Dutchess Community College

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Introduction

"Solid Earth" is a broad concept, representing processes at the surface of the Earth, as well as the subsurface all the way to the solid inner core (Figure 1). Fields of study encompassed in this domain include geomorphology, historical geology, mineralogy, petrology, stratigraphy, structural geology – all topics that are touched upon in introductory coursework, and constitute the core of an undergraduate geology curriculum. Combined with cognate coursework in biology, chemistry, physics, and mathematics, the conceptual load in the Solid Earth curriculum is daunting, to say the least. The vision of the *Framework for K-12 Science Education (NRC, 2012) and the Next Generation Science Standards* (NGSS Lead States, 2013) places Earth science as a capstone to the secondary science curriculum, which would be a natural springboard to undergraduate geoscience studies. But this vision is far from the current, or even near-future reality, with Earth science often relegated to early in the secondary curriculum if offered at all, and in many cases seen as an option for lower-achieving students. The risks of poor understanding of solid Earth concepts are non-trivial, ranging from the economic costs of commodities and energy to the potentially fatal impact of hazards from mass-wasting, flooding, volcanic activity, and earthquakes.

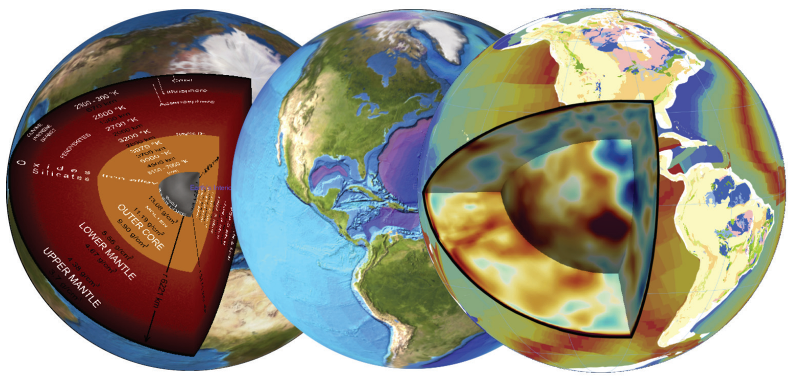

Figure 1. Research on students' conceptual understanding of solid Earth science concepts impacts the core of much course-work in undergraduate geology degree programs. Determination of students' misconceptions and then optimal learning progressions for geology concepts are two research challenges that need to be addressed.

As a result of this gap between the vision and reality, undergraduate geoscience studies are faced with two main problems: (a) the determination of students' solid Earth misconceptions when they participate in geoscience coursework, including their persistence and the means to address them, and (b) the determination of optimal learning progressions in geoscience instruction to accommodate preparation of geoscience professionals and Earth science teachers, as well as general education students. There is a growing and robust body of literature for misconceptions among undergraduate geoscience students, yet more work needs to be done; and an optimal learning progression for undergraduate geoscience does not yet exist. Many of the methodological approaches to addressing these two problems can be sought and adopted from pre-college education research, thus a dialogue between geoscience content faculty and their education peers, including pre-college teachers, is a necessary component.

Grand Challenges

Grand Challenge 1: What are ways to further develop current, and to discover new, ways of understanding critical concepts for developing Earth Systems thinking on processes from the surface to the core, and links to other Earth system components?

Historically, Earth science education at the secondary level has not instilled a deep understanding of Earth science concepts nor strong connections to other science content areas; this affects students' conceptual understanding in undergraduate geology coursework. If students have misconceptions about fundamental components of the solid Earth, then the complexity of solid Earth systems and their connections to other Earth systems will continually be beyond their grasp, and these misconceptions will become an impediment to further learning.

Grand Challenge 2: What is the optimal learning progression (i.e., conceptual scope and sequence) in an undergraduate geology degree program to best support growth in conceptual understanding and career preparation?

The undergraduate curriculum in the geosciences follows a general pattern that is governed largely by faculty expertise and workforce expectations, but is not necessarily well-informed by students' prior knowledge and naïve ideas. There is little empirical information that supports the notion that a traditional approach to the undergraduate geoscience curricular design meets the needs of majors or non-majors. Learning progressions are an approach to understanding the construction of learning environments, which can provide a structure for what should be learned about a topic and the sequence of topic components of increasing complexity. Geoscience education research can, and should, inform the development of optimal learning progressions.

Grand Challenge 1:

What are ways to further develop current and to discover new ways of understanding critical concepts for developing Earth Systems thinking on processes from the surface to the core, and links to other Earth system components?

Rationale

Historically, Earth science education at the secondary level has not instilled a deep understanding of Earth science concepts nor strong connections to other science content areas. And while the more recent *Framework for K-12 Science Education* (NRC, 2012) and the subsequent publication of the *Next Generation Science Standards* (NGSS Lead States) in 2013 situate the geosciences curriculum as a natural capstone for secondary students' science education and a natural transition to the undergraduate experience, this vision has not yet been achieved. As a result, undergraduate students enter college with largely distant memories of "Earth science" having some "geology" concepts, but are likely to conflate the two in their decision-making. Without a complete picture of what is known (and unknown) about these students' conceptions and misconceptions in solid Earth concepts, the divide between expert faculty and the majority of undergraduate students is unlikely to be bridged by curricular innovations. The *Earth Science Literacy Principles* (ESLP) (2009, p.1) states that an Earth science literate person "understands the fundamental components of Earth's many systems". If students have misconceptions about fundamental components of the solid Earth (ESLP Big Ideas 3 & 4), then the complexity of solid Earth systems and their connections to other Earth systems will continually be beyond their grasp and thus they will remain illiterate about the Earth. In fact, these misconceptions will become an impediment to further learning.

Addressing student misconceptions requires a consideration of conceptual understanding as seen by both instructors and students (as is the case with learning progressions), and require specific strategies to correct (Cohen, 1995). According to Korom (2002, p.139), "...misconceptions are such flaws in the definitions, concepts, and models in the cognitive structure of children and adults alike that are incompatible with the current scientific concepts, and are so deeply embedded in the cognitive structure that they can hardly be changed". Donovan & Bransford (2004) stress that the way in which people best learn science starts with a foundation of students' pre-instructional concepts, both accurate conceptions as well as misconceptions. Once understood, the design of inquiry-based learning experiences can be facilitated, targeting misconceptions. This cycle is complete when students have had the support of instructors in developing metacognitive connections across ideas. Applied to an undergraduate setting, the cycle extends the 3-dimensional learning structure of *A Framework for K-12 Science Education* (2012) to the college science education experience.

In the geosciences, the role of the introductory course as a cross-roads is not widely appreciated. This course marks the transition from pre-college to undergraduate geoscience for majors, while also effectively being the end-point of students' geoscience education experience in general education. The introductory course is further complicated by a consideration of the needs of pre-service teachers across the K-12 curriculum (Mosher et al., 2014).

Geoscience is also an interdisciplinary domain, and undergraduate curricula typically require more cognate science and mathematics courses than other science domains. What has not been considered extensively is the role that cognate science courses, and their curricular timing, play in undergradate students' conceptual development. Conceptual entrenchment (Vosniadou & Brewer, 1992) and persistent misconceptions (Chi, Sotta, and de Leeuw, 1994) in science have been shown to limit subsequent student learning in an area (Tammer & Allen, 2005). Anderson & Libarkin (2016) have suggested that entrenchment of physics and chemistry misconceptions, largely refractory to instruction, can be contrasted with Earth science concepts, which are more mobile but no more correct, as students lack conceptual anchoring by prior educational experience.

Identifying gaps in the research literature on undergraduate students' solid Earth misconceptions is important for understanding their prior educational and personal experiences (Figure 2). From 1984 to 2009, Duit (2009) maintained an active, subject/topic referenced bibliography of students' and teachers' concepts in science education. Initially biased towards physics concepts, the database grew to nearly 600 pages, with several thousand entries, including an increasingly large body of Earth science related concept-based manuscripts. A total of 76 references applicable to solid Earth and surface processes (Microsoft Word 2007 (.docx) 23kB May31 18) are available in this database. Although somewhat dated and weighted towards K-12 students, the relative lack of solid Earth/surface processes misconceptions research at the pre-college level suggests that gaps in our understanding are likely to exist, and are likely more prevalent at the undergraduate level. Therefore, understanding the relationship between K-12 and undergraduate students' misconceptions of the solid Earth is likely to inform the course of misconceptions research among undergraduate students.

Figure 2. To address student misconceptions about solid Earth processes researchers first need to identify what those misconceptions are and explore why they are held. Here is an example showing the misconception of the scale of Kilauea lava eruption on the Big Island of Hawaii in 2018. From the USGS.

Recommended Research Strategies

1. Perform a Gap Analysis of existing solid Earth concepts literature compared with contemporary solid Earth system science to identify misconceptions, describe conceptual progressions, and develop frameworks to evaluate instructional practices. Dove (1998) and later Francek (2013) have been largely successful in summarizing the literature from the standpoint of the research that has been done, inductively identifying persistent misconceptions held by students. But this approach has had limited success in identifying particular gaps in the literature, especially in light of changing educational goals for science education.

2. Identify the best research practices (quantitative, qualitative, and mixed methods) for identifying misconceptions. Scherer, Holder, & Herbert (2017), as well as Holder, Scherer, & Herbert (2017) provide a basic framework through which a gap analysis of complex near-surface Earth systems literature might inform practice. It is not a stretch to extend such an approach to finding the "holes" in the literature from the near-surface to the deep subsurface, encompassing the entirety of the solid Earth.

Grand Challenge 2:

What is the optimal learning progression (i.e., conceptual scope and sequence) in an undergraduate geology degree program to best support growth in conceptual understanding and career preparation?

Rationale

The undergraduate science education experience is unique in that it must attend to three different populations of students: (a) students seeking a degree in the geosciences, (b) non-major students satisfying general education requirements, and (c) pre-service teachers of science, including both elementary as well as secondary. Lacking an accrediting body, such as the role that the American Chemical Society (ACS) provides for chemistry, the undergraduate curriculum in the geosciences follows a general pattern that is governed largely by faculty expertise both within individual programs and in conversations at the national level, (e.g., Mosher et al, 2014). Perspectives from potential employers (e.g., meeting outcomes) and/or the requirements for professional registration/licensure (e.g., Professional Geologist) also play a role. However, curriculum design is not necessarily well-informed by students' prior knowledge and naïve ideas. By the same token, there is little empirical information that supports the notion that a traditional approach to geoscience curricular design meets the needs of all, or any of the populations listed above. Detailed curriculum maps, outlining expected knowledge, skills, and dispositions (KSDs) can inform the development of learning progressions, but the maps are, in themselves are a retrospective look at what has happened in students' experiences, not what a span of development towards future goals should look like.

Learning progressions are an approach to understanding the construction of learning environments, such that they are "descriptions of increasingly sophisticated ways of thinking about or understanding a topic" (NRC, 2007). They can provide a map of what should be learned about a topic and the sequence of topic components of increasing complexity. As opposed to a conventional "top-down" approach to curricular design (i.e., "Tyler Rationale"), learning progressions emphasize both "big ideas" that would be top down from a scientist's perspective as well as a "bottom-up" approach, based on students' initial naïve ideas about the topic and following them towards more complicated and detailed understandings of the topic at hand (Gotwals & Alonzo, 2012).

Much of the research with learning progressions is limited to the K-12 realm, but to the extent that they have influence on students' prior knowledge upon entering undergraduate coursework, they are worth examining. Many of the learning progressions that have been empirically developed or documented have been done within the physical and life sciences, with relatively little work done with Earth science learning progressions. The Next Generation Science Standards (National Research Council, 2012) offer prototype learning progressions for disciplinary content in K-12

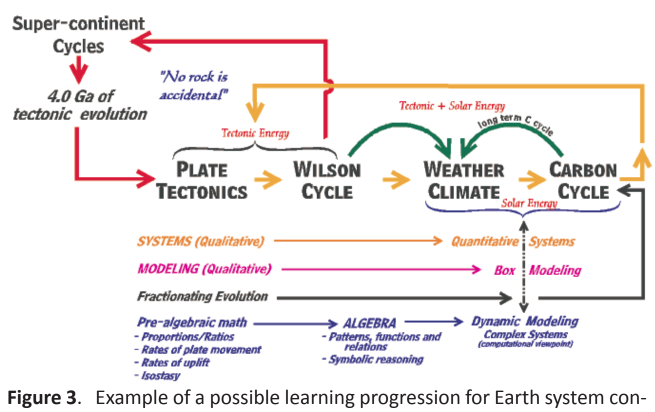

Figure 3. Example of a possible learning progression for Earth system concepts. By Lynn Fichter and Eric Pyle, James Madison University.

Earth science, as well as for cross-cutting concepts and science & engineering practices. As NGSS becomes more widely employed, it will have an impact on students entering undergraduate programs. Thus, an understanding of pre-college Earth science learning progressions, and how they were developed, provides information for future curricular development in undergraduate programs, developing learning progressions to suit the needs of the student populations an undergraduate program needs to serve. What is currently unavailable are optimized learning progressions for core solid Earth ideas in undergraduate geoscience programs.

But learning progressions also need to go far beyond student understanding of specific components in isolation, and the Earth systems connections between these concepts are just as important as the concepts themselves (Figure 3). Learning solid Earth concepts in depth also requires connections to cognate sciences, such as biology, chemistry, physics, and mathematics, more so perhaps than in disciplines outside of the geosciences. Through these relationships within and across disciplines, the disparate solid Earth concepts can be tied together in an evolutionary sense (Fichter, Pyle & Whitmeyer, 2010), but also tied to other Earth system components. Assaraf & Orion (2005) defined the requirements for Earth systems thinking, which suggest an upper boundary to students developing Earth systems thinking and providing a template against which many curricula fall short. Thus, another challenge is determining the relative roles that introductory geoscience and cognate science courses play within solid Earth learning progressions.

Recommended Research Strategies

1. Identify the best research practices (quantitative, qualitative, and mixed methods) for conceptual progressions. The methods and conventions for documenting and developing learning progressions employed by pre-college science education researchers should be examined and adapted for different undergraduate geoscience student audiences;

2. Engage with education research faculty to develop learning progressions for critical concepts in a manner similar to those used in NGSS. Many learning progressions can be defined by the collaboration of experts in solid Earth concepts, the psychology of learning, and the nature of assessment;

3. Outline methods of determining the efficacy of curricular innovations grounded in learning progressions for solid Earth concepts. The NRC (2001) suggests including a cognitive component of knowledge and misconceptions, an observational component of student understanding, and an interpretation component of student behaviors and assessment results.

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Figures

Figure 1:
Provenance: Images generated by Eric Pyle using Celestia, including the Planetary Interiors Module created by user "Fenerit" and made available for non-commercial uses.

Figure 2:
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Research on Students' Conceptual Understanding of Environmental, Oceanic, Atmospheric, and Climate Science Content

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Introduction

At the interface between atmosphere, hydrosphere, and biosphere, this theme covers content that is societally crucial but publicly controversial and fraught by misconceptions and misinformation (Figure 1).

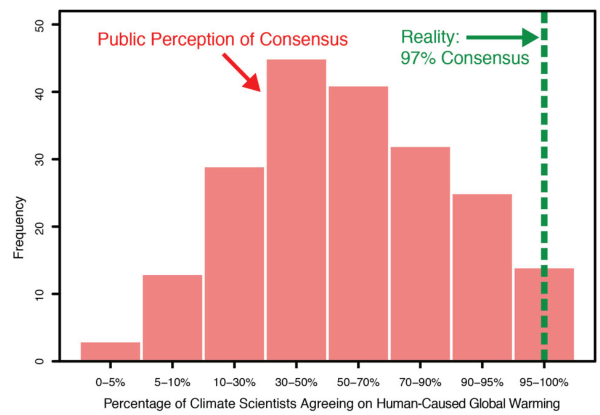

Figure 1: From Skeptical Science; data from 2012 Pew Survey. The disconnect between public perception and scientific consensus continues to persists today as demonstrated by other recent surveys.

Climate science is an interdisciplinary field that straddles the natural and social sciences; understanding its processes requires system-thinking, understanding mathematical models, and appreciation of its human and societal components. Recent data show that extreme weather and climate events have become more frequent in the past decades (EASAC, 2018). These include extreme temperatures, floods, like the ones associated with the series of very powerful hurricanes that made an unprecedented number of landfalls in August and September 2017 (Figure 2) and unusual drought conditions and forest fires across the Western US in the summer of 2017 (Figure 3).

Studies like these emphasize the complexity of climate science and highlight the importance of climate change adaptation. However, there is a significant disparity in the distribution of vulnerability and readiness to impacts of climate change with most of Africa and South Asia disproportionately more vulnerable and less equipped to deal with them (Swanson, 2015).

We have identified five Grand Challenges to the conceptual understanding of environmental, oceanic, atmospheric and climate science, and proposed strategies for the geoscience education research community.

Grand Challenges

Grand Challenge 1: How do we identify and address the challenges to the conceptual understanding specific to each discipline: environmental science, ocean sciences, atmospheric sciences, and climate science?

Misconceptions, pre-conceptions, partially correct conceptions, or naive conceptions are a challenge to students' conceptual understanding of the core science. Identifying common misconceptions that are specific to each discipline of the fluid Earth is the first step in addressing these alternative conceptions and ultimately achieving a higher level of conceptual understanding.

Figure 2: Category 5 hurricanes José and Maria on September 19, 2017. Hurricane formation and evolution involve complex interactions between ocean and atmosphere. They are connected to the climate system and affect environmental change. Research on how to effectively foster students' conceptual understanding of this and other Earth systems' phenomena is important to teaching and learning in the geosciences. Image courtesy of NOAA.

Grand Challenge 2: How do we teach complex interconnected Earth systems to build student conceptual understanding of, for example, climate change?

Teaching about complex systems, like changes in climate over multiple temporal and spatial scales, represents a challenge that has been studied extensively. Reviewing existing studies, proposed learning strategies, and drawing from other disciplines would be a valuable contribution to the Geoscience education research community.

Grand Challenge 3: What approaches are effective for students to understand various models (numerical and analytical) that are used for prediction and research in atmospheric, oceanic and climate sciences, including model limitations?

The study of the atmospheric, oceanic, and terrestrial systems is based on models that help simplify these complex systems and are used for prediction. Knowledge of computer programming and advanced math is needed to create, validate or understand these models, making the field less accessible to the broad student population. Thus, instruction in the geosciences needs to increase advance math and programming skills.

Grand Challenge 4: How do the societal influences, affective elements, personal background and beliefs, and prior knowledge impact students' conceptual understanding of Earth system sciences?

Wildfire smoke crosses the U.S. via the jet stream on September 4, 2017, affecting air quality in the northern and central part of the continent. How to effectively use models of atmospheric circulation is one area in which education research can inform teaching practice. Images courtesy of NASA.

Students enter classes with a complex array of beliefs and personal history that shapes their learning and their perception of the relevance of what they are learning within their own lives. Literature about cognitive and metacognitive aspects of learning shows that these external factors have significant influence on students' conceptual understanding, particularly on topics perceived as controversial. Therefore, instruction in these fields requires sensitivity to the context and the prior knowledge and belief systems of students.

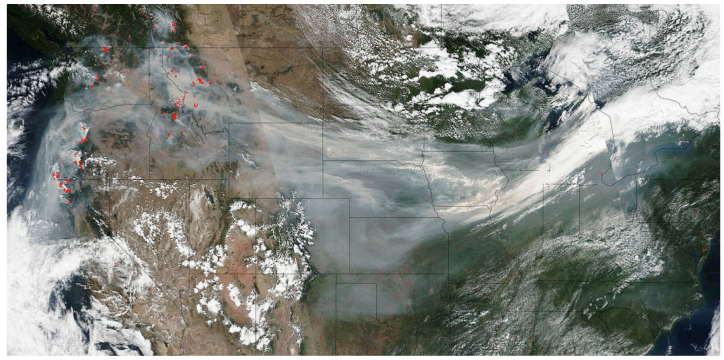

Figure 3: Wildfire smoke crosses the U.S. via the jet stream on September 4, 2017, affecting air quality in the northern and central part of the continent. How to effectively use models of atmospheric circulation is one area in which education research can inform teaching practice. Images courtesy of NASA.

Grand Challenge 5: How do we broaden the participation of faculty who are engaged in educational research in environmental sciences, atmospheric sciences, ocean sciences and climate sciences and encourage implementation of research-based instruction?

In the U.S. there are approximately 1,200 faculty in oceanography and atmospheric science/ meteorology at 4-year institutions, and four times as many faculty are in the broad field of geology or solid Earth. Overall, there are 75 faculty that identify themselves as Earth science education researchers nationwide, and most of them have a background in geology. This relatively small number of faculty members in fluid Earth science is reflected in the small fraction of the community that is engaged in education research. Such small numbers make it challenging to create a research agenda for this field.

Grand Challenge 1:

How do we identify and address the challenges to the conceptual understanding specific to each discipline: environmental science, ocean sciences, atmospheric sciences, and climate science?

Rationale

As we define the best undergraduate geoscience learning experience, we build longitudinal connections with K-12 education, in which core Earth science concepts are well defined and articulated. Earth systems, Earth and human activity, weather and climate, natural hazards, and human sustainability are disciplinary core concepts in the Next Generation Science Standards that represent the foundation to the conceptual understanding of environmental science, ocean sciences. atmospheric sciences, and climate science. These disciplines are also central to the Big Ideas in the Earth Science Literacy Principles that identify the Earth as a complex, constantly changing system on which life evolves and modifies it (Big Ideas 3, 4, 6 and 9). Humans' dependence on natural resources and the risk that hazards pose to humans are the theme of Big Ideas 7 and 8, while the role of water on the planet is Big Idea 5.

Misconceptions, pre-conceptions, partially correct conceptions, or naive conceptions are a challenge to students' conceptual understanding. Identifying prior conceptions that are specific to each discipline of the fluid Earth is the first step in achieving a higher level of conceptual understanding. This can be done using concept inventories, surveys, or focus group interviews (e.g., Arthurs et al., 2015; Robelia & Murphy, 2012).

Project 2061 contains assessment items that target core concepts and misconceptions in the Earth, life, and physical sciences. Each question contains data on the percentage of middle and high school students that answered it correctly. It also contains information on the misconception held by students who answered incorrectly (Prud'homme-Generaux, 2017). There are more than 80 documented misconceptions in the weather and climate theme, including basic concepts and seasonal differences. The website also includes an extensive list of references to studies that explore or unveil misconceptions. Since they are challenging to replace, it is likely that misconceptions held by middle and high school students will persist in college, making the Project 2061 information very valuable for the GER community (Prud'homme-Generaux, 2017).

A review of the literature on misconceptions is available for the solid Earth (Francek, 2013) but research on conceptual understanding of the fluid Earth is scattered among several journals: misconceptions related to tornadoes (Van Den Broeke and Arthurs, 2015), climate change (Huxter et al., 2015), environmental issues (Khalid, 2001; Robelia and Murphy, 2012), ozone formation (Howard et al., 2013), atmospheric pressure (Tytler, 1998), air motion (Papadimitriou, 2001), ocean acidification (Danielson and Tanner, 2015), the greenhouse effect (Boyes & Stanisstreet, 1993; Harris & Gold, 2017)(Figure 4), and sea-level rise (Gillette and Hamilton, 2011). Making available a compilation of common misconceptions to educators through an organized review would be a valuable contribution of the GER community.

Recommended Research Strategies

1. The most common barrier to conceptual understanding are existing misconceptions or pre-conceptions, thus identifying them is the first step. Assessment instruments, like the Force Concept Inventory used in physics or the Geoscience Concept Inventory, are commonly used to identify misconceptions: we recommend the creation and/or dissemination of concept inventories about oceanography, climate, and weather as a valuable contribution from the GER community to educators. The Fundamentals in Meteorology Inventory assessment exam (Davenport et al., 2015) could be used as a starting point. The Climate Literacy Principles (USGCRP, 2009) could be used as a compilation of the big ideas in climate science and to organize common misconceptions.

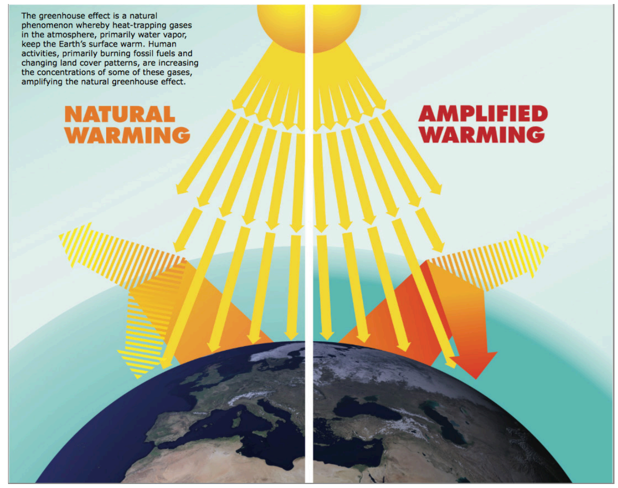

Figure 4: The Greenhouse Effect (From USGCRP, 2009), is one topic in which misconceptions persist in the undergraduate student population.

2. Existing literature focuses on specific misconceptions within the fields of oceanography, environment, climate and weather science for specific populations. An extensive overview of misconceptions on weather and climate is included in Project 2061 but this tool is not widely used by college instructors. A literature review that summarizes what we already know, why students hold these conceptions, and how they compare in different populations, will be a useful guide for future research and educators.

Grand Challenge 2:

How do we teach complex interconnected Earth systems to build student conceptual understanding of, for example, climate change?

Rationale

Teaching about complex systems (e.g. Scherer et al., 2017, Holden et al., 2017), like changes in climate over multiple temporal and spatial scales, represents a challenge that has been studied extensively. Reviewing existing studies, proposed learning strategies (e.g. Gunckel et al., 2012, Mohan et al., 2009; McNeal et al., 2014; Bush et al., 2016), and drawing from other disciplines would be a valuable contribution to the Earth science community. Learning progression research conducted in the K-12 realm (Songer et al., 2009) can inform instruction in higher education, in particular within the area of interconnected Earth systems. Learning progressions are "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time." (Duschl et al., 2007). An example of a tool that explores the history of life on Earth within a deep-time plate tectonics and climate framework to inform students about future climate change is HHMI Changing Planet: Past, Present, and Future (Figure 5).

Recommended Research Strategies

Figure 5: Opening image of HHMI Changing Planet site. Not only is an interconnected Earth systems perspective important for understanding modern Earth conditions, it is important for considering the causes and consequences of change in the geologic past and future.

1. Recent literature reviews on student learning of complex Earth systems (Holder et al., 2017; Scherer et al., 2017) provide the GER community with a foundation that can be used to study the conceptual understanding of climate change. Identifying examples from other disciplines (e.g., engineering) can provide a broader context for future research.

2. Inquiry and problem-based education have shown promise in enhancing learning of complex systems like climate change (e.g., Bush et al., 2016). We propose to expand testing of instructional strategies that have shown impact on learning to a broad range of learning environments (e.g., online, introductory, upper-level undergraduate, pre-service teachers, informal) and student populations.

3. Examination of learning progression research conducted in and developed for the K-12 setting can inform GER strategies used to research undergraduate students' development of understanding complex Earth systems. Adapting such research findings and strategies also has the potential to better align and understand the knowledge that students hold upon entering the higher education system to study earth and environmental sciences.

4. Study how conceptual understanding evolves from introductory to upper-level courses within different programs (oceanography, atmospheric sciences), and how we should prepare geoscience majors for graduate school and the profession (Mosher et al., 2014).

Grand Challenge 3:

What approaches are effective for students to understand various models (numerical and analytical) that are used for prediction and research in atmospheric, oceanic and climate sciences, including model limitations?

Rationale

The study of the atmospheric, oceanic, and terrestrial systems is based on models that are used for prediction and for the conceptual understanding of these complex systems (Figure 6). Knowledge of computer programming and advanced math is needed to create, validate or understand these models, making the field less accessible to the broad student population (Ledley et al., 2011; Hamilton, 2015; Hamilton et al., 2015). One possible approach to reduce the mystery in the 'black box' approach to computer models is through the use of simple, familiar models like flow charts, graphs, and pictures, and physical models, like sand tanks for groundwater flow (Harrison and Treagust, 2000; Schwartz et al., 2009).

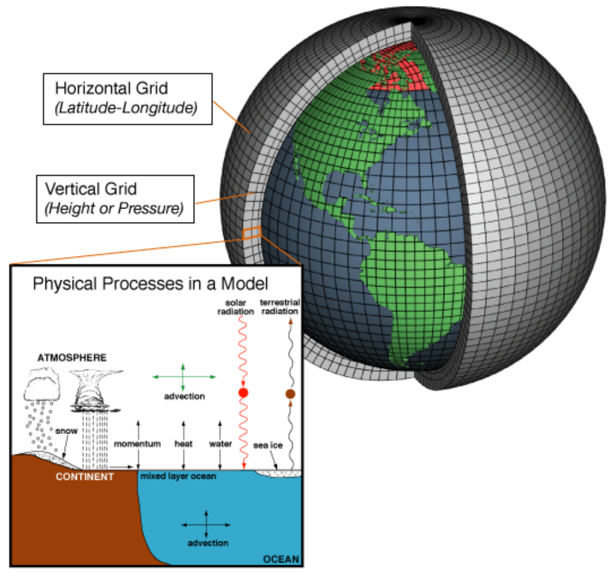

Figure 6: This image shows the concept used in climate models. Each of the thousands of 3-dimensional grid cells can be represented by mathematical equations that describe the materials in it and the way energy moves through it. The advanced equations are based on the fundamental laws of physics, fluid motion, and chemistry. To "run" a model, scientists set the initial conditions (for instance, setting variables to represent the amount of greenhouse gases in the atmosphere) and have powerful computers solve the equations in each cell. Results from each grid cell are passed to neighboring cells, and the equations are solved again. Repeating the process through many time steps represents the passage of time. The complexity inherent in these models make them conceptually challenging for undergraduate students. Image source: NOAA.

Another challenge to the use of systems models in atmospheric science is the fact that uncertainty is inherent in them, yet education research shows that novices are not comfortable with uncertainty. This requires a simplification of the models to adapt them to the student population and the implementation of targeted approaches (e.g., Gold et al., 2015).

Unanticipated changes in the forcing functions of the system resulting from unpredictability of human behavior (Konikow, 1986) that commonly involve activities such as increased water use and land conversion further demands continuous upgrade and creation of new models (Oreskes, 2003). Therefore, time-to-time update in our modeling curriculum makes it challenging for students to grasp completely new materials.

Recommended Research Strategies

1. Two working groups (Cognitive - Spatial and Temporal Reasoning, and Cognitive - Problem-Solving, Quantitative Reasoning, and Models) are focusing on the cognitive understanding of complex systems. Other DBER communities (like ecology) have conducted research in educational approaches that are effective for the understanding of models. The science education community

has studied extensively how best to teach students about models (Gilbert, 2011) and we can apply what they have learned to weather and climate models. If the difficulty is related to understanding the concepts of deterministic vs. probabilistic models, perhaps research in statistics education can provide valuable information. We recommend that education researchers refer to contributions of these groups to identify research paths for the fluid Earth community.

2. An important aspect of teaching models is to be able to minimize, or even eliminate, the widespread skepticism students have about outcomes of the models. We recommend expanding research on learning impacts of various models that can be broadly divided into two groups: i) models that have their validation index reported or that can be validated with existing data, and ii) models that lack validation measures. What is the learning impact of one vs. the other group within the realm of weather and climate models?

3. Research students' attitudes towards models and modeling, and the efficacy of different approaches to stimulating students' interest to learn about models. For example, one could show and test the use of models as decision-support tools in the context of resource management.

Grand Challenge 4:

How do the societal influences, affective elements, personal background and beliefs, and prior-knowledge of students impact their conceptual understanding of Earth system sciences?

Rationale

Students enter classes with a complex array of beliefs and personal history that shapes their learning and their perception of the relevance of what they are learning within their own lives. Literature about cognitive and metacognitive aspects of learning shows that these external factors have significant influence on students' conceptual understanding, particularly on topics perceived as controversial (e.g., Vaughn & Robbins, 2017; Walker et al., 2017). Religious beliefs, political inclination, and social identity are strongly correlated with the acceptance or rejection of perceived controversial science topics like evolution, vaccination benefits, and climate change (Walker et al., 2017).

The strong disconnect between scientific views of climate change and the public perception of the scientific consensus (Figure 1), fueled by media and various interest groups, is a formidable challenge for educators (Walker et al., 2017) and has striking similarities to challenges encountered in teaching evolution in the United States.

Social identity theory hypothesizes that people sort themselves into groups based on perceived similarities (e.g., religion, political inclination) and that they hold onto the opinions of the group to remain part of it, a phenomenon known as identity-protective cognition (IPC, Kahan et al., 2007; Kahan, 2010). Studies have shown that, for example, teaching the evidence of climate change is not sufficient, or even counterproductive (Maibach et al., 2009; Kahan, 2015; Walker et al., 2017). However, a recent study shows that students' perception of risks associated with climate change increases with their level of knowledge of climate change science (Aksit et al., 2017). Addressing the connection between student identity and acceptance of certain scientific conclusions (Walker et al., 2017), building from personal background and beliefs, rather than challenging them (e.g., Nadelson & Southerland, 2010; Catley, Lehrer, & Reiser, 2005), and focusing on solutions as well as challenges (McCaffery & Buhr, 2007) are powerful teaching approaches.

Recommended Research Strategies

1. We recommend the use of research-based evidence in developing curriculum and formal and informal instructional guides for instructors in how to approach teaching about controversial topics like climate change. Instructional guides, like the ones available for teaching evolution, would focus on best practices for teaching students about identity-protective cognition (i.e. the tendency of individuals to selectively credit and dismiss evidence in patterns that reflect the beliefs predominant in their group) and acknowledging external influences on scientific opinions (Kahan, 2017).

2. The perceived controversy about anthropogenic climate warming is created by groups that organize climate change deniers; learning more in detail about the efforts and agenda of these

groups can be used to inform students about misinformation. The GER community should draw on literature in the information sciences, specifically on the importance of information literacy in higher education (Flierl, 2017) and the use of misinformation as a teaching tool (Bedford & Cook, 2013).

3. Incorporating feedback of human-induced alterations in complex natural system and realizing effects of extreme events of climate change in society requires collaboration between natural and social scientists. Connecting with social scientists doing similar work to create multidisciplinary research and then spreading the resulting messages to community would broaden the impact of this field (Morss et al., 2016; Morss & Zhang, 2008).

Grand Challenge 5:

How do we broaden the participation of faculty who are engaged in educational research in environmental sciences, atmospheric sciences, ocean sciences and climate sciences and encourage implementation of research-based instruction?

Rationale

In the U.S. there are approximately 1,200 faculty in oceanography and atmospheric science/ meteorology at 4-year institutions, and four times as many faculty are in the broad field of geology or solid Earth. Overall, there are 75 faculty that identify themselves as Earth science education researchers nationwide, and very few of them have a background in oceanography/ atmospheric science/meteorology (Wilson, 2016). This difference in numbers is reflected in the size of the community engaged in education research in the fluid Earth field, which makes it challenging to create a research agenda for it (Figure 7).

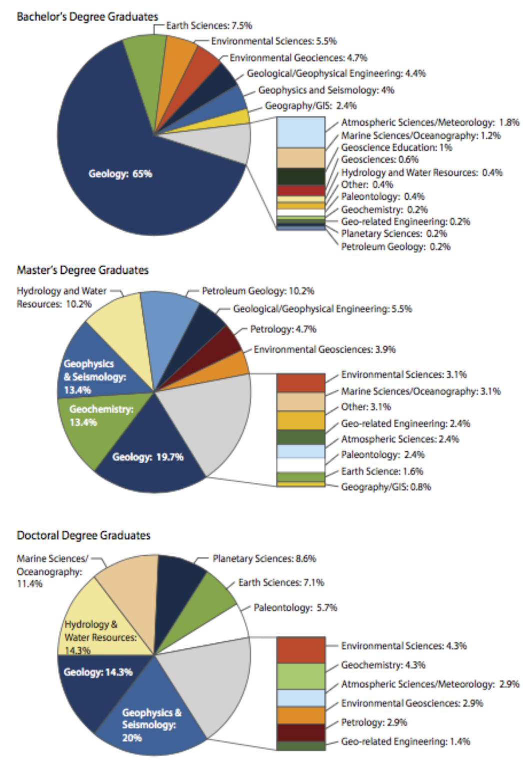

Figure 7: Breakdown of degree fields of geoscience graduates in the U.S. from Wilson (2016). Note that the PhD graduates in the environmental, ocean, atmospheric, and climate sciences are only about 15% of all doctoral graduates. A smaller fraction of these will enter academia, accounting for the small number of faculty in these fields that are engaged in GER.

Calls for a more research-based approach to understanding student learning were made a decade ago (e.g., Charlevoix, 2008), and with only limited GER in the environmental science, atmosphere, ocean, and climate science (compared to solid Earth science), there is reluctance for university departments to dedicate faculty lines to education research in these fields. The interdisciplinary nature of GER is also a challenge for many universities as it relates to tenure-track positions with the tenure process being either less clear or more onerous (O'Meara & Rice, 2005; Trower, 2008; O'Meara, 2010). Efforts and collaborations are underway in the social sciences to connect the research, application, and operation aspects of atmospheric sciences. The GER community could learn from this group as we develop and expand our community (Jacobs et al., 2005; Feldman & Ingram, 2009). Making the work of GER meaningful to faculty across the country can help broaden participation.

Recommend Research Strategies

1. Information on the importance and relevancy of GER is critical to our ability to engage additional faculty in the GER community as well as institutionalize GER within the Earth and environmental sciences. The value of GER to the university community should be communicated in terms of the benefits to students, the individual institutions, and the disciplinary field. This would

contribute to growing the DBER/SoTL community within the fluid Earth disciplines. Resources like the GER Toolbox would be helpful for faculty who are interested in expanding their research into SoTL/DBER. Additionally, documenting and adapting lessons learned from partnerships between social scientists and operational scientists can inform the methods in which GER advocates for and informs faculty of research-based instruction. This in turn would generate interest in implementing research-based instructional strategies.

2. Grow the footprint of GER at professional society meetings and functions. The professional societies of NAGT, GSA and AGU have been important in the growth of the Earth science education research community. More engagement with NSTA and NARST would also help. Efforts should continue to link DBER who attend NAGT, GSA and AGU meetings with DBER working in the atmospheric and oceanic sciences. The AMS has a small group of atmospheric sciences education researchers not connected to the NAGT/GSA/AGU established communities. A presence of NAGT at the AMS Annual Meeting could engage those DBER who do not attend annual meetings of the GSA, AGU, or Earth Educator's Rendezvous.

3. Survey the entire atmospheric science community to assess their interest, support, value, and recognition of DBER/SoTL research and/or research-based teaching practices. This would provide useful information to better quantify the size of the DBER/SoTL community, and identify what kind of support there is within the broader community. The survey could be administered by AMS.

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Figures

Figure 1.
Provenance: Skeptical Science Graphics by Skeptical Science, Retreieved from https://skepticalscience.com/graphics.php?g=78.

Figure 2:
Provenance: NOAA

Figure 3:
Provenance: NASA, Retrieved from https://www.nasa.gov/multimedia/guidelines/index.html

Figure 4:
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Figure 5.
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Research on Elementary, Middle, and Secondary Earth and Space Sciences Teacher Education

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Introduction

The release of the *Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* in 2012 and the subsequent publication of the *Next Generation Science Standards* (NGSS) in 2013 represents a new vision for K-12 science learning culminating from decades of science education reform efforts. Several aspects of the NGSS are critical to the geoscience education community. First, the NGSS place the Earth and Space Sciences (ESS) on equal footing with Life Sciences, Physical Sciences (chemistry and physics), and Engineering and Technology applications across K-12 grades. Second, the NGSS promote a vision of "three-dimensional learning" in which core disciplinary knowledge, concepts that cut across disciplines, and practices used in science and engineering are given equal prominence.

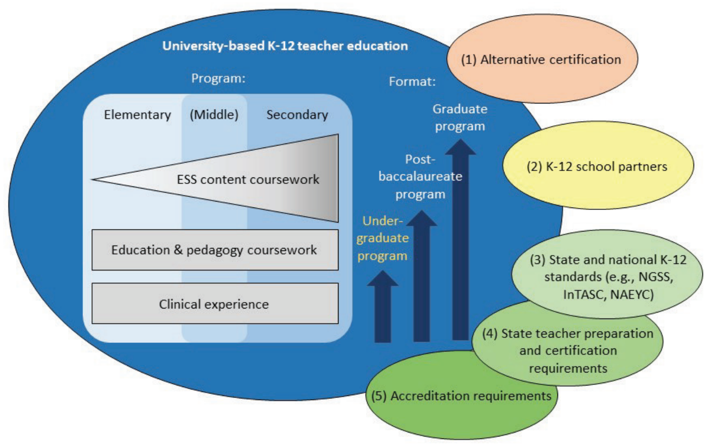

Figure 1. A generalized conceptual model of university-based K-12 teacher education in Earth and Space Sciences and key external factors that impact teacher preparation. These factors make teacher education a complex and dynamic endeavor. Research Grand Challenges and recommended strategies were developed that one part of this landscape: teacher education at the undergraduate level (shown in yellow in the model).

In order to fully engage with the vision of the *Framework for K-12 Science Education* and the *NGSS*, however, our nation needs a diverse and well prepared K-12 science teacher workforce. And in order for ESS to gain equal status with other sciences, the geoscience community must ensure that the K-12 science teacher workforce is adequately prepared to teach ESS core knowledge and practices. This is a challenging endeavor and complicated by the fact that the K-12 teacher education landscape is highly variable across institutions in terms of how much ESS content is included, how programs are structured, and how ESS fits into the larger institutional context. Figure 1 is our model of this complex landscape.

Within institutions, ESS may be part of an elementary, middle, and/or secondary teacher preparation program. Depending on the state, middle grades may be a separate certification, or may be included within elementary and/or secondary certification (shown in parentheses in the Figure 1 model). Teacher preparation programs usually have components of content-area coursework, education and pedagogy coursework, and in-school clinical experience. ESS content courses may be part of a generalized science (or education) program of study, or may be a disciplinary major or minor; in general, secondary teacher preparation programs require more disciplinary content than do elementary programs (Figure 1, width of the triangle). The quantity of education and pedagogy coursework and clinical experiences may also vary within individual programs. Program models vary from those in which the undergraduate degree leads directly to initial teacher certification, those at the post-baccalaureate level providing initial certification for candidates who already have a content undergraduate major, and those in which certification is obtained during a graduate program (such as a Master of Arts in Teaching program). Most post-baccalaureate and graduate programs are of shorter duration but are faster paced than undergraduate programs (Figure 1, arrow height).

Teacher education is also influenced by a push-pull of many external factors such as higher education and K-12 institutional pressures and priorities, changing teacher education accreditation standards, high stakes testing, state-by-state NGSS adoption, and public perception of the value of ESS. In addition, several external factors (#1-5 in the Figure 1 model) directly impact teacher education programs: Both nonprofit and for-profit organizations offer alternate routes to teacher certification (e.g., Teach for America, Teachers of Tomorrow) which may be in partnership with, or in competition with, university-based programs. Programs, especially clinical experiences, rely heavily on partnerships with K-12 districts. And teacher education programs are accountable to accrediting bodies (such as the Council for the Accreditation of Educator Preparation [CAEP]), state teacher preparation standards, and state or national standards such as the NGSS, the Interstate New Teacher Assessment and Support Consortium [InTASC], and the National Association for the Education of Young Children [NAEYC]). These factors directly influence one another, for example, accreditation requirements include national standards, and state teacher certification requirements may mirror both accreditation requirements and national standards.

Clearly, teacher education exists in a complex landscape that involve many domains of research. Here we focus on teacher education research that most directly aligns to the undergraduate teaching and learning experience (yellow text in Figure 1). Three grand challenges emerged from discussion and reflections on the existing literature and are poised to guide future research on undergraduate K-12 teacher education.

Definitions

We recognize that many states include programs of study leading to certification in preschool through grade 12 (e.g., PreK-12). In this paper we use “K-12” as the amount of Earth and Space Sciences content in preschool grades is typically minimal. The K-12 education community uses “Earth and Space Sciences” to include the disciplines of astronomy, geology, meteorology, and oceanography. In this paper, we preferentially use “Earth and Space Sciences” or “ESS” to align with the common language of K-12. We also use the term “geosciences” interchangeably with ESS in reference to college-level disciplines or coursework, or when authors we cite specifically use this term.

Grand Challenges

Grand Challenge #1. How do we attract and support a greater number of future K-12 ESS teachers who represent and can effectively engage diverse K-12 learners?
With less than 3% of secondary STEM teachers holding a geoscience degree we have a tremendous opportunity to grow the ESS teaching workforce. Yet growth of this workforce should reflect the growing diversity of K-12 learners, inclusive of gender, race/ethnicity, ability status, and more.

Grand Challenge #2. What are effective models for incorporating ESS into undergraduate K-12 teacher preparation and in providing professional development for inservice teachers?
In order to produce K-12 teachers that are well-prepared to teach ESS, we must first determine what makes teacher preparation and professional development programs successful.

Grand Challenge #3. How do we best prepare future and practicing K-12 teachers to engage in ESS to promote three-dimensional learning that involves the integration of disciplinary core ideas, science and engineering practices and crosscutting concepts?
The NGSS and Framework reflect a new vision for K-12 teaching in science and engineering. Science is an interconnected enterprise encompassing three dimensions: science and engineering practices, crosscutting concepts, and disciplinary core ideas. To effectively teach ESS, K-12 teachers need to understand not only the geoscience concepts they teach, but also the practices of geoscientists.

Grand Challenge 1:

How do we attract and support a greater number of future K-12 ESS teachers who represent the diversity of K-12 learners?

Rationale

Nationally, fewer college students are enrolling in teacher education programs, with a decline of 30% enrollment reported over the last five years (Barth et al., 2016). However, students entering teacher education programs now have stronger academic profiles (as measured by incoming SAT/ACT scores), and more entering students are completing their programs (Barth et al., 2016). Yet as many as a quarter to half of graduates of teacher preparation programs do not go into teaching (DeMonte, 2016). Retention of new teachers has also improved nationally, with 17-20% leaving the profession in the first four to five years - as opposed to older reports of nearly 50% leaving the profession within the first five years (Gray and Taie, 2015; Goldhaber, 2015; Brown, 2015). These same reports suggest that higher quality incoming teachers are retained in the profession at higher rates.

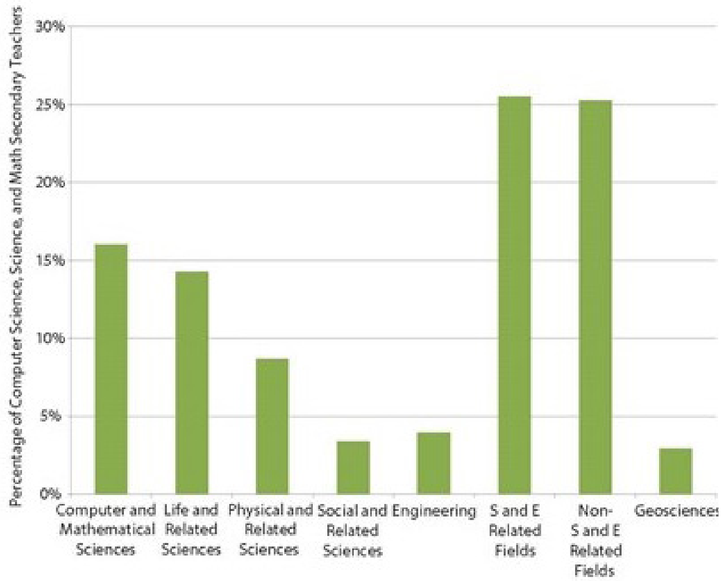

Figure 2. Percentage of secondary STEM teachers prepared in the geosciences. Reproduced from Wilson, 2016.

Amid this mixed news of national teacher preparation and retention, the ESS continue to have the least number of discipline-trained teachers within the sciences (Figure 2). Teachers of young children typically teach a wide range of content (e.g., Language Arts, math, science, and social studies) with increasing disciplinary specialization as grade levels go up. Thus elementary teachers have limited preparation in ESS content, whereas middle and secondary teachers may be prepared as content specialists. Based on analysis of data provided by the National Science Foundation, however, Wilson (2016) estimates that only 3% of secondary teachers hold a degree in the geosciences. Sixty-five percent of elementary teachers, 75% of middle school teachers, and 61% of high school teachers report taking at least one ESS course at the undergraduate level (Banilower et al., 2013). According to the same report (Banilower et al., 2013), only 28% of middle school and 30% of high school teachers have taken one or more ESS courses beyond the introductory level. Clearly, opportunity exists across all grade levels to expand the Earth and Space Science teacher workforce.

Yet growth of this workforce should reflect the growing diversity of K-12 learners, inclusive of gender, race/ethnicity, ability status, and more. Nationally, four out of five teachers are white, yet nearly 50% of school-age youth are ethnically diverse (AACTE, 2013). This issue is compounded in the geosciences, where less than 11% of bachelor's degrees in geoscience are conferred to students of African American, Hispanic/Latino, or Native American/Alaskan race or ethnicity (Wilson, 2016). Compounding this issue, minority-serving institutions are less likely to offer degrees in the geosciences; Petcovic et al. (2016) found that only 2.5% of institutions with degree granting geoscience departments were designated as minority-serving. As yet the fraction of teacher preparation programs in ESS at minority-serving institutions remains unknown.

Research is needed to identify roadblocks that deter individuals, especially persons of color, from choosing or staying on the path to become ESS teachers. Research is also needed to identify mechanisms that are successful in both attracting individuals to K-12 ESS teaching and supporting their long-term success. This research will need to consider how pathways for entry into and persistence in ESS teaching may differ depending the grade bands that an individual intends to teach; in other words, different factors likely influence whether someone enters and persists in teaching elementary, middle, or high school grades.

There is considerable overlap between this challenge and GC#2; here the focus is on understanding how to better attract and support the individuals who make up a diverse pool of future K-12 ESS teachers, whereas GC#2 focuses on broader institutional models, partnerships, and best practices in ESS teacher education.

Recommended Research Strategies

Here we recommend short and long-term strategies that could yield insight into Grand Challenge #1 and ultimately drive forward both knowledge and practice. While short and long term strategies can both be approached immediately and simultaneously, short term strategies (#1-4) tend to focus more on synthesis of current literature, surveys of our current state of knowledge, or application of excising research to the field of teacher education. In contrast, long term strategies (#5-7) require more significant time and resource investment (such as support by external funding), focusing on more large-scale empirical students that can build the knowledge base.

1. At present, the research community lacks a baseline understanding of how individuals, especially persons of color, decide to become K-12 ESS teachers. Understanding how and when individuals decide to become K-12 ESS teachers is important foundational data to collect and compile. We call for a systematic review of existing literature that would establish our current understanding of what attracts individuals to ESS teaching. This review should encompass literature in other STEM fields in order to establish what may be unique to ESS teaching in addition to what is common with other fields. It should also highlight critical theoretical and conceptual frameworks that provide explanatory power to findings.

2. The research community also lacks a baseline understanding of what efforts in recruiting a diverse pool of students to K-12 ESS teaching have been successful. Again there is a need for systematic literature review that identifies the existing strategies for attracting students and determine what components of these are effective for underrepresented populations. Learning what external factors contribute to or inhibit interest in becoming a K-12 ESS teacher, especially among persons of color can help us move forward. We should look to other STEM

fields for examples of successful interventions as well as to the results of programs specific to ESS teacher recruitment. Along these lines, there may be a need for comprehensive evaluation of NSF-funded GEOPATHS programs that focus on ESS teacher recruitment and preparation.

3. To better understand the population of current and future K-12 ESS teachers, we suggest a survey of teacher preparation institutions that focuses on their recruitment methods. We especially would want to know how these institutions reach a diverse pool of potential applicants and the extent to which partnerships with two-year colleges and minority-serving institutions exist. It would also be useful to survey current K-12 ESS teachers to determine what other courses they teach, what certification(s) they hold, and how they describe their preparation to teach the ESS. This work could also refine our knowledge of the current and potential future demand for ESS teachers.

4. The broader K-12 teacher education community has a good understanding of what factors support the transition from preservice teacher education to inservice teaching, inclusive of teachers of color (e.g., Ingersoll & May, 2011). However this work has not been communicated within the ESS teacher education community. We call for review and synthesis of this existing literature from which researchable questions specific to K-12 ESS teacher transitions may arise.

5. The geoscience education community has done some work examining awareness of, and barriers to, underrepresented populations pursuing study and careers within the geosciences (e.g., O'Connell and Holmes, 2011; Levine et al., 2007; Huntoon & Lane, 2007; Stokes et al., 2015; Baber et al., 2010; see also references in GC#5 Access and Success). To our knowledge, no work has yet been done to identify barriers and attractors to careers in K-12 ESS teaching. Building this understanding could take an ethnographic or phenomenological approach, drawing experiences from current K-12 ESS teachers of color to identify critical experiences (e.g., Levine et al., 2007). Initial work could be followed up with broader surveys of the current K-12 STEM teaching community to identify critical experiences, incidents, or factors that lead to greater interest in ESS teaching. Conversely, these surveys could also identify factors that serve as barriers or deterrents to students interested in K-12 ESS teaching.

6. Significant research supports the notion that reformed teaching practices lead to greater retention of STEM students, especially women and students of color (e.g., Freeman et al., 2014). Is the same true for future STEM teachers? To address this question, we call for a comparative study of whether institutions with transformed STEM course design might attract and support a more diverse pool of future K-12 ESS teachers than institutions with more traditional courses.

7. We see a need for longitudinal phenomenological research that follows pre-service ESS teachers into the first few years of teaching to identify factors that contribute to thriving. This is especially important for teachers of color, who are more likely to leave the profession within the first five years than are white teachers (Ingersoll & May, 2011). Current work points to organizational factors (such as the level of collaboration and autonomy, institutional support, and pressure of high stakes testing) as driving minority teachers from the profession (Ingersoll & May, 2011). Similar to the research agenda described above, we suggest an initial qualitative study followed by broad survey research to identify widespread factors that both contribute to K-12 ESS teacher retention, and those that ultimately drive teachers to leave.

Grand Challenge 2:

What are effective models for incorporating ESS into undergraduate K-12 teacher preparation and in providing professional development for inservice teachers?

Rationale

Current and future science teachers are being asked to teach science in ways that may differ radically from the ways they learned science (Figure 3; National Research Council, 2015). In order to produce K-12 teachers that are well-prepared to teach the Earth and space sciences (ESS), we must first determine what makes teacher preparation programs successful. Teacher preparation programs across the nation vary widely across several characteristics, including (but not limited to) content, course requirement, recruitment methods, graduation and placement rates, and student demographics. This is due in part to state- and district-level differences in teaching standards, differences in the types of institutions that offer teacher preparation programs, and the grade levels for which the programs are designed (elementary, middle, secondary). For example, most teacher preparation programs are offered at four-year and Masters granting colleges and universities, but some are offered at two-year colleges. Other types of institutions, like museums and non-profits, offer masters' degrees (e.g., the American Museum of Natural History MAT in Earth and space science) as well as professional development workshops. A rigorous evaluation of teacher preparation and professional development must consider the diversity of contexts in which teacher learning takes place. It must also consider what is known about the key features that characterize effective professional development (National Research Council, 2015). Inservice teacher learning is not limited to professional development, as professional learning communities (PLCs) and instructional coaching can also contribute to teacher learning.

Recommended Research Strategies

Here we recommend short and long-term strategies that could yield insight into Grand Challenge 2 and ultimately drive forward both knowledge and practice. While short and long term strategies can both be approached immediately and simultaneously, short term strategies (#1-4) tend to focus more on synthesis of current literature, surveys of our current state of knowledge, or application of excising research to the field of teacher education. In contrast, long term strategies (#5-7) require more significant time and resource investment (such as support by external funding), focusing on more large-scale empirical students that can build the knowledge base.

1. There is a need to identify and evaluate (i.e., measure the efficacy of) existing models of teacher preparation and professional development, particularly those that specifically address the needs of elementary, middle, and/or high school pedagogical content knowledge (PCK) necessary for teaching ESS. For example, while reasoning with models is a feature of all science disciplines, it is especially important in the ESS where many processes and events occur at spatial and temporal scales that cannot be directly experienced. For example, research that focuses on ways to help teachers use models effectively with their students could be beneficial for teachers of earth and space science at all grade levels (Miller & Kastens, 2018). Information about current models of

teacher preparation and professional development that are relevant for ESS teaching could be obtained through a national survey, systematic literature review, or other mechanisms. Evaluation of existing programs should include methods for identifying their strengths and weaknesses

2. While most teacher preparation programs exist at 4YC and Masters-granting universities, some are hosted at other types of institutions, including 2YC, museums, non-profits, etc. These alternative pathways into teaching should also be identified and evaluated.

3. After existing models are identified and evaluated, additional research could be conducted to define the specific PCK and CK needed by teachers of ESS at elementary, middle, and high school, including special needs and/or underrepresented groups. This could be achieved through a literature review of research on ESS PCK and CK and would benefit from research on PCK in other science disciplines.

4. While ESS teacher preparation has unique characteristics, challenges, and opportunities, research on teacher preparation would benefit from collaboration with other science education organizations (e.g., the Association for Science Teacher Education [ASTE], the National Association for Research in Science Teaching [NARST], the National Science Teachers Association [NSTA], the National Earth Science Teachers Association [NESTA], the National Association of Geoscience Teachers [NAGT], etc.). Such a collaboration could also help teacher educators capitalize on the interdisciplinary aspects of ESS.

5. Standards and other specific requirements for initial and continued teacher licensure vary widely from state to state. Successful teacher preparation programs can remain informed of local needs and ensure that teachers are fully prepared to enter the classroom by building robust partnerships with local districts. Many teacher preparation programs actively cultivate partnerships with local school districts and typically focus on the nature and extent of clinical experiences teacher candidates have. Partnerships that simultaneously support pre-service and in-service teachers could have broad impact on the quality of ESS instruction. It is estimated that most teachers teach within 30 miles of where they grew up or went to college (Barth et al., 2016), so programs can be revised or designed with the knowledge that students enrolled in the program are very likely to teach in that region. Programs should be tailored to the unique needs and standards of ESS teaching in local districts.

6. How is "success" defined for ESS teacher preparation and professional development programs? Several metrics (e.g., recruitment of pre-service teachers into teacher preparation programs, retention, graduation rates, post-graduation employment, student learning and performance indicators, etc.) are used for measuring the success of a teacher preparation program, and so measuring "success" is a complex endeavor. Measuring the success of professional development programs for in-service teachers is equally complex. Furthermore, there are significant regional differences in teacher preparation requirements (e.g., state standards, district requirements, student populations, etc.), so direct comparison of programs is not always possible. We need to develop a methodology or tool for evaluating ESS teacher preparation programs and models, so that we can determine and implement the most effective models.

7. The success of ESS teacher preparation programs must include the long-term success of graduates after they leave the program and enter K-12 classrooms. Our evaluation of ESS teacher

preparation programs would benefit from the same type of longitudinal phenomenological research recommended above for GC#1. Successful teacher preparation programs should produce a K-12 ESS teacher workforce that teaches well, reflects the demographics of the student population, experiences low rates of attrition, among other factors. This can be evaluated best through longitudinal studies of ESS teachers as they move from teacher preparation programs into the workforce.

Grand Challenge 3

How do we best prepare future and practicing K-12 teachers to engage in ESS to promote three-dimensional learning that involves the integration of disciplinary core ideas, science and engineering practices and crosscutting concepts?

Rationale

The *Next Generation Science Standards* (NGSS Lead States, 2013) and *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2012), upon which the NGSS are based, reflect a new vision for K-12 teaching in science and engineering. Science is an interconnected enterprise encompassing three dimensions (Figure 4): science and engineering practices, crosscutting concepts, and disciplinary core ideas (NRC, 2012). Focus on an integration of the three dimensions into performance statements, or "three-dimensional learning," is based on decades of research on student learning and knowledge transfer. While not all states have formally adopted NGSS, many states have adopted standards that closely mirror NGSS. The practices, crosscutting concepts, and disciplinary core ideas of the NGSS, and the *Framework* on which it is based, have received widespread acceptance in the science education community and serve as a defacto consideration when developing any program that serves a national, if not local, audience. The geosciences education community has a great deal to gain from engagement with NGSS, or at least the concept of 3-dimensional learning, regardless its is role in state and local curricula, including but not limited to collaborations with other discipline-based science education research in the physical and biological sciences and a common language with which to discuss curricular elements across the country.

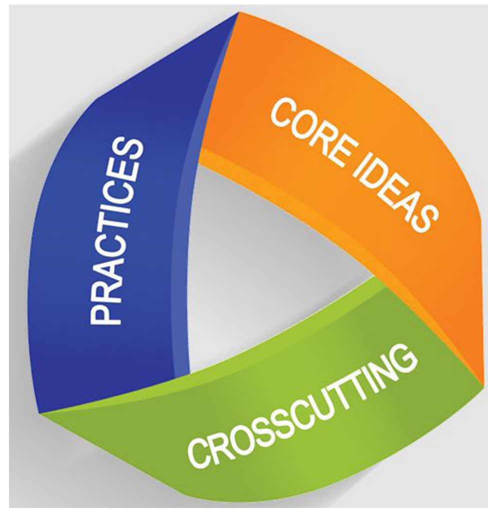

Figure 4. The NGSS recognizes that science is an interconnected enterprise encompassing three dimensions (3D): science and engineering practices, crosscutting concepts, and disciplinary core ideas (NRC, 2012). Resarch is needed on how to best prepare future K-12 teachers to engage with ESS 3D learning. Figure from NGSS at https://www.nextgenscience.org/.

To effectively teach ESS, K-12 teachers need to understand the geoscience concepts they teach. Teachers need to be able to engage in the types of instructional practices that will help students progress in their learning of ESS core ideas over time (Duschl, Maeng, & Sezen, 2011). However, K-12 science instruction as envisioned by the *Framework* is about more than teaching science content. There are important crosscutting concepts that cut across science disciplines (e.g., patterns; scale, proportion, and quantity; stability and change, etc.). Teachers must understand how these crosscutting concepts apply in the ESS and be able to embed them in instruction. The *Framework* emphasizes that science learning occurs as students engage in the practices of science and engineering (e.g., engaging in argument from evidence, developing and using models, etc.). Teachers must be able to engage in those practices themselves and be able to design instruction that will enable their students to develop facility with those practices. We know little at present about what effective three-dimensional teaching and learning looks like in ESS education or what pedagogical content knowledge (PCK) is needed to teach effectively in the unique space of ESS across K-12 (e.g., is there PCK for teaching in the field? for using big data? for visualizations?). There has been some research on students' use of model-based reasoning (e.g. Gobert, 2000; Rivet & Kastens, 2012) and argumentation (e.g. Kelly and Takao, 2002; Lee et al., 2014) in the earth and space sciences, but literature that explores how students develop facility with other science and engineering practices in K-12 classrooms is lacking. Also, while research exists on systems thinking (e.g. Raia, 2005) and thinking within and across scales (e.g. Libarkin et al., 2007), data on how students, teachers, or teacher candidates acquire crosscutting concepts is also lacking. It will be important to learn how struggles in teacher learning of ESS content, recognition of crosscutting concepts within science, and understanding of the nature of science impact instructional choices.

Recommended Research Strategies

Here we recommend short and long-term strategies that could yield insight into Grand Challenge 3 and ultimately drive forward both knowledge and practice. While short and long term strategies can both be approached immediately and simultaneously, short term strategies (#1-2) tend to focus more on synthesis of current literature, surveys of our current state of knowledge, or application of excising research to the field of teacher education. In contrast, the long term strategy (#3) requires more significant time and resource investment (such as support by external funding), focusing on more large-scale empirical students that can build the knowledge base.

1. There is a need to identify teacher education instructional models that promote three-dimensional thinking in teachers, particularly as they relate to an understanding of the nature of the ESS. This is especially important as few K-12 teachers have strong backgrounds in geoscience (Wilson, 2016). A first step is a literature review to determine what teacher education models currently in use support three-dimensional learning, either specifically in the ESS or in science education more broadly. There is some literature exploring practicing teachers' use of scientific argumentation (McNeill & Knight, 2013; Sampson & Blanchard, 2012) and model-based reasoning (Miller & Kastens, 2018), but we are not aware of studies that have investigated the development of teacher expertise with other science and engineering practices. We do not know how teachers acquire crosscutting concepts nor how to help them infuse these important themes into instruction. Once current teacher education models that promote three-dimensional thinking have been identified, we call for qualitative research that investigates specific teacher education models in the ESS to determine their effectiveness in the promoting the nature of the ESS.

2. As NGSS-aligned assessments are developed, geoscience education researchers will need to conduct a literature review of available assessments for measuring the "three-dimensionality" of classroom instruction that could be applied to ESS-specific instructional models. While many of these assessments are still in the early phases of development and evaluation (National Academies, 2018), continued research that examines the effectiveness of those models and their applicability for Earth & Space Science courses is called for.

3. K-12 student achievement in science is linked to the content and pedagogical content knowledge of their teachers (Jin et al, 2015). A review of literature on the effectiveness of conceptual change instructional approaches in ESS found far more research on astronomical phenomena than on geological ones (Mills et al, 2016). What is lacking is data that connects conceptual

change instructional practices to three-dimensional learning. Research that measures the connection between teacher education instructional models that promote three-dimensional learning in the ESS and the instructional practices K-12 teachers engage in in their classrooms will be important for both classroom teachers and ESS teacher educators.

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Figures

Figure 1:
Provenance: Heather Petcovic, Western Michigan University

Figure 2:
Provenance: Wilson, C. (2016). Status of the Geoscience Workforce 2016. American Geosciences Institute. Available from https://www.americangeosciences.org/workforce/reports/status-report

Figure 3:
Provenance: https://www.nextgenscience.org/
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Research on Teaching about Earth in the Context of Societal Problems

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Introduction

The use of societal problems as an effective context for teaching about the Earth was suggested in projects (e.g., InTeGrate) and conversations leading up to the 2017 workshops on the future of Geoscience Educational Research. Around the same time, the Summit on the Future of Undergraduate Geoscience Education (Mosher et al., 2014) indicated that among the content and competencies of graduating geoscientists, students "must understand the societal relevance of geoscience topics as well as their ethical dimensions." (Summit Summary Report, p. 3) Similarly, at a societal level, as our population likely exceeds 9 billion by 2050, there will be increasing pressures on Earth systems (e.g., water, energy, soils, biochemical cycles) so efforts to understand how to live sustainably on our planet will require interdisciplinary, applied skills and experiences for the next generation of geoscientists.

AGI: Geoscience for America’s Critical Needs:

1. Ensuring sufficient supplies of clean water
2. Developing energy to power the nation
3. Building resiliency to natural hazards
4. Managing healthy soils
5. Providing raw materials for modern society
6. Expanding opportunities and mitigating threats in the ocean and at coasts
7. Confronting climate variability
8. Managing waste to maintain a healthy environment
9. Meeting the future demand for geoscientists

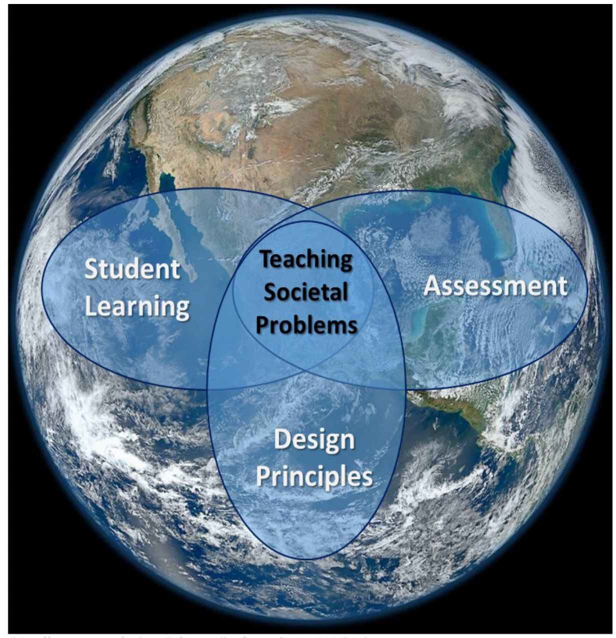
Modified from AGI, 2016

Figure 1. Geoscientists have scientific expertise and valuable perspectives needed to address a range of economic, environmental, health, and safety challenges as identified by AGI (2016) in their report Geoscience for America’s Critical Needs. Research is needed on how societal problems can serve as effective context for teaching and learning in the geosciences.

Knowledge and consideration of societal issues are critical for students majoring in the geosciences, as well as for non-science students (Figure 1) and the general public who vote and make decisions that should be based on sound science. Thus, the importance of integrating geoscience with other disciplines such as urban planning, social justice, politics, communications and more has become a critical call to action for geoscience researchers and educators merits examination.

Improving undergraduate STEM education with the use of relevant issues such as societal problems is a useful mechanism to help students find science to be personally relevant and to develop their interest based on societal contexts. Increased use of student-centered pedagogies in STEM teaching is consistent with research examining student learning and persistence.

The Grand Challenges in this chapter examine the use of societal issues to teach about the Earth, which include consideration of the impact on student learning, the design principles of curricula that best integrate geoscience content within the context of societal issues, and the assessment needed to measure the efficacy of these methods (Figure 2).



https://www.nasa.gov/multimedia/imagegallery/image_feature_2159.html

Figure 2. Components considered in the Teaching about Earth in the Context of Societal Problems Grand Challenges included here. Graphic modified from NASA, 2012.

Grand Challenges

Grand Challenge 1: How does teaching with societal problems affect student learning about the Earth?

Societal issues are of high interest to students, which provides an opportunity to increase student exposure to, and interest in, the geosciences. The efficacy of teaching with societal issues merits further research to characterize curriculum that exists and the extent to which it increases student learning and motivation as they develop their geoscience literacy.

Grand Challenge 2: What are the design principles for curriculum needed to teach with societal problems?

As curriculum is designed to incorporate the use of societal problems, there must be a clear set of design principles that clarify best practices that promote student learning. There are a variety of research-based teaching strategies available but characteristics of effective curriculum must also be considered in the context of teaching with societal issues. An important strategy is to assess the use of research-based design principles that operate at different scales of issues (e.g. local vs. global scale) and at different scales of course activities (e.g. within a class period or across a course or program).

Grand Challenge 3: How do we assess the influence of teaching with societal problems in terms of student motivation and learning about the Earth?

Teaching about the Earth through the use of societal issues or problems can theoretically increase student motivation, engagement, and learning. New research should measure changes in both cognitive (e.g. problem solving and learning) and affective domains (e.g. motivation, engagement, self-efficacy) at short term (course) scales as well as in multi-institutional longitudinal studies.

Grand Challenge 1:

How does teaching with societal problems affect student learning about the Earth?

Rationale

Geoscience plays a critical role in building sustainable societies and managing environmental issues, both in the types of research that address societal needs as well as creating scientifically literate citizens (Lewis & Baker 2010). Geoscientists have long been involved with research that intersects with societal issues, including resource issues (food, water quantity, mineral/aggregate resources, energy), environmental stability (environmental degradation, environmental justice) and health and safety issues (natural hazards, climate change, water quality; InTeGrate, 2017). However, there is a need to increase the number of undergraduate students choosing geoscience subjects to prepare them with skills and content required in the workplace (Wilson, 2016), and this requires us to examine novel approaches to teach geoscience.

Increasing undergraduate student engagement and motivation are key. Societal issues are of high interest to students (e.g. Pelch & McConnell, 2017). Science education research has shown that the disconnect between school science and students' day-to-day lived experiences contributes to lack of interest in science (Basu & Barton 2007, DeFelice et al., 2014; Lemke 2001, Roth & Tobin, 2007). As a result, this disconnect has created a false impression among students that science has little relevancy. Furthermore, students need to recognize the usefulness of the knowledge or skill in their lives and future goals for learning experiences to lead to usable knowledge (Edelson et al., 2006). Underrepresented and urban students (often with great diversity) are often at greater risk of losing interest in science as there is the added cultural and linguistic disconnects between school, school science, and their life-worlds (Basu & Barton, 2007; Rahm, 2007; InTeGrate, 2017). The world is becoming increasingly urbanized and it expected that the proportion of the world's population to live in urban areas will rise from 55% to 68% by 2050 (United Nations, 2018).

Teaching geoscience in societal contexts opens avenues to increase student exposure to and interest in geosciences (InTeGrate, 2017). Students tackle open-ended, real world, and often complex problems that are relevant, especially if using placed-based pedagogy and high impact teaching approaches (e.g., learning communities; service learning or other courses with a community-based project component; study abroad experiences; internships capstone courses or culminating senior experiences, and research with a faculty member) (NSSE, 2016). Students today, especially millennials, want to make a difference in their communities and the world at large. By providing societal contexts, they become interested, empowered, and motivated to become agents of change (Kang et al., 2016).

Whether or not students choose geoscience as a career, exposure to societal issues increases the role of science in building sustainability and can directly or indirectly affect attitudes and behaviors toward sustainable consumption (Kang et al., 2016) According to the United States National Center for Education Statistics, "scientific literacy is the knowledge and understanding of scientific concepts and processes required for personal decision making, participation in civic and cultural affairs, and economic productivity" (NASEM, 2016, p. 139). Lack of geoscience literacy makes society less informed and more vulnerable to resource use, disasters, and impacts of climate change.

The Summary Report for Summit on Future of Undergraduate Geoscience Education contributed toward building a collective community vision for the undergraduate geoscience instruction focusing on three areas: (1) curriculum, content, competencies, and skills, (2) pedagogy and use of technology, and (3) broadening participation and retention of underrepresented groups and preparation of K-12 science teachers (Mosher et al., 2014, p.1). This provides a framework in which to research how the inclusion of societal issues contributes to student learning about the Earth.

To examine the efficacy of using societal problems to teach about the Earth, we need to determine the theoretical frameworks that connect the use of societal problems with student motivation to learn about the Earth and student motivation to act (e.g. solve problems/change behaviors), and also determine if learning progressions are important considerations and what the ideal progressions are (e.g. use of issues/activities/solutions appropriate to introductory to advanced levels and STEM/non-STEM majors).

Recommended Research Strategies

Specific research strategies to determine how the use of societal problems impacts student learning and contributes to content goals and general geoscience literacy should include:

1. Literature reviews to identify relevant theoretical frameworks that will help explain the mechanisms through which teaching about the Earth through societal problems leads to student learning.

2. Investigations of questions on how best to integrate issues of societal relevance in a geoscience curriculum to achieve geoscience literacy among non-majors, as well as geoscience workforce knowledge and skills (e.g, from the Summit Workforce document; Mosher et al., 2014) at the upper level. For example are there important learning progressions that indicate how much and what type of attention to societal issues results in learning and changing attitudes, and if there is specific timing in which societal problems should be included (e.g. use of issues appropriate to level and STEM/non-STEM majors)?

3. Both shorter-term and longitudinal studies to examine if/how students use new-found knowledge of societal problems in their own lives and whether such issues contribute to student motivation to act (e.g. solve problems/change behaviors).

4. Investigations to determine if the use of societal problems contributes to expanding diversity in the geosciences, which may be addressed through short term or longitudinal research on the current and evolving diversity in the geosciences, along with demographic analyses and interviews with students in various stages of courses in the geosciences.

Grand Challenge 2:
What are the design principles for curriculum needed to teach with societal problems?

Rationale

An important next step in supporting teaching about the Earth with societal problems is to identify the design principles that are needed to develop additional relevant curricula. Teaching with societal problems as a means to enhance student interest, motivations, dispositions, and learning outcomes, has emerged as a common design principle (i.e. a proposed relationship between an educational design and student learning; Sandoval, 2004) in recent reform efforts. Notably, the materials design rubric for the InTeGrate project tasks materials developers to create curricula that “connect geoscience to grand challenges facing society.” This design strategy has resulted in a large body of modules and courses (~40) that incorporate the grand challenges in a variety of ways.

Efforts such as the Serving Our Communities blog have collected stories about how faculty are engaging with this work in creative ways that involve communities outside the campus. While the theoretical underpinnings of this conjecture are sound (see Introduction and Grand Challenge 1), there is a wide variety of possible teaching strategies that can be used, many of which are not yet well studied (e.g. service learning; NASEM, 2017). Documenting how this design conjecture is embodied in learning environments can lead not only to information about the efficacy of these approaches, but also lead to new insights into the underlying mechanisms for learning that are at play (Sandoval, 2004).

Of particular importance for supporting development and implementation of strategies for teaching with societal problems are considerations of scale. Societal problems can be used to address issues at a variety of scales (local, regional, global), leading to questions about implications for student outcomes (e.g., how does the scale of the issue impact student motivation?). Additionally, instructors can use societal problems to engage learners at different scales (e.g., activity scale within class periods, modules, courses, cross-cutting themes across a degree program). Identification of research-based design principles that operate at different scales on both dimensions should be a principal focus of this work. Future directions for this work include determining how best to support faculty in the use of the design principles to incorporate teaching with societal problems into their courses. This could include structures for developing action plans and repositories of examples for issues on multiple scales.

Recent efforts in the GER community show promise for moving this work forward in meaningful ways, lending credence to the claim that this is a timely pursuit and providing guidance for recommended strategies. Throughout this work, we encourage researchers to consider linkages between geoscience classrooms and other entities that can support this work, such as community groups and artists.

Recommended Research Strategies

1. Inventory existing resources and promising practices that integrate issues of societal relevance in geoscience instruction. The rich body of practitioner-developed resources, coupled with the

research literature, provides an ideal starting point for this work. We recommend conducting systematic analyses of approaches and strategies identified through conducting literature reviews, developing inventories of current practices found in existing databases (e.g. InTeGrate, On the Cutting Edge Exemplary Teaching Activities collection, SENCER model courses), and collecting narratives from faculty. Kastens and Krumhansl (2017) describe a method for identifying design patterns in practitioner-developed resources that could be implemented here.

2. Determine what resources lead to student learning and engagement. Large scale investigations of the efficacy of existing resources can serve as a starting point for identifying targets for further research. For example, students who participated in InTeGrate modules demonstrated higher scores on systems thinking (Gilbert et al., 2017) and interdisciplinary essays (Awad et al., 2017) when compared to control groups. Modules with particularly high gains could be identified through further analysis of these datasets as a starting point. Determine what characteristics of approaches are effective at what scale and in what contexts. We recommend conducting design research studies of existing resources and promising practices, with a particular emphasis on identifying practices that lead to target student learning outcomes. This approach has the “dual goals of refining both theory and practice” (Collins et al., 2004) and embraces the real-world context in which teaching and learning occurs (Sandoval, 2004). Holder et al. (2017) proposed the Problem-Solving in Practice model, which identifies elements of instructional design that can be used to guide student engagement in real-world problem solving; this model could serve as the basis for design research studies.

Grand Challenge 3:

How do we assess the influence of teaching with societal problems in terms of student motivation and learning about the Earth?

Rationale

Teaching about the Earth through the use of societal issues or problems can theoretically increase student motivation, engagement, and learning. The NRC (2012) advocates for the use of societal problems in the K-12 classroom in multiple disciplines, but this can be especially useful in the geosciences at K-12 and at the undergraduate levels because our field focuses around the surface of the Earth where humans live:

> "studying and engaging in the practices of science and engineering during their K–12 schooling should help students see how science and engineering are instrumental in addressing major challenges that confront society today, such as . . . solving the problems of global environmental change'' (NRC, 2012, p. 9).

Societal issues may serve as the vehicle to increase cognitive and affective skills like problem solving, as a student may be more motivated or engaged during problem solving that has personal significance (Gilbert, 2006; Sawyer, 2006; McConnell & Van Der Hoeven Kraft, 2011). Furthermore, in today's society, students must be able to distinguish between "fake news" and scientific facts, especially when there is an issue that impacts their local community. By teaching about these types of situations early and often during students' academic careers, we can prepare them to be informed citizens that can vote accordingly:

> "Scientists must make critical judgments about their own work and that of their peers, and the scientist and the citizen alike must make evaluative judgments about the validity of science-related media reports and their implications for people's own lives and society. (NRC, 2012, p. 71)"

In order to know if teaching through the use of societal problems is valid, we as a community should produce research to substantiate the claims that we make about increases in engagement, motivation, and problem solving and learning. We should also investigate how student-centered course activities like flipped courses or service-learning could help to increase engagement and motivation:

> "... the geosciences... offer fertile ground for service-learning programs that address intersections between science and society" (National Academies, 2017, p. 6).

All of the calls for integration of societal-relevant approaches to teaching and learning, however, require that quality assessment techniques are used to measure changes in both the cognitive (e.g., problem solving and learning) and affective domains (e.g., motivation, engagement, self-efficacy). In the future, we will need to conduct multi-institutional longitudinal studies that robustly measure the impact of teaching with societal issues.

Research on the efficacy of teaching about the Earth through the use of societal problems should include student data, but should also explicitly link defined student learning outcomes to validated assessment techniques. To do this, we must first fully explain student learning outcomes and the numerous variables related to these, such as defining "geoscientific literacy" as this phrase may have different definitions. In general, GER will need to define the best ways to measure the effect of using societal problems on student learning and on resulting motivations to act (e.g. solve problems/ change behaviors). To do so, we will need to determine what instruments currently exist or need to be developed to assess the use of societal problems that allows for future meta-analysis. We suggest that although there are generalized problem solving, argumentation, engagement, and motivation surveys, it may be useful to tailor these specifically for the geosciences.

Recommended Research Strategies

1. In the cognitive domain, we should assess general problem solving skills as well as how students approach a problem, make decisions, argumentation, and solution generation. To do this, we can use validated assessment techniques like the Social Problem-Solving Inventory-Revised (SPSI-R; D'Zurilla et al., 2004). This inventory examines the ways in which students orient themselves towards the problem, rational problem solving, impulsivity, and avoidance, and self-efficacy. Instructors can also use open-ended responses to further examine problem solving-skills from a quantitative view. In some instances, new instruments may need to be developed to measure problem solving skills when societal problems are integrated into curriculum.

2. Argumentation may also be an effective way to engage students in problem solving and learning (Driver et al., 2000; Osborne et al., 2004), but needs further research. While assessment of argumentation is difficult, there are methods such as Toulmin's (1958) argumentation model, and revisions of this model, based upon warrants and claims; however, this data is much more qualitative in nature, which merits consideration of review of existing quantitative instruments (or the development of new instruments) that measure argumentation learning strategies.

3. General learning in the geosciences as a result of teaching using societal issues could be assessed using the Geoscience Concept Inventory (GCI; Libarkin and Anderson, 2005), a validated bank of questions that assess learning, or through the use of the Learning and Study Skills Inventory (LASSI; Cano, 2006). General learning can also be assessed using open ended response questions; however, these questions often take much longer to assess and rubrics are typically subjective depending upon the nature of the question.

4. Student affective domain is of equal importance when considering societal issues because of the claim that teaching with these issues may lead to increases in engagement and motivation. To measure engagement, instructors and researchers can use a variety of instruments, but one of the most popular of these is the National Survey of Student Engagement (NSSE; Kuh, 2003). However, this instrument is expensive, and fairly generalized and so it may be useful to develop additional engagement surveys that relates more directly to the geosciences. Additionally, we should investigate changes in engagement over the course of one semester, but also examine changes in students' affective domain in geoscience departments that teach primarily in the context of societal issues.

5. Examine the relationship between students' motivation and attitude and teaching with societal problem. In terms of motivation and attitude, there are several validated options including: Attitudes toward Science Survey (ATSS; Bickmore et al., 2009), Motivated Strategies for Learning Questionnaire (MSLQ; Pintrich et al., 1991), Intrinsic Motivation Inventory (IMI; Ryan and Deci, 2000), and the Academic Motivation Scale (AMS; Vallerand et al., 1992). In addition to these instruments, there are quite a few instruments listed on the NAGT GER Toolbox (GER Toolbox, 2017). Student engagement, motivation, and attitudes can also be linked to the teaching style of the instructor (instructor centered or student centered), and so using a observation protocol like the Reformed Teaching Observation Protocol (RTOP) could be useful to gauge the impact of the instructor (Piburn and Daiyo, 2000)

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Figures

Figure 1:
Provenance: Modified from AGI (2016), *Geoscience for America's Critical Needs*.

Figure 2:
Provenance: Modified from NASA/NOAA/GSFC/Suomi NPP/VIIRS/Norman Kuring *Teaching about Earth in the Context of Societal Problems.*

Research on Access and Success of Under-Represented Groups in the Geosciences

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Introduction

The geosciences as an allied group of fields touch virtually all aspects of the human enterprise: locating and providing water, energy and mineral resources; assuring a safe and resilient environment for civilization; and providing an understanding of how the Earth system functions today, in the past and into the future. Given how the geosciences touch the lives of all people, it should also be a field that is representative of all people, but this is not yet the case (Figure 1). Especially with the global importance of the geosciences growing and the geoscience workforce projected to encounter shortfalls of qualified practitioners in the coming decades, it is imperative that the geoscience education research community frame and investigate central questions that can help increase the diversity of the geosciences at all levels. We must find ways to attract all kinds of students, especially those from under-represented groups to our sciences and build programs, experiences and careers in which they thrive. We deliberately embrace the notion of "attract and thrive" after the work of Roberto Ibarra and colleagues (e.g., Ibarra, 2001, 1999) that rejects the notions of "recruit and retain"—involuntary, or at least passive, actions that happen to under-represented people in the field—and embraces more active and supportive concepts of attraction and thriving. The theory of multicontextuality advanced in their work acknowledges the effect of complex, interwoven identities of under-represented students at they learn in and interact with STEM fields, and the explicit importance of institutional attention and action to identify and lower barriers to success while providing necessary support. These ideas also provide a way forward in addressing the challenges of diversifying STEM fields shared across

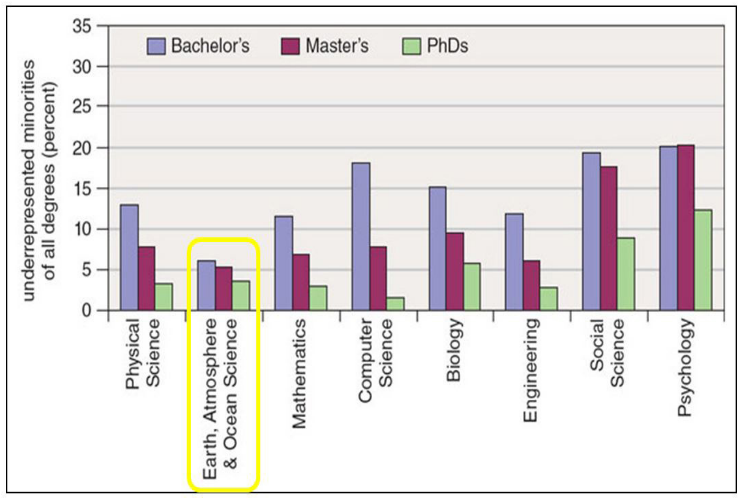

Figure 1. Ethnic and racial diversity are extremely low in geoscience degrees at all levels. A recent report from Bernard and Cooperdock (2018) indicate that, while significant advances in gender diversity have taken place, no progress on ethnic and racial diversity in the geosciences has been made in 40 years at the national level at the doctoral level despite measurable gains at the undergraduate level as reported in Wilson (2016). Modified from a figure in Johnson and Harrison Okoro (2016), based on data in National Academy of Sciences (2011).

all science and engineering fields, as articulated by the National Academies report on "Expanding Underrepresented Minority Participation" (2011). The research questions and challenges posed in that report undergird much of the analysis and synthesis we pose in our Grand Challenges, in addition to work specifically in the geosciences.

The research challenge boils down to two essential and interdependent perspectives, specifically: (1) the point of view of the individual students, faculty and professionals as they manage their own internal balance of identities as they traverse

curricula, programs and career pathways, and (2) a view that captures system-wide interactions around the individuals at all stages, including family, culture, department, university and society. The Grand Challenges focus on these two approaches.

Grand Challenges

Grand Challenge 1: Supporting the Individual in the Geosciences: How can we recognize and support the individual identities and personal pathways of students as they are attracted to and thrive in the geosciences?
Many of these issues are now well-informed by research from outside the geosciences, and we have the programmatic experience and our community have access to more nuanced theory to make significant steps forward in understanding program design and student pathways.

Grand Challenge 2: Geoscience Community Efforts to Broaden Participation: How can the geoscience community capitalize on evidence from different scale efforts to broaden participation?
Solutions and programs must scale appropriately to the situation and communities at hand. Success and solutions in diversity has no singular solution - healthy programs and communities who are diverse and welcoming exhibit sets of characteristics which are repeated

Grand Challenge 1:

Supporting the Individual in the Geosciences: How can we recognize and support the individual identities and personal pathways of students as they are attracted to and thrive in the geosciences?

Rationale

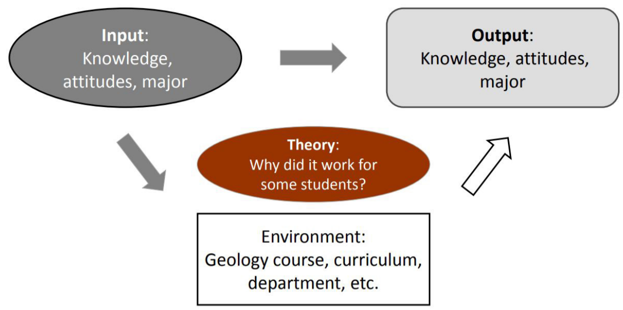

Figure 2: A highly generalized, schematic model showing points of investigation to address this Grand Challenge using an Input-Environment-Output model for student experience. Model modified from Callahan et al., 2017.

Many of these issues are now well-informed by research on the structure and nature of student science identity from outside the geosciences (cf. Jones & Abes, 2013), and we have the programmatic experience and our community have access to more nuanced theory to make significant steps forward in understanding program design and student pathways. For a review of background theory and application to the geosciences, see Callahan et al. (2017). A fundamental aspect of developing expertise in any discipline is the process of learning the language, normal practices, and habits of thinking specific to that discipline (Posner, 1988). While community college and undergraduate geoscience programs are arguably not producing experts—based on common definitions of expertise (e.g. Ericsson, Krampe, & Tesch-Römer, 1993)—such programs do provide a substantial foundation for later training, education, and work experience. The geoscience community has articulated a suite of skills and understandings that students should acquire during their undergraduate education (Mosher, 2015); examples include: strong written and verbal communication skills; integration of observations in the natural world with experimental or modeling data; and solving problems requiring spatial, temporal, and uncertainty interpretations. The level to which students achieve these skills and understandings is one measure of a student's success in developing expertise. This metric for success, however, assumes equivalence of experiences in education; it makes no differentiation for the reality that students not only arrive in the geosciences along different pathways (Sherman-Morris & McNeal, 2016), but also carry with them other identities beyond the shared identity of a geoscientist. Thus, we propose the following question as an area in need of further research in order to improve access and success for underrepresented students in the geosciences: How can we recognize and support individual identities and personal pathways of students as they are attracted to and thrive in the geosciences? This broad question has two main facets in need of explication.

Recommended Research Strategies

1. If we wish to recognize and support under-represented students' identities in the geosciences, we need to have a richer understanding of their lived experiences as members of the community. Callahan et al. (2015, 2017) argue for the importance of and suggest multiple theoretical frameworks from the social sciences that may be useful in this effort; for instance, Baber et al. (2010) used the theory of self-efficacy to investigate the success of summer research programs for recruiting minority students to the geosciences. Theoretically-driven research can build our understanding of whether

and how students from underrepresented groups develop their geoscience identity alongside existing identities. In what ways are those identities compatible and in what ways are they in conflict?

2. If our intent is to increase diversity in the discipline, we may also need to ask uncomfortable questions about how the "norms" of the community impose barriers to students from under-represented groups at all points as they flow through programs and curricula. Figure 2 presents a highly generalized, schematic model showing points of investigation using an Input-Environment-Output model for student experience. For example, photographs on websites for geoscience departments commonly feature outdoor environments, more men than women, and almost everyone is white (Sexton et al., 2014); are websites unintentionally sending a message of who fits the accepted role of an expert geoscientist and who does not? How is privilege implicit in the structure of programs and curricula? How can we integrate culturally-responsive pedagogy into geoscience curricula (e.g. Gay, 2010)? Ultimately, we recognize that how we define success may not change so readily; we posit, though, that there are ways to broaden our approach to how we move students toward geoscience expertise.

Grand Challenge 2:

Geoscience Community Efforts to Broaden Participation: How can the geoscience community capitalize on evidence from different scale efforts to broaden participation?

Rationale

Solutions and programs must scale appropriately to the situation and communities at hand. Success and solutions in diversity has no singular solution - healthy programs and communities who are diverse and welcoming exhibit sets of characteristics which are repeated. Studies have shown that while overall success in recruiting and retaining underrepresented minorities has only improved modestly at the undergraduate and masters level (Wilson, 2016) and has not improved at the doctoral level nationally (Bernard & Cooperdock, 2018), research suggests that certain efforts have been more effective that others. Implementations can be divided into large-scale implementations that are national in scope and focus on change within an entire science community and those that are smaller scale and local in scope aiming for change on a particular campus or department. The Macrosystems Framework (Wolfe & Riggs, 2017) below (Figure 3) incorporates the important elements and interactions between the broader "System" and the "Individual."

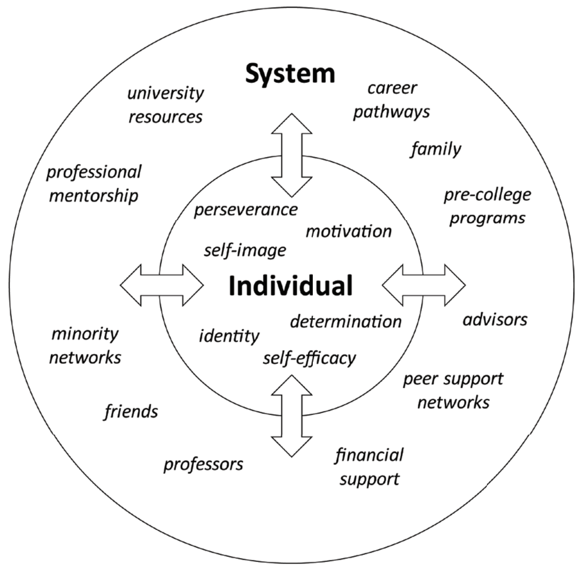

Figure 3: Macrosystems Model. This model is a graphical representation situating the individual student (or faculty member) within the many systems which surround them in an academic setting. The arrows show the bi-directional continuous interactions that shape the individual and the system and influence the direction and persistence of both. The italicized features illustrate a few of the specific examples of elements of the individual and system. These will all be engaged in interactions between an individual and the system around them, and should be taken into account when working to understand and optimize supportive programs for advancing students from diverse backgrounds. From Wolfe and Riggs, 2017.

Ambiguity about where to aim resources derives in part from failure to differentiate what kind of approaches and resources should be afforded to each and using the same measures of success for both broad community-wide (e.g. Peer et al., 2004) and more local, focused or campus-scale efforts (e.g. Blake, Liou, & Chukuigwe, 2013; Blake, Liou, & Lansiquot, 2015; Semken, 2005) . Research literature examining both approaches illuminate ways to focus efforts toward success and suggest that both can contribute to success in recruiting and retaining underrepresented minority students and it is up to the geoscience community to incorporate what has been learned into what we do. Both large scale and smaller local efforts must both be valued, funded and facilitated if the Grand Challenges of providing access and success for underrepresented students in the geosciences are to be met.

Recommended Research Strategies

1. Efforts to broaden participation that are likely best for large-scale implementations include those that critically examine the way the geosciences are viewed by underrepresented minority students. This is important when students first make decisions about what major to pursue and second as students internalize some sort of personal reconciliation between those elements of geoscience study which appear personally foreign or culturally off-putting and elements of a value proposition

that can be accepted. Making our disciplines more relevant and more welcoming to a broader group of students will require a broad national geoscience community effort. Refashioning what is relevant about of our disciplines to the cultures we are trying to reach and discarding those things that keep or drive students away will need to be a grand scale effort with everyone on board.

2. While implementation will come down to what goes on locally in departments, there is a need for the broad geoscience community to articulate the need for change and suggest goals and a timeline for them to be reached. There is a need for community consensus about how to illustrate career paths so that students (and their families) have some sense that a rational paths exist and that future progress is not haphazard. Templates for how to access and maintain financial support need to be refined and broadly disseminated. Guidelines for and examples of professional mentorship need to be shared. Professional networks for faculty, particularly those working with underrepresented students at community colleges and minority serving institutions, need to be strengthened where they exist and new ones initiated. There must be opportunities for faculty to work together to share student success and engage in student learning focused professional development experiences. Unfortunately, published analyses about what works and what does not in all of these activities is sparse at best, and focused research on geoscience education systems is required at all scales.

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Figures

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Research on Cognitive Domain in Geoscience Learning: Temporal and Spatial Reasoning

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Introduction

The geosciences are characterized by their particular application of and reliance on temporal and spatial reasoning. Geoscientists must be able to apply their knowledge across a variety of scales. In the words of Arthur Conan Doyle in his book A Study in Scarlet, "*From a drop of water, a logician could infer the possibility of an Atlantic or a Niagara without having seen or heard of one or the other. So all life is a great chain, the nature of which is known whenever we are shown a single link of it.*" Geoscientists should be able to look at, say, physical and chemical differences in ocean surface waters (Figure 1) or in sedimentary layers from a core of the seafloor and infer changes in patterns (spatial) over time (temporal). The ability to engage with this kind of task represents a great shift in thinking from where most students begin their studies, be that in K-12 or college. In order to understand how people's ability to spatial and temporal reasoning changes over time requires us to identify what skills are essential, how to properly assess those skills, and then to explore the impacts of different targeted interventions in geoscience contexts.

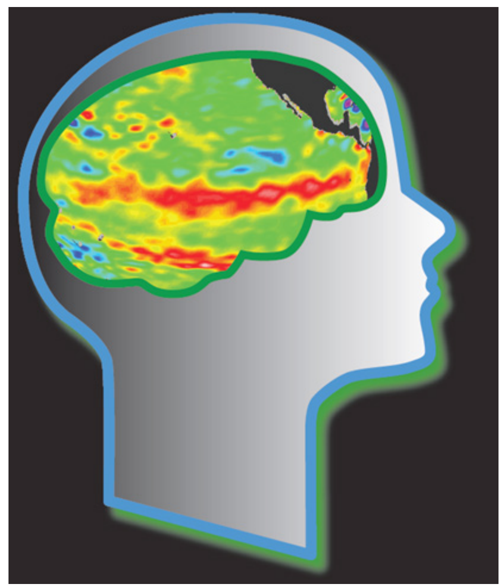

Figure 1. Developing a geoscience understanding of Earth processes requires thinking across different spatial and temporal scales, such as those involved with changing El Niño-La Niña conditions inferred from NASA sea surface height anomaly data in the equatorial Pacific Ocean as shown here. Figure originally created by Kirk and Pisolesi for the cover of Kastens and Manduca (2012), Earth and Mind II: A Synthesis of Research on Thinking and Learning in the geosciences. GSA, v. 486.

While more is known about how people reason spatially as compared with temporally, there are still significant gaps in our understanding of spatial reasoning in the geosciences. We believe that there are opportunities to build on lessons learned from previous investigations of spatial thinking (e.g. the Spatial Intelligence and Learning Center, or SILC), including how a community can investigate a specific line of reasoning. There is also a need to build on established research from other domains, from anthropology to cognitive science to physics.

We identified three Grand Challenges to better understand the need for and growth of spatial and temporal reasoning in geoscience education. These include identifying what reasonings or skills are essential to the geosciences (both broadly and within subdisciplines), and the intertwined challenge of how to assess those reasonings and use those results to improve on what students are learning from their geoscience experiences.

Grand Challenges

Grand Challenge 1: What skills and tasks are essential to the different specialties within the geosciences? What spatial and temporal reasoning skills map onto these specific tasks?
To ensure that our work is relevant to the broader geoscience community, we need to target our research to the primary specialties within the community (e.g., perhaps as defined by AGU's sections or GSA's divisions). Because these specialties can vary greatly in terms of their scale, scope, and methods, it is necessary to identify the primary defining skills and tasks in each area. Once the essential tasks and skills of these specialties are identified, the types of spatial and temporal reasoning in each need to be "mapped" so we can understand if and how these fields differ.

Grand Challenge 2: Do current measures of spatial and temporal reasoning accurately assess the skills required in the various geoscience specialties? If not, what other types of assessments need to be developed?
With an understanding of the essential tasks required in each of the primary specialties in the geosciences, we can then proceed to empirically test whether these tasks actually recruit the spatial and temporal reasoning skills that were "mapped" in GC 1. That is, if we think locating fossils requires penetrative thinking, disembedding, mental rotation, and transformation, does performance on these measures predict success in fossil locations and identification? Are there any domain-specific geoscience tasks or skills that do not seem to align with an existing spatial or temporal reasoning measure? If not, can we design a more appropriate measure?

Grand Challenge 3: How can geoscience education foster the spatial and temporal reasoning skills that are required in each specialty?
With an understanding of the essential types of spatial and temporal reasoning for each geoscience specialty, and an understanding of how to measure them, we can then proceed to develop and assess instructional methods that support these specific skills. Specific instructional manipulations can be conducted with the intention of assessing how these interventions support content learning, but also how they support the development of spatial and temporal reasoning. If two different specialties require the same variety of spatial or temporal reasoning, can the same style of instructional intervention be used in both context?

Grand Challenge 1:

What skills and tasks are essential to the different specialties within the geosciences? What spatial and temporal reasoning skills map onto these specific tasks?

Rationale

To ensure that our work is relevant to the broader geoscience community, we first need to focus the research on the primary specialties within the community, for example using AGU's sections or GSA's divisions. Because these specialties can vary greatly in terms of their scale, scope, and methods, it is necessary to identify the primary defining skills and tasks in each area.

Several efforts have been made to summarize the kinds of skills and tasks necessary to master in order to be a geoscientist. For example, the 2014 Summit on the Future of Undergraduate Geoscience Education brought together ~200 post-secondary educators and representatives from industry and professional geoscience societies. The Report from that meeting stresses that geoscientists "need to be able to think spatially and temporally... [and] think critically and readily solve problems, especially those requiring spatial and temporal (i.e. 3D and 4D) interpretations" (Mosher et al., 2014). In a survey following the Summit, "problem-solving with spatial and temporal data" was ranked as the second most critical geoscience (non-professional scientist) skill in undergraduate education (Survey Results), with more than 60% of 455 respondents identifying it as "very important." Further, attendees of the Geoscience Employers Workshop provided thoughts on the various concepts they thought geoscience graduates should be able to understand (Meeting Outcome). Many of these concepts rely on spatial and temporal thinking, including understanding how systems work and interact, geological time/Earth evolution, age dating, events and rates, and landscape alteration (i.e., geomorphology).

Researchers have also tried to make sense of the complex array of spatial and temporal skills required for geoscientists (Kastens & Ishikawa, 2006; Liben & Titus, 2012; Newcombe & Shipley, 2015; Tarampi et al., 2016; Zen, 2001; Krantz, Ormand, & Freeman, 2013; Cervato & Frodeman, 2012). Some of these tasks include things like "recognizing, describing, and classifying the shape of an object; describing the position and orientation of objects; making and using maps; envisioning processes in three dimensions; and using spatial-thinking strategies to think about nonspatial phenomena" (Kastens & Ishikawa, 2006). A 2009 report by Kastens and others suggested that geoscientists possess a distinctive set of approaches and perspectives when it comes to studying the Earth. Specifically, they identified four themes in how geoscientists think and learn which includes their ability to think about time, their understanding of the earth as a complex and complicated system, their experience with categorization, identification and transformation in fieldwork, and their use of spatial thinking for interpreting visualizations and seeing patterns in data. These four themes are meant to generalize across all specialties within the geosciences, but it is likely the case that some skills and tasks are more (or less) critical to certain specialties. For example, map reading (spatial) and time-sequenced data interpretation are important to many specialties such as ocean sciences and global environmental change, but may be less immediately important to other specialties (e.g. a geochemist doing bulk chemical analysis to assess re-opening an old quarry might not be as concerned with temporal data, but could still want to map where their samples came from and the extent of the potential quarry). Once the essential tasks and skills of these specialties are identified, the types of spatial and temporal reasoning in each needs to be “mapped” so the community can understand if and how these fields differ.

Recommended Research Strategies

1. Kastens & Manduca (2012) created concept maps of Spatial Thinking and Temporal Thinking in Geosciences (Figure 2). These should be revisited and used as a model for creating a map of the various kinds of spatial and temporal reasoning skills and the geoscience specialties that rely on these skills. This kind of representation would allow us to see where specialists may overlap in particular skills and where they may draw upon a unique set of skills.

2. While some specialties within Geoscience have been investigated in terms of the kinds of spatial and temporal reasoning they require (e.g., Tarampi et al., 2016), many have not. Thus, an important research strategy is to conduct process and task analyses in these less explored specialities to make inferences about how the geoscience skill aligns with spatial or temporal reasoning skills. For example, it could be said that the field of paleontology requires spatial thinking in the form of penetrative thinking, disembedding, mental rotation, and mental transformation. That is, locating fossils requires being able to imagine the layers of rock (penetrative thinking), being able to “see” relevant structures within the rock (disembedding), and the ability to mentally rotate fossils (mental rotation) in order to generate inferences about what the entire creature should look like (mental transformation).

3. Select specific, well-defined areas of geoscience and have people in those fields describe the spatial and temporal tasks they do as part of their job in focus groups. We recommend that focus groups might help elicit more ideas than one-on-one interviews or surveys. This cognitive task analysis with specific experts could be used to identify the most important, or essential, spatial and temporal reasoning tasks they do. This could also be completed as a modified Delphi study, or by studying geoscientists doing expert tasks, and coding for different reasonings being used.

Grand Challenge 2:

Do current measures of spatial and temporal reasoning accurately assess the skills required in the various Geoscience specialties? If not, what other types of assessments need to be developed?

Rationale

Before assessing a spatial or temporal reasoning skill, a researcher must first establish that the particular reasoning they are studying is critical to some aspect of success in the geosciences (see GC 1). With an understanding of the essential types of spatial and temporal reasoning required by the primary geoscience specialties and tasks, we can then proceed to empirically test whether these tasks actually recruit the spatial and temporal reasoning skills that were "mapped" in GC 1. That is, if we think locating fossils requires penetrative thinking, disembedding, mental rotation, and transformation, does performance on these measures predict success in predicting fossil locations? If through this investigation there are domain-specific geoscience tasks or skills found that do not seem to align with an existing spatial or temporal reasoning measure, an important next step would be to design a more appropriate measure.

Measurement is a critical part of documenting student progress towards skill mastery, and assessing the impacts of different learning experiences (see GC 3). Many tools already exist, especially to assess spatial thinking (see spatiallearning.org for some examples), while others likely need to be developed. For example, Resnick & Shipley (2013) introduced a new measure to assess mental brittle transformation in order to distinguish some of the differences in visualization practices between geologists and organic chemists, while Dodick & Orion (2006) designed three instruments to measure perceptions of time with middle and high school students. Previous studies have used a wide array of measurement instruments to measure spatial thinking including the Geologic Block Cross-Sectioning Test (used by Atit, Gagnier, & Shipley, 2015), the Topographic Map Assessment, visualization, rotation and perceptual speed tests (used in Hambrick et al., 2012) and open-ended interviews with children (Ault, 1982) to assess different types of spatial thinking (e.g. mental rotation, penetrative thinking and disembedding in Ormand et al., 2014). Temporal thinking has received less attention, but instruments include the Geological Time Aptitude Test (GeoTAT, used in Dodick & Orion, 2003a), the Temporal Spatial Test and Strategic Factors Test (TST and SFT, respectively; used in Dodick & Orion, 2003b).

Newcombe & Shipley (2015) provide a recent review of the types of spatial thinking and assessments on spatial thinking, especially on measures for disembedding, spatial visualization, mental rotation, spatial perception and perspective taking. Uttal & Cohen (2012) and Uttal et al., (2013) reviewed studies that assessed the impact of spatial training; these reviews included reference to numerous spatial assessment instruments. Determining which of the current instruments measure domain-specific geoscience tasks or skills is an important next step.

With respect to temporal thinking, Shipp, Edwards, & Lambert, (2009) provides an extensive review of temporal focus ("the attention individuals devote to thinking about the past, present, and future," p. 1), as well as a brief overview of the other temporal constructs including a short definition, sample measures, whether the domain assessed is cognitive, affective or behavioral, and known covariates or consequences. These dimensions include time perspective, temporal orientation, temporal depth, time attitude, preferred polychronicity, hurriedness and pacing style, and have not been addressed in depth within the geoscience education research literature.

Recommended Research Strategies

1. Additional literature reviews would be of great benefit in establishing what assessment tools already exist and what they measure. These would be invaluable in bringing together disparate literature from cognitive science and other DBER fields, like Physics Education Research (PER; e.g., Dori & Bara, 2001 examined the development of spatial understanding using virtual and physical molecular modeling).

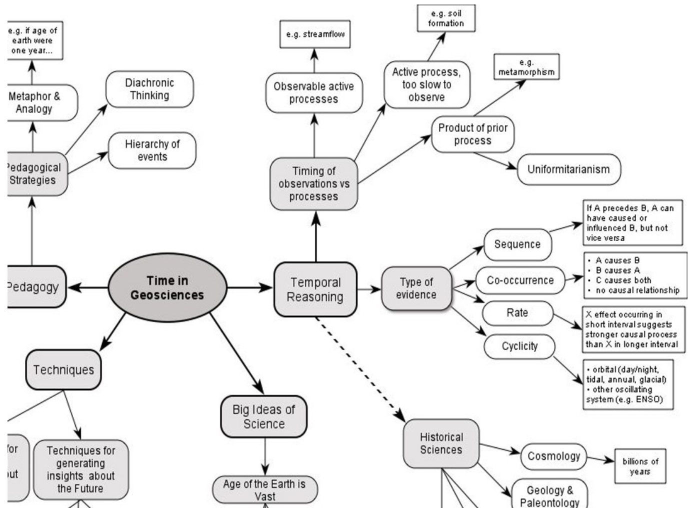

Figure 2. Kastens and Manduca's (2012) concept maps of spatial and temporal thinking in the geosciences may serve as a starting point for an important next step in research: creating a map of the various kinds of spatial and temporal reasoning skills and the geoscience specialties that rely on these skills. For example, being able to apply the principle of superposition to a rock outcrop is a specific skill that could be mapped onto the sequence type of temporal thinking.

2. Proof of concept tests are needed to assess the "fit" of existing assessment tools. For example, if we hypothesize X domain-specific task requires Y type of spatial reasoning (see Grand Challenge 1), do we see that spatial reasoning test predicting performance of the domain specific task? Going further with that example, we might assume that mapping a bedrock anticline requires penetrative thinking; is someone's ability to map that anticline correlated with measures of penetrative thinking?

3. Identify or develop additional metrics as appropriate to assess the spatial and temporal nature of geoscience tasks. This is a follow-up to Strategy 2 that may be necessary if domain-specific tasks are not found to correlate with existing measures of spatial and temporal thinking.

Grand Challenge 3:
How can geoscience education foster the spatial and temporal reasoning skills that are required in each sub-specialty?

Rationale
Once an understanding of the essential types of spatial and temporal reasoning for each geoscience specialty, and an understanding of how to measure them, is established we can then proceed to developing and assessing instructional methods for supporting these skills. Targeted instructional manipulations should be investigated with the intention of assessing if and how these interventions support content learning and the development of spatial and temporal reasoning skills. A further question within this Grand Challenge is to consider whether the same instructional interventions can be used across content areas that recruit the same (or similar) spatial and temporal reasoning skills.

Some work in the Geoscience Education community has begun to investigate these questions. For example, research has demonstrated benefits for instruction that utilizes predictive sketching (Gagnier et al., 2017; Ormand et al., 2017), student produced gestural aids (Atit, Gagnier, & Shipley, 2015; Kastens, Agrawal, & Liben, 2008), embodiment and modeling (Hall-Wallace & McAuliffe, 2002; Kastens & Krumhansl, 2017; Plummer, Bower, & Liben, 2016; Woods et al., 2016), and various forms of active learning strategies (Cheek, LaDue, & Shipley, 2017; McConnell et al., 2017; Sit & Brudzinski, 2017). While the Geoscience Education community has made strides in developing and testing methods for supporting content learning and spatial and temporal reasoning, other DBER areas have laid significantly greater groundwork (e.g. Wu & Shah, 2004; Stieff, Hegarty, & Dixon, 2010; Stieff & Uttal, 2015; Augusto, 2005; Montanegro 1992,1996). Of broader relevance, Freeman et al. (2014) conducted a meta-analysis including 225 studies that compared student performance in STEM courses taught in a lecture format versus an active learning format. Encouragingly, this analysis demonstrated a strong positive effect for active learning formats, however only two of the studies included in his review were conducted in geoscience classrooms (compared to 33 biology, 31 physics, 29 math, 22 chemistry, 19 English, 14 psychology, 8 computational science). Though this was a meta-analysis of papers on active learning, there is likely a very similar need for controlled studies of temporal and spatial reasoning in the geosciences. The geoscience education community should use the research conducted in other fields to inform their own future research and should also be sure to conduct research that provides strong and reliable evidence (St. John & McNeal, 2017).

Finally, it is critical that the community make an effort to identify tasks or learning goals that are transferable and context-independent so they can be applied more widely throughout the discipline. This may extend to applying temporal and spatial skills learned within a geoscience context to other disciplines, especially as most students in introductory geoscience courses are non-majors. It is an assumption that the skills taught in those classes will be of broader applicability and therefore value to the students, but additional work is needed to support that hypothesis.

Recommended Research Strategies

1. Apply theories of attention and learning that have come out of cognitive science to more theoretically inform the instructional techniques we develop (e.g., selective attention, inhibition, cognitive capacities, principles of multimedia learning, student engagement, to name a few). For example, apply theories of selective attention to better understand why students "miss" key pieces of data during field mapping exercises.

2. Following work out of physics, identify explicit models that novices and experts rely on when completing various reasoning tasks. Use this to identify where novice reasoning goes awry and where future investigations/instructional interventions should be focused. For example, have students complete sorting tasks (e.g., in order of size or amount of time) to better understand what information they use and/or consider relevant (see example from Tinigin, Petcovic, & LaDue, 2017). This could then be compared to the information experts use to complete the same sorting task. Some specific spatial and temporal misconceptions can be found outlined by Francek (2013), Ishikawa & Kastens (2005), Kusnick (2002), and Gautier,Deutsch and Rebich (2006).

3. Study transferability from general, content-agnostic skills to discipline-specific skills and possibly vice-versa. Does training in a content-agnostic skill influence the development of a discipline-specific skill in any way?

4. Develop studies that provide strong evidence and begin to elucidate why certain techniques are effective. What are the underlying cognitive mechanisms at play?

5. An additional long term research strategy is to generate learning progressions for critical cross-cutting spatial and temporal skills. For example, how does a typical individual's ability to access temporal depth (Bluedorn, 2002) develop from the time they are a freshman to when they graduate? What are the specific learning strategies that support the development of temporal depth?

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Figures

Figure 1.
Provenance: Image created by Karin Kirk and Linda Pisolesi for the cover of Kastens, Kim A., and Cathryn A. Manduca, eds. Earth and mind II: a synthesis of research on thinking and learning in the geosciences. Vol. 486. Geological Society of America, 2012.
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Research on Cognitive Domain in Geoscience Learning: Quantitative Reasoning, Problem Solving, and Use of Models

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Introduction

Human cognition is the process of acquiring knowledge and understanding through thought, experience and the senses. Cognitive processes are habits of the mind and therefore affect learning, including the learning of geoscience concepts and skills. The GER Framework includes two chapters on areas of cognitive research that are particularly important to geoscience education: the previous chapter tackled spatial and temporal reasoning, and this chapter addresses quantitative reasoning, problem-finding and problem-solving, and the use of models.

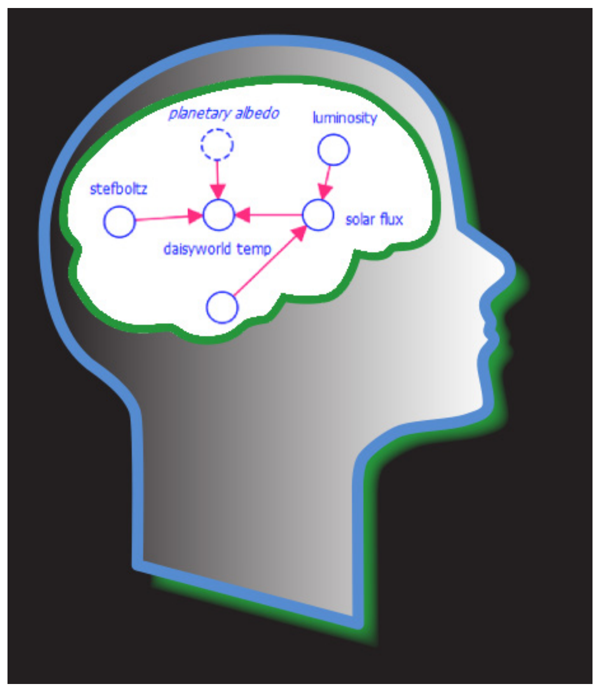

Figure 1. Computational models, such as the STELLA Daisyworld model shown in this diagram, aim to help geoscientists figure out and describe how the world works. Components are identified and linked to explore quantitative relationships of cause and effect and feedbacks, evaluate system behavior, and make predictions. Effective teaching with models benefits from cognitive research on the use of models. Figure created by Dana Chayes.

Models (from simple mental models to complex computational models) are used by geoscientists to conceptualize and better understand the Earth system and to make predictions (Figure 1). Earth processes affect the human condition and result in hazards and complex issues that require both expert and citizenry decision-making about mitigation and adaptation. In addition, a wide range of Earth materials (e.g., mineral, rock, water) are valued resources that need sustainable management. All of these challenges require recognition of the problem (problem-finding), and the development and application of problem-solving skills. In addition, Earth system understanding and problem-solving benefit strongly from quantitative reasoning. Quantitative reasoning, problem-solving, and use of models present many daunting challenges to both students and instructors. All are valued by the professional geoscience community and by employers, and all would benefit from more education research.

In defining the Grand Challenges and recommended strategies, we favored those that are: high impact, under-researched, addressable on a ten-year time scale, and/or central to how geoscientists think about the Earth and about Earth/human interactions. Addressing each of these challenges will require innovative, creative thinking, along research pathways that are not yet clear, along with vast amounts of hard work. But we are confident that each of them is ripe for new discoveries, and we look forward to both the intellectual and practical outcomes of these efforts.

Grand Challenges

Grand Challenge 1: Quantitative Thinking: How does quantitative thinking help geoscientists and citizens better understand the Earth, and how can geoscience education move students toward these competencies?
The ability to think quantitatively is an important part of what transforms an introductory student into a geoscience major and then into a professional geoscientist. Employers value quantitative thinking. Quantitative thinking may be a sweet spot for GER research, in that there is rich trove of math education research to build upon.

Grand Challenge 2: Problem-finding and Problem-solving: How can we help students find and solve problems they care about concerning the Earth, in an information-rich society (e.g., of big data, emerging technologies, access to a wide-variety of tools, and rich multimedia)?
Historically the problems that students tackle in science classes, including geoscience classes, have been assigned by the teacher and rather constrained in scope. But many of the problems geoscience students will confront in the future are complex, messy, ill-defined, and require working across disparate knowledge, methods, and data sources.

Grand Challenge 3: Use of Models: How can we help students understand the process by which geoscientists create and validate physical, computational, mental, systems, and feedback models and use those models to generate new knowledge about the Earth?
Geoscientists use an ambitious and iterative process of building models, starting with mental working models and working up to computational models, testing their models against empirical data at every iteration. Only after many such cycles is the model considered robust enough to make predictions about the earth where we have no data–including the past or the future. Lack of understanding of how modern scientific modeling works allows skeptics and deniers to dismiss evidence that comes from modeling, for example evidence that climate change is anthropogenic.

Grand Challenge 1:

How does quantitative thinking help geoscientists and citizens better understand the Earth, and how can geoscience education move students toward these competencies?

Rationale

The ability to think quantitatively is an important part of what transforms an introductory student into a geoscience major and then into a professional geoscientist. Employers value quantitative thinking. Quantitative thinking may be a sweet spot for GER research, in that there is rich trove of math education research to build upon. The set of recommended strategies listed below is not meant to comprehensively cover the entirety of geoscience quantitative thinking; we have prioritized strategies that we think offer the highest leverage and that will produce a strong foundation upon which future efforts can build.

The literature in quantitative reasoning outside of geoscience is extremely rich, including contributions in mathematics, mathematics education, statistic education, engineering education, computer science education, and educational psychology. Good starting points include Ashcraft (2002), Madison (2014), & Wing (2006). Several sources have indicated that modest gains in student attitudes can be achieved with some effort (Wismath & Worrell 2015; Lipka & Hess 2016; Follett et al., 2017; Ricchezza & Vacher, 2017). However, results are mixed and not all interventions have produced desired results (Sundre et al. 2012; Mayfield & Dunham 2015). Research on quantitative reasoning specifically within geoscience education is a fertile field for future work (Vacher, 2012; Ricchezza & Vacher, 2017).

Recommended Research Strategies

1. Collaborate with mathematics education researchers and quantitative literacy experts. There is already a large community outside of the geosciences who has thought about issues of quantitative thinking, and we want to be able to build on their efforts rather than start from scratch. Two anticipated research process outcomes from such collaborations would be gains in: (a) vocabulary and constructs with which to talk about how experts and novice participants in our studies are thinking and learning and (b) insights about mathematical habits of mind and partnering to better understand how these habits of mind come into play in thinking about the Earth. The following are example contact points to initiate collaborative research with mathematics education researchers and quantitative literacy experts.

    - National Numeracy Network
    - Research in Undergraduate Mathematics Education
    - Transforming Post-secondary Education in Mathematics
    - EDC Math Education group: Authors of Cuomo, Goldenberg, & Mark, 1996

2. Research how novices and experts take an Earth phenomenon that they understand holistically or experientially and transform it into a mathematical representation (e.g., word equation, mathematical equation, mathematical or computational model; Figure 2). Personal experiences as educators tell us that this is a skill that many students lack, and it is generally not being taught in math

classes. For geoscience majors, this is an essential skill for doing original research. For non-majors, this is a valuable life skill. There is very little research on this, and also not much guidance for educators. Models include the work of W.-M. Roth (e.g., Roth & Bowen, 1994) and the 1990's vintage Jasper Woodbury series (Vanderbilt, 1992).

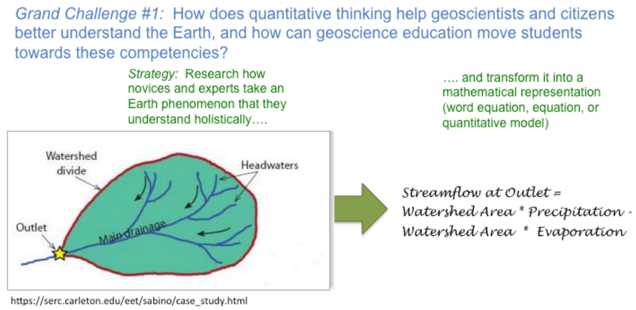

Figure 2. Illustration of the process of transforming holistic understanding of a situation or phenomenon into a mathematical representation.

3. Research what quantitative habits of mind expert geoscientists use in understanding the Earth. Research suggests that habits of mind are more enduring and transferable than specific skills. We do not know what the geoscience careers of the future will entail, or what specific skills might be needed. Habits of mind should prepare students for whatever specific tasks are required. We and our math colleagues have put a lot of effort into teaching math skills; we now want to move beyond teaching quantitative skills to teaching quantitative habits of mind. This topic is seriously under-researched.

4. Work towards a community consensus on what quantitative skills and habits of mind are needed to function effectively as a citizen of the planet. Many of the critical Earth-related problems facing humanity can be broadly understood at either a qualitative or quantitative level; for example climate change, resource depletion, and resilience in the face of natural disasters. However, to move beyond merely understanding the problems, so as to be able to weigh the costs and benefits of conflicting paths forward, requires quantitative thinking. There is not a consensus on what the elements of such thinking should be, but the traditional algebra-calculus sequence seems not to be an optimal match. Deciding what needs to be learned is a necessary pre-cursor to designing a comprehensive research program in this area. This could be approached as a community discussion. Or it could be approached as a research question, looking out in the world at what kinds of tasks and decisions citizens face in the context of Earth/human interactions, and what quantitative capacities are needed to succeed at these tasks and make wise decisions.

5. Research what learning experiences can help students with poor math preparation or attitudes feel the power of math to answer questions or solve problems they care about concerning the Earth. Extensive literature in and out of the geosciences and uncounted personal experiences as educators tell us that many of our students enter our classes or our major(s) with a negative attitude about math (e.g., math anxiety, math phobia) combined with a lack of proper math preparation, that leads to math avoidance (Wenner & Baer, 2015; Maloney & Beilock, 2012). This shuts them off to the rich possibilities of the power of math to solve problems and open entire career opportunities they had not considered before. Improving quantitative thinking about the Earth is important for all students, but we prioritize this population for research attention because the problems here are so gigantic and so important, and because we think that this can be a pathway to transform math from "something I hate" into "something I want and need."

6. Collaborate with assessment experts to develop and validate assessments for the learning goals articulated in Strategies 2 and 5, and to begin to shape the findings of Strategies 3 and 4 into assessable constructs. There are few to no tested, validated, research-grade assessment instruments that tackle quantitative reasoning in the context of Earth education. The building of such assessments requires both deep knowledge of the Earth and serious expertise in assessment; collaboration will be helpful. It might be possible to: (a) build Earth content into existing quantitative reasoning assessments, or (b) increase the quantitative component of existing Earth literacy assessments, or (c) formalize and validate assessments that have been developed as summative or formative assessments for coursework. Any of these pathways would need to begin with a clear articulation of learning goals and of what student behavior and/or product would demonstrate that each learning goal had been met. This is a long path; all the more reason to start sooner rather than later.

Grand Challenge 2:

Problem-finding and Problem-solving: How can we help students find and solve problems they care about concerning the Earth, in an information-rich society (big data, emerging technologies, access to a wide-variety of tools, rich multimedia)?

Rationale

Historically the problems that students tackle in science classes, including geoscience classes, have been assigned by the teacher and rather constrained in scope. But many of the problems geoscience students will confront in the future are complex, messy, ill-defined, and require working across disparate knowledge, methods, and data sources. Such work has been coined "convergent" science, as solutions for problems must be converged on from different directions. We are at a time where technology can leverage the power of undergraduates so that they can make real contributions to solving authentic, messy problems, rather than being constrained to well-bounded classroom problems. Information technology has changed, and will continue to change, the kinds and quantities of resources that are available for problem solving. Students need to learn to navigate this rapidly changing space, identifying and harnessing resources (e.g. tools, data, models, experts, collaborators) that can be brought to bear on their problem. We anticipate that young people who learn to identify and solve convergent science problems as students will carry that skill-set and habit of mind into their personal, civic and professional adult lives (Figure 3).

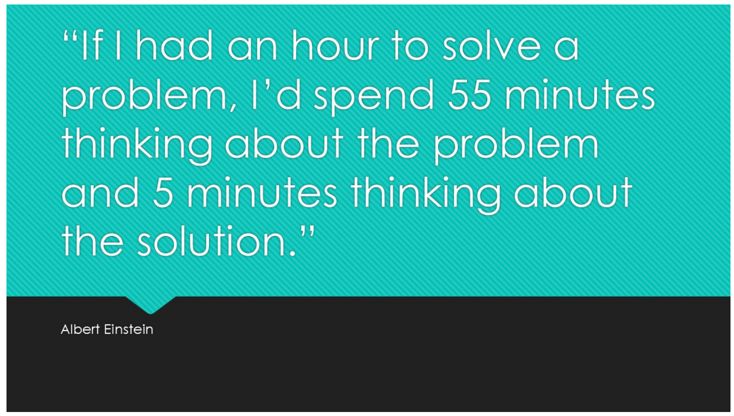

Figure 3. Defining authentic problems is not easy, but is the first critical step to solving them.

The current state of knowledge on problem-finding and problem-solving comes from many fields of study that can inform future geoscience education research:

- There is existing research on the process of diffusions of innovation and on technology adoption (Rogers, 2003). Both of these identify awareness, perceived usefulness, and initial training as key early phases in the process of technology adoption. However, there is little research on how to enable these early phases in the sciences in general and the geosciences in specific.
- There is existing research on computational thinking and data analysis skills, mostly within computer science education (Elliot et al., 2016; Fox & Hendler, 2014; Hey, Tansley, & Tolle, 2009). Yet, there is very little research on this topic in geoscience, beyond identification of general categories of skills needed (Nativi et al., 2015). The Geoscience Employer's Workshop Document identifies a set of existing technologies with which students need to be familiar; this list will change continually in the future but general types of technologies (e.g., GIS as oppsed to the more specific software ArcGIS) may be an appropriate anchoring for tailoring research foci.
- There is a body of literature on problem-based learning, including in medicine, business,

engineering, and to a lesser extent in geosciences (Holder, Scherer, & Herbert, 2017; Pennington et al., 2016). Much of this literature comprises "curriculum & instruction" style papers rather than discipline-based educational research. Given the messy and heterogeneous nature of problems and problem-solving, it is hard for researchers to produce generalizable knowledge on problem-based learning, findings that can be extended beyond the immediate context of a study site.

- There is a body of literature on the science of team science and cognition in groups (National Research Council, 2015; Pennington, 2016; Pennington, et al., 2013). This has mostly been developed through case studies of teams in different contexts – mostly within large organizations, medical teams, and community organizations. There is some emerging research on how learning occurs in teams (Borrego & Cutler, 2010; Bosque-Pérez et al., 2016; Roschelle & Teasley, 1995), and how activities can be designed in geoscience classrooms to develop these capabilities (Pennington et al., 2016).

Recommended Research Strategies

1. Research the problem-finding process; the techniques by which vague, open-ended problems are turned into solvable problems, and how these can be taught. Problem identification in convergent science requires the ability to co-create a shared conceptualization of the problem to be solved based on what each participant can contribute. There are an infinite number of ways to frame research on ill-defined problems; solutions depend on the expertise at hand. The challenge is to learn enough about the different contributing perspectives to determine how they can be collectively leveraged. Moreover, to make serious headway on a substantial problem, the problem and proposed solution has to be one that is of high importance to the solver or solving team; otherwise, they won't have the motivation to push onward through the inevitable challenges and setbacks. Finding a problem that is both solvable and of passionate personal interest is doubly hard. We need evidence on how skilled problem-solvers do this, models for how learning occurs in these situations, and pedagogical approaches to help students learn to do the same. Employers, including those involved in the Future of Geoscience Education Employers Workshop, articulate the importance of learning to work on problems with no clear answers and manage the uncertainty associated with solving these types of problems.

2. Research the process by which geoscience students learn and adopt new methods and technologies. As technology advances, new tools are available that generate ever larger datasets. Such datasets are potentially valuable to help solve complex problems, but the most effective strategies for learning how to manage and extract solutions from large datasets are not clear. Skills are needed to: (a) skillfully collect, integrate and analyze data that are increasingly generated automatically by advanced sensors and/or simulation models; (b) understand advanced methods and technologies for conducting data-intensive science; and (c) timely identify and learn technologies that are relevant to the problem and are emerging at an increasingly rapid pace. Likewise, new technologies could be used to process data in new ways or to advance learning, but more research is needed on how to most effectively use such technologies, especially when technological developments constantly evolve. In addition, employers, including those involved in the Future of Geoscience Education Employers Workshop, articulate the importance of the ability to use data to solve problems.

3. Collaborate with experts on team science (from cognitive or learning science) to research effective strategies to teach collaboration and teamwork in undergraduate geoscience education. Convergent science requires the ability to collaborate effectively across disciplines and/or with external stakeholders, especially with experts from social sciences, engineering, and computer science. Employers, including those involved in the Future of Geoscience Education Employers Workshop, consistently emphasize the importance of ability to work in teams, including interdisciplinary teams. Although many classes incorporate team projects, most provide little training to students on how to work effectively in a team. There are few relevant models of teamwork training for geoscience faculty to follow, and most do not have the knowledge and expertise to construct their own models. Although there exists decades of research on teamwork in other contexts, there is little GER research on how what is known about teamwork can be applied in geoscience contexts.

Grand Challenge 3:

Use of Models: How can we help students understand the process by which geoscientists create and validate physical, computational, mental, systems, and feedback models and use those models to generate new knowledge about the Earth?

Rationale

We have prioritized this Grand Challenge because we think that many or most citizens do not understand how modern scientific models are developed and tested, and how they are used to make predictions. Geoscientists use an ambitious and iterative process of building models, starting with mental working models and working up to computational models, testing their models against empirical data at every iteration. Only after many such cycles is the model considered robust enough to make predictions about the Earth where we have no data - including times in the past and the future. Lack of understanding of how modern scientific modeling works allows skeptics and deniers to dismiss evidence that comes from modeling, for example evidence that climate change is anthropogenic.

There is some good literature on how scientists create and validate models, including external runnable models (e.g.Nersessian, 1999), and including in geosciences (e.g. Weart, 2011; Turcotte, 2006). There is active research on how students and teachers understand the scientific practice of modeling (Clement, 2000; Gilbert & Justi, 2016; Gobert & Buckley, 2000; Grosslight et al., 1991; Justi & Gilbert, 2002; Lehrer & Schauble, 2006; Pluta, Chinn, & Duncan, 2011) and on scientists' normative, conceptual models (Schwarz & White, 2005; Schwarz & Gwekwerere, 2007; Schwarz et al., 2009). There is less understanding of how students and teachers understand external runnable models, including physical models (Miller & Kastens, 2018), and modern computational models (such as global climate models) (Bice, 2006; Colella, 2000).

There are frameworks for model-based instruction, ready for testing (e.g. Sell et al., 2006; Sibley, 2009; Wndschetl, Thomson, & Braaten, 2008; Gilbert & Ireton, 2003), but a lack of good assessments of students' ability to create and use geoscience computational models (Figure 1). There is a particular shortage of educational research at the interface between models and data: how to help students learn to use data to test models, and how to help students learn to use models to interpret data. As pointed out in an earlier theme chapter, we need further research on how to help students find the sweet spot between being overly skeptical about models and being overly trusting of models. Model-building as a collaborative process (Pennington et al, 2016) may be part of the process of creating trusted models around difficult problems.

Recommended Research Strategies

1. Research what students at various levels understand the process by which geoscientists create and validate models (especially modern computational models) and use those models to generate new knowledge about the Earth. It has been asserted (e.g. Kastens et al., 2013) that students and the general public have little understanding of the process by which the computational models of modern science are created, validated, and used to make predictions. The breadth, depth, distribution and nature of this ignorance needs to be probed, to lay the groundwork for a comprehensive research agenda.

2. Collaborate with cognitive/learning scientists to understand how the human mind runs mental models of the future and/or the past, and then use this understanding to research how geoscience education can improve and leverage that ability. The first step towards generating a scientific computational model of a part of the Earth system is to develop a conceptual model that can be "run" in the mind (i.e. one can envision processes that produce observable products or behaviors, and can think through how those products or behaviors would differ as circumstances or inputs change.) The ability to run mental models is thought to be unique to the human brain and is therefore a powerful cognitive tool we have to understand the world around us. Even without formal training, our brains have this inherent ability (for example, anticipating where one will and will not be able to find parking on campus), but it is unclear how this ability is applied to understanding earth systems and how we can leverage this power of the mind to inform education practices.

3. Research how the human mind understands positive and negative feedback loops, how geoscience education can foster that ability, and how can we assess this. The Geoscience Employers' Workshop Outcomes lists the ability for students to do "systems thinking" as a valuable habit of mind. Cognitive research on ALL of systems thinking is beyond the scope of what could be accomplished in the 10 year timeframe to meet the GER Framework Goal); therefore we prioritize one critical aspect of system thinking for near-term cognitive research: feedback loops. Many, and maybe even most, environmental problems are underlain by reinforcing (aka positive) feedback loops; for example, the albedo feedback loop that strengthens the impact of climate change in the Arctic as the polar sea ice melts. Many of the potential solutions to environmental problems work by strengthening balancing (aka negative) feedback loops, or by weakening positive feedback loops. To understand environmental problems or contribute to environmental solutions in a deep and impactful way, students need to understand such processes. Practitioners find that these topics can be taught, but are challenging to teach and to assess. Feedback systems can be taught at a qualitative level or a quantitative level, and both are challenging. Understanding the cognitive underpinning of teaching and learning about feedback loops is a challenge that could benefit from collaboration with other DBER's, perhaps through the DBER-A alliance, as feedback loops are very important in life sciences (ecology, physiology) and engineering.

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Figures

Figure 1.
Provenance: Kim Kastens, Columbia University in the City of New York. Figure was created by Dana Chayes.

Figure 2:
Provenance: Kim Kastens, Columbia University in the City of New York

Figure 3:
Provenance: Kristen St. John, James Madison University

Research on Instructional Strategies to Improve Geoscience Learning in Different Settings and with Different Technologies

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Introduction

Strategies for teaching geoscience have evolved considerably in recent decades, owing to several factors that include (a) advances in teaching practice in STEM as a whole, particularly a trend from passive, instructor-centered pedagogy to use of more active and student-centered methods; (b) better correspondence between reflective teachers of geoscience and researchers in Geo-DBER and Geo-SoTL; (c) continuing rapid advances in instructional technologies, including virtual and online instruction; and (d) deeper interest across the entire geoscience community in improving accessibility, equity, and diversity within what has historically been among the least accessible or diverse branches of science.

Figure 1. Geoscience instruction is carried out in many different ways and in diverse settings—each with its own set of advantages and challenges. Geoscience education research must keep pace with the instructional strategies and settings we select.

Geoscience instruction today is carried out in a range of settings (Figure 1): from the traditional triad of classroom, laboratory, and field to informal or free-choice learning venues such as museums and science centers, and to fully online and immersive virtual environments. Teaching can now be carried out by instructors in-person (face-to-face) with large or small groups of learners; remotely over the web; synchronously during a scheduled class session or webinar; or asynchronously according to students' own schedules. Various situated and richly contextualized teaching modalities, such as place-based, case-based, problem-based, multicultural-multilingual, and experiential instruction have been adopted by geoscience educators.

However, it is a fact that practicing geoscience educators greatly outnumber practicing geoscience education researchers, and that the pace and the excitement of technological and methodological advances in education tend to outstrip the more deliberate progress of relevant educational research and assessment. Further, geoscience education receives less attention and support on a national scale than do biology, chemistry, and physics education. As a result, many recent influential studies such as that by Freeman et al. (2014), which demonstrated the effectiveness of active learning in undergraduate STEM, actually include little or no data from geoscience education. It is not surprising that changes in instructional strategies in geoscience have often come on the basis of instructor experience or preference, or anecdotal knowledge, rather than on a foundation of rigorous research and evaluation.

Our Working Group recognizes that, in order to close these gaps and render future instructional strategies as effective as possible, (a) there must be better coordination among researchers and educators in our own professional community and with those in other STEM disciplines; (b) higher standards of evidence must be applied to research in many cases; and (c) certain barriers at the instructional level to full and effective implementation of best practices must still be overcome. We have identified and enumerated five wholly soluble Grand Challenges that, if addressed by geoscience education researchers in partnership with practitioners, will lead to more effective, accessible, inclusive, relevant, and practical geoscience teaching and learning.

Grand Challenges

Grand Challenge 1: How can research and evaluation keep pace with advances in technological and methodological strategies for geoscience instruction, and with evolving geoscience workforce requirements?
Technological advances in science education, including geoscience education, tend to occur rapidly, and educators may adopt them ahead of any methodical research on their effectiveness or rigorous evaluation of their learning outcomes in different learning environments. In addition, geoscience curriculum and instruction may be poorly aligned with, or unresponsive to, continually evolving geoscience workforce requirements. These issues are interrelated and need more attention from researchers.

Grand Challenge 2: How can undergraduate geoscience instruction benefit from and contribute to effective research-based practices in other domains?
Many research-based instructional and assessment practices in other disciplines and in different settings have been shown to be effective, and merit attention from geoscience educators. However, it is noteworthy that these studies incorporate scant data from teaching and learning in geoscience, and that strategies that have emerged from this research may be little-known and little-used by geoscience educators. Further, the realm of free-choice or informal STEM education daily engages with a far greater number and diversity of learners than does formal education although the two

realms tend to operate in isolation from each other.

Grand Challenge 3: What instructional practices and settings are most effective for the greatest range of geoscience learners?

The greater geoscience community does not reflect the demographic diversity of the nation as a whole, although it is progressing in that direction. This progress may be better facilitated by the geoscience-education community with increased use of instructional strategies, context-rich subject matter, and learning settings that leverage greater accessibility, equity, and relevance in engaging and retaining diverse students.

Grand Challenge 4: How do we overcome structural barriers at the level of instructional practice that impede effective teaching and learning of geoscience?

Undergraduate teaching modalities in the geosciences today largely remain bound by the long-established lecture-lab format characteristic of most STEM courses, with the additional aspect of field trips and field camps of longer duration. However, as student demographics change and bring changes in student needs and dispositions, and academic units are increasingly pressed for financial and logistical resources, geoscience educators must overcome habit and institutional inertia in order to render geoscience instruction flexible enough to accommodate and engage future generations of increasingly diverse geoscience students.

Grand Challenge 5: How can we better engage learners as co-discoverers of knowledge and co-creators of new instructional strategies in geoscience?

Instructional strategies that involve direct student participation in scientific discovery or instruction are effective. However, much more work needs to be done in geoscience classrooms to make them truly student-centered with learners becoming co-discoverers of knowledge rather than just passive consumers of instruction. In addition, the idea of engaging students as co-creators of curriculum and instruction in their own courses, another strategy for student-centered active learning that also draws on student interest and creativity, has been proposed in the context of other disciplines but has not been tested in geoscience education.

Grand Challenge 1:

How can research and evaluation keep pace with advances in technological and methodological strategies for geoscience instruction, and with evolving geoscience workforce requirements?

Rationale

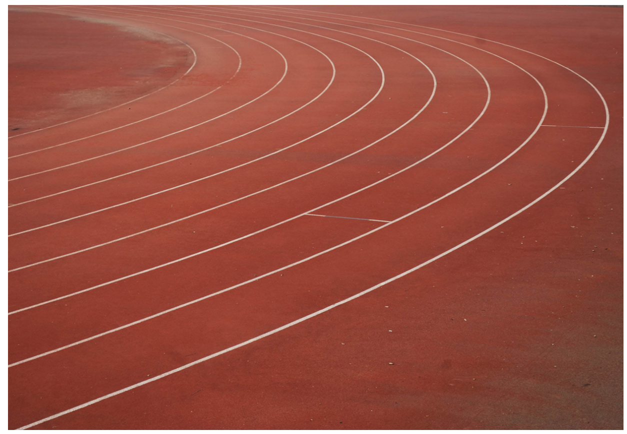

Figure 2. Sometimes the instructional strategies employed by educators outpace the research that is needed to evaluate effectiveness and determine whether, or how, the strategies aid in student learning of concepts, skills, and dispositions. Photo from Public Domain. (https://www.publicdomainpictures.net/en/view-image.php?image=16745&picture=track-running-lanes)

Technological advances in science education, including geoscience education, tend to occur rapidly, and enthusiastic and forward-looking educators may adopt them in their teaching ahead of the dissemination of methodical research findings on their effectiveness or of rigorous evaluation of their learning outcomes (Means et al., 2014; Bull et al., 2017). Many technological innovations in science teaching, including some that have direct relevance to geoscience education, have encountered challenges to making significant, lasting, and economical impacts at scale (Dillenbourg, 2017; Poulin & Straut, 2017; Horodyskyj et al., 2018). Further, geoscience curriculum and instruction may be poorly aligned with or unresponsive to continually evolving geoscience workforce requirements (Mosher et al., 2014; Mosher, 2015) for knowledge, skills, and dispositions (which are the attitudes and behaviors that foster effective use of knowledge and skills). These requirements themselves may be driven by technological advances. Therefore, these three challenges are interrelated, and they sum to a Grand Challenge to geoscience education researchers to keep pace (Figure 2); i.e., to maintain vigilant of (a) innovations in technological and methodological strategies for teaching geoscience, and (b) expectations that employers will have of our geoscience graduates; so as to most effectively direct future research efforts into both of these realms.

Recommended Research Strategies

1. Expand on studies of technological attributes, cognitive factors, and behaviors that variously facilitate or hinder the effectiveness of virtual, augmented, online, and blended instruction for teaching geoscience knowledge, skills, and dispositions (e.g., Clary & Wandersee, 2010; Young, 2012; Means, Bakia, & Murphy, 2014; Bursztyn, Shelton, & Pederson, 2017; Horodyskyj et al., 2018).

2. Expand on and validate methods for true and meaningful comparative studies of geoscience teaching and learning in virtual or online versus in-person or face-to-face settings, and at and at different scales (e.g., Perera et al., 2017).

3. Explore ways of reconfiguring or redesigning curriculum, instruction, and assessment modalities

that are specific to geoscience education, in order to better facilitate timely and demonstrably effective applications of innovations and advances in instructional technology as they appear.

4. Study faculty instructional design theories and models (e.g., Reigeluth, Beatty, & Myers, 2017; Kastens & Krumhansl, 2017; Ertmer, Quinn, & Glazewski, 2018), to determine the forms of of research designs that will best inform future instructional strategies.

5. Study and apply methodological and technological advances in assessment of knowledge, skills, and dispositions across disciplines, including assessment methods and technologies that were not specifically designed for formal teaching and learning (e.g., Vedung, 2000; Kline, 2013).

Grand Challenge 2:

How can undergraduate geoscience instruction benefit from and contribute to effective research-based practices in other domains?

Rationale

Many research-based instructional and assessment practices in other disciplines (e.g., other natural sciences, social sciences, arts and humanities) and in different settings (e.g., K-12 education, informal or free-choice education, and internships) have been shown to be effective, and merit attention from geoscience educators. For example, Freeman et al. (2014) point out that irrespective of class size and course content, students in traditional lecture-based STEM classrooms are 1.5 times more likely to fail than those in classrooms using active learning strategies. Similarly, reflective assessment techniques like two-stage exams (Wieman, Rieger, & Heiner, 2014) and application of growth mindset (e.g., Dweck, 2006; Yeager et al., 2016) are shown to increase student engagement and learning. However, it is noteworthy that these studies incorporate scant data from teaching and learning in geoscience, and that strategies that have emerged from this research may be little-known and little-used by geoscience educators (McConnell et al., 2017). The realm of free-choice or informal STEM education (museums, science centers, parks, media, etc.) daily engages with a far greater number and diversity of learners than does formal STEM education (Bell et al., 2009), but the two realms tend to operate in isolation from each other.

Figure 3. Colleagues from many different disciplines have much to contribute to geoscience education, and vice versa, but we need to communicate better. Image from www.tallinn.ee/est/lasteaed-ojake/Uudis-Lastevanemate-koosolek-12.

Meta-analyses of currently effective research-based teaching, assessment, and professional-development practices in other fields and in other settings (e.g., Kober, 2015; Lund et al., 2015; Cleveland, Olimpo, & DeChenne-Peters, 2017), and more direct collaborations with researchers and practitioners in these domains in the future, will lead to fruitful implementation of new instructional strategies in geoscience. In turn, greater dissemination of methods used in and findings obtained from geoscience-education research, beyond our own disciplinary community, would benefit STEM education as a whole. It is clear that there should be many more connections and collaborations (Figure 3) between geoscience-education researchers and colleagues in other domains.

Recommended Research Strategies

1. Connect and collaborate more with education researchers and practitioners in different STEM disciplines and settings, facilitated by participation in emerging interdisciplinary programs (such

as the STEM DBER Alliance) and interdisciplinary professional societies (such as the National Association for Research in Science Teaching and the American Educational Research Association).

2. Connect and collaborate more with researchers and practitioners in the free-choice (informal) STEM educational community, facilitated by participation in organizations such as the National Association for Interpretation.

3. Engage with cognitive psychologists who have interests in geoscience teaching and learning (e.g., Jaeger, Shipley, & Reynolds, 2017; Shipley & Tikoff, 2017) in conducting action research on undergraduate geoscience instruction.

4. Collaborate with K-12, postgraduate, and workforce partners in longitudinal research about transfer of learning (e.g., Kuenzi, 2008; National Research Council, 2013) to enhance the the effectiveness of undergraduate geoscience instruction.

5. Expand on studies of the relative effectiveness of common transdisciplinary teaching and learning strategies in geoscience instruction (e.g., McConnell et al., 2017).

Grand Challenge 3:

What instructional practices and settings are most effective for the greatest range of geoscience learners?

Rationale

The greater geoscience community (encompassing practicing geoscientists, geoscience educators, and geoscience students) does not reflect the demographic diversity of the nation as a whole, although it is progressing in that direction (e.g., Wilson, 2014a; 2014b; 2017). This progress may be better facilitated by the geoscience-education community with increased use of instructional strategies, context-rich subject matter, and learning settings that leverage greater accessibility, equity, and relevance in engaging and retaining diverse students.

Figure 4. Considerably more research and evaluation are needed to foster wider dissemination of accessible, barrier-free field-based geoscience instruction, such as seen here at Sunset Crater in northern Arizona. Photo courtesy of the IAGD.org.

Traditional and still-essential modalities of geoscience education, such as teaching and learning in the field, can and should be reformed to enhance their accessibility and relevance to a wider range of learners while maintaining their pedagogical value and intellectual rigor (Gilley et al., 2015; Figure 4). Further, nearly all geoscience teaching practiced in the United States, as is STEM teaching in general (e.g., McKinley & Gan, 2014) is reflective of a predominantly Euro-American cultural worldview and teaching practices that may hinder the access and learning of students from non-mainstream, underrepresented cultural and linguistic backgrounds (e.g., Ibarra, 2000; Nelson-Barber & Trumbull, 2007; Aikenhead & Michell, 2011; Ward et al., 2014). Instructional strategies that have been proposed to combat such cultural discontinuities, which include but are not limited to (a) blending of culturally different teaching philosophies and practices (e.g., Chávez & Longerbeam, 2016) and (b) preferential use of local settings and communally relevant examples and issues as context for geoscientific subject matter (e.g., Semken et al., 2017), have thus far been rigorously studied only in a limited number of learning environments, with small study populations, and over short time periods. These diverse approaches merit greatly expanded study that is driven jointly by geoscience-education researchers and by reflective practitioners, including those in the free-choice or informal science education community, who routinely serve a larger and more diverse population of STEM learners (Bell et al., 2009; see also Grand Challenge 2).

Recommended Research Strategies

1. Apply new evidence-driven approaches (St. John and McNeal, 2017) to conduct meta-analyses of effective instructional strategies, teaching tools, and assessments for different populations

of learners and different instructional settings.

2. Expand on research on reformed and more accessible field-based geoscience education (e.g., Whitmeyer, Mogk, & Pyle, 2009; Gilley et al., 2015).

3. Identify and address factors that variously foster or limit participation of underrepresented students in the geosciences (e.g., NASEM, 2011; Callahan et al., 2017; McDaris et al., 2017; Wolfe and Riggs, 2017).

4. Test validity and effectiveness of strategies for curriculum design, instruction, and assessment that are explicitly focused on engaging and retaining more underrepresented cultural-minority students, such as place-based and culturally informed geoscience teaching (e.g., Riggs, 2005; Semken, 2005; Apple, Lemus, & Semken, 2014; Ward, Semken, & Libarkin, 2014; Semken et al., 2017),with larger study populations and over longer time periods.

5. Expand research on and research-informed practice of geoscience instructional practices and settings that better serve students with disabilities (e.g., Carabajal, Marshall, & Atchison, 2017).

6. Promote collaborations among researchers and practitioners in formal and informal (free-choice) geoscience education in examining instructional practices and settings most effective for the greatest range of geoscience learners.

Grand Challenge 4:

How do we overcome structural barriers at the level of instructional practice that impede effective teaching and learning of geoscience?

Rationale

Undergraduate teaching modalities in the geosciences today largely remain bound by the long-established lecture-lab format characteristic of most STEM courses, with the additional aspect of field trips and field camps of longer duration. However, as student demographics change and bring changes in student needs and dispositions, and academic units are increasingly pressed for financial and logistical resources, geoscience educators must overcome habit and institutional inertia in order to render geoscience instruction flexible enough to accommodate and engage future generations of increasingly diverse geoscience students. Our Working Group has targeted a number of structural barriers at the level of instructional practice that include (but are not necessarily limited to): inertia within academic units, pedagogy unsupported by learning research, limited understanding of diverse students' prior preparation, inaccessible or poorly accessible geoscience learning activities in the field or indoors, and indifferent or hostile learning environments. As shown by the proposed research strategies and symbolized in Figure 5, barriers can be overcome in many different ways.

Figure 5. There are many different ways to overcome barriers. Photo showing construction of Hoover Dam bypass bridge in 2010, from the blog of the State Geologist of Arizona, arizonageology.blogspot.com/2010/07/progress-on-hoover-dam-bypass-bridge.html.

Recommended Research Strategies

1. Draw on research on theories of change (e.g., Lewin, 1947) and cultural cognition (e.g., Kahan, Jenkins-Smith, & Braman, 2011) to analyze views and habits of geoscience faculty that may cause conflict and hinder change in their instructional practices, and determine new research strategies to mitigate them.

2. Expand on current research on specific barriers at the faculty and academic-unit levels to use of effective research-based pedagogy by geoscience instructors at different types of academic institutions. With few exceptions (Markley et al., 2009), current published research on such barriers (e.g., Kezar, 2001; Henderson, Beach, & Finkelstein, 2011; Brownell & Tanner, 2012), though relevant, has not been focused on geoscience instruction.

3. Devise and evaluate new mitigation strategies at the instructional level that can help compensate for extrinsic barriers to geoscience learning by students from underserved communities, such as inadequate high-school preparation for undergraduate geoscience studies, lack of meaningful

access to technology and media ("digital inequality;" e.g., Wei & Hindman, 2011), and lack of access to STEM enrichment programs.

4. Devise and evaluate new strategies at the instructional level that explicitly address intrinsic (unit-level and faculty-level) barriers to geoscience learning by female students, underrepresented minority students, LGBTQ students, and students with disabilities, such as indifferent or hostile learning environments (e.g., St. John, Riggs, & Mogk, 2016) or insufficient mentoring by faculty (e.g., McCallum et al., 2018).

5. Expand on current research (e.g., Gilley et al., 2015; Atchison & Libarkin, 2016; Carabajal, Marshall, & Atchison, 2017) on rendering geoscience instruction, whether done in classrooms, laboratories, in the field and community, or online, more accessible to students with disabilities.

Grand Challenge 5:

How can we better engage learners as co-discoverers of knowledge and co-creators of new instructional strategies in geoscience?

Rationale

Research shows that student-centered active instructional strategies that involve direct student participation in scientific discovery or instruction, such as peer instruction (e.g., Mazur, 2013), service learning, research experiences, and internships, are effective (Figure 6). Benefits of faculty-student collaborative research in STEM disciplines have been well documented (e.g., Russell, Hancock, & McCullough, 2007; Bangera & Brownell, 2014; Carpi et al., 2017; NASEM, 2017a). Recent efforts to replace standard laboratory-based science courses with discovery-based research activities in the curriculum (e.g., National Academies of Science, Engineering and Medicine, 2015) and course-based research experiences (CUREs; Corwin, Graham, & Dolan, 2015) highlight the growing awareness of these benefits. Similarly, the importance of service-learning as a way to infuse deep learning in the geosciences is also receiving attention (e.g., NASEM, 2017b).

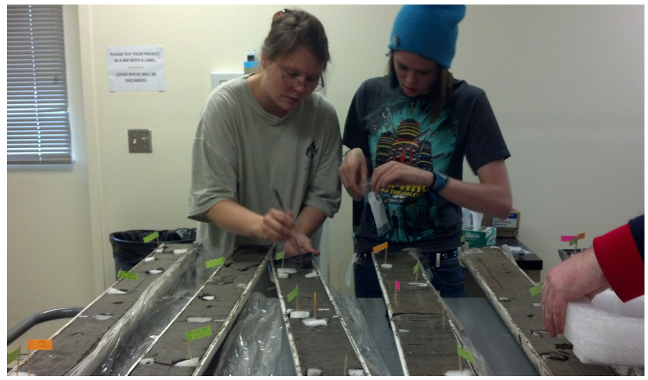

Figure 6. Peer instruction, research experiences, service learning, and internships are ways students can become co-creators of knowledge. How to effectively implement these strategies and better engage learners warrants more attention from GER.

The idea of engaging students as co-creators of curriculum and instruction in their own courses, another strategy for student-centered active learning that also draws on student interest and creativity, has been proposed in the context of other disciplines (e.g., Bovill, Cook-Sather, & Felten, 2011; Bovill et al., 2015) but has not been tested in geoscience education. Certain students may have expertise in technologies that are useful for geoscience teaching and learning (such as web design, geographic information systems, or drones). Engaging such students as co-creators of new curriculum or instructional strategies can help instructors take fuller advantage of technological advances (e.g., Gros & López, 2016). Greater and more active participation by students in the instructional design process can also enhance the power and validity of assessment tools and learning analytics (Dollinger & Lodge, 2018). However, as Teasdale et al. (2017) pointed out, much more work needs to be done in geoscience classrooms to make them truly student-centered with learners becoming co-discoverers of knowledge or co-creators of teaching and learning, rather than just passive consumers of instruction.

Recommended Research Strategies

1. Expand on and apply the body of existing knowledge related to undergraduate participation in research accrued by organizations such as the Council on Undergraduate Research.

2. Expand research on cognitive and affective outcomes of student participation in course-based undergraduate geoscience research (e.g., Bangera & Brownell, 2014; Brownell & Kloser, 2015).

3. Review and assess different models of service-learning projects used in teaching geoscience and allied disciplines (e.g., Mogk & King, 1995; Tedesco & Salazar, 2006; Coleman et al., 2017; National Academies of Sciences, Engineering, and Medicine, 2017b).

4. Study and evaluate potential benefits of implementing strategies for involving geoscience students in the co-creation of curriculum and instructional strategies as part of their learning process (e.g., Bovill, Cook-Sather, & Felten, 2011; Bovill et al., 2015).

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Research on Geoscience Students' Self-Regulated Learning, Metacognition, and Affect

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Introduction

When we think of learning, we commonly focus on the content. However, it is how individuals navigate that content through their affect (emotional response, attitudes, beliefs), their ability to self-regulate (which includes one's motivations and interests) and their metacognitive capabilities (ability to reflect on what they know, what they don't know and what they need to do to improve on those weaknesses) that ultimately determines whether and how they interact with the content. While research clearly indicates that the ability to self-regulate is critical for success in learning in general (Figure 1; for example, Pintrich & Zusho, 2007; Zimmerman, 2001; Schraw, 1998), we are still trying to determine what this looks like for the geosciences. In addition, while there is initial evidence that the same motivational and affective factors that impact student learning in general also apply to learning in geoscience contexts (Lukes & McConnell, 2014), much more needs to be explored. We still need to learn how self-regulation, metacognition, and affect can enhance (or inhibit) one's ability to navigate content necessary for specific skill sets within the geosciences (e.g., spatial reasoning). Findings might be different for various populations and in a range of contexts, and research in the geosciences needs to investigate these variations. We also need to better determine how we can support faculty in facilitating student development of these skills and capabilities.

Figure 1. This image represents the value that metacognitive capabilities have in student learning. When students hone the ability to be self-regulated learners they take greater control over their actions as they strive toward academic acheivement goals and development of transferable skills.

Many of the questions researchers in the fields of education psychology, cognitive science, and science education still have about matters of self-regulated learning, metacognition, and affect are in direct alignment with the interests of GER. Some of these emergent lines of inquiry in these other fields can inform GER through the use of more-established theories and methodologies. The geosciences may be a unique context in which these questions can be investigated and the findings generated from GER researchers may be of interest to the broader learning science audience which, in turn, may provide GERs new dissemination outlets and interested audiences to publish and communicate their research findings.

Below, we articulate four Grand Challenges that highlight needed areas of research on self-regulated learning, metacognition and affect. These are organized around important ways in which these factors emerge in teaching and learning: in the development of student skills, in the support of a diverse population of learners, in the support of educators teaching these students, and in assuring that research on these factors is of the highest standards.

Grand Challenges

Grand Challenge 1: Student Skills: How do we support students in developing their ability to learn, regulate, and apply the skills and ways of thinking in the geosciences along the novice to expert continuum?
Supporting student success and preparing students for careers and social/civic involvement after college is an important aspect of the undergraduate teaching and learning experience. Integrating skill development beyond academic and technical skills, to include metacognition and self-regulation, is important in developing life long learners and expertise.

Grand Challenge 2: Inclusion: What are effective strategies in engaging a diverse population of students in their learning and sustaining their interest in the geosciences?
The geosciences have been known for having low numbers of underrepresented students participate and major in the field. In order to increase underrepresentation in the geosciences, and to assure success for all students, we must determine what strategies are most effective in engaging students and to effectively learn geoscience content.

Grand Challenge 3: Assessment: How can we measure student experiences in the geosciences through the lens of self-regulation, motivation and other components using the most cutting edge research technology and methodologies?
The GER field should utilize established assessment methods, tools, and instruments and build on the approaches that other disciplines (e.g., science education, psychology, learning sciences, etc.) have developed. Researchers should apply these methods and approaches to the specific learning needs of students within the variety of geoscience learning settings and contexts.

Grand Challenge 4: Educators: How support the geoscience community in learning and implementing classroom strategies that are known to be effective in supporting students affect, metacognition and self-regulation of learning?
Faculty guidance is vital for coaching students to be self-regulated learners. In order for Challenges 1 and 2 to be implemented broadly and successfully, instructors must be knowledgeable and comfortable using classroom strategies related to affect, metacognition, and self-regulation of learning.

Grand Challenge 1:

Student Skills: How do we support students in developing their ability to learn, self-regulate, and apply the skills and ways of thinking in the geosciences along the novice to expert continuum?

Rationale

Part of preparing students for careers and social/civic involvement after college, as well as contributing to students' academic success, is helping them acquire and hone skills beyond domain knowledge and technical skills. Students need adequate "soft skills" that help them succeed when working in teams, communicating information, and managing their own time and effort. Acquisition of such transferable learning skills is critical in helping students advance along the novice-expert continuum. Individually, these learning skills have been shown to be malleable, such as students' ability to self-regulate their learning (Schraw et al., 2006), effectively monitor their metacognitive processes (e.g., Nietfeld, Cao, & Osborne, 2006), and improve aspects of their affective responses to learning science (such as task value, e.g., Zapeda et al., 2015).

Direct instruction of learning strategies has been suggested as the most effective means of improving these student variables for science learning (e.g., Zapeda et al., 2015). Additionally, prior work has suggested that within the sciences, there is domain (i.e., discipline) specificity in the efficacy of certain self-regulated learning behaviors that warrant further investigation (Schraw, Crippen, & Hartley, 2006; Greene et al., 2015). While efforts have been made to characterize student abilities in other domain-specific applications via inquiry specifically related to student approaches to chemistry learning (e.g., Pintrich & Zusho, 2003, Zuscho, Pintrich, & Coppola, 2003), biology learning (e.g., Stanton et al., 2015), and physics learning (e.g., Zapeda et al., 2015), little focused work has been conducted to characterize and improve instruction of many of these skills as applied to the learning of the geosciences. This is not to say, however, that no attention has been paid to any of these endeavors. The construct of the affective domain in the geosciences has been elucidated (van der Hoeven Kraft, 2011) and reviewed (McConnell & van der Hoeven Kraft, 2011) in recent work. Future work should seek to similarly investigate students' approaches to the self-regulatory behaviors and metacognitive processes associated with geoscience learning. In addition, acquisition of such transferable skills is critical in helping students advance along the novice-expert continuum (Petcovic & Libarkin, 2007).

In addition, within education psychology, learning skills represent a separate but related construct seeking to understand how students can share their regulatory behaviors via a "Socially-Shared Regulation of Learning" (SSRL; Panadero & Järvelä, 2015 for a review), which can be described as a social-constructivist perspective on learning where students collaborate and work together to form new shared knowledge. Given the importance of collaborative work in the geosciences (both academically and professionally), inquiry into effective teamwork in the geosciences via SSRL would also serve the community.

Recommended Research Strategies

1. Since there have been few studies in the geosciences related to this field of study, there is a strong need to identify the self-regulatory and metacognitive skills that lead to student success in geoscience learning and to determine if these learning skills are similar or different than those identified in other domain specific fields (e.g., chemistry, biology).

2. Similarly, it is important to understand what sorts of skills those that are successful in the geosciences employ and to specifically isolate whether these skills are different between different populations along the novice-expert continuum.

3. Once it is clear what self-regulatory and metacognitive skills are needed by students to succeed in the geosciences, then it will be important to identify ways to support and implement classroom strategies aimed to develop these student skills.

4. Finally, in order to broader larger adoption and propagation of these approaches aimed to support student affect and development of self-regulatory and metacognitive skills, it will be important to design and assess interventions aimed to foster these skills in a variety of learning settings.

Grand Challenge 2:
Inclusion: What are effective strategies in engaging a diverse population of students in their learning and sustaining their interest in the geosciences?

Rationale
In order to increase representation of systemically non-dominant populations in the geosciences, and to ensure success for all students, we must determine what strategies are most effective in engaging students to effectively learn the geoscience content. Even more importantly, we must determine how students can connect to the content in a way that allows them to identify with the content and feel as though they belong within the geoscience community.

Self-regulated learning has origins in socio-cognitive processes, and as such has been hypothesized that it may vary across ethnic and cultural groups (McInerney, 2011). Towards this end, efforts have been made in other disciplines to characterize the experiences and self-regulatory behaviors of diverse populations during both general science learning and the learning of specific science disciplines (e.g., chemistry; Lopez et al., 2013; Tang & Neber, 2008). As students in the geosciences must utilize an important set of cognitive skills (e.g., spatial thinking and abstraction) to find success (e.g., to learn mineral crystallography or draw cross sections), a similar approach should be developed and enacted within the geosciences. Potential differences and/or barriers to students of diverse populations should then be targeted via interventions designed to maximize the potential for both success and equity across all populations.

In addition, there are barriers that exist within the classroom and the institution that need to be identified in order to develop strategies to support students in developing and maintaining interest and connection to the community. Though the generation and encouragement of situational interest in the geosciences is a diverse and nuanced construct that has been approached in recent work related to geoscience learning (van der Hoeven Kraft et al., 2011; LaDue & Pacheco, 2013; van der Hoeven Kraft, 2017). Future inquiry should seek to isolate potential (and/or differential) barriers to students' situational interest and how it can be sustained during course activities and instructional support. Additionally, if students can effectively learn the content, but are not supported or feel disconnected from the community, they will likely not persist regardless of their comprehension (Chang et al., 2014; Callahan et al, 2017). The strategies that emerge as a result of these potential barriers may look different across different populations and contexts, so future inquiry should seek to investigate and eventually attempt to mitigate potential barriers.

Recommended Research Strategies

1. Since self-regulatory learning has been hypothesized to vary among socioeconomic and ethnic groups, it is important to identify successful strategies that engage and support diverse student populations in the geosciences, and understand what, if any, barriers prevent such engagement.

2. Once a variety of self-regulatory learning approaches have been identified for specific populations it will be important to measure the impact of such developed strategies on student learning and equity across populations in the geoscience classroom.

Grand Challenge 3:

Assessment: How can we measure student experiences in the geosciences through the lens of self-regulation, motivation and affect using the most cutting edge research technology and methodologies?

Rationale

There currently exists established methods, tools, and instruments within and outside of the geoscience education community (e.g., educational psychology, science education, other discipline based education fields, and cognitive science) for measuring affect (for a geoscience perspective, see McConnell & van der Hoeven Kraft, 2011) and processes associated with self-regulated learning (Panadero, 2017). The GER field should leverage and build on these approaches and apply them to the specific learning needs of students as they are engaging with geoscience content and developing skill sets within the variety of geoscience learning settings. Both research grade instruments and surveys, as well as classroom level assessments for instructor use should be targeted.

With the advancements and increases in the technology available to assess student variables in real-time (e.g., classroom response systems, course management systems), focus should be paid to developing novel ways to *measure and record* students' self-regulation, metacognition, and affect during the course of geoscience learning. In addition, technological approaches to measuring these variables should be designed to *promote* self-regulation and metacognitive behaviors during geoscience learning (both in-class and potentially in the field). Directed feedback related to the success and relative frequency of learning strategy use during technology-based learning has been shown to be effective in fostering self-regulative behavior (e.g., Fernandez & Yemet, 2017), improving metacognitive thought (e.g., Callender, Franco-Watkins, & Roberts, 2016) and increasing performance of students (e.g., Fernandez & Yemet, 2017). Additionally, real-time measurements of student engagement through wearable skin conductance devices (known as galvanic skin response or GSR) have been made in geoscience classrooms (McNeal et al., 2014). This technology can perhaps support both students and instructors in their self-assessment of their learning and teaching. Consequently, future technology should be designed to assess students' learning process in addition to their level of content knowledge. Such instruments have the potential to yield more effective geoscience learning (and teaching).

Recommended Research Strategies

1. Given there are existing methods and approaches in other fields that can be leveraged by geoscience educators, it is important to explore the literature and expertise from fields outside the geosciences (education psychology, science education, cognitive science, other STEM discipline-based education fields) to ensure we are using the most valid, reliable, and up to date instruments, techniques, and methodologies.

2. To ensure these instruments and methodologies are valid within the context of the geosciences, tests (e.g., lab based studies) need to be conducted with appropriate populations and disciplinary content using these existing techniques and tools. After validation occurs, they can then be applied more broadly and used in geoscience classrooms and field environments.

Grand Challenge 4:

Educators: How support the geoscience community in learning and implementing classroom strategies that are known to be effective in supporting students affect, metacognition and self-regulation of learning?

Rationale

It should not be assumed that students arrive in geoscience courses with the ability to successfully self-regulate their learning or to use metacognitive strategies. Faculty guidance is vital for coaching students to be self-regulated learners as these skills are not guaranteed (e.g., Pressley & Ghatala, 1990) and in most cases must be explicitly taught to students for greatest effectiveness (Schraw & Gutierrez, 2015). In order for Grand Challenges 1 and 2 in this research theme to be implemented broadly and successfully, instructors must be knowledgeable and comfortable using classroom strategies related to affect, metacognition, and self-regulation of learning. With these skills at their fingertips, members of the geoscience community will be a valuable resource for students who are not familiar with (or even aware of) strategies to take control of their own learning.

Instructors' self-efficacy for teaching both the science content *and the learning strategies* has been isolated as an important factor in the instructor's decision to provide students opportunities for self-regulation and metacognitive support (Schraw, Crippen, & Hartley, 2006). As a result, dissemination of effective, yet accessible, approaches to teaching learning strategies as related to the geosciences should be addressed. These dissemination strategies may include faculty professional development, such as face-to-face workshops and webinars, and published research studies that focus on adoption strategies in various learning environments. Other options include content-based activities that are specifically designed to include built-in pedagogical support of students' self-regulation and metacognition (e.g., reflection exercises, self-regulatory prompts).

Barriers to helping instructors learn about these strategies can be psychological (e.g., instructors' resistance to change/lack of interest), institutional (e.g., lack of support to make changes by administrators), and logistical (e.g., no time/funds to attend professional development workshops). Regardless of these potential barriers, however, effective professional development (e.g., On the Cutting Edge) has been shown to impact the diversity of teaching practices educators employ, with even one-time participation in a workshop with peers leading to changes in teaching practice (Manduca et al., 2017) or teaching beliefs (Chapman, 2017). Though these results were largely in relation to the adoption of active learning strategies and/or the development of reformed teaching beliefs, one may assume that similar change may be elicited via professional development more targeted towards the adoption of practices that specifically support the self-regulatory, metacognitive, and affective aspects of students' learning in the geosciences. Furthermore, this assumption of transferability can be an additional direction of future research.

Recommended Research Strategies

Since the instructor needs to guide the learner in developing self-regulatory and metacognitive skills, it is important that we better understand the geoscience practitioner and administrator community and how to support the implementation of these skills by instructors in their classrooms.

To accomplish this task, three strategies have been outlined below:

1. Determine the relationship between attitudes about and adoption of approaches that support student development of self-regulation, metacognition and affect across different members of the geoscience community (practitioners and administrators) from those that represent both formal and informal learning environments.

2. Take inventory of faculty professional development programs inside and out of the geosciences that have been successful in employing self-regulation, metacognition, and affect in their pedagogical contexts and leverage successful approaches and dissemination methods in order to best support geoscience educators in adopting these approaches.

3. Design, implement, and evaluate professional development programs which aim to develop teaching and learning strategies that incorporate supporting student self-regulation, metacognition, and affect for all geoscience educator ranks/positions (e.g., Teaching Assistants, Post-Doctoral Scholars, Instructors, Faculty, Administrators, etc.) and learning settings (e.g., community colleges, Historically Black Colleges and Universities, Minority Serving Universities, Primarily White Institutions, Four-Year Intuitions, Research Universities, etc.).

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Figures

Figure 1.
Provenance: Karen McNeal, Auburn University Main Campus

Research on Institutional Change and Professional Development

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Introduction

Over the past 20 years, numerous institutions and groups have repeatedly called for changes in undergraduate STEM education in the United States in order to develop a stronger, more diverse STEM workforce, to foster a more scientifically literate society, and to improve equitable access to education for all. We now know that students frequently leave science majors because of instructional experiences and lack of advising and mentoring, rather than because they lack the ability to succeed (e.g., Griffith, 2010; Seymour & Hewitt, 1997). Pressing environmental and societal challenges require additional geoscience majors from a wider range of backgrounds, well-prepared K-12 Earth science teachers, and a scientifically-literate citizenry. To achieve these goals, geoscience education must make substantial improvements in areas as broad as instruction, mentoring and advising, and departmental climate. Our ability to change can be supported by a better understanding of how educators, departments, and institutions change and how professional development opportunities foster and support productive change.

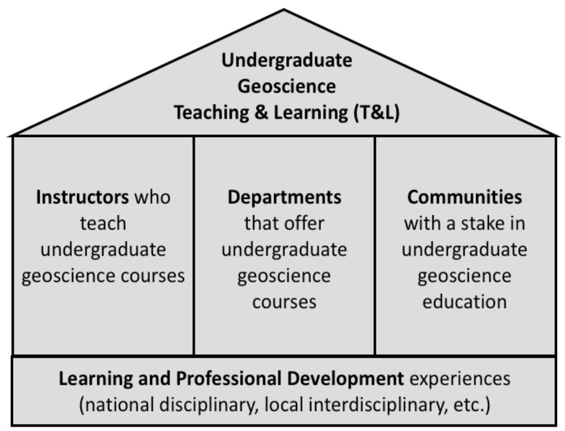

Figure 1: Instructors, departments, and communities are influenced by a variety of learning and professional development experiences, coming together to inform and enact undergraduate geoscience teaching and learning experiences.

Undergraduate geoscience education brings together students' experience in the classroom, field, and laboratory, in co-curricular activities, and in the formal and informal interactions among students, faculty, staff, and administration. Improvements in geoscience education require change in this complex system. Here we consider how future GER can address issues of change in institutions of higher education and professional development that will promote high-quality geoscience education. Specifically, we focus on three components with the potential to influence geoscience education: the individual geoscience instructor, the departments and programs in which geoscience instructors teach, and the broader communities in which these departments operate (Figure 1).

Drawing on this context and the strong research base in institutional change and education-related professional development, we identified the three Grand Challenges (below) to guide research on institutional change and professional development in the geosciences.

Grand Challenges

Grand Challenge 1: How can we best support the continual growth of geoscience instructors' ability to teach effectively and implement research-supported teaching practices as they progress in their practice? How does the individual's cumulative experience, position type, institutional context, and the nature of the desired learning impact the type of learning opportunities that are most effective?
Instructors design and implement learning experiences, interact individually with students and manage classroom climate, and are commonly on the front lines of mentoring and advising. As we seek to broaden participation and accelerate change, further work is needed to understand how an instructor's personal history and identity interact with departmental, institutional, and disciplinary context and culture to motivate and sustain continual geoscience instructor growth and learning.

Grand Challenge 2: How can departments and programs support continuous improvement in undergraduate geoscience education?
Healthy geoscience departments and programs can be conceptualized as complex systems in which new and potentially valuable ideas about teaching and learning enter the system continuously and are discussed, experimented with, and implemented freely. Further work will need to clarify factors contributing to department or program health from both within (departmental climate) and beyond the department itself (e.g. academic advising, employers, disciplinary societies).

Grand Challenge 3: What roles do different types of professional development experiences play in promoting, facilitating, and sustaining ongoing evolution in geoscience instructors' teaching practices over time?
Geoscience educators have a rich palette of ways to learn and improve their practice, including on-campus interdisciplinary professional development, geoscience-specific opportunities offered by professional societies, in-department trainings, and national community of transformation meetings, as well as formal and informal exchanges.with peers. Changes in practice over time that may follow these learning experiences are often non-linear and multi-directional, and must be further explored.

Grand Challenge 1:

How can we best support the continual growth of geoscience instructors' ability to teach effectively and implement research-supported teaching practices as they progress in their practice? How does the individual's cumulative experience, position type, institutional context, and the nature of the desired learning impact the type of learning opportunities that are most effective?

Rationale

Instructors play a central role in the students' geoscience education. Instructors design and implement learning experiences, interact individually with students and manage classroom climate, and are commonly on the front lines of mentoring and advising. Thus, professional development supporting their growth is a first-order strategy for improving geoscience education. Prior work has demonstrated that identity, motivation, context, the design of professional development, and participation in a supportive community all impact an instructor's learning and willingness to make changes in their practice (Andrews & Lemons, 2015, Condon et al., 2016; Chapman & McConnell, 2017; Gehrke & Kezar, 2016; Henderson, Beach, & Finkelstein, 2011; Kastens & Manduca, 2017; Kastens & Manduca, 2018; Pelch & McConnell, 2016, Yerrick, Parke, & Nugent, 1997). In the past 15 years, many faculty have participated in both institutional and disciplinary professional development opportunities, but others have not; practices have changed, but practices across the community have not been transformed (Manduca et al., 2017).

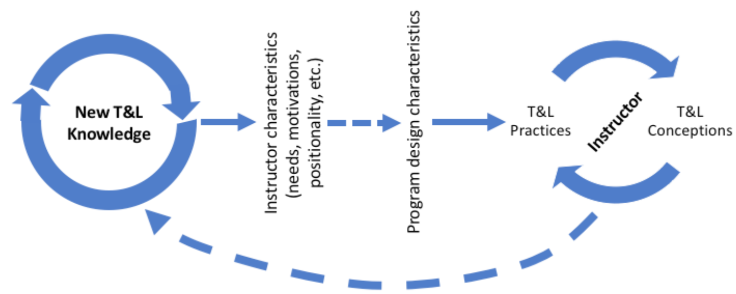

Figure 2: New knowledge about teaching and learning (T&L) generated by GER and other learning science fields is continuously generated. Uptake of that knowledge is filtered by an instructor's needs, motivations, and positionality, and is influenced by characteristics of the professional development program(s) in which the instructor learns about that new knowledge. The instructor may also produce and disseminates new knowledge.

As we seek to broaden participation and accelerate change, further work is needed to understand how an instructor's personal history and identity interact with departmental, institutional, and disciplinary context and culture to first motivate learning and then support change (Figure 2). While prior research has largely focused on single professional development programs, further work is needed to understand how an individual's learning and change are supported by multiple experiences. Preliminary evidence also suggests that different types of learning may require different types of engagement: for example, beliefs about teaching may be relatively difficult to change (Yerrick, Parke, & Nugent, 1997) but can be effectively targeted through collaborative and authentic long-term engagement (Pelch & McConnell, 2016), while changes in practice that are consistent with the beliefs already held by a participant might be easier to achieve (e.g., Glackin, 2016). Further work is also needed to investigate the most effective strategies to motivate and sustain continual geoscience instructor growth and learning of various types.

Recommended Research Strategies

1. Conduct longitudinal studies of individual geoscience instructors representing a variety of identity characteristics and institutions, with special attention to how they make decisions about potential instructional learning and change over time, and what motivational factors are at play.

2. Conduct interviews with geoscience professional development leaders and review existing literature to identify common learning objectives for geoscience instructors. Convene a small working group to sort those objectives according to the cognitive processes, level of challenge, and type of change required to provide a typology of learning objectives.

3. Based on the typology of learning objectives, identify or design assessment measures for each category. Recommend the use of those assessment instruments across future professional development programs to allow consistent comparisons and future meta-analyses.

4. Construct and widely-administer a survey designed to develop a broader picture of the teaching-related needs among a diverse geoscience instructor population (e.g., gender, race, ethnicity, socio-economic status, type of employment/position, career stage, etc.).

5. Conduct longitudinal studies of individual geoscience instructors representing a variety of identity characteristics and institutions, with special attention to how they make decisions about potential instructional learning and change over time, and what motivational factors are at play.

6. Evaluate the impact that existing types of professional development programs have on supporting diverse geoscience instructors in changing their choice and implementation of instructional strategies using longitudinal multi-case studies on programs' impact on instruction.

Grand Challenge 2:

How can departments and programs support continuous improvement in undergraduate geoscience education?

Rationale

Undergraduate geoscience content is taught in a wide variety of departments and programs beyond only traditional geoscience or geology departments, including physical science departments at community colleges, departments focused on ocean, atmospheric science, and environmental science, and even embedded within courses taught by departments such as sociology and engineering. All of these departments and programs can be conceptualized as complex systems comprised of instructors, students, staff, and administrators, as well as curricula, courses, and assessment mechanisms, as well as physical structures such as classrooms and labs (Condon et al., 2016; Manduca, 2017). These systems support students' geoscience education, the professional environment of the instructor, and the long-term character and evolution of the degree program (Tobias, 1992; NASEM, 2016). Geoscience education research can assist departments, institutions, and professional development programs in understanding how these systems function to support students and instructors in learning.

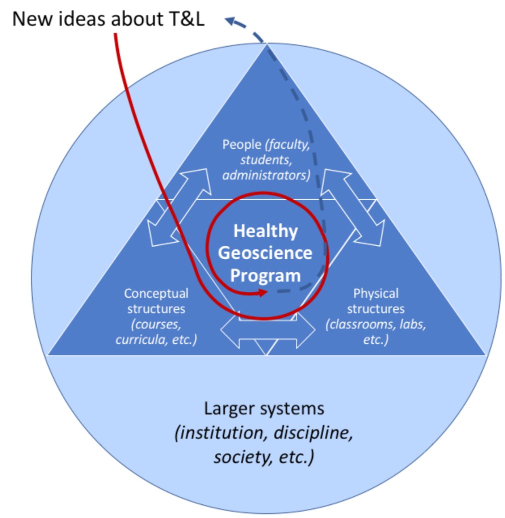

Figure 3: Geoscience programs are complex systems made up of humans, physical structures (e.g. classrooms/labs), and conceptual structures (e.g., courses, curricula). In programs with healthy teaching cultures, new ideas about T&L continuously enter the system with minimal impediment; new ideas about T&L also flow outward and back into the community. Teaching cultures are developed and maintained within the program, but are also influenced by various larger complex systems (institutions, disciplines) within which they are embedded.

Viewed from this systems perspective, in "healthy" departments and programs, new and potentially valuable ideas about teaching and learning enter the system continuously and are discussed, experimented with, and implemented freely (Manduca, 2017). A healthy department or program can respond and adapt quickly to new challenges and opportunities, drawing on this capacity for learning. Considerations affecting the health of the program include teaching-related rewards structures; resources and opportunities for professional development; collegiality among faculty, students, and staff; leadership; and other factors (Andrews et al., 2016; Walter et al., 2014).

While each geoscience department or program is a system unto itself, it is embedded within larger systems such as the college, institution, discipline and its component professional organizations, and local, national, and global societies, all of which exert various types of influences on the health of a department or program. Furthermore, individuals from a department or program may participate in communities of transformation that transcend individual disciplines (Gehrke & Kezar, 2016), and these ties may also contribute to systems health within a department or program. Thus, further work will need to clarify factors contributing to department or program health from both within (departmental climate) and beyond the department itself (e.g. academic advising, employers, disciplinary societies). An understanding of the departmental system and its response to both internal and external influences is foundational to sustaining the highest-quality geoscience education. This Grand Challenge is summarized in Figure 3.

Recommended Research Strategies

1. Collaborate with and draw upon the work of organizational psychologists who study workplace climate to conduct mixed-methods case studies describing the health of a variety of geo-science programs, including measures of departmental climate (e.g., Walter et al., 2014) and interviews with students, alumni, faculty (full- and part-time), staff, and administrators that seek to determine their perceptions of internal and external influences on teaching and learning information flow and changes in practice.

2. Based on those case studies, formulate hypotheses about internal and external variables that appear to have the greatest impact on department or program health, and design quantitative survey instruments to test those hypotheses across a representative subsection of geoscience departments and programs in the U.S.

3. Investigate how departments and programs that support high-quality undergraduate geoscience teaching evolved to that state. Longitudinal multi-case studies of departments and program from the range of institutional types would aid in addressing this strategy.

4. Identify what chairs/heads of a diverse range of departments and programs need to foster a teaching culture that supports high-quality undergraduate geoscience education and the extent to which they think those needs are being met. A critical incident analysis of the chairs/heads experiences would assist the pursuit of this strategy.

5. Conduct social network analyses at a variety of scales within the geoscience education community, including departments and disciplinary societies, to identify the characteristics of change agents to understand of how those change agents support program health.

Grand Challenge 3:

What roles do different types of professional development experiences play in promoting, facilitating, and sustaining ongoing evolution in geoscience instructors' teaching practices over time?

Rationale

Geoscience educators have a rich palette of ways to learn and improve their practice. On-campus centers for teaching and learning typically involve participants from many disciplines, and typically focus on general teaching knowledge (Pallas, Neumann, & Campbell, 2017) and other issues that cross disciplines. Geoscience-specific learning opportunities, including those offered by NAGT, GSA, AGU, and NSF-funded programs (e.g., Manduca et al., 2017), typically focus on challenges and opportunities specific to the geosciences, including pedagogical content knowledge such as common misconceptions, pathways students follow in becoming geoscientists, and approaches to guiding geoscience learning (Pallas et al., 2017). In-department graduate teaching assistant training (Bitting, Teasdale, & Ryker, 2017), on-campus STEM centers (NSEC, 2017), and communities of transformation such as SENCER and PKAL (Gherke & Kezar, 2016) include a variety of hybrid models. Collaborative activities (e.g., co-teaching) and informal learning from peers interact with formal professional development (Condon et al., 2016). Over the arc of a career, instructors are likely to participate in multiple types of professional development and gain different benefits from each. Investigation into this mosaic of impacts will clarify the differential roles of each as well as the interaction effects that promote continual learning and growth underpinning improved practice (Figure 4).

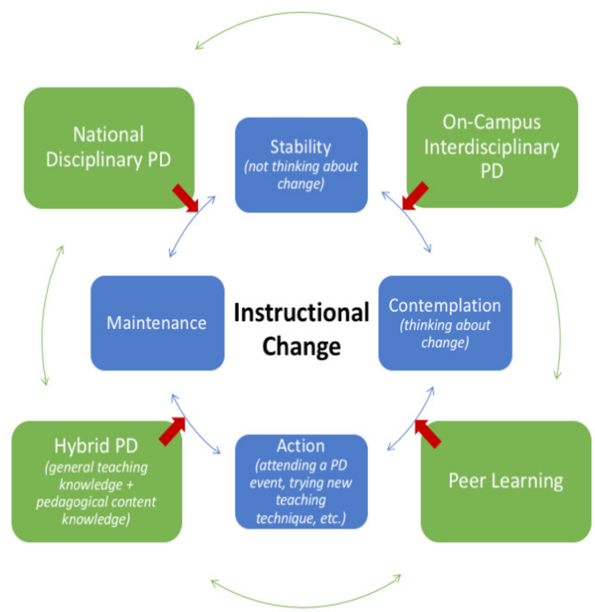

Figure 4: During one's career, learning about teaching & learning may take place via many types of experiences, including on-campus interdisciplinary professional development (PD) programs, national disciplinary programs, hybrid disciplinary-and-general teaching and learning programs, and peer interactions. These and other factors may influence instructor conceptions and practices in non-linear and complex ways, resulting in non-linear and complex changes.

Pathways through the change process (much like the rock cycle) can be non-linear and multi-directional (DiClemente & Velasquez, 2002). One instructor may participate in many different professional development experiences before deciding to experiment with a new practice, while another may incorporate small incremental changes based on each professional development experience as their thinking about teaching evolves, and another may transform their practice substantially after only one professional development experience. Future work must explore how teaching knowledge and practices change over time in non-linear ways (Manduca, 2017).

Recommended Research Strategies

1. In collaboration with and drawing upon existing work of educational psychologists, especially those who study K-12 teacher beliefs, conduct a longitudinal study following early-career geoscience instructors (graduate teaching assistants and early-postgraduates) for 10+ years to explore participants' growth and evolution in both teaching conceptions and practices, how they make decisions to pursue learning opportunities, and why they consider, adopt, and abandon or sustain changes in their practice. This strategy may be pursued in conjunction with longitudinal studies proposed under Grand Challenge 1, but those addressing Grand Challenge 1 would need to go beyond early-career instructors to capture the full range of identity and career characteristics that may be relevant.

2. Collaborate across institutions and disciplinary societies to develop and deploy common end-of-program instruments to identify different learning outcomes for instructors participating in professional development. Iteratively redesign these instruments at three- to five-year intervals, as hypotheses about relationships are formulated and reformulated with progressive analyses of the combined datasets. Using this dataset, analyze the pathways that instructors follow through multiple experiences, and the range and variety of characteristics of changes they choose to make as a result.

3. Design protocols for follow-up interviews and classroom observations with program attendees for use before and three, six, or 12 months after participation. Seek to determine how participants connect what they learned during the professional development program to their prior thinking and practice, whether they have implemented changes, and what elements of the program most strongly influenced their motivation, learning, and decision-making regarding the implementation of new practices.

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Figures

Figure 1.
Provenance: Leilani Arthurs, University of Colorado at Boulder

Figure 2.
Provenance: Kelsey Bitting, Northeastern University

Figure 3.
Provenance: Kelsey Bitting, Northeastern University

Figure 4.
Provenance: Kelsey Bitting, Northeastern University

Synthesis: Discussion and Implications

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This project was a formidable undertaking, necessary to position our community to achieve an important goal: to improve undergraduate teaching and learning about the Earth by focusing the power of Geoscience Education Research (GER) on a set of ambitious, high-priority, community-endorsed grand challenges (see Framework Development for a detailed description of the supporting project objectives). Working groups, through examination of the literature and with the aid of reviewers' insights, identified two to five grand challenges for each of the ten research themes. The thematic grand challenges illuminate interconnected paths for future geoscience education research (GER) that create a guiding framework to harness the power of GER to improve undergraduate teaching and learning about the Earth; This framework is represented by the abstract drawing in Figure 1.

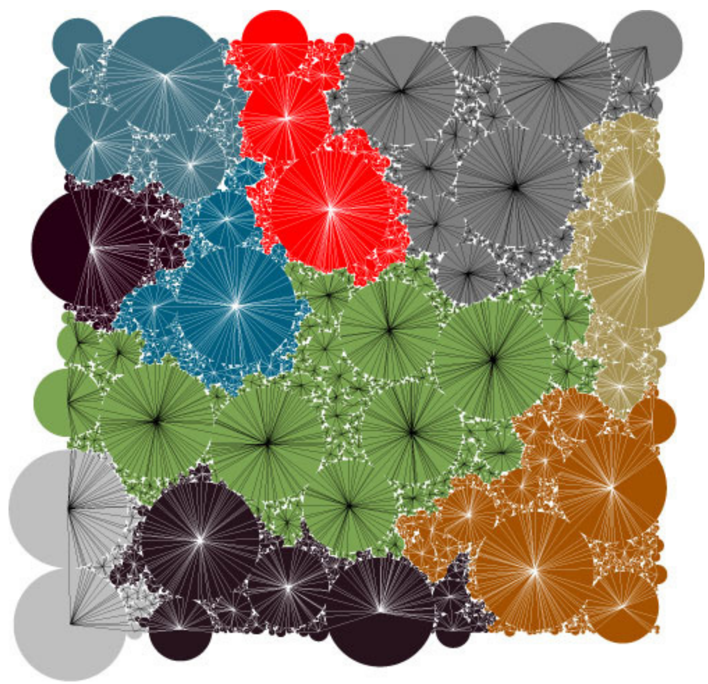

Figure 1. The thematic grand challenges illuminate interconnected paths for future geoscience education research (GER) that create a guiding framework to harness the power of GER to improve undergraduate teaching and learning about the Earth. In this drawing, colors represent different themes, and the strands are the interconnected paths of research. The drawing, Constellations no.5, was designed by architects Andrew Kudless and Laura Rushfeldt, 2006 (https://www.matsys.design/constellations) and is used with their permission.

While the individual theme chapters lay out the rationales for those large-scale "grand challenge" research questions and offer strategies for addressing them, here the purpose is to summarize and synthesize - to highlight thematic research priorities and synergies that may be avenues for research efficiencies and powerful outcomes.

Thematic Research Priorities at a Glance

The nature of the thematic grand challenges articulated by each working group (WG) is a reflection of the state of research knowledge and practice in that area, as well as a projection of research needs and opportunities going forward. Collectively, this document lays out a prioritized geoscience education research

agenda. It aims to be a catalyst for action - for getting important work done. The following are key take-away points from each of the theme chapters (Table 1), and links to each of the chapter descriptions are provided.

	Research on:
1	Students' Conceptual Understanding of Geology/Solid Earth Science Content
2	Students' Conceptual Understanding of Environmental, Oceanic, Atmospheric, and Climate Science Content
3	Elementary, Middle, and Secondary Earth and Space Sciences Teacher Education
4	Teaching about Earth in the Context of Societal Problems
5	Access and Success of Under-represented Groups in the Geosciences
6	Cognitive Domain in Geoscience Learning: Spatial and Temporal Reasoning
7	Cognitive Domain in Geoscience Learning: Quantitative Reasoning, Problem Solving, and Use of Models
8	Instructional Strategies to Improve Geoscience Learning in Different Settings and with Different Technologies
9	Geoscience Students' Self-Regulated Learning, Metacognition, and Affect
10	Institutional Change and Professional Development

Table 1. Themes that span the spectrum in which GER operates and have the potential to impact undergraduate geoscience teaching and learning.

1. Research on Students' Conceptual Understanding of Geology/Solid Earth Science Content (WG1):

While more work needs to be done on identifying and correcting student misconceptions of geology/solid Earth concepts, a foundation already exists to also tackle another large-scale challenge: determining optimal learning progressions (i.e., conceptual scope and sequence) for undergraduate geology degree programs - from introductory and cognate sciences through upper level course work - to best support growth in conceptual understanding and career preparation. Such learning progressions would coordinate well with work done in K-12 on Earth science learning progressions (especially the Framework for K-12 Science Education and the related Next Generation Science Standards [NGSS]; NRC, 2012, NGSS Lead States, 2013), as well as outcomes from the Summit on the Future of Undergraduate Education (Mosher et al., 2014). This research theme highlights the important point that the current undergraduate curriculum in the geosciences follows a general pattern that is guided largely by faculty expertise, as well as workforce expectations, but rarely takes into account students' prior knowledge and naïve understanding of solid Earth concepts. There is scant empirical evidence to support the notion that a traditional construct for undergraduate geoscience curricular design meets the needs of geoscience majors (including pre-service secondary education teachers [WG3]) or non-majors. In addition, while this working group focused on the future education research on teaching and learning of solid Earth/geology, there was also clear emphasis of how the solid Earth fits within broader Earth system thinking and the need to link to other Earth system components (e.g., WG2).

2. Research on Students' Conceptual Understanding of Environmental, Oceanic, Atmospheric, and Climate Science Content (WG2):

Recommended research in this theme focuses on both identifying and overcoming students' misconceptions of each of the more "fluid" (non-solid Earth) components of the Earth system, and how to more effectively teach about the complex interconnectedness of these components. The recommended research emphasizes the need to expand education research in the environmental, oceanic, atmospheric, and climate sciences, which historically has lagged behind similar research on geology/solid Earth concepts. Increased research attention on conceptual understanding of these parts of the Earth system means a more integrated approach in other ways too, including examination of how tools, such as models (e.g., Global Circulation Models) essential to teaching integrated concepts, are best used, and how the path and identity of the learner impact student learning about the Earth system sciences. New research directions will depend on adapting and/or developing new instruments (e.g, perhaps with the Fundamentals in Meteorology Inventory assessment exam as one starting point; Davenport, Wohlwend, & Koehler, 2015), and can capitalize on existing content frameworks, such as the Climate Literacy Principles (USGCRP, 2009) or the Summit outcomes (Mosher et al., 2014), as compilations of the big ideas to organize research on common misconceptions.

3. Research on Elementary, Middle, and Secondary Earth and Space Sciences (ESS) Teacher Education (WG3):
Teacher education research, including research on ESS teacher education, has historically developed in isolation from research on undergraduate geoscience education. This working group considered the challenges unique to undergraduates preparing to teach ESS across grades K-12, and identified several themes that link to those identified by other working groups. Grand challenges for future research include attracting, supporting, and retaining a greater number of, and a more diverse population of, future K-12 ESS teachers who can effectively engage diverse K-12 learners, and identifying effective models for incorporating ESS into undergraduate K-12 teacher preparation that successfully promote the three-dimensional learning (i.e., science and engineering practices, crosscutting concepts, and disciplinary core ideas) of the NGSS (NRC, 2012). In order to fully realize a diverse and well-prepared K-12 ESS teacher workforce, teacher education research must also recognize the complex landscape in which teacher education takes place, involving an interplay of programmatic, institutional, demographic, political, state, and national factors.

4. Research on Teaching about the Earth in the Context of Societal Problems (WG4):
The use of societal problems for teaching about the Earth highlights a potentially effective context for teaching that supports needs identified in AGI's report on Geoscience for America's Critical Needs (2016), and can build upon two recent large-scale initiatives: the InTeGrate project and the Summit on the Future of Undergraduate Geoscience Education (Mosher et al., 2014). These may provide the initial platforms and/or potentially large datasets to robustly investigate how such a teaching approach impacts student learning and student motivation to learn about the Earth. Successful research outcomes will also depend on the identification and/or development of assessments to measure the efficacy of these approaches. In addition, issues of both theory and practice should be studied to understand the optimal design principles of curricula that integrate geoscience content within the context of societal issues.

5. Research on Access and Success of Under-represented Groups in the Geosciences (WG5):
As geoscience programs seek to broaden participation and reach more diverse audiences, two broadly interdependent and complimentary research perspectives are recommended in the construction and assessment of innovations. These two paths build on the modern theories of multicontextuality and intersectionality in diversity, and on the active and supportive perspective of "attracting and thriving", over the more passive "recruiting and retaining" (Ibarra, 2001, 1999).

These aim to determine how to support the individual identities and personal pathways of students as they are attracted to and thrive in the geosciences, and how to create solutions that capitalize on different scales of efforts to broaden participation that are appropriate to the situations and communities. Research addressing these grand challenges in geoscience education directly connects to challenges of diversification across STEM fields that were outlined in the National Academies report on "Expanding Underrepresented Minority Participation" (2011).

6. Research on Cognitive Domain in Geoscience Learning: Temporal and Spatial Reasoning (WG6):
While research on spatial thinking already has a well-established foundation (e.g., SILC), the research priorities laid out here give a clear, multi-step path for identifying and supporting the development of temporal and spatial reasoning skills expected of geoscientists. A first step is to determine how spatial and temporal reasoning skills correlate to specific tasks essential to different specialties within the geosciences. Then it is important to empirically test whether these tasks actually draw on the spatial and temporal reasoning skills that were mapped. This process will require examination of current measures of spatial and temporal reasoning to determine if they accurately assess the skills of interest, and also the development of new assessments, if needed. Outcomes can then be used to develop strategies for geoscience educators to foster spatial and temporal reasoning skills in each specialty area.

7. Research on Cognitive Domain in Geoscience Learning: Quantitative Reasoning, Problem Solving, and Use of Models (WG7):
Similar to WG6, the research here focuses on understanding and developing habits of mind important to geoscientists. One research priority is to learn how quantitative thinking helps geoscientists and citizens (i.e., general education students) better understand the Earth and how geoscience educators move students towards these competencies. There are rich opportunities to link future work in this area to mathematics education research. A second research priority is to determine how using big data and emerging technologies can help students find and solve problems that they care about concerning the Earth. That this challenge is both about identifying problems, as well as solving them, highlights the need to help learners confront the reality of complex, messy, ill-defined problems, which may be quite different from narrowly constrained problems they may have become accustomed to in their science classes and labs. Third, research is needed to address how we can help students understand the process by which geoscientists create and validate a wide range of models (e.g., conceptual to computational) and use them to generate new knowledge about the Earth.

8. Research on Instructional Strategies to Improve Geoscience Learning in Different Settings with Different Technologies (WG8):
Research for this theme aims towards more effective, accessible, inclusive, relevant, and practical geoscience teaching and learning. Five challenges highlight different aspects of instruction, and research on all of these challenges will benefit from greater partnership between geoscience education researchers and practitioners. Because the pace and the excitement of technological and methodological advances in education (and in the geoscience workforce) tend to outstrip the more deliberate progress of relevant educational research and assessment, finding ways to close the research gap is a first-order research priority. This work will require researchers to maintain vigilance of innovations in technological and methodological strategies for teaching in other fields and other

domains (e.g., free-choice or informal STEM education) as well as in the geosciences, and testing across instructional contexts. As instructional practices and settings of undergraduate geoscience instruction also evolve, researchers need to determine what works best for the greatest range of learners. This will also mean identifying and overcoming structural barriers that impede effective teaching and learning. Lastly, research that explores the role of the learner as a co-discoverer of knowledge and a co-creator of new instructional strategies will fill in gaps in our understanding of the design of mentored research and course-based research experiences (CUREs), and will also give attention to new ways of student-centered active learning that have been proposed in the context of other disciplines but have not yet been tested in geoscience education.

9. Research on Geoscience Students' Self-Regulated Learning, Metacognition, and Affect (WG9):
One important take-away about this theme is that it is not getting enough attention overall in the geosciences. Very little research exists on how students' self-regulation, metacognition (i.e., reflection on what they know, what they don't know, and what they need to do to improve), and affect (i.e., emotional response) can enhance (or inhibit) their ability to navigate tasks within the geosciences. Focusing research to help geoscience educators better support students in developing the ability to self-regulate their learning and metacognition, should also result in movement along the novice to expert continuum. In addition, more research is needed to understand the role that affect may play in determining effective strategies for engaging a diverse population of students and sustaining their interest in the geosciences. Research success in all of these areas will depend on identifying (e.g., RTOP) and/or developing robust research-grade instruments and surveys, as well as classroom-level assessments for instructor use, which also may include incorporating new research technologies to assess and record student variables in real-time.

10. Research on Institutional Change and Professional Development (WG10):
Recommended research in this area addresses important challenges in the landscape in which instructors work and in which undergraduate geoscience teaching and learning happens. Research on professional development programs has a long and robust history (e.g., On the Cutting Edge program in the geosciences; Manduca et al., 2017). Building on Manduca (2017), we recommend a new lens for professional development research - where the faculty member is viewed as the learner, and we research ways to support that learner over time. Seen through this lens, there is a need for longitudinal studies that focus on continual growth of geoscience instructors - in their ability to teach effectively and implement research-supported teaching practices, as well as on how their personal histories and identities interact within the larger institutional context. Research is also needed on the roles that different types of professional development experiences play in geoscience instructors' evolving teaching practices over time. Lastly, borrowing from the systems approach to teaching about the Earth, we might re-conceptualize geoscience departments and programs as complex systems too, and through research identify the factors and feedbacks that create and sustain healthy undergraduate geoscience programs.

Synergies Across Multiple Themes

The 10 theme areas of GER do not stand in isolation from each other. As described in the Framework Development chapter, these themes emerged from the review of several reports, discussions, and survey feedback (Manduca, Mogk, & Stillings, 2003; Lewis & Baker, 2010; Kastens & Manduca, 2012; NRC, 2012b; the 2015 GER workshop; and 2017 GER survey). These sources of information provided working groups with perspectives on the role of education research, and GER specifically, in improving undergraduate teaching and learning, and on what areas of research are garnering the attention of researchers. The 10 themes have distinct-enough characteristics to offer organizational structure and research sub-discipline "homes" for investigators; nevertheless these themes also interconnect. Out of the fuzzy boundaries of the themes emerge opportunities for research synergies across multiple themes (Figure 2).

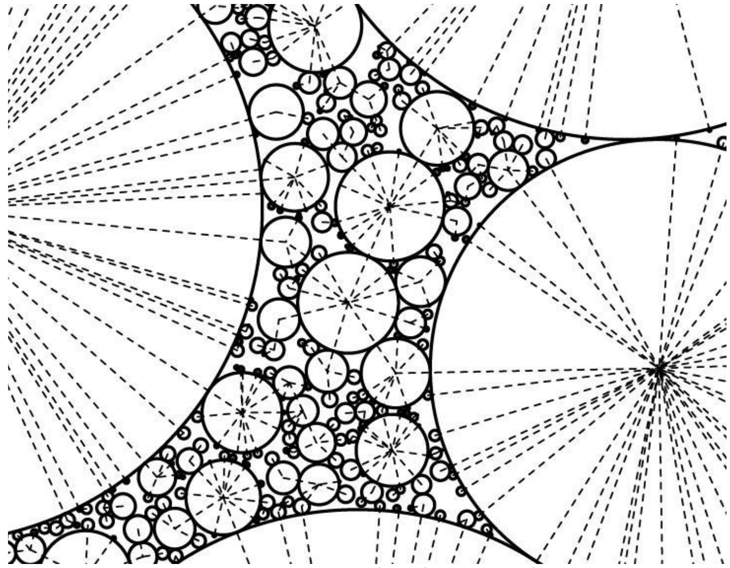

Figure 2. Chemical bonds are used as analogies for different types of connections that link research themes. The drawing, "Constellation no. 2, detail" is by Andrew Kudless and Laura Rushfeldt (https://www.matsys.design/constellations) and is used here with their permission.

One way to get a first-order understanding of the opportunities for research synergy among the themes is to categorize the types of connections between themes. Three types of connections emerged based on a review of the rationales for the thematic grand challenges and their recommended research strategies. Each type of connection is important, and no hierarchy exists among them. These are perhaps best understood by analogy to chemical bonds. In chemical bonds electrons are transferred or shared, or are held by electrostatic attraction; the bonds are the forces that connect atoms and molecules together. The three types of connections between geoscience education research themes can therefore be thought of as being like three main types of chemical bonds - covalent, ionic, and hydrogen bonds:

- A strong sharing of research foci or process is like covalent bonding between atoms.
- A supportive, give-and-take research connection is like ionic bonding between atoms.
- A dispersed research connection at a larger level is like hydrogen bonds between water molecules.

A simplified correlation matrix (Table 2) of the 10 themes uses colors to represent these different types of research connections. A summary of these research connections is described below, and a DETAILED CORRELATION MATRIX is accessible in the Downloadable Spreadsheet. In addition, we encourage researchers to read in detail the theme chapters that align with their areas of interest and use those as a foundation for designing targeted research studies that address questions of high importance to the geoscience education researcher and practitioner community.

Themes with Strong Research Connections: Covalent Bond Analogy

A few themes have strong research connections (shown in yellow in Table 2), some of which result from our "splitter" vs "lumper" approach in defining themes for this project. As noted in the Framework Development chapter, although there is widespread interest in teaching with an Earth

Geosci Edu Research on:	1. Concepts: Geology/ Solid Earth	2. Concept: Ocn-Atm-Env-Clim	3. K-12 Teacher Edu	4. Special Context: Societal Problems	5. URG Access & Success	6. Cognition: Temp & Spatial	7. Cognition: Quant-Probl-Models	8. Instruct Strategies	9. SRL-Metacog-Affect	10. Institu Change & Prof Dev
1. Concepts: Geology/ Solid Earth	grey	yellow	light blue	pink	pink	light blue	light blue	pink	pink	light blue
2. Concepts: Ocn-Atm-Env-Clim	yellow	grey	light blue	pink	pink	light blue	yellow	pink	pink	light blue
3. K-12 Teacher Edu	light blue	light blue	grey	yellow	pink	light blue	light blue	yellow	light blue	light blue
4. Special Context: Societal Problems	pink	pink	yellow	grey	pink	light blue	light blue	yellow	pink	light blue
5. URG Access & Success	pink	pink	pink	pink	grey	pink	pink	pink	pink	light blue
6. Cognition: Temp & Spatial	light blue	light blue	light blue	light blue	pink	grey	yellow	pink	light blue	light blue
7. Cognition: Quant-Probl-Models	light blue	yellow	light blue	light blue	pink	yellow	grey	pink	light blue	light blue
8. Instruct Strategies	pink	pink	yellow	yellow	pink	pink	pink	grey	pink	light blue
9. SRL-Metacog-Affect	pink	pink	light blue	pink	pink	light blue	light blue	pink	grey	light blue
10. Institu Change & Prof Dev	light blue	light blue	light blue	light blue	light blue	light blue	light blue	light blue	light blue	grey

yellow	= Strong sharing of research foci or process; analogy is covalent bonding between atoms.
pink	= Supportive, give-and-take research connection; analogy is ionic bonding between atoms.
light blue	= Dispersed research connection at larger level; analogy is Van der Waals forces between molecules.

Table 2. Simplified correlation matrix that uses color to show research relationships among the 10 themes. A more detailed correlation matrix that includes brief descriptions of the research relationships can be downloaded (see link to Excel file).

system science perspective, much of the published research in students' conceptual understanding lies in (Working Group [WG] 1) geology/solid Earth concepts, (unintentionally) resulting in less emphasis on the other parts of the Earth system. Therefore we deliberately choose to split research on students' conceptual understanding into two working groups to give visibility to the need for more research on environmental, oceanic, atmospheric, and climate science content (WG2). Nevertheless, conceptual understanding of Earth systems requires an integrated understanding of all system spheres. The two themes share strong research foci on identifying and addressing misconceptions, and on developing Earth-system interconnections.

Strong research synergies also exist between the two themes that focus on cognitive domain (WG6 and WG7) because all cognitive domain research involves study of how students think - how they acquire, process, and make use of knowledge. While WG6 focused on research on temporal and spatial reasoning, and WG7 focused on research on quantitative reasoning, problem solving, and use of models, these cognitive tasks are often intertwined. In particular, many spatial and temporal tasks involve use of models and have related quantitative learning goals. For example, a general understanding that some Earth phenomenon varies upstream to downstream, or offshore to onshore, or in urban vs rural settings can be mathematicised into a quantitative gradient. A general understanding that sometimes an Earth phenomenon is fast and sometimes it is slow can be mathematicised to a quantitative measure of rate. Rate and gradient look like simple math, but they are powerful concepts in geosciences, that once mastered can be used again and again. Understanding how to harness that quantitative power is a challenge for education researchers to tackle. A related strong research connection exists between WG2 with WG7: models and quantitative reasoning are used to represent and understand properties and changes in the environment, ocean, atmosphere, and climate to better understand the Earth system, and to make predictions. Research on problem-based learning for teaching about complex issues such as climate change, and on the use of models to teach about concepts in atmospheric, oceanic and climate sciences were specifically raised as grand challenges by both working groups.

While the research connections above were anticipated, others were more surprising, perhaps because they involve themes that were generally not included in previous formal discussions of undergraduate geoscience education research needs (see Table 2 in Framework Development chapter), such as the connection between research on K-12 teacher education (WG3) and research on teaching about the Earth in the context of societal problems (WG4). Research on reformed teaching practices, including teaching in the context of societal problems at the undergraduate level may support the development of future teachers' pedagogical content knowledge, and help support teacher recruitment and retention efforts. In addition, the K-12 Next Generation Science Standards (NGSS; NRC 2012a; NGSS Lead States, 2013) explore the use of transdisciplinary approaches, meaning our future college students will bring those skills, experiences, and content knowledge to our classrooms. Similarly, students coming into our geoscience courses may be familiar with societal issues in their local community, proving an opportunity to explore geoscience-society connections. This connects to research on instructional strategies (WG8), in particular place-based learning, and therefore may have good linkages to co-investigate.

Themes with Supportive, Give-and-Take Research Connections: Ionic Bond Analogy

Many themes have supportive, give-and-take research connections (shown in pink in Table 2). Some of these connections are common to multiple themes because they link characteristics about the learner to approaches to curriculum and instruction. Metrics of success for learning any geoscience content (WG1 and WG2), skill (WG6 and WG7), or disposition (WG9) may depend on the situational context: the instructional strategies, the setting, and the technology used (WG8). For example, targeted instructional approaches should be investigated to assess if and how these interventions support the development of spatial reasoning, temporal reasoning, quantitative reasoning, problem solving, and modelling skills.

Metrics of success for learning any geoscience content (WG1 and WG2), skill (WG6 and WG7), or disposition (WG9) may also depend on the whole experience, identity, and pathway of the learner (WG5). For example, research on what learning experiences can help students with poor math preparation or attitudes have an experience where they can feel the power of math to answer questions or solve problems they care about concerning the Earth (and develop the self-efficacy to persist in learning to use math as a tool to do so) has the potential to help many students, and may help with underrepresented student groups' access and success.

The pathways and identities of students (WG5) also affect their self-regulated learning, metacognition, and affect (WG9), which in turn affect likelihood of being attracted to and thriving in the geosciences. Given how the geosciences touch the lives of all people, it should also be a field that is representative of all people, but this is not yet the case. It is important to determine how we can construct learning environments that help all students identify with the content and feel as though they belong within the geoscience community.

In addition, we must determine how students can connect with the content and apply their classroom learning to support real-world decision making. It is important for students to know not just what we know, but how we know it, why it is important, , and how it applies to their own lives and the lives of those around them. Risks of poor understanding of geology, environmental, ocean, atmospheric, and climate concepts (WG1, WG2) are non-trivial, ranging from the economic costs of commodities and energy to the potentially fatal impact of hazards - these are societal problems (WG4). Teaching with societal problems may be a mechanism to increase student interest (WG9) in the geosciences. In addition, teaching using societal problems may be especially important for teaching students about the sources and reliability of data (WG7) in considering issues they may see in the news, and may also be important when considering ways to develop geoscience learning progressions (WG1).

There are also parallel research challenges in different themes that can be opportunities for more coordinated research. Many of the challenges in recruiting, preparing, and retaining a diverse K-12 ESS teacher workforce (WG3) parallel issues of diversity and inclusion broadly in the geosciences (WG5).

Themes with Dispersed Research Connections at a Larger Level: Hydrogen Bond Analogy

While hydrogen bonds are considered weak or less "connected" compared to covalent or ionic bonds, they are actually quite important, especially between water molecules. They help create the medium through which all other chemical reactions take place and allow the transport of dissolved constituents from one place to another. In our analogy, like hydrogen bonds, the connections between some geoscience education research themes are more dispersed and happen at a large scale (shown in blue in Table 2). And like hydrogen bonds between water molecules, such research connections are important, giving critical structure to research and opportunities for movement of ideas and results within geoscience education.

This analogy is especially true for connections between institutional change and professional development (WG10) and the other themes. Research on supporting instructors' growth through professional development, and on building structural supports that foster effective teaching and learning, impact all of the other themes. This relationship exists is because instructors play a central role in the students' geoscience education: they design and implement learning experiences to teach content, skills, dispositions; they interact individually with students and manage classroom climate; they mentor and advise. For example, barriers to helping instructors learn about strategies to support students in self-regulated learning can be psychological, institutional and logistical - these need to be understood and overcome. The challenge of attracting and supporting future geoscience majors and future Earth and space science teachers has an institutional context that needs to be addressed. In addition, teaching for and through society's most pressing problems is a different way of approaching teaching and learning, which will require instructor professional development; the InTeGrate program has made strides in this way that may be useful to build upon. Improvement in geoscience students' quantitative literacy will also require more effective professional development and the motivation of instructors who want to develop students' quantitative skills. Professional development and institutional change may also play important roles in addressing the challenge of broadening participation of faculty who engage in education research in environmental, oceanic, atmospheric, and climate science by making the work of GER meaningful to faculty. Interestingly, research on professional development and faculty preparation in higher education has many of the same challenges as does research on teacher education, so there are opportunities for synergy there as well. Without stronger strategies to promote individual instructor learning and programmatic design changes that incorporate findings from across GER, faculty and their institutions may not put into practice research findings with sufficient fidelity to the underlying theories to enhance the outcomes of our undergraduate students.

Other large-scale connections between themes tie together K-12 and undergraduate education: conceptual understanding of Earth system processes and materials (WG1 and WG2) are embedded in K-12 science education and therefore important to pre-service teacher education (WG3). Future teachers struggle with the same cognitive (WG6 and WG7) and metacognitive (WG9) learning challenges as do other undergraduate students. In addition, climate and environmental change (WG2) are prominent in NGSS Earth and space science core ideas, and systems thinking, scale, proportion, and modelling are all cross-cutting concepts of NGSS. Thus, K-12 preparation shapes the broad student population entering our undergraduate programs and those connections need greater attention by researchers, especially when considering the pathways for undergraduate geoscience learning progressions.

There are also the embedded connections between thematic concepts and skills: geologic, environmental, oceanic, atmospheric, and climate processes (WG1 and WG2) all have broad temporal and spatial scales (WG6). Geoscience processes produce resources and result in hazards and complex issues relevant to the human condition (WG4). All of these challenges require problem-solving skills and may involve quantitative reasoning and modeling (WG7).

In addition, there are linkages between research on metacognition (WG9) and cognition (WG6 and WG7). Helping students become aware of their own cognition can also help with research about the mental process that develops understanding. In particular, the processes by which we take a holistic understanding and morph it into a mathematical form invite deep reflection on our own cognitive processes (i.e., metacognition).

Cross-Theme Recommendations

In addition to research directions that connect themes (addressed in the sections above), there are also strategies for moving forward that are common to multiple themes. Therefore, we provide the following cross-theme recommendations regarding strategies for future research:

1. Future geoscience education research should be better grounded in theory.

Theories and models (e.g., theories on learning, theories on student development, theories on social-cognitive behavior) give a framework for research design that can inform the questions to be asked and the methods to be used. This does not negate or override the real world context in which teaching and learning occur, but gives valuable insights into thinking about research problems, why they exist, and ways to address them. For example, the need to consider social identity theories was raised for research related to student learning of climate change concepts (WG2), for research on access and success of underrepresented groups in the geosciences (WG5), and to help explain the mechanisms through which teaching about the Earth through societal problems leads to student learning (WG4). Substantial testing of theory-informed designs in courses, workshops, and seminar settings can help build a body of evidence that can lead to best practices.

2. The collaborative network needs to expand within and outside of GER to include additional expertise.

Dedicated groups of people working on topics within the same area help propel research forward. Geoscientists are quite used to tackling complex issues through collaborations among researchers with different expertise (e.g., ocean expeditions to recover and study seafloor cores draw on teams of paleomagnetists, paleontologists, sedimentologists, geochemists, and physical property specialists). The GER grand challenges are similarly complex and multifaceted, and addressing them will benefit from teams of researchers, including those from outside of GER. Past research on spatial thinking in the geosciences clearly demonstrates how collaborations with experts from complementary fields (cognitive scientists and education psychologists) can rapidly advance our understanding of how people think and learn. New collaboration should also be made to advance progress in all areas of GER. For example, strategies for geoscience education instruction (WG8) can benefit from effective research-based practices in other domains, such as free-choice, informal education. Research on institutional change and geoscience professional development (WG10) can benefit from collaboration of higher education researchers and organizational psychologists. Research on ESS teacher education (WG3) connects GER to the broader discipline of science teacher education research. And as WG9 noted, many of the questions researchers in the fields of education psychology, cognitive science, and science education still have about matters of self-regulated learning, metacognition, and affect are in direct alignment with the interests of GER. Some of the emergent lines of inquiry in these other fields can inform GER through the use of more-established theories and methodologies. The geosciences may be an important context in which questions of interest can be investigated. Furthermore the findings generated from GER researchers may be of interest to the broader learning science audience which, in turn, may provide GERs new dissemination outlets and interested audiences to publish and communicate their research findings.

3. More attention needs to be given to assessment to ensure that the most valid, reliable, and up-to-date instruments and techniques are used in GER.

This will require identifying established assessment methods, tools, and instruments that other disciplines (e.g., science education, psychology, learning sciences, etc.) have developed, and evaluating them for use within the variety of geoscience learning settings contexts, as well as developing and rigorously testing new instruments and surveys. Grand challenges from several themes directly highlighted these assessment needs. For example, there is a need to develop a stronger methodology for evaluating ESS teacher preparation programs (WG3), so that we can determine and implement the most effective models. There is a need to identify and/or develop instruments that accurately assess the spatial and temporal skills (WG6) required in the various geoscience specialties (e.g., geomorphology, stratigraphy, structural geology). And there are few to no tested, validated, research-grade assessment instruments that tackle quantitative reasoning in the context of Earth education (WG7). In addition, learning management systems are evolving rapidly, especially in the accessibility and usefulness of learning analytics data of all kinds. This creates an opportunity for researchers to collect and measure student's knowledge, skills, and attitudes, before, during, and after class for research and evaluation.

4. Focusing the power of GER to improve undergraduate teaching and learning about the Earth needs to involve both geo-DBER and geo-SoTL research.

The development and testing of GER questions and hypotheses (geo-DBER) is essential to addressing most grand challenges. The results from such research should inform the development, application, and evaluation of new geoscience teaching innovations and curricula (geo-SoTL), as well as professional development of current and future faculty (e.g., TAs), and preparation of pre-service teachers. This need is perhaps best expressed in the point made by WG8 that changes in instructional strategies in geoscience have often come on the basis of instructor experience or preference, or anecdotal knowledge, and less so on a foundation of rigorous research and evaluation. This needs to change.

5. Future work needs to happen at all stages of the GER strength of evidence pyramid.

In some cases the starting point will be at the top (Figure 3) - writing review papers; for example, to characterize what is known about misconceptions of Earth system concepts (WG1 and WG2), and summarize what we know about what attracts individuals to ESS teaching (WG3). Meta-analyses are also called for; for example, of effective research-based teaching, assessment, and professional-development practices in the geosciences and in other domains because it would benefit undergraduate geoscience instruction. However, meta-analyses will depend on access to data (a challenge in GER, as well as in other STEM education fields), therefore current and future original GER studies should work to make their data accessible while still protecting human subjects. Original research at multiple-

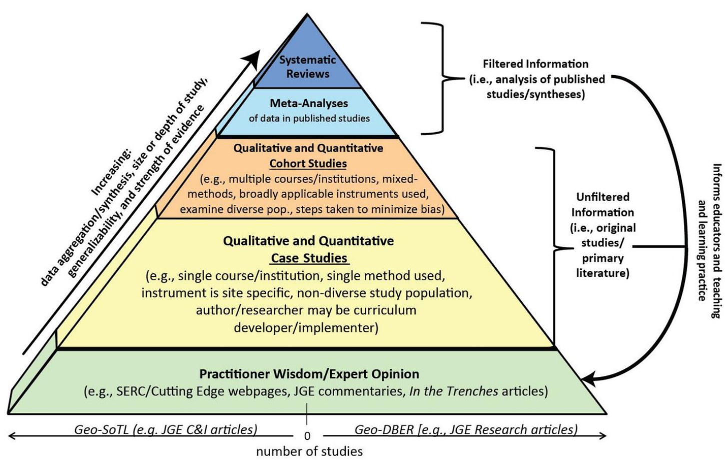

Figure 3. GER Strength of Evidence Pyramid, from St. John & McNeal 2017.

scales (e.g., qualitative research case-studies to large-scale multi-institutional studies, see Figure 3) is expected across all themes. For example, the application of existing research to the field of teacher education (WG3) may occur in smaller, short-term studies. And research on problem-based learning (WG7) will depend heavily on the context of each unique study case-study site. The need for longitudinal studies were particularly noted in research on institutional change and professional development (WG10), on instructional approaches with larger and more diverse, populations (WG8 and WG5), and to explore learning progression in undergraduate geoscience education (WG1).

Synergies with Other National Efforts on Geoscience Education and STEM

This Framework for Geoscience Education Research does not exist in a vacuum; some of the ideas raised here either echo or complement other national efforts to improve STEM education in general, or geoscience education specifically. The GER community has an important role to play by contributing to other projects described below either through direct collaborations or through broader impacts that result from work spurred by this Community Framework for GER.

Figure 4. Advancing research in GER can benefit from and contribute to the GER Toolbox.

Opportunity for Synergy with the GER Toolbox

Addressing the thematic grand challenges means using instruments, surveys, and analytical tools; conducting GER studies across institutions; publishing research results; and translating research results into practice. These are all practices that align with the GER Toolbox of resources to help faculty start or improve how they do research on geoscience teaching and learning. Therefore advancing research in GER can benefit from and contribute to the GER Toolbox (Figure 4). In particular, as researchers identify and test instruments and surveys for use in GER, these can be submitted to the GER Toolbox collection; useful analytical tools can be submitted as well. In addition, comments and suggestions can be submitted on all of the existing GER Toolbox resources (e.g., on navigating a career in GER) so advice and "lessons learned" can be shared with other researchers, which supports a healthy community of practice, and new resource pages can be developed, such as on the topics of Research Theories and Research Design and Assessment.

Opportunities for Synergy with Outcomes from the Summit on the Future of Undergraduate Geoscience Education

The Summit on the Future of Undergraduate Geoscience Education was designed to create a "collective community vision for undergraduate geoscience education" (Mosher et al., 2014). More than200 educators from a wide range of institutions as well as industry and professional society representatives attended and participated. This Summit led to recommendations on the content, skills, and experiences needed to prepare undergraduate students for graduate school and/or for future careers in the geosciences. The Summit also explored issues of pedagogy, technology, and broadening participation of under-represented groups in the geosciences. Clearly there is a convergence of what educators and employers see as important issues in undergraduate geoscience education and the thematic research priorities identified in this Community Framework for GER. Geoscience educators, administrators, professional society representatives, and employers can better achieve their curriculum and career preparation goals by working with geoscience education researchers to design curriculum and instruction (including learning progressions) that are grounded in evidence-based research.

Opportunities for Synergy with Broader Initiatives for Improving Undergraduate STEM Teaching and Learning

The 2017 Association of American Universities report Essential Questions and Data Sources for Continuous Improvements in Undergraduate STEM Teaching and Learning aimed to facilitate conversations at multiple levels inside higher education (i.e., from the course level to the institutional level) on pedagogy, scaffolding (i.e., support), and cultural changes to improve undergraduate STEM education. It also includes a compiled list of established and emerging data sources and analytical tools to inform those conversations and support evidence-based decision-making. Geoscience education shares many of the challenges facing STEM education described in this report, and geoscience education researchers need to be part of those conversations at all types of institutions. In addition, GER should explore the analytical tools and surveys compiled to determine if these may be useful in geoscience teaching and learning contexts.

Geoscience Education Research Themes from Shipley et al., (2017) and addressed in the GER Framework. In addition, themes that were specifically discussed by interdisciplinary working groups at the cross-DBER meeting in May 2017 are indicated by asterisks (*).	**Potential Cross-STEM DBER connections**
Students' conceptual understanding of geology/ solid Earth science content (e.g., misconceptions, how to teach particular concepts, systems)	Complex systems permeate the natural world. Understanding students' conceptual understanding of components and linkages between components crosses discipline boundaries. Bioscience (e.g. ecology) may have significant overlap, as does Engineering (e.g., sustainable engineering)
Students' conceptual understanding of ocean, atmosphere, climate and environmental content (e.g., misconceptions, how to teach particular concepts, systems)	
Teaching about Earth in the context of societal problems (e.g., resource use and sustainability)	
Elementary, middle, and secondary Earth science teacher education (i.e., working with teachers and future teachers in all settings)	Quality K-12 STEM education depends on high impact education/training of pre and in-service teachers
Access and success of under-represented groups* in the geosciences (i.e., diversity, broadening participation)	All STEM fields struggle with issues of access and success of underrepresented groups
Cognitive domain and problem solving* in geoscience courses (e.g., quantitative reasoning, temporal reasoning, spatial reasoning, use of models)	Most sciences and math require visualizing and reasoning about unfamiliar scales and spatial/temporal patterns
Instructional strategies* to improve geoscience learning in different settings and with different technologies (e.g., place-based instruction, teaching large lectures, online instruction)	STEM education draws on a wide range of teaching settings, from field-based learning in ecology to lab-based learning in chemistry. All also share the challenge of teaching large lectures and the expansion of online learning.
Geoscience students' self-regulated learning/metacognition and affective domain* (e.g., attitudes, motivations, values of students)	Negative attitudes and a diminished value of science in society are issues that can affect all science fields, especially in introductory courses.
Institutional change* (e.g., geoscience programmatic change), faculty professional development* (e.g., faculty workshops) and TA training	Professional development is a primary conduit for translating STEM education research findings into practice.

Table 3. Comparison of GER research themes and potential cross-STEM DBER connections. Modified from Shipley et al., 2017.

In addition, there are opportunities to work with other disciplines of STEM education research to build competence and capacity. Growing and nurturing a healthy GER community of practice can occur concurrently with growing and nurturing a broader STEM education research community of practice. Based on recent cross-DBER conversations at workshops and presented in commentaries

(Henderson et al., 2017; Shipley et al., 2017), several areas of common research interest include the examination of students' conceptual understanding of complex systems in the natural world; K-12 teacher preparation; access and success of under-represented groups in STEM; students' ability to visualize and reason about unfamiliar scales; teaching in the field and lab settings; students' attitudes about science and society; and best practices for professional development (see Table 3; Shipley et al., 2017).

Opportunities for Synergy with the Big Ideas for Future NSF Investments

In 2016 the National Science Foundation released a report articulating ten long-term research and process ideas that identify areas for future investment at the frontiers of science and engineering. Research to address several of the grand challenges in the GER Framework would also address several of the NSF Big Ideas: Research on access and success of under-represented groups in the geosciences also works to address the NSF Big Idea of Enhancing Science and Engineering Though Diversity. Addressing the GER challenges of research and evaluation needing to keep pace with advances in technological and methodological strategies for geoscience instruction and with evolving geoscience workforce requirements are examples of how future GER will work at the Future of Human-Technology Frontier, another NSF Big Idea. This Big Idea can also be addressed as GER seeks to incorporate new research technologies to assess and record student variables (e.g., knowledge, skills, and dispositions) in real-time. Research on quantitative reasoning and problem-solving in an information-rich society of big data, emerging technologies and access to a wide-variety of tools and rich multimedia converges with the NSF Big Idea of Harnessing Data for 21st Century Science and Engineering. Finally, GER is inherently interdisciplinary - a merging of the geoscience discipline with social science theory and methods - all aimed at improving teaching and learning about the Earth. All of GER therefore works within the Big Idea of Growing Convergent Research at NSF as GER is a merging of ideas, approaches and technologies from diverse fields of knowledge to stimulate innovation and discovery

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Closing the Loop: Communication for Transformation of Geoscience Teaching Practice

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The goal of the GER Framework is to improve teaching and learning about the Earth, by focusing the power of Geoscience Education Research (GER) on the set of ambitious, high-priority, community-endorsed grand challenges outlined in this document. This goal has an underlying assumption - that research results are effectively shared with educators and are used to reform teaching practice; consistent with the feedback loop on the strength of evidence pyramid (Figure 1). Closing this loop is intimately tied to research theme 10, Institutional Change and Professional Development. But closing this loop has a broader scope as well. Raising awareness of research results, and then applying the research results, will require engaged, respectful dialogue as well as strategic communication to extend the community of reflective practitioners and gain needed support from administrators.

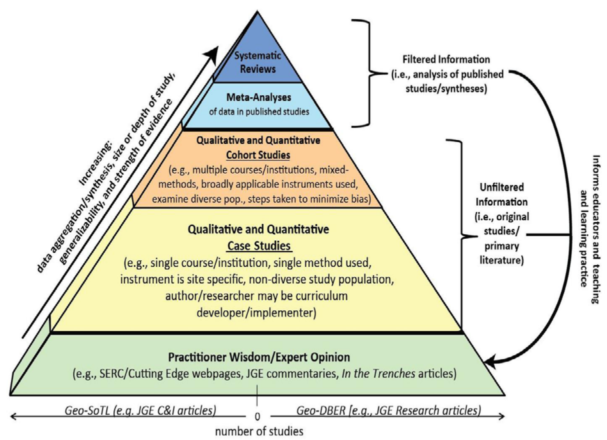

Figure 1: GER Strength of Evidence Pyramid, from St. John & McNeal 2017.

Expanding and Sustaining Dialogue

Many of the characteristics that allow application of research results revolve around dialogue. Reflective practitioners, defined as those educators who are trained or choose to think about how their students respond to their teaching (and external influences on learning), and re-think their own teaching to accommodate greater student understanding, are a desired product of teacher education (Adler, 1991) and professional development; they are also necessary collaborators in fostering progressive dialogue between researchers and educators. Improvement within the research community can be made by enhancing communication of research and access to practitioner-friendly content through published teaching materials (e.g., InTeGrate modules, see Fortner, Scherer, & Murphy, 2016). But a limiting factor is arguably determining the most effective ways to recruit and maintain education research relationships with practitioners. There are lessons to be learned from K-12 and free-choice (informal) learning settings about the challenges and successes of such dialogue. Situated in a free-choice learning context, an example is found in the Trail of Time Exhibition at the Grand Canyon (Karlstrom et al., 2008; Crow et al., 2011; Frus, 2011), which provides a dramatic opportunity for Park Rangers and informed visitors to interact with research-informed display materials and interested visitors. In the Trail of Time example, Rangers are the practitioners who have interacted with education researchers and geoscientists to maintain an exhibition visited by millions of people each year. Further, the practitioners' influential role in promoting diversity and continuation to higher education must not be overlooked (Bensimon, 2007). Promoting Earth science education nationwide is especially relevant to Earth science literacy among the general population because of a lack of K-12 Earth science teaching practitioners in the U.S., where around 7% of high schools offer such a subject (Lewis & Baker, 2010).

Dagenais et al. (2012) provide a review of educational studies that inquire about how educational research is viewed and implemented in international K-12 education via thorough a literature review of papers published between 1990 and 2010. Their analysis found that the "use of research-based information is hardly a significant part of the school-practice scenario. If such use occurs, it is mainly conceptual and research-based information is a source of inspiration to accommodate or modify the practitioners' frame of reference.... However, the literature reports a variety of factors that may affect the process of research use" (p. 296). These included several positive characteristics of communication between researchers and practitioners: (a) facilities for collaboration, (b) access to research and data, (c) collegial discussions, (d) collaboration with researchers, and (e) sustained collaboration (p. 297, Dagenais et al., 2012). With deeper investigation, it could be determined how and when these characteristics can facilitate or impede the necessary dialogue.

Dialogue between practitioners learning from researchers and researchers learning from practitioners is essential to achieve a shared goal of improving learning outcomes in people involved in any project seeking to inform the public on scientific process and findings. Practitioners from across all aspects of education can offer useful experience to improve understanding of learning, share with other practitioners, and provide information that can frame research questions (Adler, 1991; Wagner, 1997; Bensimon, 2007). Our vision also maintains the importance of practitioners (and administrators) being aware of, and responsive to, research as a discipline and implementing improvements in thinking and teaching that are derived from evidenced-based research results (see review by Dagenais et al., 2012).

Recommended Strategies to Develop and Support Practitioner-Researcher Dialogue

1. Develop and advertise moderated online forums in which K-16 and informal educators can post questions or directly talk to GER experts, and where GER experts can ask questions of educators. Or consider models, such as the K-12 Research+Practice Collaboratory, which is an online space to bring educators and researchers together to "develop more equitable relationships between research and practice' and innovations for STEM teaching and learning.

2. Expand and maintain face-to-face researcher-practitioner forums at geoscience and science-education conferences. These forums could be thematic, (e.g., selecting themes or more

narrow grand challenges from this Framework each year) and follow a similar format as that of the Geoscience Education Research and Practice Forum at the 2017 Earth Educators' Rendezvous (EER) or the Moving from Learning Opportunities to Learning Pathways Forum at the 2018 EER.

3. Encourage practitioner participation as co-developers of new knowledge through SoTL and DBER, especially for local-scale research. This might include local field trips to landscapes or outcrops that are accessible to area schools where researchers collaborate with practitioners to produce research products relevant to practitioners. For example it may focus on misconceptions and the placement of these experiences within a learning progression, or on affect and meta-cognition.

4. Incorporate modestly greater DBER experiences, in subjects of interest or in greatest need, in faculty professional development and teacher preparation programs, so that the dialogue between practitioners and researchers can be initiated more readily.

5. Discuss curriculum with state-level departments of education and local school boards and teacher groups. Approach administrators and teachers with an emphasis on supporting connections between teaching, geoscience education research results, and school standards.

Dissemination and Marketing

Better tested, more effective, and targeted dissemination techniques are necessary to share findings of GER with, and encourage adoption of best practices by, the greater community of geoscience educators and program administrators as well as interested educators in allied disciplines. Compiled across education, Dagenais et al. (2012) report several communication factors that generally contributed to people choosing to use research findings: (1) timely access to research, (2) results communicated in a way that is easy to understand and implement, (3) research foci that are connected to school and classroom context, and (4) a perception that some aspect of the research is relevant (p. 297, Dagenais et al., 2012). These findings help show the important of communicating the relevance and value of the research to the target audiences. Communication and marketing research can help geoscience education researchers make more effective use of in-person (e.g., conferences, colloquia, field trips), print (e.g., journals and news magazines), and online and virtual (e.g., social media, webinars, blogs, list serves, websites, virtual reality) modalities of dissemination.

Recommended Strategies for Expanding Communication to Target Audiences

1. Apply research on effective mass marketing techniques including advertising and social media (e.g., Newsome, 2006; Goske et al., 2008; Bohon et al., 2013) to reach the broader geoscience community.

2. Include science communication training with professional development opportunities online and at professional conferences to science education researchers, both discipline-specific (e.g., Geological Society of America, American Geophysical Union) and interdisciplinary (e.g., American Association for the Advancement of Science; American Education Research Association, Educational Research Association; National Association for Research in Science Teaching).

3. Publish findings and practices in journals that accept geoscience-education papers and also reach into the broader geoscience community, such as *Geosphere and Geological Society of America Bulletin*.

4. Publish findings and practices in disciplinary science-education journals in other fields, such as *CBE-Life Sciences Education* and the *Journal of Chemical Education*.

5. Publish findings and practices in interdisciplinary science-education journals such as *Science Education, Journal of Research in Science Teaching, International Journal of Science Education, and Journal of College Science Teaching.*

6. Target graduate students and postdoctoral fellows, as well as faculty, for dissemination of relevant research findings and best practices in geoscience education, as has been effectively done by in-person and online means by the On The Cutting Edge and InTeGrate programs.

7. Disseminate effective arguments for incentivizing research and publication in geoscience education (SoTL and GER alike) for academic promotion and tenure at a wide range of institutions.

8. Improve access to education research, possibly by supporting publication in open-access journals or by advocating for ways that K-12 and informal educators can gain better access to journal articles if they are not associated with institutional subscriptions.

9. Create translations of research for educators to reduce the gap in language barriers, such as ensuring that GER abstracts (and papers) include sections that address the implications for teaching, or by providing a second abstract or summary specifically for educators that explains the practical uses of the article. These abstracts can be published directly in conjunction with research articles, or summarized in a "practitioner's annotated bibliography" to be disseminated through practitioner journals (i.e., In the Trenches) or through the NSTA Learning Center. This latter platform reaches a broad audience of science teaching methods instructors, who influence the development of new teachers, as well as interface with science content faculty. This could be produced on an annual or biennial basis, and include guest contributing teams of geoscience researchers and geoscience teachers.

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