A Community Framework for Geoscience Education Research: Summary and Recommendations for Future Research Priorities

Kristen St. John, James Madison University; Karen McNeal, Auburn University; Heather Macdonald, William & Mary; Kim Kastens, Lamont-Doherty Earth Observatory; Kelsey Bitting, Elon University; Cinzia Cervato, Iowa State University; John McDaris, SERC at Carleton College; Heather Petcovic, Western Michigan University; Eric Pyle, James Madison University; Eric Riggs, Texas A&M University; Katherine Ryker, University of South Carolina; Steven Semken, Arizona State University; and Rachel Teasdale, California State University-Chico

Abstract

The geoscience education research (GER) community has produced a collaborative research framework that summarizes guiding questions for future research to inform and improve undergraduate geoscience teaching and learning. The GER Framework (St. John [Ed.], 2018a) was developed through an iterative process involving multiple stages of community input. In total, approximately 200 geoscience educators and researchers contributed to this project in one or more of the following capacities: as authors, reviewers, survey respondents, workshop participants, webinar participants, town hall participants, and/or focus group participants. Review of survey data, reports, publications, and discussions resulted in a set of guiding questions and research strategies for ten research areas where individual researchers can make important contributions. While presented as distinct research areas, the ten themes have numerous cross-theme opportunities that integrate content areas, skills, and types of students. Cross-theme recommendations regarding strategies for future research are described here, along with suggested synergies with other national efforts in geoscience and STEM education.

Introduction

The geoscience education research (GER) community successfully engaged in a Grand Challenges Initiative in 2016-2019 focused on improving undergraduate geoscience teaching and learning through GER (St. John et al., 2019). This effort offers the GER community and funding agencies a framework for prioritizing future research by pointing to areas where individual researchers can make important contributions, without prescribing particular projects that should be pursued. The full report of the outcomes of that process, *A Community Framework for Geoscience Education Research* [herein abbreviated as the “Framework”; St. John [Ed.], 2018a], is accessible online from the National Association of Geoscience Teachers (n.d.a.), and can be downloaded from the James Madison University Library Scholarly Commons (2018). The purpose of this Commentary is to distill the full 160-page report into a digestible summary for geoscience educators, geoscience education researchers, and other discipline-based education researchers (DBER). The description of the project development, the recommendations for future research, and the discussion of synergies with other programs included in this summary are partially excerpted from chapters (St. John, 2018b; St. John, et al., 2018) in the original Framework report (St. John [Ed.], 2018a) to maintain consistency of message.

Embracing an Inclusive Definition of Geoscience Education Research

Underlying the Framework initiative is the premise that building geoscience expertise and an Earth-literate society both depend on high-quality education. This premise is the vision of our professional society, the *National Association of Geoscience Teachers* (NAGT), and is what motivates many geoscience educators to reflect on their teaching practice, to tweak and in some cases totally overhaul their courses, to engage in professional development, and to participate in geoscience education sessions at conferences. While *what* we teach (i.e., content and skills) is informed by practices and findings from the broad array of geoscience research fields, *how* we teach in the geosciences also has a research foundation grounded in the rapidly-growing field of geoscience education research (GER).

In the Framework, we use the term geosciences to encompass the breadth of the Earth sciences (atmospheric science, climate science, environmental science, geology, and oceanography). Space science was not specifically addressed. In addition, we embrace an inclusive definition of GER to reflect the evolution of the field (e.g., Arthurs, 2018; Shipley et al., 2017; St. John & McNeal, 2017; Lukes et al., 2015; Petcovic & St. John, 2015; Piburn, van der Hoeven Kraft, & Pacheco, 2011; Perkins, 2004) and to include the broadest scope of scholarly work in which GER community members engage (e.g., inclusive of Curriculum and Instruction, Research, and Literature Review article categories in the *Journal of Geoscience Education;* JGE). We see GER as including the development, application, and evaluation of new geoscience teaching innovations and curricula, as well as the development and testing of geoscience education research questions and hypotheses. These can be broadly characterized as the scholarship of geoscience teaching and learning (geo-SoTL) and geoscience discipline-based educational research (geo-DBER), respectively. Geo-SoTL typically involves action research: doing research on student learning in the process of teaching, and directing findings specifically toward informing and assessing more effective teaching in their own classroom or for others (Perkins, 2004). Geo-DBER typically involves the use of social science theoretical models and methods to develop and test hypotheses and construct generalizable insights. Both geo-SoTL and geo-DBER are important for improving the geoscience community's teaching practices (Figure 1). They reciprocally inform one another (i.e., serve as a positive feedback loop, Shipley et al., 2017), as theoretical models developed in GER are refined in geo-SoTL, and findings from geo-SoTL open new areas of theoretical inquiry for GER.

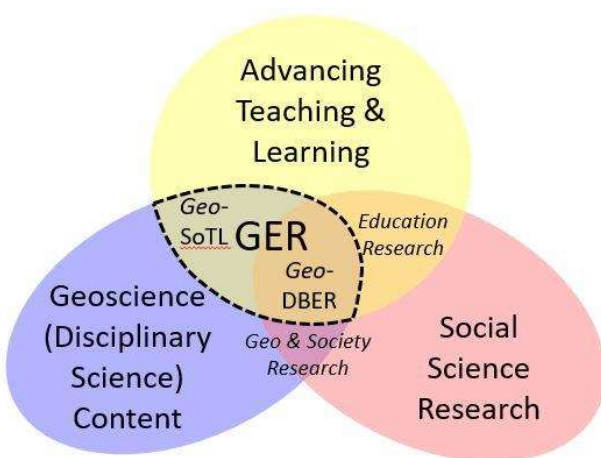


Figure 1. Geoscience education research Venn diagram. Figure by St. John in NAGT (n.d.b), modified from Lukes et al. (2015).

Scope and Process of the GER Grand Challenges Initiative

While GER may investigate learning about the Earth in any context, the Framework focuses on GER that has the potential to inform teaching and learning at the undergraduate level. The undergraduate scope allowed us to tap into a broad community of geoscience faculty who teach and do GER at this level.

The Framework is organized around ten GER themes (Table 1), which span a web of topics. Theme selection was informed by published reports, discussions, and surveys, including the Wingspread workshop report (Manduca, Mogk, & Stillings, 2003), an editorial on a possible research agenda for GER (Lewis and Baker, 2010), the Earth and Mind II Synthesis report (Kastens & Manduca, 2012), the DBER Report (Singer et al., 2012), focus group discussions at a 2015 workshop (NAGT, 2015), and results from a 2017 community survey (NAGT, 2017a).

Table 1. Alignment of GER Framework Themes with topical areas addressed by Working Groups (WG) in relevant prior discussions, surveys, and reports (from St. John, 2018b)

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 and 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		√		√	√	√

Development of the Framework was an iterative process that depended on extended efforts by theme-based working groups (WG) at the 2017 GER workshop at the Earth Educators Rendezvous (NAGT, 2017b) as well as broader community input prior to and following this central workshop (Figure 2).

Figure 2. Major steps in the development of the Framework (modified from St. John, 2018b).

An online survey in 2017 was the first of a series of community activities in this project. The purpose of the survey was to share tentatively-defined themes based on the literature review conducted by project leaders, and to develop an initial database of key developments, recommended resources, and important research questions for each of the themes. Survey respondents (n=66) 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 (shared in a follow-up webinar, n=38; Figure 2; NAGT, 2017c) demonstrated community 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 add this new research theme area). While prior reports (Table 1) emphasized research on conceptual understanding and on cognition, the 2017 GER survey results suggested it would be valuable to make thematic distinctions between different sub-areas of conceptual understanding (Table 1, WG1 and WG2) and different sub-areas of cognition (Table 1, WG6 and WG7). The distinction between the "solid Earth" (WG1) and the "fluid Earth" (WG2) made sense in terms of representation: within the cohort of geoscience faculty in the U.S. there are about four times more geologists of traditional fields (e.g., geology, geophysics, paleontology, etc.), than oceanographers, meteorologists, and climate and atmospheric scientists, according to American Geosciences Institute (AGI) data (Wilson, 2016). In addition, research methodologies (i.e., questions, technology, and instrumentation) used for fluid earth research often have more affinities with each other than with solid Earth research. The distinction of different geoscience cognitive domains was useful because of its broad scope – ranging from temporal and spatial reasoning (WG6) to quantitative reasoning, problem solving, and use of models (WG7).

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 (NAGT, 2017b). Prior to the face-to-face workshop, ten working groups were defined, one for each GER theme (Table 1). Applicants' interests and expertise were matched to the thematic working groups. Working group leaders were nominated and selected by the project leadership team based on their experience and expertise for that theme. Each working group included three to five geoscience education researchers. Workshop participants were from a range of career stages and institution types (Table 2). Groups were charged with identifying two to five high-priority, large-scale "guiding questions"(also called "grand challenges" in the Framework report; St. John [Ed.], 2018) for their research theme and recommending strategies for addressing them. Literature reviews (including the 2017 *JGE* theme issue on *Synthesizing Results and Defining Future Directions of GER*; McNeal et al., 2017) and community input were critical to the process of identifying guiding questions. Also helpful was a web-based participant workspace (NAGT, 2017b), hosted by the Science Education Research Center (SERC) for program management, note-taking, resource archiving and sharing, and commenting.

Table 2. Demographic data from the 2017 GER workshop.

Demographic Category	Total
Gender	
Female	34
Male	12

Career Stage (Role)	
Full / Associate Professor	19
Assistant professor / Instructor	11
Researcher (non-teaching)	10
Post Doctorate / Graduate Student	6
Type of Institution	
4-Year College / University	38
2-Year College	4
Other (non- teaching institution)	4

To ensure broad community input in the Framework development, there were multiple opportunities for sharing with - and getting feedback from - other community members (Figure 2). The largest of these was the EER Geoscience Education Research and Practice Forum (NAGT, 2017d), 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. The forum provided an opportunity to identify promising practices and puzzling questions that are important and suitable for research as well as a means of gauging 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 guiding questions and raised awareness among GER working group members of educators' interests, concerns, and priorities.

Other opportunities were also available for the community to provide feedback on the development of the Framework (Figure 2). A preliminary set of theme-based GER guiding questions and supporting strategies was presented in a town hall at the 2017 Geological Society of America (GSA) meeting that was attended by ~50 people. Following a series of “lightning talks” by working group representatives, town hall attendees had the opportunity to visit and write comments on theme posters. Their critiques, ideas on prioritization, and suggested strategies were taken into account by working groups as they revised the draft guiding questions and expanded upon the rationales and recommended strategies. The outcome of that work was later presented at the 2017 American Geophysical Union (AGU) meeting.

The AGU meeting coincided with the start of a two-month Open Comment Period. Draft GER Framework materials (at this point referred to as theme "chapters") were hosted on a Science Education Research Center (SERC) website; comments could be entered in 'Discussion' boxes directly on the webpages for each of the ten theme chapters. Efforts to alert and encourage community members to contribute comments included distribution of a flier (with a QR code to the webpage) at the AGU National Association of Geoscience Teachers (NAGT) booth; notices in the NAGT newsletter, the NAGT GER Division newsletter, and the GSA Geoscience education listserv; direct emails to attendees of the 2015-2017 EER GER workshop, to authors that published articles in the JGE theme issue on *Synthesizing Results and Defining Future Directions of GER*, and to 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 three to five 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 guiding questions and recommended strategies in a meaningful context.

In sum, between 2017 and 2018, ~200 members of the GER community engaged with the Framework development by participating in a working group and/or one or more of the following activities: the online survey, the webinar, the workshop, the forum discussion, the town hall, and the online open-comment review.

GER Framework Outcomes: Thematic Guiding Question for Future Research

The primary outcome from working group efforts and community-engagement activities is a rationale for prioritization of future research around 33 guiding questions (Table 3) of high interest to the geoscience education researcher and practitioner community. Addressing these guiding questions through well-designed and widely disseminated research will improve undergraduate geoscience teaching and learning. The rationale and recommendations for each guiding question are described in the theme chapters of the Framework (St. John [Ed.], 2018a); which are cited in Table 3. We encourage researchers to read the theme chapters that align with their areas of interest and use these as a foundation or justification for designing targeted research studies that address one or more of the thematic guiding questions.

Table 3. Summary of Thematic Guiding Questions to Guide Future Geoscience Education Research (summarized from St. John [Ed.], (2018), with chapter citations included in the table.

	GER Themes	Guiding Questions to Guide Future Geoscience Education Research
1	**Students' Conceptual Understanding of Geology/ Solid Earth Science Content** (Pyle, et al., 2018)	● 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? ● 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?
2	**Students' Conceptual Understanding of Environmental, Oceanic, Atmospheric, and Climate Science Content** (Cervato, et al., 2018)	● 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? ● How do we teach complex interconnected Earth systems to build student conceptual understanding of, for example, climate change? ● 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? ● How do the societal influences, affective elements, personal background and beliefs, and prior knowledge impact students' conceptual understanding of Earth system sciences?

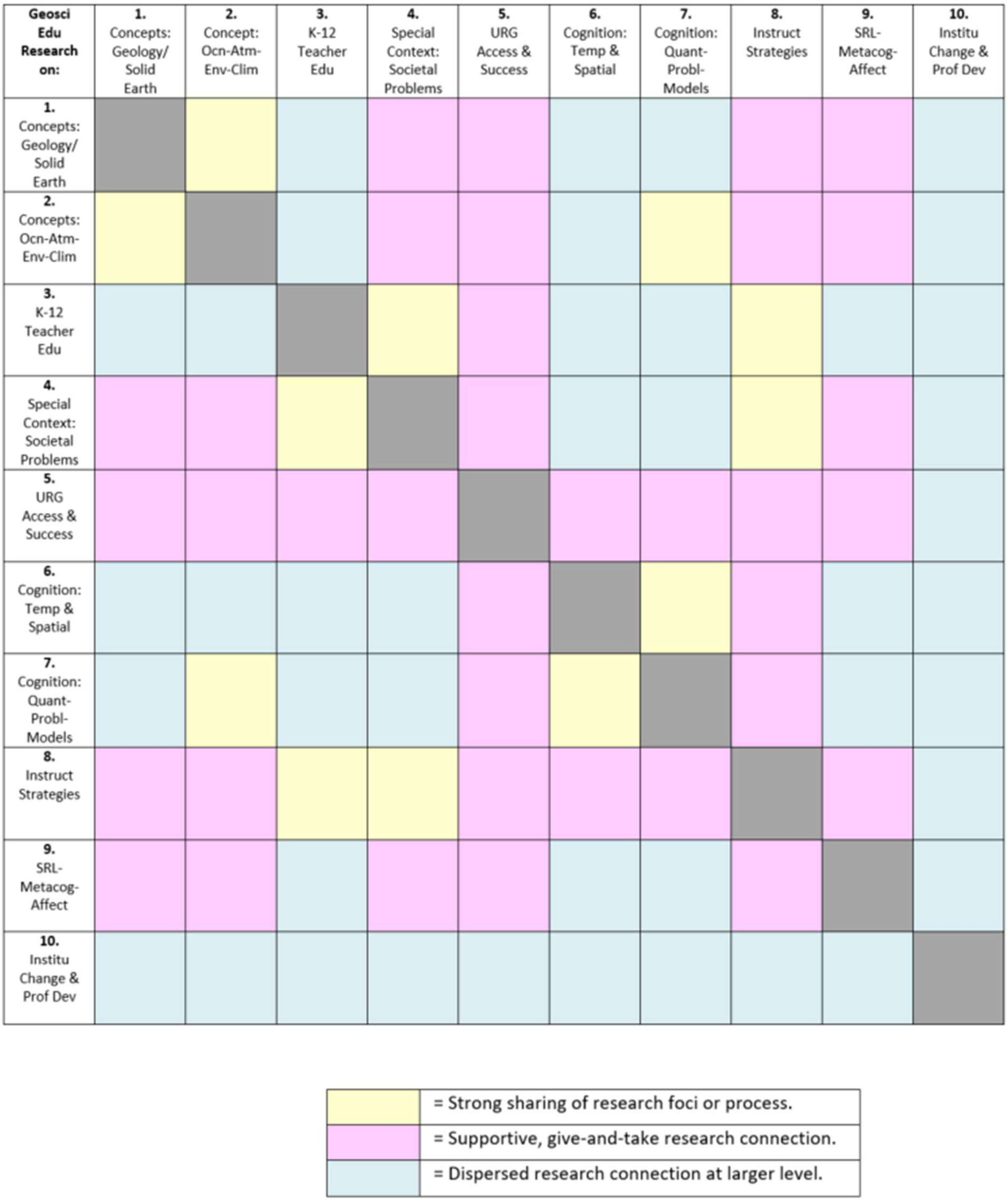
		● How do we broaden the participation of faculty who are engaged in educational research in environmental sciences, atmospheric sciences, ocean sciences and climate sciences and encourage implementation of research-based instruction?
3	**Elementary, Middle, and Secondary Earth and Space Sciences Teacher (ESS) Education** (Petcovic,et al., 2018)	● 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? ● What are effective models for incorporating ESS into undergraduate K-12 teacher preparation and in providing professional development for in-service teachers? ● 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?
4	**Teaching about Earth in the Context of Societal Problems** (Teasdale et al., 2018)	● How does teaching with societal problems affect student learning about the Earth? ● What are the design principles for curriculum needed to teach with societal problems? ● How do we assess the influence of teaching with societal problems in terms of student motivation and learning about the Earth?
5	**Access and Success of Under-represented Groups in the Geosciences** (Riggs, Callahan, & Brey, 2018)	● 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? ● Geoscience Community Efforts to Broaden Participation: How can the geoscience community capitalize on evidence from different scale efforts to broaden participation?
6	**Cognitive Domain in Geoscience Learning: Spatial and Temporal Reasoning** (Ryker et al., 2018)	● What skills and tasks are essential to the different specialties within the geosciences? What spatial and temporal reasoning skills map onto these specific tasks? ● 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? ● How can geoscience education foster the spatial and temporal reasoning skills that are required in each specialty?
7	**Cognitive Domain in Geoscience Learning: Quantitative Reasoning, Problem Solving, and Use of Models** (Kastens et al., 2018)	● Quantitative Thinking: How does quantitative thinking help geoscientists and citizens better understand the Earth, and how can geoscience education move students toward these competencies? ● 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)? ● Use of Models: How can we help students understand the process by which geoscientists create and validate physical, computational, and mental, systems, and feedback models and use those models to generate new knowledge about the Earth?
8	**Instructional Strategies to Improve Geoscience Learning in Different Settings and with Different Technologies** (Semken et al., 2018)	● How can research and evaluation keep pace with advances in technological and methodological strategies for geoscience instruction, and with evolving geoscience workforce requirements? ● How can undergraduate geoscience instruction benefit from and contribute to effective research-based practices in other domains? ● What instructional practices and settings are most effective for the greatest range of geoscience learners? ● How do we overcome structural barriers at the level of instructional practice that impede effective teaching and learning of geoscience? ● How can we better engage learners as co-discoverers of knowledge and co-creators of new instructional strategies in geoscience?
9	**Geoscience Students' Self-Regulated Learning, Metacognition, and Affect** (McNeal et al., 2018)	● 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? ● Inclusion: What are effective strategies in engaging a diverse population of students in their learning and sustaining their interest in the geosciences? ● 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? ● Educators: How do we 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?
10	**Institutional Change and Professional Development** (Bitting et al., 2018)	● 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? ● How can departments and programs support continuous improvement in undergraduate geoscience education?

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

GER Framework Outcomes: Opportunities for Cross-Theme Research

While the ten GER themes have distinct-enough characteristics to offer research sub-discipline "homes" (i.e., primary areas of study) for investigators and the organizational structure for the 33 guiding questions, these themes also interconnect. Cross-theme connections were apparent throughout the development of the framework – from project leadership discussions on initial identification of the themes to discussions within and among working groups both at and after the workshop. In particular, on the concluding day of the 2017 workshop (NAGT, 2017b), a plenary session discussion took place responding to the prompt: *What are the emerging big ideas that unite multiple themes?* Several months later following the open comment period (Figure 2), the lead author (as editor of the Framework) reviewed the descriptions and recommendations of each of the ten themes to identify big cross-cutting ideas. Based on that review, a spreadsheet was constructed to organize and analyze the information; the outcome was a matrix of intersectionality among the themes, which was shared with the lead authors of the theme chapters (who are also the authors of the Framework synthesis chapter and this manuscript) for their comments. Based on their comments, minor edits were made to the matrix, which is presented here (Table 4). Levels of connection are represented by color-coding in Table 4. Examples of the types of connections are described below and in the online supplemental table.

Table 4. Simplified correlation matrix that uses color to show research relationships among the ten themes. A more detailed correlation matrix that includes brief descriptions of the research relationships is available in the Supplemental Resources (modified from St. John et al., 2018).



A few themes have strong existing research connections (e.g., yellow boxes in Table 4). For example, although interest in teaching with an Earth system science perspective is widespread, much of the published research on students' conceptual understanding lies in geology/solid Earth concepts (Theme 1). However, conceptual understanding of Earth systems requires an integrated understanding of all system spheres. Thus, Themes 1 and 2 share strong research foci on identifying and addressing misconceptions and on developing Earth system interconnections. These two themes are also embedded in K-12 science education and therefore are important for pre-service teacher education (Theme 3).

Strong research synergies also exist between the two themes that focus on cognitive domain (Themes 6 and 7) because all cognitive domain research involves study of how students think - how they acquire, process, and make use of knowledge. While Theme 6 focuses on research on temporal and spatial reasoning, and Theme 7 focuses on research on quantitative reasoning, problem solving, and use of models, these cognitive tasks are commonly 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 Earth phenomenon are sometimes fast and sometimes slow can be mathematicised to a quantitative measure of rate. Rate and gradient are powerful concepts in geosciences; once mastered they can be used again and again.

A related strong research connection exists between Theme 2 and Theme 7; 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 guiding questions by both working groups.

Research on effective teaching practices, including teaching in the context of societal problems (Theme 4), may support the development of future teachers' pedagogical content knowledge and help support teacher recruitment and retention efforts (Theme 3). In addition, the K-12 Next Generation Science Standards (NGSS; NRC 2012; NGSS Lead States, 2013) explore the use of transdisciplinary approaches, meaning our future students will bring those skills, experiences, and content knowledge to our college classrooms. Similarly, students coming into our geoscience courses may be familiar with societal issues in their local community, providing an opportunity to explore geoscience-society connections. These connections relate to research on instructional strategies (Theme 8), in particular place-based learning, and therefore may have good linkages to co-investigate.

Some guiding questions are common to multiple themes because they link characteristics about the learner to the design of curriculum and instruction. Metrics of success for learning any geoscience content (Themes 1 and 2), skill (Themes 6 and 7), or disposition (Theme 9) may depend on the situational context, including the instructional strategies, setting, and technology used (Theme 8) – all factors that are front and center in this time of (pandemic-related) distance learning. Targeted instructional approaches should be investigated to assess if, and how, interventions support the development of spatial, temporal, and quantitative reasoning, problem solving, and modelling skills. Metrics of success for learning geoscience content, skills, or dispositions may also depend on the whole experience, identity, and pathway of the learner (Theme 5). For example, research on what learning experiences can help students see the power of mathematics to answer questions or solve problems that 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.

In addition, the different pathways and identities of students can result in differential undergraduate experiences (Theme 5) that may influence the development of valuable skills, such as self-regulated learning and metacognition as well as affect (Theme 9). These factors, in turn, may impact the likelihood of students being attracted to and thriving in the geosciences. Geoscience processes touch the lives of all people, so geoscience should also be a field that is representative of all people. This is not yet the case. Therefore, determining how to construct learning environments that help all students identify with the content and feel that they belong within the geoscience community is imperative.

We also must investigate the most effective strategies to ensure that students apply their classroom learning to real-world decision making (Theme 4). 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 misunderstanding geology, environmental, ocean, atmospheric, and climate concepts (Themes 1 and 2) are non-trivial, ranging from the economic costs of commodities and energy to the potentially fatal impact of hazards; these are societal problems (Theme 4). Teaching within the context of societal problems may increase student interest (Theme 9) in the geosciences, provide an opportunity for teaching students about the sources and reliability of data (Theme 7) in considering issues in the news, and may also be important when considering ways to develop geoscience learning progressions (Theme 1).

Importantly, research on supporting instructors' growth through professional development (Theme 10), and on building structural supports that foster effective teaching and learning, impact all of the other themes. This relationship exists because instructors play a central role in the students' geoscience education: they design and implement learning experiences to teach content, skills, and 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 (Theme 9). The challenge of attracting and supporting a diverse population of future geoscience majors and future Earth and space science teachers has an institutional context that needs to be addressed (Themes 3 and 5). In addition, teaching through society's most pressing problems is a new and different way of approaching teaching and learning (Table 1; Theme 4), one that will require instructor professional development. 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 (Theme 7). Research on professional development and faculty preparation in higher education has many of the same challenges as research on teacher education (Theme 3), therefore there are opportunities for synergy there as well. Without stronger strategies to promote individual instructor learning within contexts (i.e., departmental, institutional, discipline, community contexts) that support change, faculty and their institutions may not put into practice research findings with sufficient fidelity to the underlying theories to enhance the outcomes for our undergraduate students.

GER Framework Implications: Cross-Theme Recommendations

Some strategies for moving forward are common to multiple themes. These recommendations were identified using a process similar to that used for the identification of cross-theme connections: initial intersectionality emerged out of the 2017 workshop (NAGT, 2017b) plenary session on: *What are the emerging big ideas that unite multiple themes?* More details emerged through the lead author's review of the recommendations of each of the ten themes after the open comment period (Figure 2). Based on that review, a spreadsheet was constructed to organize the information, and then was summarized and shared with the lead authors for the theme chapters (who are also the authors of the Framework synthesis chapter and this manuscript) for their comments. Based on their comments, edits were made to the cross-theme recommendations on strategies for future research, which are presented below:

1. **Future geoscience education research should be better grounded in theory.** Theories and models (e.g., theories on learning, on student development, on social-cognitive behavior) give a framework for research design that can inform the questions asked and the methods used. This need to ground research in theory does not negate or override the real-world context in which teaching and learning occur, but does provide valuable insights for 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 (Theme 2) to help explain the mechanisms through which teaching about the Earth through societal problems leads to student learning (Theme 4), and for research on access and success of underrepresented groups in the geosciences (Theme 5). Substantial testing of theory-informed designs in courses, workshops, and seminar settings can help build a body of evidence that should lead to effective instructional practices for a wider range of student populations.

2. **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 work 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 contexts, as well as developing and rigorously testing new instruments and surveys to augment our existing assessments. Guiding questions 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 (Theme 3) to determine and implement the most effective teacher preparation models, as well as a need to identify and/or develop instruments that accurately assess the spatial and temporal skills required in the various geoscience specialties (Theme 6). Similarly, there are few tested and validated research-grade assessment instruments that tackle quantitative reasoning in the context of Earth education (Theme 8). In addition, learning management systems are evolving rapidly, especially in the accessibility and usefulness of learning analytics data of all kinds. These advances provide an opportunity for researchers to collect and measure students' knowledge, skills, and dispositions, before, during, and after instruction for research and evaluation.

3. **The collaborative network needs to expand within and outside of GER to include additional expertise.** Geoscientists commonly tackle complex issues through collaborations among researchers with different expertise (e.g., ocean expeditions to recover and study seafloor cores draw on teams of geochemists, paleomagneticists, paleontologists, physical property specialists, and sedimentologists). The GER guiding questions 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 (e.g., cognitive science and learning science) can rapidly advance our understanding of how people think and learn (e.g., SILC, Spatial Intelligence and Learning Center, n.d.). New collaborations would help advance progress in all areas of GER. For example, strategies for geoscience education instruction (Theme 8) can benefit from effective research-based practices in other domains, such as informal education (e.g., museums, science centers). Research on institutional change and geoscience professional development (Theme 10) can benefit from collaboration of higher education researchers and organizational psychologists. Research on ESS teacher education (Theme 3) connects GER to the broader discipline of science teacher education research. Many of the questions researchers in the fields of educational psychology, cognitive science, and science education have about matters of self-regulated learning, metacognition, and affect are in direct alignment with the interests of GER (Theme 9). Findings generated from studies in the context of GER may be of interest to the broader learning science and DBER audiences which, in turn, may provide new dissemination outlets to communicate GER findings.

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 the guiding questions. 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., graduate students/teaching assistants), and professional development of current (in-service) and future (pre-service) teachers. Sustained professional development has been shown to be successful in affecting changes in instructional practice with both classroom teachers and college instructors (Roehrig, et al., 2012; Viskupic et al., 2019), with implications for future teachers of science as well. We recognize that broad propagation and systemic change throughout undergraduate STEM education will require a focus on the larger institutional context as well as on communities of learners (Borrego & Henderson, 2014; Gehrke & Kezar, 2016; Henderson, Beach, & Finkelstein, 2011; Kastens & Manduca, 2017; Manduca, 2017). 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. Professional development approaches that build a bridge between instructor experience and research will enable evidence-based advances in instructional practice a chance to take hold.

5. **Future work must be done at all stages of the GER *strength of evidence* pyramid.** In some cases the starting point will be at the top of the strength of evidence pyramid (St. John & McNeal, 2017, Figure 3) by writing review papers. For example, such papers could characterize what is known about misconceptions of Earth system concepts (Theme 1 and Theme 2), or summarize what we know about what attracts individuals to ESS teaching (Theme 3). Meta-analyses of effective research-based teaching, assessment, and professional-development practices in the geosciences and in other domains are also called for because these would benefit undergraduate geoscience instruction. However, meta-analyses will depend on access to education research data (i.e., student data; a challenge in GER, as well as in other STEM education fields); therefore, current and future GER should make data more accessible while still protecting human subjects. Primary research at multiple scales (e.g., qualitative research case-studies to large-scale, multi-institutional studies) is expected across all themes. For example, the application of existing research to the field of teacher education (Theme 3) may occur in small short-term studies. Research on problem-based learning (Theme 7) will depend heavily on the context of each case-study site. The need for longitudinal studies was particularly noted in research on institutional change and professional development (Theme 10), on instructional approaches with larger and more diverse populations (Themes 8 and 5), and to explore learning progression in undergraduate geoscience education (Themes 1 and 2).

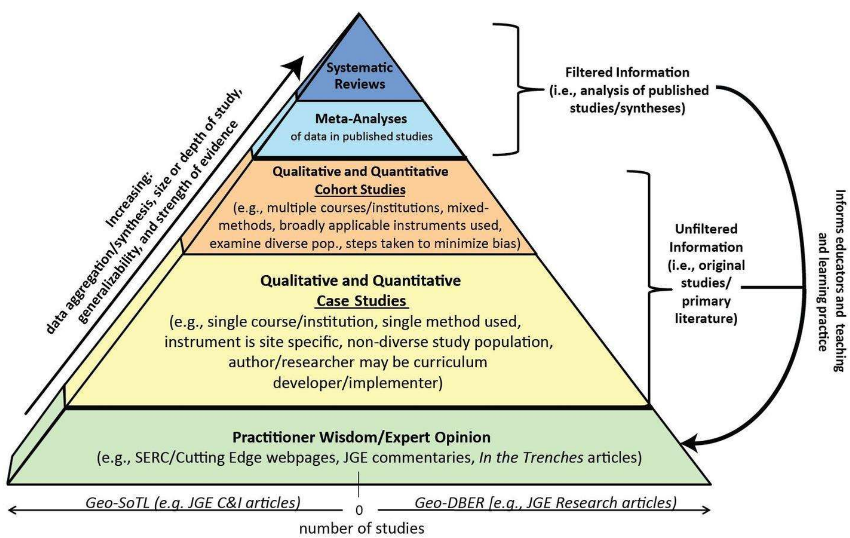


Figure 3. GER Strength of Evidence Pyramid, from St. John & McNeal (2017).

6. **Future work should leverage synergies with other national programs.** The Framework for GER does not exist in a vacuum; ideas raised here complement other national efforts to improve geoscience education specifically, and STEM education more broadly. One of the most direct connections between the Framework and other national geoscience education efforts is with the Summit on the Future of Undergraduate Geoscience Education (NAGT, 2014; Mosher et al., 2014), which aimed to be a collective community vision for undergraduate geoscience education. In addition, the Framework also aligns with a national GER effort: the development of an online GER

Toolbox (NAGT, n.d.d), which includes resources to help geoscience faculty start (or improve) their scholarship on geoscience teaching and learning.

At a broader level, extending the reach of GER by working with DBER specialists in other fields can help build competency and capacity across STEM education. Discussions within cross-DBER organizations (e.g., Association of American Universities [AAU], 2017; Association of American Colleges and Universities [AACU]/Project Kaleidoscope [PKAL], n.d.; Accelerating Systematic Change in STEM Higher Education [ASCN], n.d.) and recent commentaries (Henderson et al., 2017; Shipley et al., 2017) identify several DBER research areas that align with the priorities in the GER Framework. These include the examination of students' conceptual understanding of complex systems; 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 (Shipley et al., 2017). Findings from studies in all of these area will help support evidence-based decision-making from the course to institutional level, as outlined by the AAU (2017). Finally, research to address several of the guiding questions in the GER Framework would also address several of the National Science Foundation's Big Ideas (NSF, 2016), including the NSF Big Ideas on: *Enhancing Science and Engineering Though Diversity* (NSF INCLUDES), *Harnessing the Data Revolution,* and *Growing Convergent Research*.

Conclusion

Research across the GER themes is expected to produce a web of cross-cutting and interconnected ideas that will mutually inform one another over the coming years. We hope that the GER Framework guiding questions, the cross-theme recommendations, and synergies with other national efforts will form the basis of grant applications, research study designs, and future professional development for the coming decade. The Framework and other GER efforts will allow us to better understand our students, improve teaching in individual courses, structure learning around necessary skill sets, and improve the design of undergraduate curricula. Together these outcomes will improve geoscience education, enrich student learning, and diversify future geoscientists, which will strengthen the geosciences as a whole and help society better understand the critical importance of our discipline.

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