Synthesis: Discussion and Implications

Kristen St. John, James Madison University; Kelsey Bitting, Northeastern University; Cinzia Cervato, Iowa State University; Kim A. Kastens, Lamont-Doherty Earth Observatory; Heather Macdonald, College of William & Mary; John R. McDaris, SERC at Carleton College; 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-Tempe; Rachel Teasdale, California State University-Chico.

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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.

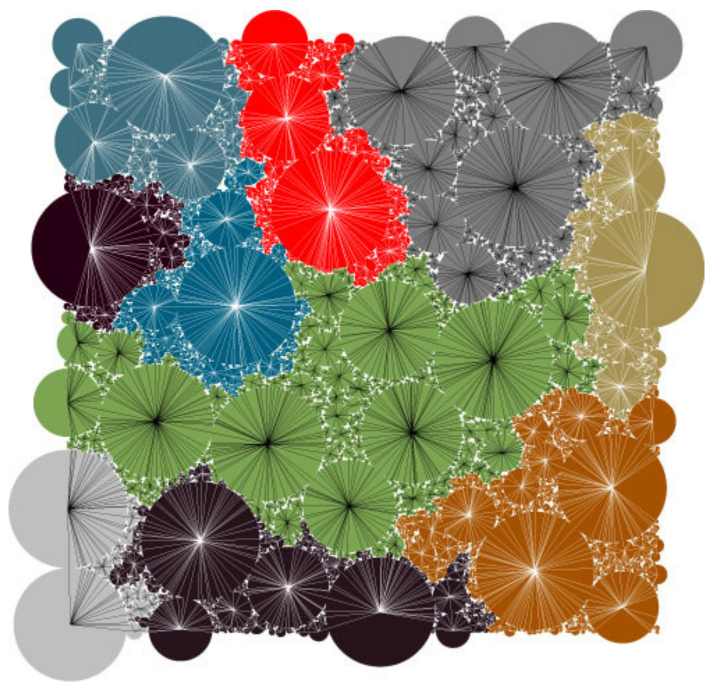

Figure 1. The thematic grand challenges illuminate interconnected paths for future geoscience education research (GER) that create a guiding framework to harness the power of GER to improve undergraduate teaching and learning about the Earth. In this drawing, colors represent different themes, and the 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).

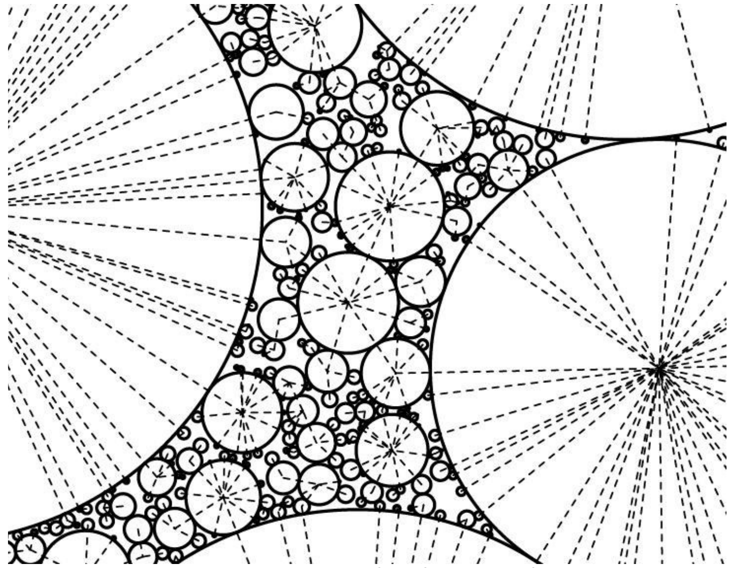

Figure 2. Chemical bonds are used as analogies for different types of connections that link research themes. The drawing, "Constellation no. 2, detail" is by Andrew Kudless and Laura Rushfeldt (https://www.matsys.design/constellations) and is used here with their permission.

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

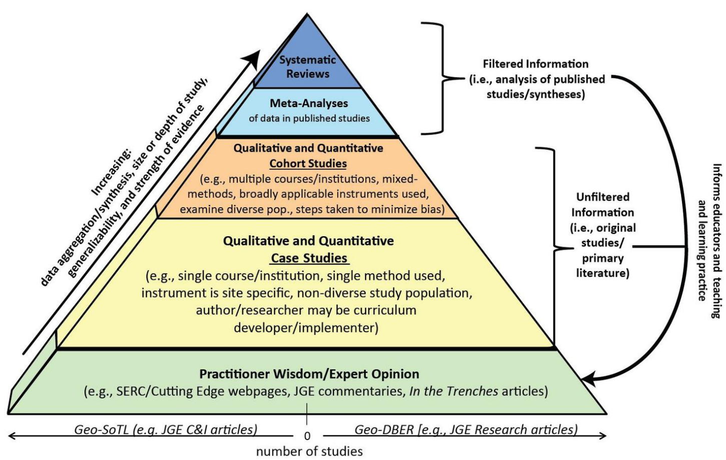

Figure 3. GER Strength of Evidence Pyramid, from St. John & McNeal 2017.

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-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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