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

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Introduction

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

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

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

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

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

Grand Challenges

Grand Challenge 1: How can research and evaluation keep pace with advances in technological and methodological strategies for geoscience instruction, and with evolving geoscience workforce requirements?

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

Grand Challenge 2: How can undergraduate geoscience instruction benefit from and contribute to effective research-based practices in other domains?

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

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

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

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

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

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

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

Grand Challenge 1:

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

Rationale

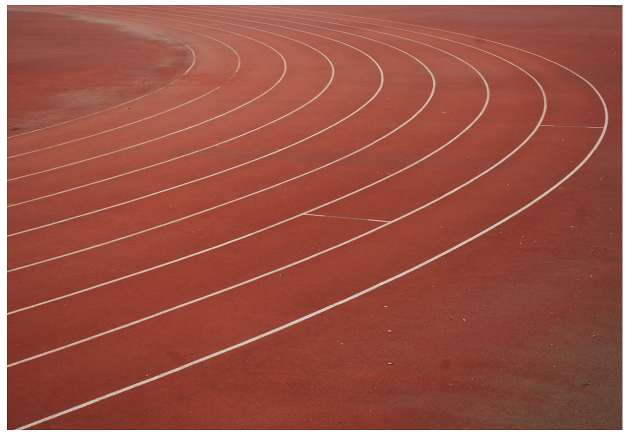

Figure 2. Sometimes the instructional strategies employed by educators outpace the research that is needed to evaluate effectiveness and determine whether, or how, the strategies aid in student learning of concepts, skills, and dispositions. Photo from Public Domain. (https://www.publicdomainpictures.net/en/view-image.php?image=16745&picture=track-running-lanes)

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

Recommended Research Strategies

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

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

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

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

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

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

Grand Challenge 2:

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

Rationale

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

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

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

Recommended Research Strategies

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

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

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

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

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

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

Grand Challenge 3:

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

Rationale

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

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

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

Recommended Research Strategies

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

of learners and different instructional settings.

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

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

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

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

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

Grand Challenge 4:

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

Rationale

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

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

Recommended Research Strategies

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

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

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

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

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

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

Grand Challenge 5:

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

Rationale

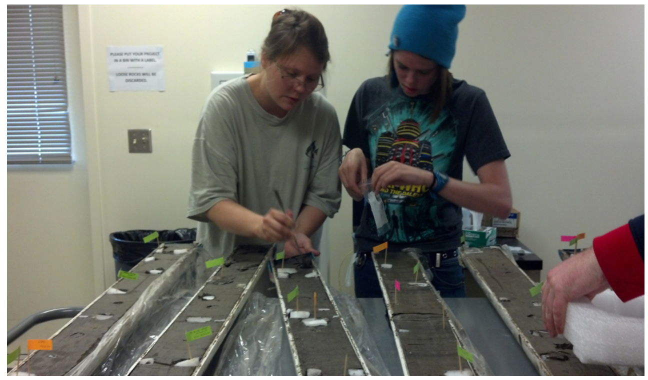

Figure 6. Peer instruction, research experiences, service learning, and internships are ways students can become co-creators of knowledge. How to effectively implement these strategies and better engage learners warrants more attention from GER.

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

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

Recommended Research Strategies

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

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

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

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

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