Research on Students' Conceptual Understanding of Geology/Solid Earth Science Content

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Introduction

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

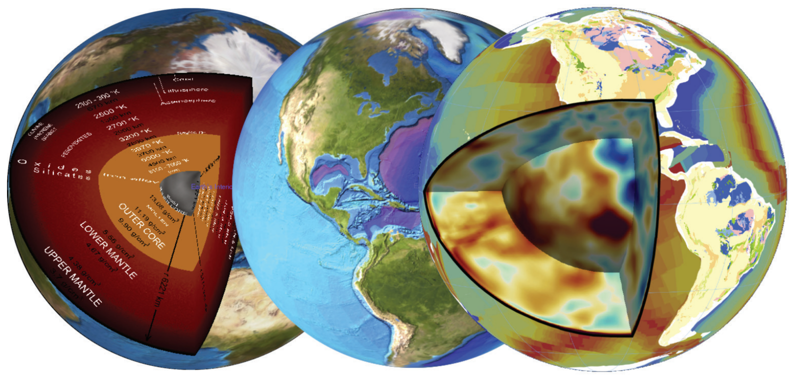

Figure 1. Research on students' conceptual understanding of solid Earth science concepts impacts the core of much course-work in undergraduate geology degree programs. Determination of students' misconceptions and then optimal learning progressions for geology concepts are two research challenges that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

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

Grand Challenges

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

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

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

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

Grand Challenge 1:

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

Rationale

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

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

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

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

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

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

Recommended Research Strategies

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

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

Grand Challenge 2:

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

Rationale

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

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

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

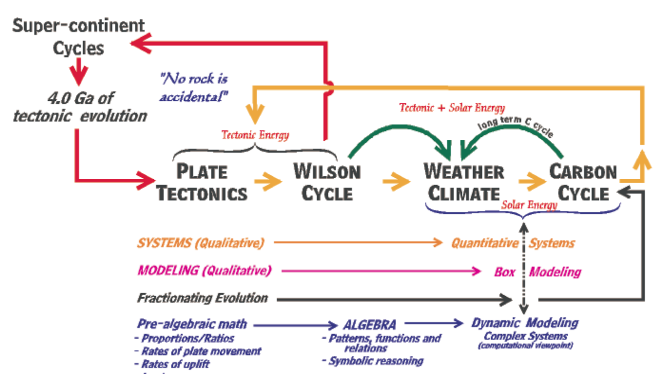

Figure 3. Example of a possible learning progression for Earth system concepts. By Lynn Fichter and Eric Pyle, James Madison University.

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

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

Recommended Research Strategies

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

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

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

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Figures

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