Establishing A Consensus Of Geology Concepts Using U.S. National Science Education Reform Documents

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ABSTRACT

An important practice of science teachers and science teacher educators is identifying standards and learning objectives before developing curriculum, instructional materials, and assessments. In the Earth sciences, determining a consensus of learning targets from the multiple national reform documents to provide direction to Earth science educators at the K-12 and post-secondary level has proven to be ambiguous. In this study, the purpose was to identify the core ideas that are taught in an introductory geology course and that students would know. Using a simple random sampling scheme, 134 geology educators, which we refer to as content experts, working at the collegiate level across the United States were surveyed to review and provide feedback on the following current national standards reform documents: 1) Next Generation Science Standards; 2) Earth Science Literacy Principles; 3) National Science Education Standards; and 4) Benchmarks for Scientific Literacy. With a 29.9% response rate, 11 core ideas of geology were identified by the geology educators. Additionally, national reform documents and the top reviewed state science standards were used to verify the 11 core ideas. The final product is a consensus document that provides the 11 core ideas proposed by a consensus of four national reform standards documents, content experts (geologists and geology educators), and the top state science standards.

Keywords: Discipline-Based Geoscience Education Research; Geology Teaching, Standards, NGSS

ESTABLISHING A CONSENSUS OF GEOLOGY CONCEPTS USING U.S. NATIONAL SCIENCE EDUCATION REFORM DOCUMENTS

Geoscience educators can generally agree with the notion that improving teaching and learning requires clearly specified content standards to guide instruction and guide assessment. Some researchers go so far as to argue that identifying standards is equally as important as identifying instructional materials and assessments (Van Der Hoeven Kraft, Husman, Semken, & Fuhrman, 2011). In any event, content standards are intended to function as the framework to which everything else is attached, forming the groundwork for curricular activities and leading standards-based educational reform (Lerner, 2000; Li, Klahr, & Siler, 2006; Mosher, 2011; Penuel, Fishman, Gallagher, Korbak & Lopez-Prado, 2009). However, there are challenges that the United States as a composite of individual states face when adopting standards-reform standards documents, especially with states themselves being responsible for making the decision on whether or not to adopt national-reform standards (Bianchini & Kelly, 2003; Settlage & Meadows, 2002).

The U.S. has devoted considerable effort an expense in establishing national reform documents for science standards across all disciplines to guide states in decision making in response to the International Association for the Evaluation of Educational Achievement's *Trends in International Mathematics and Science Study* (Mullis & Martin, 2014). Mathematics and science scores for U.S. students remain average in comparison to students in top-scoring countries such as Singapore, Korea, Hong Kong, Japan, and China (Stephens, Landeros, Perkins, & Tang, 2016). Currently, there are at least four national interpretations and 50 different state-level interpretations of how to implement widespread science education content standards. Largely unique across the world, in the U.S., individual states largely have control over what standards are taught at the K-12 level. Moreover, the actual process of generating standards for schools varies tremendously from state to state.

There have been at least four national-scale attempts in creating national reform documents for science education standards in the last several decades, including the American Association for the Advancement of Science (1993) *Benchmarks for Science Literacy*; The National Research Council's (1996) *National Science Education Standards*; The Earth Science Literacy Initiative's (2009) *Earth Science Literacy Principles*; and what was originally initiated by the National Research Council, but coordinated entirely by non-profit-entity Achieve, Inc. *Next Generation Science Standards* (2013). As part of these projects, geology educators themselves invested significant effort in creating several competing standards reform documents to guide Earth science education specifically but have been largely unsuccessful in coming to a widespread, uniform consensus of which core concepts related to geology all students should know (Guffey, Slater, Schleigh, Slater, & Heyer, 2016; Gilbert, Stempien, McConnell, Budd, van der Hoeven Kraft et al., 2012; Hoffman & Barstow, 2007; King, 2008; Orion, King, Krockover, & Adams, 1999).

It seems only reasonable that geology educators would benefit from knowing what the overarching consensus is on the range and domain of what specific content should be taught and tested. For one, if geology educators are going to be creating instructional materials for widespread adoption, curriculum developers need to know what topics to address. For another, given that we live in an accountability-based era wherein an increasing number of teachers want to assess their students' learning and the various teaching methods implemented, there is interest in discovering valid and reliable assessments that can be utilized across teaching paradigms that allow comparisons to be made (Freeman, Eddy, McDonough, Smith, Okoroafor et al., 2014). In this instance, people need to know the consensus of what geology concepts that will be tested.

Speaking to assessment specifically, the geology education community has needed an instrument that coves the wide range of concepts taught in introductory geology courses (Guffey, Slater, & Slater, 2017; LaDue & Clark, 2012; Libarkin, 2008). Although a few geology education instruments exist (Guffey et al., 2017; Cervato, Rudd, & Wang, 2007; Iverson, Steer, & Manduca, 2012; Libarkin, 2008; Libarkin & Anderson, 2005), the geology education community has been unsuccessful in adopting one specified instrument (Guffey et al., 2017). This could be a result of the community at large lacking a consensus of the core ideas that should be taught and tested in an introductory geology survey course (Guffey et al., 2017; LaDue & Clark, 2012). In general, finding a way to align the concepts that you are teaching with the items that you are testing has proven to be difficult for the geoscience education community (Wysession, LaDue, Budd, Campbell, Conklin et al., 2012). Taken together, teachers, curriculum developers, and assessment experts find great value in knowing what the consensus portfolio is among leading geology educators.

LITERATURE REVIEW

One of the initial efforts to establish standards to guide science education was in 1993 when the American Association for the Advancement of Science (AAAS) created the *Benchmarks for Science Literacy* to clearly specify "what all students should know and be able to do in science, mathematics, and technology" (American Association for the Advancement of Science, 1993, p. 1). The primary goal of the Benchmarks was to outline a students' progression towards science literacy in each grade level. The standards were organized by grade levels (K-5, 6-8, and 9-12) and incorporated technology into each subject area.

The *National Science Education Standards* (NSES) were developed by the National Research Council (NRC) in 1996 and are intended to serve as "science standards for all students" (p. 2). The NSES presented "a vision of a scientifically literate populace" and outlined what students should "know, understand, and be able to do to be scientifically literate at different grade levels" (National Research Council, 1996, p. 2). The standards were organized by grade levels (K-4, 5-8, and 9-12) and incorporated inquiry and processes into each content area. A defining component of the NSES was that they were designed under the idea that teachers and teaching were the core of science education reform (Alake-Tuenter, Biemans, Tobi, Wals, Oosterheert et al., 2012; Guffey et al., 2016). The science teaching standards described what science teachers "at all grade levels should know and be able to do" (National Research Council, 1996, p. 4) and the professional development standards provided a guideline for teachers to analyze and assess their pedagogical content knowledge (Guffey et al., 2016; National Research Council, 1996).

The *Earth Science Literacy Principles* (ESLP) were created by the Earth Science Literacy Initiative (2009) to identify a set of fundamental ideas in Earth science that all citizens should know. The ESLP were the first and only standards that were specifically designated to geology with an emphasis on Earth systems, however, they were not adopted in all schools across the nation. The goal of the ESLP was to develop a geology-centered curriculum that contained the foundational geology concepts, which were referred to as the *big ideas*, and that they would be embedded into textbooks. The ESLP were divided into nine big ideas (Earth Science Literacy Initiative, 2009) but the problems were they do not specify which standards to teach with each grade level and the large amount of information in each standard (Finley, Nam, & Oughton, 2011).

In 2013, the National Research Council (NRC), the National Science Teachers Association (NSTA), the American Association for the Advancement of Science (AAAS), and Achieve Inc. worked together to create the *Next Generation Science Standards* (NGSS). The main objective of NGSS is described in The National Research Council's *Framework,* which states that the standards are "designed to help realize a vision for education in the sciences and engineering in which students actively engage in science and engineering practices and apply crosscutting concepts to deepen their understanding of the core ideas in these fields" (National Research Council, 2012, p. 8-9). To successfully demonstrate the objectives, the Framework presented three dimensions: (a) *Practices* are what scientists and engineers use in investigation while building models, theories, and explanations about the natural world; (b) *Cross-cutting concepts* are an approach of connecting the different fields of science; and (c) *Disciplinary core ideas* identify the core knowledge in a science discipline and guide curriculum, instruction, and assessment (National Research Council, 2013). The *NGSS* were the first widely to incorporate systems, processes, and technology within this content (Guffey et al., 2016).

An earlier study questioned the degree of overlap among the four national standard reform documents (Benchmarks, NSES, ESLP, and NGSS) (Guffey et al., 2016; Slater & Slater, 2015). Results showed that not only are the standards within each individual document often redundant, but also there are only two core geology concepts that overlap: plate tectonics and the water cycle. It is apparent that a common set of standards is still needed defining the minimal geology content that every K-12 student should know. Geology educators would benefit greatly from knowing overlap because of assessment, curriculum design, and identifying misconceptions (Libarkin & Anderson, 2005; King, 2010).

BACKGROUND & CONTEXT

Other science discipline-based education research fields, such as physics and biology, have been able to reach a logical level of agreement about which concepts should be taught in the classroom (Garvin-Doxas & Klymkowsky, 2008; Hestenes, Wells, & Swackhamer, 1992). In geology, Huynh and Sharpe (2013) created a concept inventory to measure expertise in geospatial thinking. In response, a research agenda identifying areas of geospatial learning that are needed to provide guidance to prospective investigators (Baker, Battersby, Bednarz, Bodzin, Kolvoord et al., 2015). Consider the recent example from astronomy, which is a domain of Earth science (Singer, Nielsen, & Schweingruber, 2012; Slater, Schleigh, & Stork, 2015). Adams and Slater (2000) provided a roadmap astronomy education agenda which drove a decade's worth of development of single-topic conceptual surveys, which included the *Star Properties Concept Inventory* (Bailey, Johnson, Prather, & Slater, 2012) and many others (Guffey & Slater, 2020). The broader astronomy community realized that from what educators and students would benefit most was a "single, comprehensive, easy-to-use, and easy-to-score assessment instrument based on natural student language, as opposed to the vocabulary of scientific jargon" (Guffey et al., 2017, p. 26; Slater, Slater, Heyer, & Bailey, 2015).

In response, Slater (2014) developed the *Test Of Astronomy STandards*, *TOAST*. Before the development of test questions on the *TOAST*, the team needed to identify the core concepts that students were expected to know and conceptually understand (Guffey et al., 2017). At the same time, the test needed to short and manageable. Recognizing that substantial human and fiscal resources had already been allocated by the community in the creation of national standards reform documents, the team established a consensus-map of overlapping astronomy and planetary science learning targets established by the National Research Council's (1996) *National Science Education Standards*, the American Association for the Advancement of Sciences's (1993) Project 2061 *Benchmarks for Science Literacy*, and the *American Astronomical Society's* Goals for ASTRO 101 document (Partridge & Greenstein, 2003). (This occurred before the *Next Generation Science Standards* were publicly released.) In short, the team decided to rely upon the existing broad wisdom of the astronomy education field, rather than devise their own learning targets.

In brief, the successful approach to establishing consensus learning goals of the astronomy education community was to list all the learning targets from the NSES, Benchmarks, and AAS and to find the places where the concepts clearly overlapped. Described elsewhere (Slater, 2014), this process resulted in 10 conceptual domains that were common to all three reform documents. An 11th conceptual domain was added that was only common to two of the three—size and structure of the universe—because it was judged that the broader astronomy teaching community would be unlikely readily to adopt any instrument that did not include this idea. The overlap of conceptual domains was subjected to an expert review panel of professional astronomers, astronomy education researchers, and experienced astronomy teachers prior to making a final determination of what the precisely targeted learning targets would be for the TOAST. In the end, the *TOAST* instrument has been widely adopted and used in tens of thousands of astronomy education research studies (Slater et al., 2015).

Given the successful approach of distilling the universe of possible concepts in astronomy education down to a manageable number that can be tested and still represent a consensus of the field, one wonders if a similar strategy used by the astronomy community of establishing the most important learning targets would work in the Earth sciences domain of geology. Because Earth science is lacking a well-agreed upon nationally specified curriculum, in fact—there are at least four national curricula—the purpose of this study was to develop a clear set of consensus learning goals for geology that would serve as the first step toward creating an acceptable geology assessment instrument that has the best chance for widespread adoption by the geosciences education community. In response, this work was driven by the overarching question: Which geology concepts repeated emerge as dominant themes when looking at the various national education reform documents and when surveying thought-leaders in geology education?

METHODOLOGY

This study adopted a modified sequential exploratory design in multiple phases based on an inquiry model (Creswell & Plano Clark, 2011). The first phase focused on collecting and analyzing qualitative data. The second phase, informed by the first, focused on quantitative data collection and analysis. The last phase involved additional qualitative collection and analysis based on questions resulting from the first two phases. Creswell and Plano Clark (2011) argue that this study design allows researchers to use quantitative data to better understand and explain the initial qualitative results. The author team added the term "modified" because an additional qualitative phase was included to help better understand the initial qualitative and quantitative results.

Target Population

The target population were geology educators employed at U.S. colleges and universities. The researchers used the Internet to search for more than 100 geology faculty members, including their email addresses, on the websites of U.S. colleges and universities, emphasizing those that publish frequently, speak at conferences frequently, and are called out by others as geology education thought leaders. Convenience and random sampling were both used to select the sample of 134 geologists who were emailed to complete the survey. A total of 40 geologists completed the survey, yielding a 29.9% response rate.

Qualitative Phase One

In the United States, geology is rarely a stand-alone subject in the K-12 schools; therefore, geoscience educators often are unsure of which geology learning targets their students should know. Our team collected the following four national standards reform documents: National Research Council's (1996) *National Science Education Standards*, the American Association for the Advancement of Science's (1993) Project 2061 *Benchmarks for Science Literacy*, Earth Science Literacy Initiative's (2009) *Earth Science Literacy Principles*, and National Research Council's (2013) *Next Generation Science Standards.* These documents were collected in an effort to sort through and identify what geology objectives educators, curriculum developers, and assessment teams should use. This was the first of two qualitative phases.

The first qualitative phase began with a content thematic analysis (Braun & Clark, 2006; Creswell, 2014) of all Earth science standards from the four national reform documents (NSES, AAAS Benchmarks, ESLP, NGSS). This resulted in a collection of all Earth science standards. The standards were organized into a table by their *big idea*, or as we called, criteria. Our initial intention was simply to overlay the four national reform documents and to establish which concepts were common to all four. This initial approach tuned out to be untenable. We reduced our criteria for consensus to commonality among the core ideas only appearing in two out of the four documents (i.e., soils, rocks and minerals, and rock cycle).

Quantitative Phase

Once the initial overlap among standards had been determined, we surveyed geologists working in academia across the United States to receive experts' feedback on the established criteria. A proposed document was uploaded into Survey Monkey. Geologists were provided a table with standards and for each row were asked a single question: "Are these standards reasonably aligned?" Additionally, they were able to provide feedback as to why they chose "yes" or "no." Convenience and random sampling were both used to select the sample of 134 geologists who were emailed to complete the survey. The response rate among 134 geologists was 29.85%.

A quantitative descriptive analysis was used (Field, 2013; Johnson & Christenson, 2019) to determine the agreement of which geology concepts should be taught to U.S. K-12 students. Two percentages were analyzed: (a) Geologists that agreed concepts overlapped; and (b) Geologists that did not agree the concepts overlapped.

Qualitative Phase Two

To respond to our surveyed experts' feedback, we performed a classical content analysis (Leech & Onwuegbuzie, 2008, this time using published state standards that received top ratings (A and A-) in the Thomas B. Fordham's Institute review (Lerner, Goodenough, Lynch, Schwartz, & Schwartz, 2012). In many cases, we found that the state standards documents were far more detailed and specific than were the national documents. We analyzed science standards from the following five states with high marks for completeness: California (A), Virginia (A-), South Carolina (A-), Indiana (A-), and Massachusetts (A-), and one federal district: District of Columbia (A). This phase of content analysis helped us better interpret the national documents because state standards setting authors had clearly devoted considerable time to digesting and recasting the national standards for actual classroom and assessment purposes. For example, only two national standards--NSES and AAAS Benchmarks–stated the importance of minerals; however, all state standards we analyzed verified that the concept of minerals serves as a core idea and clarified what students should know and why.

RESULTS

Overall, we found 14 concepts repeatedly emerged as dominant themes from our qualitative analysis, which were: (a) The Earth changes over time (gradual vs. catastrophic), (b) The geologic record, (c) Fossils, (d) Geologic time scales, (e) Tectonics, (f) Plate tectonics, (g) Earth's plates, (h) Radioactivity within the Earth, (i) Minerals as ores, (j) Earth's elements and minerals, (k) Rock cycle, (l) Water as a geologic agent, (m) Weathering and erosion, and (n) Landforms. However, quantitative results from the survey overall displays a minimal agreement of which geology concepts should be taught to U.S. K-12 students, with 42.86% of the geologists surveyed in disagreement on the standards and 57.14% in agreement. Table 1 displays the quantitative results. Unlike the consensus document readily developed in astronomy (Slater, 2014; Schleigh, Slater, Slater, & Stork, 2015), the geology experts whom we surveyed believed that the geoscience content was scientifically inaccurate, that the standards were frequently vague, and that the alignment among different standards documents was weak.

Table 1. Summary of Geology Experts' Survey Results

Overlapping Concept	Yes (%)	No (%)	Example quotes
The Earth changes over time (gradual vs. catastrophic)	71.43	28.57	*NSES* doesn't specifically say some processes are slow, just that they occur at the same rate as in the past.
The geologic record	85.71	14.29	*NGSS* and *ESLP* make no mention of absolute time but the other two do.
Fossils	100	0	
Geologic time scales	75	25	*ESLP* is too general.
Tectonics	80	20	*ESLP* is too short and general.
Plate tectonics	100	0	
Earth's plates	40	60	*ESLP* and *NGSS* give the wrong impression; They address very different aspects of differences in the crust; While *ESLP* and *Benchmark* descriptions focus on the distinction between physical "type" of crust or features of the crust, whereas the *NGSS* description focuses on the temporal differential between the two.
Radioactivity within the Earth	44.44	55.56	*ESLP* emphasizes, "cooling," which is not a primary source of heat indicated in the other standards. I think the other two more accurately reflect current scientific understanding; *NSES* explicitly notes a distinct mechanism not cited in the others; *ESLP* specifically states the Earth is cooling, whereas *NGSS*'s lack of statement about cooling suggests the Earth's internal temperature is at steady state. In addition, only *NSES* mentions anything about gravitational energy from Earth's original formation.
Minerals as ores	0	100	*ESLP* does not reflect scientific understanding; *ESLP* emphasized only a geological issue, the others cite practical implications; The *ESLP* and *NSES* statements are stupidly articulated. *Benchmarks* are ok. All the standards focus on different points, *NSES* on utility, *Benchmarks* on genesis and quantity (somewhat similar to *ESLP*).
Earth's elements and minerals	42.86	57.14	They (*NSES, Benchmarks, ESLP, NGSS*) cite different issues; *ESLP* is about the relationship between elements and minerals as components of rocks, whereas *Benchmarks* are about why types of rocks are different (i.e., mineral composition), not just that rocks are composed of minerals.
Rock cycle	28.57	71.43	The *ESLP* is not even grammatical and is so vague to not convey any core knowledge; The *Benchmarks* do not mention igneous rocks – an important part of the rock cycle; The "cycle" concept is overemphasized. Physical and chemical processes occurring in and on Earth lead to both reversible and irreversible changes; Only *NSES* actually describes actually what is usually taken to be the rock cycle. *ESLP* is just about cycles as a general notion and *Benchmarks* fail to include the metamorphic and igneous aspects of the rock cycle.
Water as a geologic agent	66.67	33.33	Unlike the *Benchmarks* and *NGSS*, *NSES* entirely fails to mention the role of water in physical processes like erosion and deposition in shaping landscapes.
Weathering and erosion	80	20	*NGSS* is not aligned with the others.
Landforms	20	80	*Benchmarks* are simply descriptive and lack mechanistic understanding; *ESLP* and *NSES* are process-oriented.

Note. Quotes are from interviewed participants.

With regard to the concept "minerals as ores," we observed a 100% disagreement on the alignment of standards, contrasting "fossils," which received a 100% agreement on the alignment of standards. The concept "rock cycle" and "landforms" also showed a high level of disagreement (71.43%, 80%, respectively) amongst our geology experts surveyed. The resulting consensus document is intended to provide a consensus vision of four national standards clarified, supported, and verified by the top five state standards and one federal district standards. Appendix A through K depicts one of the 11 concepts in the consensus document and the aligning standards from the national reform documents. After reviewing feedback from the expert community and analyzing the standards of top reviewed states (Lerner et al., 2012), the final consensus document of learning goals was reduced from 14 to 11, and are displayed in Table 2.

Table 2. Consensus of Overlapping Geology Concepts

Targeted Concepts	Description
Concept 1: Earth's moving plates	Earth's crust is broken into pieces, which slowly move in relationship to each other, driven by convection currents in the mantle.
Concept 2: Rocks and minerals	Atoms of different elements combine to make minerals, which combine to make rocks. Rocks and minerals are classified by on their chemical and physical properties.
Concept 3: The rock cycle	Earth materials take many different forms as they cycle through the geosphere. Rocks form from the cooling of magma, the accumulation and consolidation of sediments, and the alteration of older rocks by heat, pressure, and fluids. These three processes form igneous, sedimentary, and metamorphic rocks.
Concept 4: Earth's rock record	Earth's rocks allow us to reconstruct Earth's history, giving both relative and absolute dates.
Concept 5: Fossils	Fossils provide evidence about the types of organisms that lived long ago and the nature of the environments at the time.
Concept 6: Tectonic features and activity	Earthquakes, mountain building, volcanic activity, and ocean floor features occur at plate boundaries as the result of plate movement.
Concept 7: Earth's layered structure	The Earth has a layered structure with a dense metallic core, hot convecting mantle, and a brittle crust.
Concept 8: Earth's internal heat source	Earth's interior is heated primarily by radioactive decay and gravitational energy.
Concept 9: Weathering and erosion	Rocks are chemically and physically weathered into smaller pieces which are transported (eroded) by gravity, water, ice, and wind.
Concept 10: Soils	Soil is formed by weathered rocks and decayed organic materials.
Concept 11: Earth's changing landforms	Landforms result from the interplay between processes that create crust (plate movement, crust uplift, and sedimentary rock formation) and those that destroy crust (weathering and erosion). These interactions occur at a variety of time scales.

Source: National Research Council's *National Science Education Standards,* 1996; the American Association for the Advancement of Science's Project 2061 *Benchmarks for Science Literacy*, 1993; National Science Foundation's *Earth Science Literacy Principles,* 2008; and National Research Council's *Next Generation Science Standards,* 2013).

DISCUSSION

To our great surprise, the geology education community is not in uniform agreement on which Earth science concepts K-12 students should know based on our review of the standards documents. The standards listed in the national reform documents were often judged to be so vague, it was difficult to establish which content was being specified. Comments from the geologists surveyed support the idea that the Earth science education community does not agree on what to teach. This is perhaps an unpopular result but is readily seen in the data from this study.

For example, 100% of the geologists disagreed that the horizontal line of standards for "minerals as ores" were aligned. On the survey, participants claimed that the *Earth Science Literacy Principles* reflect "poor scientific understanding" and are "stupidly articulated." Participants also mentioned an inconsistency on the focus points, stating that "NSES focused on utility and *Benchmarks* and *ESLP* focusing on genesis and quantity." With the scientific content of the various standards being inconsistent, it is difficult to determine which specific concepts to teach.

The concepts surrounding "rock cycle" on the survey resulted in a high level of disagreement on the overlapping concepts (71.43%). Several respondents noted that *Benchmarks* failed to mention igneous rocks, which is a crucial component of the rock cycle. Additionally, other respondents noted that the standards address the rock cycle on different scales. Other respondents stated that the "standards are grammatically incorrect" and are "so vague that they don't convey any core knowledge." One surprising aspect of the rock cycle notion is that not all geologists noted is NGSS's failure to mention the rock cycle at all in the disciplinary core ideas. By definition, geology is the study of rocks (Lutgens, Tarbuck, & Tasa, 2018); therefore, it might seem odd that NGSS does not include the rock cycle in the disciplinary core ideas, which are supposed to represent to core ideas being taught within that content.

Based on our data analysis, the final consensus shown in Table 2 consolidates three learning goals (Earth changes over time, geological time scales, and landforms) into one (Earth's changing landforms). The processes that the Earth undergoes to change and the speed at which those changes occur are ultimately one big idea. The concept of "landforms" received a high level of disagreement amongst the geology experts (80%) for many reasons. Several geologists noted in their responses that the *Benchmarks* standard is simply descriptive, whereas the other two (ESLP and NSES) are science process-oriented. Other comments that influenced our results included pointing out that ESLP's focus on the mechanism of landform formation and the *Benchmarks'* "lack of mechanistic understanding." With regard to "geologic time scales," 25% of the geologists surveyed did not agree on the alignment of standards. The *Benchmarks* and *ESLP* were considered to be "too general" or "overly simplistic," not addressing key integration elements. Overall, 28.57% of geologists disagreed with the criteria "Earth changes over time (gradual vs. catastrophic)" were aligned, with many comments addressing the "over simplicity of the standards" and "too vague." One geologist surveyed mentioned that NSES does not sufficiently convey the range of spatial scales.

Results further show that 55.56% of geologists do not agree that the various standards overlap for the learning goal "radioactivity within the Earth." After reviewing experts' feedback, this goal was changed to be more clearly specified as, "Earth's internal heat source." Several comments mention ESLP's emphasis on the cooling of the Earth, which is not a primary heat source indicated in the other standards. Other comments include NGSS's failure to mention cooling of the Earth, which suggests that "the Earth's internal temperature is at steady state." One respondent noticed that NSES mentions gravitational energy from Earth's original formation as being a heat source. However, the respondent followed up with, "this heat has long been dissipated and even if Earth started cold, radioactive decay would be sufficient to account for its current heat budget." According to the content experts surveyed, it is still unclear what students should know about Earth's internal heat source.

The goal "Water as a geologic agent" was consolidated with "weathering and erosion," with 66.67% agreeing that this line of standards was reasonably aligned; however, several geologists noted "confusion of two distinct concepts," one being chemical weathering, wherein water acts as a solvent, and the second being landscape evolution, wherein moving water and ice act as mechanisms of erosion and sediment transport. Other geologists mentioned that NSES failed to highlight the role of water in physical processes like erosion and deposition and in shaping landscapes. After reviewing these comments, it was logical to consolidate "water as a geologic agent" with "weathering and erosion."

Only 40% of geologists surveyed agreed that the overlap of the various standards describing the concepts surrounding "Earth's plates" were actually aligned with one another. After data analysis, this learning goal was more clearly specified to "Earth's moving plates" in the resulting consensus document. Several geologists specifically criticized that ESLP and NGSS "give the wrong impression." Others suggested that each standard addresses different aspects of differences in the crust and that the standards should instead clearly "address Earth's lithosphere, which comprises the crust and rigid outer mantle to form a plate." A few noted that the ESLP and the Benchmarks descriptions focus on the "distinction between the physical type of crust or features of the crust (continents vs. oceans), whereas the NGSS description focuses on the temporal differentiation between the two." To us, this seems to be an important distinction. Continuing with the previous concept domains, we are still left questioning much of which specific concepts teachers need to teach and the learning targets that students need to meet in this domain.

CONCLUSION

By looking at the conceptual overlaps in the geology domain of the leading national and state science education reform documents—in concert with interpretive analysis by geology educators, a single "consensus" of experts' roadmap to the standards is revealed. Such a consensus document can readily serve to inform teachers, curriculum developers, and assessment specialists. Moreover, reviewing each of the national reform documents and analyzing experts' feedback as a single entity for synthesis, a few dominant themes emerge across the dataset. For one, although NGSS attempted to improve standards by reducing the amount of content (e.g., wind and water can change shape of land, National Research Council, 2013), the standards resulted in being vaguely uninformative for curriculum and assessment developers. What's worse, the assessment parameters suggested by NGSS seem to do nothing more than limit instruction to those topics, which are obviously being tested, despite empty claims otherwise. Schwartz, Sadler, Sonnert, and Tai (2009) emphasized the importance of "depth versus breadth" in national and state science standards to help students develop a conceptual understanding of science. However, when standards are uninformative, it leaves the rubber-meets-the-road classroom teacher with the arduously difficult task of deciding which concepts to teach and how (Schwartz et al., 2009).

Geology content in the NRC's NSES and AAAS's Benchmarks do overlap in many areas; but also, they include the majority of the same content being taught to similar age groups. For example, NSES and the Benchmarks both agree that the rock cycle should be taught to elementary school children (Grades K-2; Ages 5-8). Constituents of the science education research community consistently agrees that young children are extremely curious of the natural world and quickly learn processes such as observing and classifying (Bransford, Brown, & Cocking, 2000), which is why teaching the rock cycle to a 6-year-old student is relatively simple. However, the rock cycle is not included in Achieve's NGSS disciplinary core ideas, which are supposed to serve as the framework for the core ideas being taught to K-12 students. This leads the authors to two unresolved questions, what other content is excluded in NGSS's disciplinary core ideas, and is this the reason for the difficulty in creating a consensus document including the core geology ideas that K-12 students should understand?

Ultimately, the entire geology education community wants students to be successful in learning geology and seeing where they agree that the first step is to identify the core ideas that we want our students to know. Once our teaching objectives are identified; we are only then able to select best instructional practices for those core ideas (Wiggins & McTigue, 2015). Moreover, we are able to measure our students' learning gains with an assessment aligned to our selection of core geology ideas. We have had some preliminary success in developing broad-based assessments in this domain (*viz*., Guffey et al., 2017; Guffey & Slater, 2020) using this consensus roadmap, but much more work needs to be done. In any event, education research consistently confirms that specifying clear content and teaching objectives must precede curriculum and assessment development (Hunter, 1982; Lerner, 2000; Li, Klahr, & Siler, 2006; Mosher, 2011; Penuel et. al., 2009, Wiggins & McTigue, 2015), and the author concurs with this perspective.

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APPENDIX A

Concept 1 – Earth's Moving Plates

ESLP	NSES
Earth's interior is in constant motion through the process of convection, with important consequences for the surface. Convection in the solid mantle drives the many processes of plate tectonics, including the formation and movements of the continents and oceanic crust. (4.3) Earth's tectonic plates consist of the rocky crust and uppermost mantle and move slowly with respect to one another. New oceanic plate continuously forms at mid-ocean ridges and other spreading centers, sinking back into the mantle at ocean trenches. Tectonic plates move steadily at rates of up to 10 centimeters per year. (4.4) Earth's crust has two distinct types: continental and oceanic. Continental crust persists at Earth's surface and can be billions of years old. Oceanic crust continuously forms and recycles back into the mantle; in the ocean, it is nowhere older than about 200 million years. (2.4)	The outward transfer of Earth's internal heat drives convection circulation in the mantle that propels the plates comprising the Earth's surface across the face of the globe. (D 9-12)
Benchmarks	**NGSS**
The outward transfer of the earth's internal heat causes regions of different temperatures and densities. The action of a gravitational force on regions of different densities causes the rise and fall of material between the earth's surface and interior, which is responsible for the movement of plates. (4C/H3) The Earth's plates sit on a dense, hot, somewhat melted layer of the Earth. The plates move very slowly, pressing against one another in some places and pulling apart in other places, sometimes scraping alongside each other as they do. (4C/M12) Matching coastlines and similarities in rock types and life forms suggest that today's continents are separated parts of what was long ago a single continent. (4C/M9) The outer layer of the earth—including both the continents and the ocean basins—consists of separate plates. (4C/M11)	Motion of the mantle and its plates occur primarily through thermal convection. (HS-ESS2-3) Continental rocks, which can be older than 4 billion years, are generally much older than the rocks of the ocean floor, which are less than 200 million years old. (HS-ESS1-5)

Source: National Research Council's *National Science Education Standards,* 1996; the American Association for the Advancement of Science's Project 2061 *Benchmarks for Science Literacy*, 1993; National Science Foundation's *Earth Science Literacy Principles,* 2008; and National Research Council's *Next Generation Science Standards,* 2013.

APPENDIX B

Concept 2 – Rocks and Minerals

ESLP	NSES	Benchmarks	NGSS
The atoms of different elements combined to make minerals, which combined to make rocks. (2.3)		Rock is composed of different combinations of minerals. (4C/E2)	

(National Research Council's *National Science Education Standards,* 1996; the American Association for the Advancement of Science's Project 2061 *Benchmarks for Science Literacy*, 1993; National Science Foundation's *Earth Science Literacy Principles,* 2008; and National Research Council's *Next Generation Science Standards,* 2013).

APPENDIX C

Concept 3 – The Rock Cycle

ESLP	NSES
Earth materials take many different forms as they cycle through the geosphere. Rocks form from the cooling of magma, the accumulation and consolidation of sediments, and the alteration of older rocks by heat, pressure, and fluids. These three processes form igneous, sedimentary, and metamorphic rocks. (4.6)	Some changes in the solid earth can be described as the "rock cycle." Old rocks at the earth's surface weather, forming sediments that are buried, then compacted, heated and often recrystallized into new rock. Eventually, those new rocks may be brought to the surface by the forces that drive plate motions, and the rocky cycle continues. (D 5-8)
Benchmarks	**NGSS**
The formation, weathering, sedimentation, and reformation of rock constitute a continuing "rock cycle" in which the total amount of material stays the same as its forms change. (4C/H2) Sediments of sand and smaller particles (sometimes containing the remains of organisms) are gradually buried and are cemented together by dissolved minerals to form solid rock again. (4C/M3) Sedimentary rock buried deep enough may be re-formed by pressure and heat, perhaps melting and recrystallizing into different kinds of rock. These re-formed rock layers may be forced up again to become land surface and even mountains. Subsequently, this new rock will to erode. Rock bears evidence of the minerals, temperatures, and forces that created it. (4C/M4)	

(National Research Council's *National Science Education Standards,* 1996; the American Association for the Advancement of Science's Project 2061 *Benchmarks for Science Literacy*, 1993; National Science Foundation's *Earth Science Literacy Principles,* 2008; and National Research Council's *Next Generation Science Standards,* 2013).

APPENDIX D

Concept 4 – Earth's Rock Record

ESLP	**NSES**
Earth's rocks and other materials provide a record of its history. Earth scientists use the structure, sequence, and properties of rocks, sediments, and fossils to reconstruct events in Earth's history. Decay rates of radioactive elements are the primary means of obtaining numerical ages of rocks and organic remains. Understanding geologic processes active in the modern world is crucial to interpreting Earth's past. (2.1)	Geologic time can be estimated by observing rock sequences and using fossils to correlate the sequences at various locations. Current methods include using the known decay rates of radioactive isotopes present in rocks to measure the time since the rock was formed. (D 9-12) The Earth processes we see today, including erosion, movement of lithospheric plates, and changes in atmospheric composition, are similar to those that occurred in the past. Earth's history is also influenced by occasional catastrophes, such as the impact of an asteroid or a comet. (D 5-8)
Benchmarks	**NGSS**
Thousands of layers of sedimentary rock confirm the long history of the changing surface of the Earth and the changing life forms whose remains are found in successive layers. The youngest layers are not always found on top, because of folding, breaking, and uplift of layers. (4C-M5) Scientific evidence indicates that some rock layers are several billion years old. (4C-H6) The predictability of decay rate allows radioactivity to be used for estimating the age of materials that contain radioactive substances. (4D-H4)	The geologic time scale interpreted from rock strata provides a way to organize Earth's history. Analyses of rock strata and the fossil record provide only relative dates, not an absolute scale. (MS-EES1-4) Local, regional, and global patterns of rock formations reveal changes over time due to Earth forces, such as earthquakes. (4-EES1-1)

(National Research Council's *National Science Education Standards,* 1996; the American Association for the Advancement of Science's Project 2061 *Benchmarks for Science Literacy*, 1993; National Science Foundation's *Earth Science Literacy Principles,* 2008; and National Research Council's *Next Generation Science Standards,* 2013).

APPENDIX E

Concept 5 – Fossils

ESLP	NSES
Fossils are the preserved evidence of ancient life. (6.1)	Fossils provide evidence about the plants and animals that lived long ago and the nature of the environment at that time. (D K-4) Fossils provide important evidence of how life and environmental conditions have changed. (D 5-8)
Benchmarks	**NGSS**
Many thousands of layers of sedimentary rock provide evidence for the long history of the Earth and for the long history of changing life forms whose remains are found in the rocks. (5F/M3a)	The collection of fossils and their placement in chronological order are known as the fossil record. It documents the existence, diversity, extinction, and change of many life forms throughout the history of life on Earth. (MS-LS4-1) Fossils provide evidence about the types of organisms that lived long ago and also about the nature of their environment. (3-LS4-1) The presence and location of certain fossil types indicate the order in which rock layers were formed. (4-ESS1-1)

(National Research Council's *National Science Education Standards,* 1996; the American Association for the Advancement of Science's Project 2061 *Benchmarks for Science Literacy*, 1993; National Science Foundation's *Earth Science Literacy Principles,* 2008; and National Research Council's *Next Generation Science Standards,* 2013).

APPENDIX F

Concept 6 – Tectonic Features and Activity

ESLP	NSES
Many active geologic processes occur at plate boundaries. Plate interactions change the shapes, sizes, and positions of continents and ocean basins, the locations of mountain ranges and basins, the patterns of ocean circulation and climate, the locations of earthquakes and volcanoes, and the distribution of resources and living organisms. (4.5)	Major geological events, such as earthquakes, volcanic eruptions, and mountain building, result from these plate motions. (D 5-8)
Benchmarks	**NGSS**
Earthquakes often occur along the boundaries between colliding plates, and molten rock from below creates pressure that is released by volcanic eruptions, helping to build up mountains. Under the ocean basins, molten rock may well up between separating plates to create new ocean floor. Volcanic activity along the ocean floor may form undersea mountains, which can thrust above the ocean's surface to become islands. (4C/H5) Mountains form as two continental plates, or an ocean plate and a continental plate, press together. (4C/M12) There are worldwide patterns to major geological events (such as earthquakes, volcanic eruptions, and mountain building) that coincide with plate boundaries. (4C/M13) Heat flow and movement of material within the earth cause earthquakes and volcanic eruptions and create mountains and ocean boundaries. (4C/M1)	The locations of mountain ranges, deep ocean trenches, ocean floor structures, earthquakes, and volcanoes occur in patterns (4-ESS2-2/ESS2.B) Plate movements are responsible for most continental and ocean-floor features and for the distribution of most rocks and minerals within Earth's crust. (HS-ESS2-1) Tectonic processes continually generate new ocean sea floor at ridges and destroy old sea floor at trenches. (HS-ESS1.C)

(National Research Council's *National Science Education Standards,* 1996; the American Association for the Advancement of Science's Project 2061 *Benchmarks for Science Literacy*, 1993; National Science Foundation's *Earth Science Literacy Principles,* 2008; and National Research Council's *Next Generation Science Standards,* 2013).

APPENDIX G

Concept 7 – Earth's Layered Structure

ESLP	NSES
Earth formed from the accumulation of dust and gas, and multiple collision of smaller planetary bodies. Driven by gravity, Earth's metallic core formed as iron sank to the center. Rock surrounding the core was mostly molten early in Earth's history, and slowly cooled to form Earth's mantle. (2.3)	The solid earth is layered with a lithosphere; hot, convecting mantle; and dense, metallic core. (D 5-8)
Benchmarks	**NGSS**
The interior of the earth is hot. (4C/M1) The earth first formed in a molten state and then the surface cooled into solid rock. (4C/M10) The outer layer of the earth—including both the continents and the ocean basins—consists of separate plates. (4C/M11) The Earth's plates sit on a dense, hot, somewhat melted layer of the Earth. (4C/M12)	Evidence from deep probes and seismic waves, reconstructions of historical changes in Earth's surface and its magnetic field, and an understanding of physical and chemical processes lead to a model of Earth with a hot but solid inner core, a liquid outer core, a solid mantle crust. (HS-ESS2-3)

(National Research Council's *National Science Education Standards,* 1996; the American Association for the Advancement of Science's Project 2061 *Benchmarks for Science Literacy*, 1993; National Science Foundation's *Earth Science Literacy Principles,* 2008; and National Research Council's *Next Generation Science Standards,* 2013).

APPENDIX H

Concept 8 – Earth's Internal Heat Source

ESLP	NSES
Earth, like other planets, is still cooling, through radioactive decay continuously generates internal heat. This heat flow through and out of Earth's interior largely through convection, but also through conduction and radiation. The flow of Earth's heat is like its lifeblood, driving its internal motions. (4.2)	Two primary sources of internal energy are the decay of radioactive isotopes and the gravitational energy from the earth's original formations. (D 9-12)
Benchmarks	**NGSS**
	The radioactive decay of unstable isotopes continually generates new energy within Earth's crust and mantle, providing the primary source of heat that drives mantle convection. (HS-EES2-3)

(National Research Council's *National Science Education Standards,* 1996; the American Association for the Advancement of Science's Project 2061 *Benchmarks for Science Literacy*, 1993; National Science Foundation's *Earth Science Literacy Principles,* 2008; and National Research Council's *Next Generation Science Standards,* 2013).

APPENDIX I

Concept 9 – Weathering and Erosion

ESLP	NSES
Weathered and unstable rock materials erode from some parts of Earth's surface and are deposited in others. Under the influence of gravity, rocks fall downhill. Water, ice, and air carry eroded sediments to lower elevations, and ultimately to the ocean. (4.8) Shorelines move back and forth across continents, depositing sediments that become the surface rocks of the land. Through dynamic processes of plate tectonics and glaciation, Earth's sea level rises and falls by up to hundreds of meters. This fluctuation causes shorelines to advance and recede by hundreds of kilometers. The upper rock layers of most continents formed when rising sea levels repeatedly flooded the interiors of continents. (4.9) Ice is an especially powerful agent of weathering and erosion. Water expands as it freezes, widening cracks and breaking apart rocks. Movement of massive glaciers can scour away land surfaces. The flowing ice of glaciers covers and alters vast areas of continents during Ice Ages. (5.7)	Water is a solvent. As it passes through the water cycle it dissolves minerals and gases and carries them to the ocean. (D 5-8)
Benchmarks	**NGSS**
Rivers and glacial ice carry off soil and break down rock, eventually depositing the material in sediments or carrying it in solution to the sea. (4C/M2b) Waves, wind, water, and ice shape and reshape the earth's land surface by eroding rock and soil in some areas and depositing them in other areas, sometimes in seasonal layers. (4C/E1) Substances may move from place to place. (4D/E5) Smaller rocks come from the breakage and weathering of bedrock and larger rocks. (4C/E2) The temperature and acidity of a solution influence reaction rates. Many substances dissolve in water, which may greatly facilitate reactions between them. (4D/M4)	Water, ice, wind, living organisms, and gravity break rocks, soils, and sediments into smaller particles and move them around. (4-ESS2-1) Water movements – both on the land and underground – cause weathering and erosion, which changes the land's surface features and create underground formations. (MS-ESS2-2)

(National Research Council's *National Science Education Standards,* 1996; the American Association for the Advancement of Science's Project 2061 *Benchmarks for Science Literacy*, 1993; National Science Foundation's *Earth Science Literacy Principles,* 2008; and National Research Council's *Next Generation Science Standards,* 2013).

APPENDIX J

Concept 10 – Soils

ESLP	NSES
	Soil consists of weathered rocks and decomposed organic material from dead plants, animals, and bacteria. Soils are often found in layers with each having different chemical components and texture. (D)
Benchmarks	**NGSS**
Soil is made partly from weathered rock, partly from plant remains—and also contains many living organisms. (4C/E2) Although weathered rock is the basic component of soil, the composition and texture of soil and its fertility and resistance to erosion are greatly influenced by plant roots and debris, bacteria, fungi, worms, insects, rodents, and other organisms. (4C/M6)	

(National Research Council's *National Science Education Standards,* 1996; the American Association for the Advancement of Science's Project 2061 *Benchmarks for Science Literacy*, 1993; National Science Foundation's *Earth Science Literacy Principles,* 2008; and National Research Council's *Next Generation Science Standards,* 2013).

APPENDIX K

Concept 11 – Earth's Changing Landforms

ESLP	NSES
Earth's systems interact over a wide range of temporal and spatial scales. These scales range from microscopic to global in size and operate over fractions of a second to billions of years. These interactions among Earth's systems have shaped Earth's history and will determine Earth's future. (3.4) Over Earth's vast history, both gradual and catastrophic processes have produced enormous changes. Super-continents formed and broke apart, the compositions of the atmosphere and ocean changed, sea level rose and fell, living species evolved and went extinct, ice sheets advanced and melted away, meteorites slammed into Earth, and mountains formed and eroded away. (2.7) Landscapes result from the dynamic interplay between processes that form and uplift new crust and processes that destroy and depress the crust. This interplay is affected by gravity, density differences, plate tectonics, climate, water, the actions of living organisms, and the resistance of Earth materials to weathering and erosion. (4.7)	Interactions among the solid Earth, the oceans, the atmosphere, and organisms have resulted in the ongoing evolution of the Earth system. We can observe some changes such as earthquakes and volcanic eruptions on a human time scale, but many processes such as mountain building and plate movements take place over hundreds of millions of years. (D 9-12) Landforms are the result of a combination of constructive and destructive forces. Constructive forces include crustal deformation, volcanic eruption, and deposition of sediment, while destructive forces include weathering and erosion. (D 5-8)
Benchmarks	**NGSS**
Some changes in the earth's surface are abrupt (such as earthquakes and volcanic eruptions) while other changes happen very slowly (such as uplift and wearing down of mountains). (4C/M2a) There are a variety of different landforms on the earth's surface (such as coastline, rivers, mountains, deltas, and canyons). (4C/M8) The Earth's surface is shaped in part by the motion of water (including ice) and wind over very long times, which acts to level mountain ranges. (4C/M2B)	Some events happen very quickly; others occur very slowly, over a period of time much longer than one can observe. (2-ESS1-1) The planet's systems interact over scales that range from microscopic to global in size, and they operate over fractions of a second to billions of years. These interactions have shaped Earth's history and will determine its future. (MS-EES2-2)

(National Research Council's *National Science Education Standards,* 1996; the American Association for the Advancement of Science's Project 2061 *Benchmarks for Science Literacy*, 1993; National Science Foundation's *Earth Science Literacy Principles,* 2008; and National Research Council's *Next Generation Science Standards,* 2013).