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Big Ideas in Earth System Science

A significant component of Outreach at Paleontological Research Institution is our continuing series of Teacher-Friendly Guides to the Geology of the United States. *Funded by the National Science Foundation, the "ReaL Earth Inquiry" project aims to help educators introduce local Earth science into their curricula. Too often, textbooks focus solely on the exotic: the volcanoes of Hawaii or the glaciers of the Arctic. By introducing local geology into the classroom, students are better informed about the Earth science of their own area, and they are therefore better equipped to make decisions regarding Earth stewardship.*

Products of the project include: (1) educator guides – with one guide for each of the seven U.S. regions – available online for free at http://www.teacherfriendlyguide.org, *(2) a database of Virtual Fieldwork Experiences* (http://www.virtualfieldwork.org) *that allow educators to bring the field to their classroom, and (3) a series of educator professional development workshops across the country to introduce the guides and supporting materials into schools. As these materials are developed and presented, they are framed within the overarching set of principles and Big Ideas discussed here. -Richard A. Kissel, PRI Director of Teacher Programs*

Part 1: The Foundation for Earth System Literacy

by Robert M. Ross

It is not uncommon in the pages of this magazine to read the claim that the 21st century will be defined by Earth science issues – climate change, energy, water resources, land use, and others. These are issues that relate to the ongoing sustainability of the ever-growing human population in every part of the planet. Because solving these issues requires the collective actions of billions of individuals, those billions must realize that actions are necessary and choose what those actions should be. The simplest actions are electing public officials who set forward-thinking evidence-based policies. But it's not possible or even desirable to regulate every action of every person – so individuals have to decide for themselves to live in ways that are sustainable for everyone. That's a tall order. As understanding necessarily precedes informed action, the urgency of addressing existing Earth science issues is in part a result of our failure thus far to convince the co-inhabitants of our planet of the ways in which humanity has become a geological force.

Although major Earth science issues are without exception areas of active scientific research, each is also already well enough known to provide a sound foundation for certain policies and personal actions. There is very little uncertainty in the scientific community about, for example, whether the climate is changing, whether fossil fuel availability is finite, whether the Earth is ancient and ever changing, whether rock sequences contain abundant records of biological evolution and extinction, or whether continents move about the Earth's surface. But reading the news, or searching the Internet, one might think that any or all of these are in serious question, even among scientists themselves. For that matter, many people might not realize who does the work that is the basis for these understandings, or realize why Earth science is such an important course in high school. There is no shortage of quality publications on how the Earth works, of course, but if a nonspecialist seeks information, how do they distinguish between mainstream scientific consensus and the remarkable amount of anti- or pseudoscientific literature on the Internet and in bookstores?

In 2008, I participated in an organizing committee (Table 1) to work with the geology and hydrology research community to summarize the most essential consensus understandings (so-called "Big Ideas" and "Supporting Concepts" that underlie them) of these fields of Earth system science. Such a set of Big Ideas would then be used in circumstances ranging from documentation for policy makers of consensus scientific views to lists of learning objectives to include in survey courses. The project was sponsored by the National Science Foundation and named the "Earth Science Literacy Initiative." Our directive was to involve as many research scientists from across the discipline as possible, to obtain perspectives and expertise from a wide range of subfields, and to ensure that the document adequately represented scientific "consensus" views. Toward this goal, we organized a two-week online

Table 1. Organizing Committee of the Earth Science Literacy Initiative

Michael Wysession, Chair (Washington University)
John Taber, Co-Chair (Incorporated Research Institutions for Seismology)
David A. Budd (University of Colorado)
Karen Campbell (National Center for Earth-Surface Dynamics)
Martha Conklin (University of California, Merced)
Nicole LaDue (National Science Foundation)
Gary Lewis (Geological Society of America)
Robert Raynolds (Denver Museum of Nature & Science)
Robert Ridky (United States Geological Survey)
Robert Ross (Paleontological Research Institution)
Barbara Tewksbury (Hamilton College)
Peter Tuddenham (College of Exploration)

Table 2. Big Ideas in Earth Science Literacy

(1) Earth scientists use repeatable observations and testable ideas to understand and explain our planet.
(2) Earth is 4.6 billion years old.
(3) Earth is a complex system of interacting rock, water, air, and life.
(4) Earth is continuously changing.
(5) Earth is the water planet.
(6) Life evolves on a dynamic Earth and continuously modifies Earth.
(7) Humans depend on Earth for resources.
(8) Natural hazards pose risks to humans.
(9) Humans significantly alter the Earth.

asynchronous workshop in May 2008 that included several hundred participants. Subgroups with interest and expertise in a given field were tasked with defining the most important concepts in that field. A face-to-face conference of several dozen participants two months later focused on hammering out the details and wording the emerging Big Ideas and Supporting Concepts. In Fall 2008, draft documents were reviewed online and at conferences of the Geological Society of America and the American Geophysical Union. The whole process took over a year. The nine resulting Big Ideas are presented in Table 2; all the Supporting Concepts and other information about the project can be found at http://www.earthscienceliteracy.org. A glossy pamphlet was produced that can be ordered in quantity through me or any of the other organizers.

The Earth Science Literacy Principles are one milestone in a larger and longer process to improve Earth system science education. Like geological features themselves, there is a history and context to the initiative that helps to explain its scope and timing. This initiative was actually the fourth literacy project to cover a portion of the Earth system sciences (what NSF calls "geosciences"), with the first three focusing on ocean, climate, and atmospheric literacy. Though the initiatives shared many goals, each was carried out in response to specific needs and objectives.

For example, because the ocean sciences were not well represented in the National Science Education Standards, in 2004, a group of ocean scientists and educators began developing Ocean Literacy Principles with K-12 education in mind. In response to the need for public understanding of climate change, another group developed a set of Climate Literacy Principles in 2007. At approximately the same time, a third group developed "Essential Principles" covering the atmospheric sciences more broadly.

After these three literacy projects, there remained a major slice of the Earth system not yet analyzed – geology (including paleontology) and hydrology (freshwater). And so the NSF Geosciences Education program facilitated development of our "Earth sciences" set of Big Ideas, choosing to make the research community central to the process of deciding what represents the most societally important and up-to-date consensus views. [Note that "Earth science" here reflects what is included in the NSF Earth Sciences Division and is not as broad as what high schools call Earth science, which usually includes the whole Earth system (geology, and atmospheric and ocean sciences) plus astronomy.]

Each of these four initiatives borrowed from the experiences and models of its predecessors, and had a largely (but not entirely) different set of participants and slightly different end goals. Although the products of the initiatives have been around for different amounts of time, all have been widely disseminated via brochures and websites, and there are a variety of examples of application to, for example, learning objectives in activities and exhibits, and breadth and structure of content in textbook development. The broader influence, however, could be yet to come.

Clearly as a community of scientists and science educators, we must mutually determine the most important Earth system concepts. It is an achievement that so many worked for so long to come to at least a tentative agreement about the Big Ideas and Supporting Concepts of the existing literacy efforts. The four lists are naturally partially redundant, and by their very nature, incompletely express the interrelationships among the major systems that each set of principles represents. Taken together, however, they are building blocks toward the holy grail of a set of Big Ideas that cover and cut across all of the Earth systems. This, in fact, has been the vision of the NSF Geosciences Education and many others who have been involved in these efforts.

The lists are not in themselves, however, pedagogical end goals, particularly for K-16 education. Clearly reading the lists does not constitute an Earth system education, and few teachers are likely to change their classroom teaching practices by adopting one (or even all) of these principles. Even a list of Earth system principles compiled from the results of the previous literacy initiatives might have only shallow impact if not designed to change the way teachers teach *and* the way students think. In this respect, the existing sets of principles from the four literacy initiatives are simply carefully chosen rocks, agreed upon by all of the builders, of a rock wall foundation. The cement matrix, however, that holds it all together, must have qualities that reflect both the way the Earth system works and the way research tells us that people learn and understand.

Some have already been thinking about such a "matrix" of Earth system Big Ideas, none more so than my PRI colleague Don Duggan-Haas. He has been writing about the pedagogical significance of Big Ideas in Earth system science since well before the earliest of the literacy initiatives, thinking in particular about how the number and nature of the Big Ideas we choose will impact Earth system teaching and learning. You can learn about his perspective in Part 2 of this article, and see more of his work on Big Ideas at the Virtual

Fieldwork website (http://virtualfieldwork.org/Big_Ideas.html) that he has developed as part of the NSF-funded ReaL Earth Inquiry Project. A chapter on Big Ideas is available in any of the regional guides at http://teacherfriendlyguide.org.

What are the Most Important Ideas to Understand About the Earth?

by Don Duggan-Haas

Interviewer*: What is the most important (or one of the most important) thing that you learned in Earth science this year?*
Student*: Um… Formulas.*

So said a student at the end of a year in Earth science class. When pressed, he followed up with, "Know the Reference Tables." His answers were typical of those of his classmates, of my own students, and of the many more that I have asked more informally. Of course, these students do know *something* about the Earth, but shouldn't they be able to articulate what is most important? What should everyone understand about Earth science? Why don't most Americans understand the fundamental tenets of Earth science now? What strategies can realistically be implemented to improve Earth science literacy?

Before reading further, I suggest that each reader stop and consider the question: "What is essential for every American to understand in the Earth sciences?" In consultation with scientists and Earth science teachers and museum educators over many years, we have assembled and constructed a coherent set of ideas that illuminates what is fundamental to Earth science and provides a conceptual framework upon which to build enduring understanding. In brief, those ideas are:

(1) The Earth is a system of systems.
(2) The flow of energy drives the cycling of matter.
(3) Life, including human life, influences and is influenced by the environment.
(4) Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system;.
(5) To understand (deep) space and time, models and maps are necessary.

These big ideas, coupled with two questions – "How do we know what we know?" and "How does what we know inform our decision-making?" – provide a coherent framework for more effective teaching of Earth science. See Box 1 for an expansion of the ideas.

Why is a Small Set of Big Ideas Needed?

Earth science literacy is of critical importance to our future. Pressing issues of the coming decades include climate change, energy and water accessibility and usage, mineral resources, and land management. These are all rooted in understanding the Earth system, yet many Americans fail to understand even the most basic Earth science. For example, most Americans believe that the earliest humans lived at the same time as the dinosaurs; just over half of the population recognizes that it takes one year for the Earth to go around the sun; only 40% of Americans accept evolution. This is clear evidence that the way we currently teach (or fail to teach) Earth system science simply does not work for most students. And the literacy challenge is not limited to Earth science, so simply having Earth science taught with the same frequency and status as biology, chemistry, and physics is unlikely to meet the challenge.

For science literacy to become widespread, we must change what we teach, how we teach, or both. The things we teach and how we teach them are inextricably linked and I argue here that we must first determine the goals of Earth science education to redesign the system to achieve literacy. Efforts to change the way that we teach, along with what we teach, have long been underway, and, indeed the goals defined in documents like *The National Science Education Standards* (1996) and *Benchmarks for Science Literacy* (1993) very much resonate with the those described here. But these documents lay out the content in a way that makes it difficult to find what is of utmost importance. For example, the *Core Curriculum Guide* for New York State's Regents Earth Science (1999) is grounded in these documents but identifies 22 "key ideas" for the course without prioritization.

A current educational reform effort that offers real promise is the development of "learning progressions," that is, coordinated instruction that builds understanding of big ideas over multiple years of instruction. Although this approach has great potential, it is a massive undertaking that requires coordination across multiple teachers within and between schools. Implementation will not be quick and cannot be done by a single teacher. By framing a curriculum around big ideas, teachers can take an immediate step toward the implementation of learning progressions without having to wait for school- or district-wide initiatives.

There have been recent initiatives involving scientists and science educators to define what is most important for everyone to understand. Four of these initiatives specifically target disciplines within the Earth sciences: oceanography, atmospheric science, Earth science (largely geology, but so named to correspond with the National Science Foundation's disciplinary classifications; see Part 1 of this article), and climate science. Sets of literacy principles have been developed for each of these content areas. See the Earth Science Literacy Initiative website (http://www.earthscienceliteracy.org) for links to download all four sets of literacy principles.

Taken collectively, these initiatives include 31 essential principles strengthened by 198 supporting concepts. Although there is distinct overlap among the sets of ideas, the current approach reinforces the problem that the typical science curriculum in the U.S. is "an inch deep and a mile wide." Although these principles represent important

Big Ideas and Overarching Questions for Earth Science

How do we know what we know?
How does what we know inform our decision-making?

The Earth is a System of Systems

The Earth System is composed of and part of a multitude of systems, which cycle and interact, resulting in dynamic equilibrium (although the system evolves). The Earth is also nested in larger systems, including the solar system and the universe. However, there is an inherent unpredictability in systems, which are composed of an (effectively) infinite number of interacting parts that follow simple rules. Each system is qualitatively different from, but not necessarily greater than, the sum of its parts.

The Flow of Energy Drives the Cycling of Matter

The Earth is an open system. The constant flow of solar radiation powers much of Earth's ocean and atmospheric processes on the surface of the system; flow of heat from inside the Earth from radioactivity drives plate tectonics. Energy flows and cycles through the Earth system. Matter cycles within it. Cycling is largely driven by the interaction of the differential distribution of solar radiation and internal heat, and gravity. Convection drives weather and climate, ocean currents, the rock cycle, and plate tectonics.

Life, Including Human Life, Influences and is Influenced by the Environment

Photosynthetic bacteria released free oxygen into the early oceans and atmosphere, making Earth habitable for later animals. Humans have changed the lay of the land, altered the distribution of flora and fauna, and are changing atmospheric chemistry in ways that alter the climate. Earth system processes affect where and how humans live. For example, many people live in the shadow of volcanoes because of the fertile farmland found there, however, they must keep a constant vigil to maintain their safety. The human impact on the environment is growing as population increases and the use of technology expands.

Physical and chemical principles are unchanging and drive both gradual and rapid changes in the Earth system

Earth processes (such as erosion, evolution, or plate tectonics) operating today are the same as those operating since they arose in Earth history, and they are obedient to the laws of chemistry and physics. Although the processes constantly changing the Earth are essentially fixed, their rates are not. Tipping points are reached that can result in rapid changes cascading through Earth systems.

To Understand (Deep) Time and the Scale of Space, Models and Maps are Necessary

The use of models is fundamental to all of the Earth Sciences. Maps and models aid in the understanding of aspects of the Earth system for which direct observation is not possible. Models assist in the comprehension of time and space at both immense and submicroscopic scales. When compared to the size and age of the universe, humanity occupies a speck in space and a blip in time.

consensuses of what is most critical to understand about different Earth science disciplines, they are not directly practical for those who teach the content. The stark reality is that there are *no* examples of creating a thick description of what everyone should understand about any topic that has led to wide swaths of the population understanding the target content, despite countless attempts to do just that throughout human history.

What if we only taught a few things in Earth science, but taught them really, really deeply? In a recent study involving 8,310 students at 55 randomly chosen colleges and universities, those students who had high school science experiences that covered at least one topic in depth but did not cover the breadth of their high school curriculum ("depth present – breadth absent") have an advantage equal to two thirds of a year of instruction over their peers who had the opposite experience ("depth absent – breadth present"). The same study concluded "that students whose teachers choose broad coverage of content, on the average, experience no benefit." So, a curriculum designed to draw clear attention to that which is decidedly most important is certainly worth a try.

About Our Big Ideas

We pursue big ideas because they provide a framework for inquiry-based science, are essential for understanding, are enduring, and cut across the Earth Science disciplines by encompassing geology, meteorology, oceanography, and astronomy. A framework of big ideas provides direction away from "inch-deep-mile-wide" curricula. An appropriately short list of big ideas, as is suggested is needed for quality instruction by some researchers, does not seem to be in the Earth science education literature. Identifying such big ideas can help teachers and students to build a conceptual framework that ties the ideas of the discipline together in a meaningful way, and that facilitates the retrieval and application of that organized knowledge. These big ideas are obviously not the full set of understandings that every high school graduate should have, but rather support all of those ideas. Indeed, each of the ideas stated in the four different literacy initiatives fall under the umbrella of one or more of these big ideas. Any content that is appropriate to teach in any Earth science course should have direct connection to at least one of these big ideas. Importantly, these are not topics, but rather ideas to be addressed in each and every topic. Understandings of the nature of science are built by integrating the overarching questions into instruction.

By our scheme, big ideas should fulfill the following criteria:

- Each idea cuts across the curriculum.
- Understanding of the idea is attainable by students and the understanding holds promise for retention.
- The idea is essential to understanding a variety of topics.
- The idea requires deeper exploration.
- The entire curriculum is represented by this (small) set of ideas.

A big idea is not simply a topic that appears in textbooks, but a key concept that cuts across all topics within a discipline. Wiggins & McTighe in 1998 explained, "A big idea can be described two ways: as involving an enduring principle that transcends its origins, subject matter or place in time; and as a *linchpin* idea – one crucial to a student's ability to understand a subject." Furthermore, big ideas require deeper exploration – a sustained inquiry with breadth and depth. Both a novice and an expert can understand a big idea, but they likely understand it in different ways and to different degrees. Although big ideas are not the same as the generative topics (which cut across the curriculum, but are not necessarily "big") described by Wiske in 1998, they are similar in that they both "often have a bottomless quality, in that inquiry into the topic leads to deeper questions."

Conclusion

Let your affairs be as two or three, and not a hundred or a thousand. -Henry David Thoreau

The Earth sciences are wide-ranging disciplines that share a common core of principle ideas, yet Earth science courses tend to teach the breadth without adequately drawing attention to central ideas. The Big Ideas of the discipline stated here can provide a scaffold to build understanding of this wonderful Earth and give us a framework with which to make sense of the challenges of the coming decades.

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