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How Geoscientists Think and Learn

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Decades ago, pioneering petroleum geologist Wallace Pratt pointed out that oil is first found in the human mind. His insight remains true today: Across geoscience specialties, the human mind is arguably the geoscientist's most important tool. It is the mind that converts colors and textures of dirt, or blotches on a satellite image, or wiggles on a seismogram, into explanatory narratives about the formation and migration of oil, the rise and fall of mountain ranges, the opening and closing of oceans. Improved understanding of how humans think and learn about the Earth can help geoscientists and geoscience educators do their jobs better, and can highlight the strengths that geoscience expertise brings to interdisciplinary problem solving.

To shed light on the nature of geoscience thinking and learning requires collaboration among those who study geosciences and those who study thinking and learning. Such a collaborative group, comprising geoscientists, geoscience educators, a philosopher of science, an anthropologist, a developmental psychologist, and a cognitive psychologist, has synthesized what is known and articulated what is most in need of further research in four areas: thinking about time on geological timescales, understanding the Earth as a complex system, learning in the field, and spatial thinking as applied to geosciences (Figure 1). Documentation of references, sources, and methods used in this study can be found in the online supplement to this *Eos* issue (http://www.agu.org/eos_elec/)

Taken together, this work shows that while geoscientists use a broad range of tools to study a diversity of problems, they share a distinctive set of approaches and perspectives that are particularly well suited to studying something as big, old, and complicated as the Earth system.

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Thinking About Time

Two key features of geoscientists' temporal thinking distinguish them from the general population: They take a long view of time, and they expect low-frequency, high-impact events. Geoscientists have internalized the vastness of the age of the Earth and the relative brevity of human history. They can envision Earth in states drastically different from the planet they have personally experienced: an Earth without humans, an Earth without life, a hothouse Earth, a snowball Earth. In the long view of time, exceedingly slow processes such as erosion or evolution can effect huge changes, such as the removal of a mountain or the establishment of new species. Infrequent but powerful processes, such as floods, volcanic eruptions, landslides, and asteroid impacts, are routine rather than aberrant when considered across the whole of Earth's history.

This perspective is unusual: Short time frames, of the order of days to years, drive most decisions in business, politics, and news cycles. If widely adopted, geoscientists' long view of time could provide a crucial counterweight and support decision making with a time horizon of decades to centuries. A society in which a long view of time is pervasive could plan more effectively for infrequent events such as hurricanes or earthquakes and might take more seriously the prospect that tiny but cumulative forcings leveraged over long intervals of time can cause profound changes to the planet.

However, having a long view of time should not be viewed as merely a practical tool for decision makers; philosophically, it is a fundamental aspect of humanity's self-image. Just as Nicolaus Copernicus's sixteenth-century discovery of the heliocentric solar system altered perceptions of humanity's place in the spatial dimensions of the cosmos, so did James Hutton's eighteenth-century discovery of deep time alter the perception of humans' place within Earth history. However, the fact that humanity's planet does not lie at the center of the universe is more widely understood and accepted in Western civilization than is the fact that human history spans only a tiny fraction of geologic time.

Substantial impediments stand in the way of society achieving a broad understanding of geologic time. Geologic time involves scales and events far removed from human experience; thus, envisioning the cumulative impact of slow processes or infrequent events over geological timescales is not intuitive. Scientists' timekeeping tools rely on exponential numbers, ratios, and proportional reasoning, all of which present well-documented difficulties for many students. Finally, some religious teachings oppose the idea of an old Earth.

Most educational research concerning geological time has focused on how accurately students understand and can recall aspects of the scientists' model of Earth history, and on what interventions can improve these metrics. One promising technique is to have students use imagery and narrative to establish the sequence of events before attaching numerical ages. Thinking about the events of Earth history as a sequence allows students to tap into their experience-based temporal reasoning, for example, their understanding that earlier events can have influenced or caused later events, but not vice versa. Teachers at all levels, including those in higher education, can capitalize on these techniques to improve students' grasp of geologic time.

As valuable as this research is, it leaves untested the assertion that taking a long view of time leads to more farseeing and environmentally responsible decision making. Testing this claim will require combining expertise in geoscience education, environmental education, conceptual change, and human decision making.

Understanding the Earth as a Complex and Complicated System

Geoscientists understand that the Earth is a system characterized by feedbacks between processes and among component parts. Geoscientists respect that such feedbacks are important and difficult to understand completely and can lead to strong effects in unanticipated places. Earth systems are "complex" in the technical sense: exhibiting nonlinear interactions, multiple stable states, fractal and chaotic behavior, self-organized criticality, and non-Gaussian distributions of outputs. Earth systems are also "complicated" in the ordinary sense of the word. Multiple mechanical, chemical,

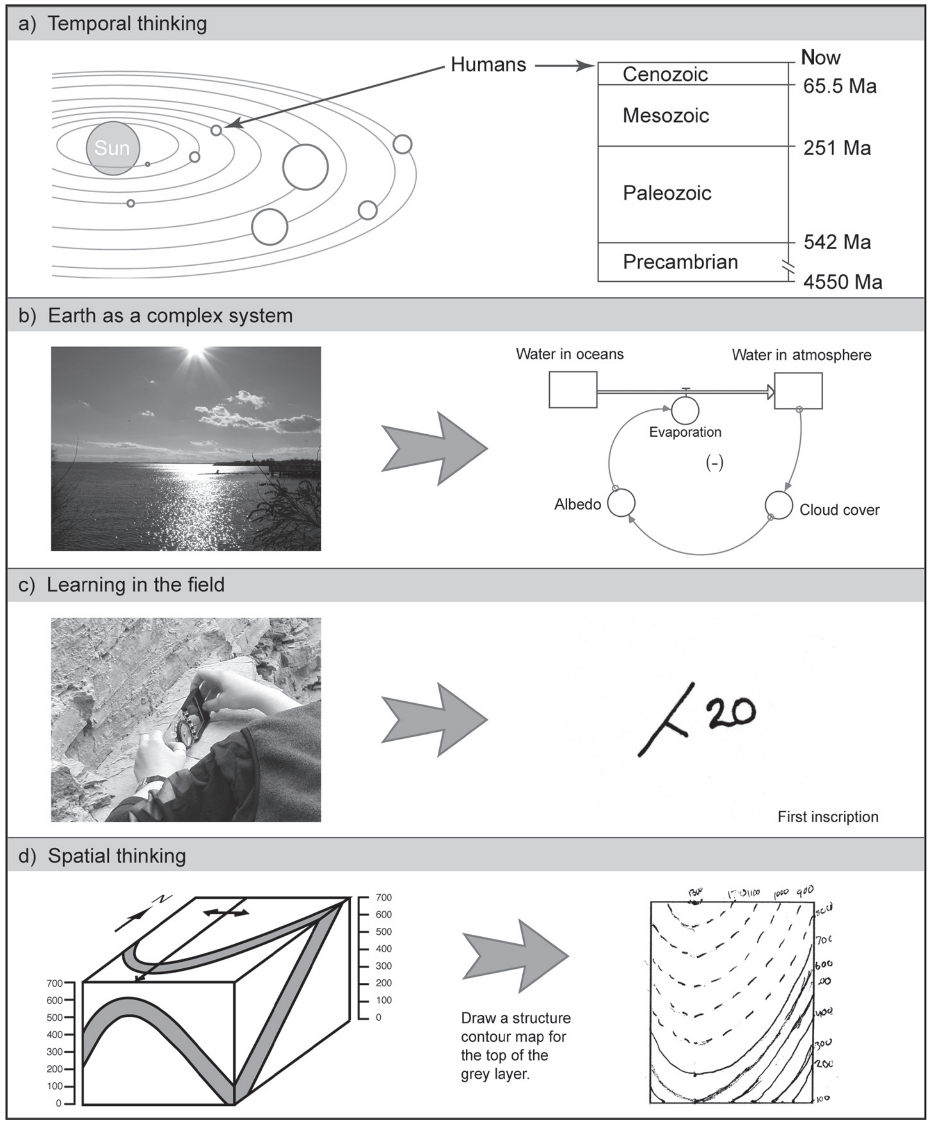

Fig. 1. Selected insights from the four themes identified with how geoscientists think and learn. (a) Like the heliocentric view of the solar system (left), the discovery of the brevity of human history within the vastness of geologic time (right) altered humanity's understanding of its place in the cosmos. (b) In understanding the Earth as a system, feedback loops are a "threshold concept." Even when the student understands a situation experientially (left), casting it into the symbolic language of flows, reservoirs, and feedbacks (right) remains exceptionally difficult. (c) Learning in the field offers many opportunities for students to experience making "first inscriptions." Using senses and sensors, students transform the raw material of nature (left) into human artifacts: tractable, transportable symbols on paper (right). (d) Spatial thinking is common in geosciences and presents a stumbling block for students who have come up through an education system that did not develop, assess, or reward spatial skills. The illustrated exercise requires "visual penetrative ability," which varies widely from student to student. Image credits are located in the supplement to this Eos *issue (http://www.agu.org/eos_elec).*

biological, and anthropogenic processes may be active and interacting at the same time and place. For example, one widely used representation of the water cycle for K-12 students includes 16 component concepts with multiple linkages among them. Although geoscientists are not the only scientists who work with complicated, complex systems, their ability and propensity to apply a systems approach to understanding the Earth is an important expertise that they bring to the table of interdisciplinary collaboration.

For understanding the Earth as a complex system, the concept of feedback loops is key. Negative (stabilizing) feedbacks keep the Earth system sufficiently stable that complex forms of life, including humans, can exist. Positive (reinforcing) feedbacks underlie many environmental problems, including loss of biodiversity, global climate change, and degradation of agricultural soils. In education, feedback loops function as a "threshold concept," a concept difficult to learn but transformative once mastered. Because feedback loops underpin a stable Earth system, fostering a working knowledge of this concept throughout the decision-making populace could increase civilization's capacity to cope with 21st-century challenges. In spite of its importance, the feedback loop concept is arguably the most under-researched topic in the entire domain of geoscience thinking and learning.

There are some success stories in the systems approach to teaching and learning about the Earth. Evidence is strong that middle-school students can reason qualitatively about interconnections between the hydrosphere, atmosphere, geosphere, cryosphere, and biosphere, and that undergraduates can create and manipulate quantitative computer models of those interactions. What is needed now is to develop learning progressions that build purposefully from primary through secondary education into college, leveraging students' increasing maturity and incorporating their growing knowledge of chemistry, math, physics, biology, and social sciences.

Learning in the Field

A hallmark of the geosciences is that theoretical advances are usually grounded in direct observations of the Earth, oceans, atmosphere, or planets. While it is not accurate to describe the geosciences as merely observational sciences, observations play a central role in geoscientists' formulation and testing of new ideas and theories.

In reflecting on their own learning trajectories, many geoscientists report that fieldwork was a central, formative experience, whether at geology field camp, on a research vessel, or during an atmospheric science field experiment. Geoscientists and geoscience educators have claimed, often passionately, that field-based learning helps students develop a feel for Earth processes and a sense of scale, and strengthens their ability to integrate fragmentary information, to reason spatially and temporally, and to critique the quality of observational data. But quantitative evidence and convincing mechanisms for these strong claims have been sparse. Two lines of reasoning may shed light on why field experiences are so fundamental.

First, field experiences provide a concentrated opportunity to develop what anthropologists call "professional vision," the ability to see features that are important to professional practice. Like a criminal investigator at a crime scene, a geoscientist in the field sees differently than a novice at the same scene. Professional vision can be developed through guided apprenticeship, as an expert watches and corrects a novice's iterative efforts to segment the observed world into meaningful categories (e.g., cloud types or rock units) and to identify features of interest (e.g., rip tides or faults) amid visual complexity. Such mentorship extends beyond the development of observational skill and includes guidance on the use of observational data to test hypotheses. The interplay between observation and testing of ideas is a central feature of a geoscientist's reasoning, and field experiences may play a critical role in developing this habit of mind.

Second, field experiences provide practice in transforming the raw material of nature into the words, signs, and symbols that geoscientists use to capture and communicate their observations. Ethnographers studying scientists refer to the "cascade of inscriptions" that scientists make, where the term "inscription" encompasses text, diagrams, graphs, tables, maps, equations, etc. The first inscription in the "cascade" transforms an aspect of nature into a human-made artifact; for example, the slope of a rock layer is transformed into a dip and strike symbol on a map, or the chill of the ocean is transformed into a number in degrees Celsius. The same or different scientists then transform the initial inscription into subsequent inscriptions (for example, a geological map or a temperature/salinity graph), and so on toward ever more abstract, transportable, generalized, and integrative inscriptions.

Although all of the steps in the cascade play important roles in science, the first inscription differs in kind because it results from a transformation of information directly from nature rather than from another human artifact. Moreover, the first inscription sets the quality of all of the subsequent inscriptions. By making first inscriptions in the field, using their own senses and simple tools, students can experience the interactions among that which is observed, the actions and thoughts of the human observer, the recorded observations (inscriptions) that the scientist brings home from the field area, and the eventual interpretation that emerges after multiple generations of more integrative inscriptions. Geoscience educators can help students make these connections by fostering discussion about pathways from observation to interpretation, and by designing activities that require students to test their interpretation against observations of the Earth.

Spatial Thinking

Geoscientists use spatial thinking extensively whenever they acquire, represent, manipulate, or reason about objects, processes, or phenomena in space. Exemplars of the power of spatial thinking include Alfred Wegener's interpretation in 1915 of the gross patterns of continental geology as a product of continental drift, and Inge Lehmann's interpretation, published in 1936, that the global distribution of earthquake *P* and *S* waves is indicative of a two-layer solid/liquid core. Geoscientists deploy a wide array of specialized spatial representations, using them not only to convey data that are inherently spatial (e.g., maps and cross sections) but also to elucidate relationships between nonspatial variables (e.g., phase diagrams of mineral composition).

Many students struggle with spatial tasks. Several factors contribute to these difficulties: Spatial skills are unevenly distributed among individuals. The formal education system tends not to develop, assess, or reward spatial skills. And instructors who are strong spatial thinkers themselves tend to be unaware of the degree to which some students are spatially challenged. However, recent studies show that performance on abstract and applied spatial tasks can be enhanced through instruction and practice. Moreover, completing a spatially intensive geoscience course can strengthen performance on nongeospecific spatial tasks.

One active line of geoscience/cognitive science collaborative research has sought to identify and strengthen the cognitive processes and concepts that underpin spatially demanding elements of the geoscience curriculum. For example, map reading builds on mastery of projective spatial concepts. Envisioning three-dimensional geological structures inside a solid mass of rock builds on visual penetrative ability. The frontier in this line of inquiry lies in understanding how people make meaning from spatial information, constructing inferences about causal Earth processes from observations of shape, size, orientation, configuration, or trajectory.

A Community of Practice

Reflecting on the nature of geoscience thinking and learning reveals that geoscientists are not merely individuals who know a lot about the oceans, atmosphere, or solid Earth. Geoscientists make up a "community of practice," who have been shaped by, and now embody, a distinctive suite of experiences, approaches, perspectives, and values. These include taking a long view of time, using temporal and spatial reasoning to formulate hypotheses and answer questions, interpreting observations in terms of a system of intertwined processes rather than a single independent variable, and building cascades of inscriptions that begin with the raw materials of nature and tap into powerful visualization techniques.

None of these attributes, taken individually, is unique to geosciences. Nor does every individual geoscientist have every one of these experiences, ascribe to every perspective, and utilize every approach. But taken collectively, this combination of attributes has proven valuable for answering questions and solving problems concerning the Earth and its environment.

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