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Geoscience and geoscientists: Uniquely equipped to study Earth

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ABSTRACT

Geoscience is the study of Earth history and processes, a study so broad that individual geoscientists may have little knowledge or skill in common. This essay asserts that there is, nonetheless, a common set of perspectives, approaches, and values that characterizes the discipline. Geoscientists are united by a common commitment to testing hypotheses against observations of the natural system using multiple converging lines of evidence. Geoscientists test hypotheses by comparing modern processes to those found in the rock record; comparing related examples to understand commonalities and differences attributable to process, history, and context; finding multiple converging lines of evidence; and comparing observations to theory-based prediction. They share the perspective that observation and a spatial and temporal organizational scheme are fundamental to understanding Earth systems and processes. Their interpretations are grounded in a common understanding that Earth represents a long-lived, dynamic, complex system for which a 4.6-billion-year history has been shaped by processes operating at different rates. These methods and approaches have evolved over time because they are particularly well adapted to studying Earth. A geoscientist brings this approach to any collaboration, as well as deep knowledge and skill for studying a particular aspect of Earth, and a set of cultural values that support collaborative problem solving. Developing such individuals is the central goal of geoscience majors and graduate programs.

INTRODUCTION

Every geoscientist is convinced that geoscience holds important keys to many of the challenges facing humanity at this time. However, as a discipline, geoscience often struggles to find a place at the scientific table. Many people are unaware that geoscience is a scientific discipline because it is omitted from the scientific preparation of college-bound students in many jurisdictions. Others who are aware of the geosciences consider it a secondary, derivative science or a qualitative field lacking rigor (Frodeman, 1995). Geoscientists have not yet succeeded in explaining to the larger population of scientists, policy makers, and citizens the nature of geoscience, or the value that they, as geoscientists, bring to solving important societal problems.

This paper takes on this challenge by articulating the distinguishing features of the discipline. What kinds of problems can geoscientists address? How do they approach these problems? What are the kinds of evidence that they accept as proof? Every geoscientist has an answer to these questions based on their own experiences. The first goal of this paper is to articulate answers that resonate with all geoscientists and are accessible to nongeoscientists. For this, we synthesize not only our own experiences

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and those of our colleagues, but also writings by geoscientists, geoscience educators, and philosophers of science. If we have been successful, expert geoscientists of all kinds reading this description should have a strong sense of the familiar.

The second goal of this chapter is to extract guidance for geoscience education from the distinguishing features of the discipline. Increasingly, we design our educational programs based on an articulation of what we want our students to learn. Lacking a common understanding of geoscience expertise, geoscience as a discipline is struggling to articulate its core. What is it that students must learn to be geoscientists? Why is this important to them as future practitioners? What part of this body of knowledge is of utility to the broad population and important to include in the K–12 curriculum? Or in the curriculum for a liberally educated person? We hope that this paper will provide a footing that allows this discussion to expand to include the processes of geoscience investigation and problem solving.

We begin with a discussion of the nature of geoscience. Our goal is to place geoscience in the broader context of science in terms of its methodology and the way that it tests hypotheses. We then turn to the nature of geoscience expertise: What are the defining characteristics of a geoscientist? By understanding the essential characteristics, we set a foundation for the preparation of future geoscientists. Looking at both the discipline and its practitioners, we conclude that geoscience is a collaborative science, where interactions among geoscientists are essential to developing knowledge and understanding about Earth and its systems and processes.

WHAT IS GEOSCIENCE?

We use the term “geosciences” in its broadest definition: the study of Earth and planetary systems. This is a vast area of study, and it includes questions that range from understanding the interrelationships between processes operating on a planetary scale to exploring the chemical reactions taking place on the surfaces of a mineral grain. Geoscientists are concerned with understanding the history of particular places and with developing integrated knowledge of Earth and planetary processes across locations and through time. They use both types of understanding to constrain likely scenarios in the future. Understanding Earth processes requires study of the individual parts of the Earth system (ocean, atmosphere, hydrosphere, solid Earth, biosphere) and of the interactions of these systems with each other.

Geoscience and the Scientific Method

Geoscience is not fully described by the experimental methods that the public often equates with science. The discussions of philosophy of science, and the science taught in our schools focus primarily on hypothesis testing using a single-variable experiment, rather than on the spectrum of methods used across the sciences (Frodeman, 1995; Hodson, 1996; Dampier, 1944; Windschitl et al., 2008; Kastens and Rivet, 2008; Dodick and Argamon, 2006; Gould, 1986). These discussions also focus on the work of the individual and the single experiment rather than on the community processes that are the hallmark of advancements in scientific thinking (Woodward and Goodstein, 1996). These descriptions are far from the experience of most modern scientists (Richards, 2009). In fact, we observe that many geoscientists have been either incredulous or uninterested in discussions of the scientific method because its common articulation is so far removed from their personal experience.

Modern science as a way of understanding is often credited to Galileo and Newton and described as using repeatable experiments and measurements to deduce laws of regular behavior in nature (Dampier, 1944). Galileo and Newton emerged from a tradition of observing nature, developing taxonomies, and deducing underlying principles from the comparison of cases (consider, for example, Galileo’s discovery of Jupiter’s moons). Aristotle and Hipparchus are examples of the beginnings of this tradition in Greek times. Leonardo da Vinci used this approach to lay down a uniformitarian theory on the origin of fossils in the Po River Valley. Thus, from the outset, we see the use of observation, comparison, and experiment together as techniques of science. Darwin and Lyell, often cited as the fathers of historical, observational science (Gould, 1986), grew from this tradition.

Philosophers of science have been interested in geoscience, particularly geology, because on the surface it is so clearly different than physics and chemistry in its approach (Cleland, 2001, 2002; Frodeman, 1995, 2003; Dodick and Argamon, 2006). Geoscience has been described as a descriptive science (Hazen, 1974; Grimaldi and Engel, 2007) or a historical science (Bubnoff, 1963; Frodeman, 1995, 2003; Cleland, 2001, 2002; Dodick and Argamon, 2006). These characterizations of geoscience highlight the relative importance of observation and description of natural phenomena, as well as the way in which geoscience develops an understanding of past events through evidence that discriminates between rival hypotheses. Gould (1986), Cleland (2001, 2002), and Frodeman (1995) made extensive arguments that historical approaches to hypothesis testing are as logically rigorous as experimental ones, and they are particularly valuable for understanding complex natural systems. Wilson (1994) argued that observational approaches to the development of scientific understanding are as valid as those driven by a priori hypotheses. Threaded throughout all of this writing, there is a defensive posture arguing for the validity of these approaches in the face of an unwarranted focus on experimental approaches. The geosciences and biological sciences in particular have suffered from this imbalance in articulation of the methods of science, and an undervaluing of the critical role of observation and comparison in connecting theoretical or experimental findings to the complex natural processes they seek to explain (Windschitl et al., 2008; Schwartz et al., 2004).

Today, the complexity of modern scientific questions requires interdisciplinary approaches, a multiplicity of methods, and convergence of different approaches to scientific problem solving. Scientists of all types have become frustrated with the oversimplification of the scientific method as presented to the public. Further, the need for the public to understand the nature of science, its strengths, and its limitations has led to the development of more robust articulations drawing from philosophy of science, scientists' experience, and science education that can be used to explain science to the public (Wolpert, 1993; Paul and Elder, 2004; Carpi and Egger, 2010; California Museum of Paleontology, 2010). This work seeks to provide a unifying context for understanding the process of science, highlighting the common elements that yield useful, robust results. It emphasizes:

(1) the interplay of multiple methods to investigate natural phenomena, including description, experimentation, comparison, and modeling;

(2) the importance of creativity in generating questions for investigation that lead to new understanding, as well as the role of insight in understanding and probing results for meaning; and

(3) science as a community process, where individual results are discussed, tested, and ultimately synthesized into the broader body of scientific knowledge and understanding.

This broad conceptualization of science is, in our view, better aligned with geoscientists' experience of their discipline and provides the context in which we describe the strengths and approaches of geoscience.

The Nature of Evidence and Reasoning in Geoscience

Geoscience is commonly identified by its focus on Earth and planetary processes and systems. However, this focus is not sufficient to define an academic or scientific discipline. We must also consider the kinds of evidence that are used, and the nature of reasoning (Toulmin, 1958). What are the defining characteristics of geoscience evidence and reasoning?

We posit that the interplay between methodical observation and hypothesis testing is a defining characteristic of geoscience reasoning. Geoscience includes a substantial component of descriptive work in which observations of Earth and planets are organized in order to generate and test hypotheses. These observations and their descriptions may be quantitative or qualitative; they can be based on advanced technical instrumentation (e.g., satellite-based remote sensing, geophysical or geochemical probing), or they can be collected by looking with an expert's eye at rocks or soils. However, characteristically, geoscience hypotheses are developed in light of observations of Earth and planets, and they are tested against these observations.

Hypothesis testing in the geosciences involves a large range of methods, including methods drawn from physics, chemistry, biology, and engineering disciplines. It may involve sophisticated computational modeling, or it may be as simple as plotting the distribution of a critical observation on a map. Classic single-variable experiments, as well as theoretical arguments derived from first principles of physics and chemistry, are also used to determine the feasibility of a hypothesized process. For example, hypotheses for rock formation within the crust and weathering at Earth's surface are fundamentally constrained by understanding of mineral stability garnered from single-variable experiments and thermodynamic arguments (and tested against observations of mineral suites exposed at Earth's surface and probed at depth with geophysical and geochemical techniques). Kastens and Rivet (2008) provided examples of six modes of inquiry used by practicing geoscientists, including observation, experiment, and modeling. Important advances in the geosciences come today from this full range of approaches. However, in all cases, the ultimate test of the hypothesis is its ability to explain the observations.

At the heart of describing the rigor of geoscience and of its authority as a discipline are the criteria used to test the validity of a result or the strength of a conclusion: When and why is a geoscientist confident in a particular conclusion? How does the community of geoscientists evaluate a conclusion and under what circumstances are new ideas incorporated into the body of accumulated knowledge? The criteria that a discipline uses for determining the strength of a conclusion are intimately related to the field of study (Ault, 1998; Kitcher, 1993). The criteria for evaluating evidence that a particular process is taking place on Earth would not as successfully evaluate a claim about atomic particles or a mathematical theorem. In addition, the criteria for evaluating a result change as new techniques and methods are developed (Ault, 1998). One of the key features of geoscience as a discipline is that it works to continually evolve and refine strategies for evaluating the strength of claims about Earth and its processes.

It is common when describing rigor to resort to quantitative arguments where numbers can be stated with precision. This is an imperfect notion of rigor. Every equation and every number has qualitative information behind it that determines its accuracy and suitability for use in a particular situation. Like social scientists and biologists, geoscientists work in complex systems where qualitative and quantitative arguments must come together to understand the ways in which general principles operate in specific situations. How then do we describe a rigorous argument in the geosciences?

Geoscientists share many standards with other parts of the scientific community, for example: Numeric arguments must be statistically sound; experimental results must be repeatable; methods must be described completely in order to allow discussion of underpinning assumptions. As with others studying the complexity of natural phenomena, they rely heavily on the use of evidence to discriminate between competing hypotheses (Cleland, 2001, 2002). In fact, this approach, described by Chamberlin as "multiple working hypotheses" in 1890 is so fundamental to geoscience that it is explained in many introductory geology courses and textbooks.

Geoscience focuses on processes that in many cases are difficult to observe, either because of their remote location (within Earth, under the ocean, on planets), their long time scales, or their occurrence in past times. Geoscience has evolved a suite of strategies for testing hypotheses under these challenging conditions. They include:

1. Comparing the products of modern processes to those found in the rock record—A stratigrapher compares the compo-

sition and shape of beds in ancient sedimentary rocks to those found in modern sedimentary environments. This strategy, developed in the 1700s, was encoded for generations of geoscientists in the words of Lyell, "the present is the key to the past" (Lyell, 1830). While it is now clear that there are unique periods in the history of Earth and other planets (e.g., early Earth), and that interpretations of the rock record require attention to postdepositional effects, this strategy remains foundational to the geosciences, both guiding our intuition and requiring that we constantly check our assumptions.

2. Studying a series of geographically or temporally specific examples to deduce underlying processes—Our understanding of processes operating inside Earth at depth over time comes from looking at products of these processes exposed in different locations and over different ages. Similarly, our understanding of the behavior of hurricanes is based on study of the variation of behavior in individual hurricanes occurring over time. Thus, geoscientists are often experts at deducing the history of a particular case or place and at finding ways in which to compare the similarities and differences of cases such that they illuminate universal Earth processes (Ault, 1998). Geoscientists have confidence when a hypothesis explains both the similarities and differences between cases. This approach is particularly suitable for learning from Earth and making sense of the highly variable products of Earth processes operating at different times, on different materials, with different previous histories.

3. Developing multiple converging lines of incomplete data—An example of this strategy is the case for plate tectonics, which includes lines of evidence from geologic studies of ancient rocks, geodetic measurements of modern plate movement, and geophysical observations of heat flow and magnetics (Cleland, 2001, 2002; Oreskes, 2002). Assembling the evidence for a geoscientific claim routinely brings together observation of the Earth system, experimental results characterizing the behavior of particular processes (for example, experiments on rock deformation; chemical equilibrium of systems under Earth conditions), theoretical constraints (e.g., time scales of diffusion), statistical analysis supporting comparison of data sets, and modeling to understand the interactions between different processes working at different time scales. Geoscientists have confidence when multiple, independent lines of evidence give the same results, for example, when a radiometric date matches that given by tree-ring analysis, or when the increase of atmospheric CO_2 recorded at Mauna Loa correlates with that measured in ice cores. This approach is particularly suitable to intertwining strands of evidence into the compelling argument needed to differentiate among competing hypotheses.

4. Testing understanding through prediction—A geoscientist validates understanding by developing a prediction based on a hypothesis and seeking evidence based on that prediction. For those working on the geologic history of an area, such a prediction is used to develop new threads of evidence; for example, a hypothesis stating that a series of strata is folded around a N-S–striking axis predicts that unit A should outcrop at the top of the hill to the west. Similarly, prediction is used to test our understanding of processes operating across Earth; for example, hypotheses regarding magma mixing derived from exposures in the Sierra Nevada mountain range are tested by looking for similar behavior in magmas exposed in another mountain range.

Geoscientists frequently make use of the predictive power of methods and findings from physics and chemistry in testing hypotheses. For example, geochemical mixing models can be used to make predictions of the isotopic composition of groundwater. The model data can be compared to measured compositions to determine the likelihood that waters from multiple sources are mixing and used to evaluate the risk of impending groundwater contamination.

Our capacity for making predictions in order to test hypotheses has increased dramatically with the advent of computational modeling. Many of the world's most powerful computers are engaged in modeling Earth systems, including the climate system (UCAR, 2010) and Earth's interior (CIG, 2011). Computational models are tested by looking at how well they predict the particular events in the past, as well as their ability to produce the range and pattern of observations. The ability of the model to effectively reproduce both specific scenarios and to generate patterns typical of Earth observations gives confidence that they are taking account of complex interactions and important variables with sufficient precision to be useful in constraining likely scenarios for the future (e.g., Weart, 2011).

These methods for hypothesis testing are aligned with those put forward by Ault (1998) for geology, which argue that a strong hypothesis must hold true across multiple cases[1] while explaining the differences among cases. Further, they must hold across spatial and temporal scales, and be verified by independent converging lines of evidence.

In sum, geoscience as a field focuses on understanding Earth and planets through a process grounded in observation. Observations are used to generate hypotheses, and the ultimate test of a hypothesis is its ability to explain these observations. In order to test hypotheses, geoscientists make use of a wide variety of methods, including those drawn from other disciplines. They have confidence in their conclusions and consider them rigorous when they are supported by observations of modern processes, explain the variability among natural cases, are supported by multiple lines of independent evidence, and have strong predictive power when applied to other cases. Geoscientists are concerned with understanding both specific cases and generalizable processes.

The geoscientist's methods are not unrelated to the methods of other scientists, nor are the knowledge and skills that are needed unknown in other fields. The unique thing about the geosciences is that knowledge, skills, and methods are brought together, refined, and evolved over time to make them most suitable for understanding the complex processes of Earth—its working in the past and the present, and its likely behavior in the

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[1] In Ault's words, it is grounded in a strong taxonomic approach, that is, a structured classification that effectively organizes the overall set of cases.

future. Just as the nature of the available food shapes the behavior of the predator in biological evolution, the nature of the object of study shapes the tools and behaviors of scientists (Weart, 2011). Geoscience as a discipline has collectively evolved and refined its approach to understanding Earth and its processes over its 200 year history, changing, expanding, and critiquing its methods of inquiry and refining its standards for evaluating claims. No other discipline can claim to have focused its energies so completely in this area.

WHAT MAKES A GEOSCIENTIST?

If geoscientists are particularly good at using scientific methods to understand Earth and planetary processes, what is the expertise that they bring to these problems? What distinguishes their expertise from those of other scientists? These questions are important to those developing interdisciplinary teams to address complex societal issues, and they are fundamental to determining how to prepare future geoscientists. Geoscience today brings together multiple subdisciplines, some of which have very different histories. For example, the heart of atmospheric science lies in the study of meteorology, which was traditionally part of physics, not geology. Oceanography brings together geology of the seafloor, biology of marine organisms and ecosystems, and the physics and chemistry of the ocean's waters and currents. Geoscience, like all other sciences, is also undergoing rapid diversification and specialization: Fields like biogeochemistry and petrophysics were not large enough to have names in the not too distant past. Can geoscientists indeed be characterized as a group or only by their specific subdisciplinary knowledge and skills? Is studying atmospheric circulation so different from understanding the origin of seamounts that we should abandon the notion of common preparation at the undergraduate level? Or is there an essential core to the study of geoscience that supports our ability to tackle problems related to Earth and its processes?

We posit that there are three critical elements of geoscience expertise, three things that one can look for in an individual that can be used to identify them as a geoscientist. First, a geoscientist has in-depth knowledge about some aspect of Earth or planetary systems and skills with which to obtain this knowledge. The details of this knowledge and associated skills vary from individual to individual, and it is not uncommon to find two geoscientists who have very little overlapping knowledge. This is not surprising: Earth is a complex system. Studying it successfully requires more knowledge than one individual can develop in a lifetime.

This leads to a second key characteristic of geoscientists: They have expertise in collaboration. As described already, central features to developing robust, rigorous arguments in geoscience are comparisons across cases and the development of multiple converging lines of evidence. In such a field, a team approach clearly leads to a competitive advantage. Thus, geoscience is fundamentally a collaborative science. Geoscientists value collaboration as an important strategy for gaining improved understanding; have social norms that support the give, take, and risk of collaboration; and have experience with multiple types of collaborations.

These collaborations are supported by a third key element: a set of shared perspectives. These are the most easily recognized attribute of a geoscientist, and we argue that they are the most important unifying features of the discipline. They encapsulate the lessons learned by generations of geoscientists about productive approaches to understanding Earth. When geoscientists come to the table, they bring these perspectives, some specialized knowledge, skill and understanding of Earth or planetary systems, and a tradition of collaborative learning. We begin our description of the characteristics of geoscientists by turning first to the perspectives that typify geoscientists.

Geoscience Perspectives

Geoscience perspectives characterize the overall intellectual frame in which geoscientists approach a problem. As such, they transcend the knowledge and skills required for a particular problem. Like the strategies for evaluating evidence described earlier, these perspectives have developed and evolved through the history of the science. Geoscientists now collaborate increasingly on problems that involve but are not limited to the physical Earth, including interactions with the biosphere and involving human society. One of the important contributions that geoscientists make in such collaboration is their perspective.

We posit four key elements to a geoscience perspective:

1. Grounded in observation of the natural system—Geoscience as a discipline is grounded in observations of Earth collected by methods as diverse as traditional geologic mapping, satellite imagery, globally orchestrated atmospheric measurements, and oceanographic expeditions. As described earlier herein, a geoscientist's perspective continually refers back to these observations, as they form the foundation of proof in geoscience.

2. Geographically, spatially and temporally organized—Geoscientists operate in a frame where the geographic, spatial, and temporal details are very important. A conversation is unlikely to proceed very far before the geoscientist seeks to make sense of information using this frame. The spatial relationship between objects is important on scales from microscopic (the relationship between mineral grains forming a rock fabric) to global (the distribution of temperatures in the atmosphere), and the location of data in, on, or around Earth is critical (latitude, longitude, and depth above or below Earth's surface). Locations can change in time (plates move, rocks deform, conditions change), making a four-dimensional view essential. Reflecting the importance of spatial, geographical, and temporal organization, geoscientists make abundant use of representations and visualizations to formulate hypotheses, organize data, and convey findings.

Like historians or archaeologists, geoscientists draw on temporal reasoning, using observations of sequence, rate, and cyclicity as constraints on process or causality. The sequence of events constrains causality: If A happened before B, then A can have caused or influenced B, but B cannot have caused or influenced A. The rate of events constrains power; for example, to move a cubic kilometer of sediment in a day requires a more powerful causal force than to move the same volume of sediment in a million years. Cyclic events (for example, Pleistocene ice ages) give rise to causal hypotheses with cyclic forcing functions (e.g., Hays et al., 1976). Geoscientists are faced with incomplete records in most cases, so they regularly construct time series by integrating data from disparate locations, a concept known as "trading place for time" (Reynolds et al., 2006).

3. Reflecting a long history of geologic time and the importance of infrequent high-impact events—Geoscientists have internalized the vastness of the age of Earth, and the relative brevity of human history. Within this time frame, there are important events shaping Earth that range from very slow processes operating continually over long periods of time to high-impact processes that occur quickly and infrequently—and everything in between. Geoscientists have a perspective that recognizes that slow processes can have a large impact over geologic time, at the same time that catastrophic events can alter the course of Earth history in seconds, minutes, days, or years. They are adroit at moving between time scales of nanoseconds and billions of years.

This perspective on Earth history contextualizes the observations that geoscientists make. Observations of any system in its current state reflect both the current conditions and the prior circumstances. For this reason, geoscientists are careful to consider the outcomes that are related to a general process and those that reflect the peculiarities of the past history of a system. This holds true when considering both planetary bodies and local systems, such as a lake, stream, or continental margin. For example, the bluffs of the Mississippi River near Minneapolis and St. Paul are large enough to support local ski areas. This relief reflects downcutting of the river in glacial times when water flows were much higher. Efforts to reconstruct the history of the river without accounting for its past history of higher flows would not lead to an accurate understanding of either the erosional processes at work in this case or of erosional processes in general.

4. Understood in the framework of a dynamic, complex Earth system—One of the most profound impacts of geoscience in the past 30 years has been the widespread understanding that Earth is a single integrated complex system composed of interacting subsystems on a wide variety of scales. However, the concept of complex systems characterized by feedbacks is not new to geoscience, nor is the notion of modeling system behavior. Hutton introduced the notion of the rock cycle in the 1700s. Feedbacks, as the fundamental process leading to a dynamic equilibrium that maintains river geomorphology, were put forward by Gilbert (1877). In the 1960s, commenting on the rise of the organismic concept of nature (e.g., Whitehead's Gaia hypothesis), Hagner (1963, p. 238) wrote a compelling description of complex systems thinking in which "structure and form [are] temporary manifestations of the interaction of processes proceeding at different rates. It is the process that is fundamental, and nature so viewed is dynamic rather than static"; then he went on to note that geologists have long dealt with these concepts in a qualitative manner. Geoscientists are adept at working with complex systems, looking for interactions and feedbacks, and modeling system behavior, and they are comfortable with emergent behaviors. A geoscientist's perspective is shaped by his or her work within and on this complex system.

Complex systems are characterized by the emergence of behavior from the interaction among components. As described previously herein, the ability to predict or explain this emergent behavior, particularly the complicated causal relationships between components, is one of the most powerful ways of testing hypotheses about Earth processes and systems. Computational modeling has provided unprecedented power for studying complex systems because it allows geoscientists to simultaneously predict the behavior of multiple variables organized in space and time. The predictions can be tested against observations of multiple types on a variety of scales to ascertain the aspects of the model that have strong explanatory power and those in need of further refinement. Thus, computational models help geoscientists to organize their hypotheses and observations to understand the behavior of complex systems. Increasingly, computational models are used to steer the collection of geoscience observations to test hypotheses generated by the model behavior. An ability to recognize complex systems, to anticipate emergent behavior, and to use models to understand this behavior is central to a geoscientist's perspective.

These perspectives form the common ground among geoscientists of all types. Our conceptionalization of them originated in the reflections of geoscientists describing their field to educators and cognitive scientists (Manduca et al., 2004). They are informed by writings of expert geoscientists and geoscience educators (Manduca and Mogk, 2006; Petcovic and Libarkin, 2007; Herbert, 2006) and through the discussions leading to this volume. They are in line with current discussions of the future of our science, which emphasize an Earth system approach, Earth's origin and history, sustaining human civilization on Earth, and the interplay between observation and modeling (NRC, 2008; NSF, 2009), and they are in line with past descriptions of a geoscience perspective (Hagner, 1963). Presentations and discussions focused on the future of the geoscience curriculum resonate with these themes, focusing on a systems understanding, the importance of developing observational skills, and the development of collaborative skill (Ormand, 2007a).

In contrast to the often-heated discussions about the skills and knowledge that form the core of geoscience, in our experience these perspectives resonate with geoscientists of all types. We offer them as an articulation of the core ideas that all geoscientists hold in common. To the extent that geoscientists reading this paper find these ideas self-evident, we have been successful. In our experience, few outside the profession, including those who take our introductory courses, can articulate these ideas as central to the geosciences. While most citizens have a grasp of what it means to be a physicist (a person who uses difficult math to understand forces like gravity or magnetism) or a chemist (a person who experiments with chemicals, often leading to useful products), few can describe a geoscientist—even at the level of knowing that they study Earth. By articulating the common ground that unites geoscientists in such a way that members of the profession find the essence has been captured, we build an understanding of the term "geoscientist" and of what it is we want to come to mind when it is heard. Development of this understanding then becomes a central goal for K–12 education, introductory courses at the college level, and interactions with the public.

Geoscience Knowledge and Skills

A geoscience perspective is a necessary but not sufficient condition for qualification as a geoscientist. Geoscience knowledge, skills, and the understanding of how to use them are also essential to answering questions about Earth. In fact, we would argue that it is difficult to develop a deep, functioning geoscience perspective without a working understanding of knowledge and skills in some area of geoscience (Bransford et al., 2000).

Knowledge

A geoscientist knows things about Earth, both factual things, such as the thickness of the atmosphere, the age of the Earth, or the pattern of circulation in the ocean, and conceptual things, like the ways in which oceanic and atmospheric circulation interact to affect climate, the ways in which feedbacks impact system behavior, or the way in which tectonic stress can lead to deformation of the lithosphere. Different experts have different specific knowledge, but all have both a broad overview of the behavior of the Earth system and a deep knowledge of some aspects of the Earth system that are absent in nonexperts.

Most geoscientists agree that there are fundamental core concepts that are widely understood across the entire discipline. These include plate tectonics, linked ocean-atmosphere circulation, the functioning of Earth as a complex system composed of fundamental subsystems, and the record of the planet's evolution and the life it supports. The *National Science Education Standards* (NRC, 1996), developed for K–12 students, articulates primary concepts fundamental to geoscience expertise. These have been extended and refined in the geoscience literacy documents (NOAA et al., 2006; Johnson et al., 2007; USGCRP, 2009; Wysession et al., 2010) and subsequently in the *Conceptual Framework for New Science Education Standards* (NRC, 2011). *Shaping the Future of Undergraduate Earth Science Education* (Ireton et al., 1997) describes this approach at the undergraduate level. These documents all emerged from community discussions and processes, representing the breadth of the geosciences, and they focus on illuminating high-level concepts of importance to all members of the discipline.

The challenge faced in implementing a geoscience course or curriculum based on these documents lies in articulating what it means to understand each concept. Consider for example the statement from the Earth Science Literacy document (Wysession et al., 2010): "Earth's rocks and other materials provide a record of its history." We expect that both a geoscientifically literate citizen and geoscientists will be able to do more than recite this line. We expect that a geoscientist will be able to read some aspect of that record. However, certainly we don't expect an individual geoscientist to read all aspects or to recount in detail the full history. What is the common expectation for all geoscientists? What is the common expectation for a geoscientifically literate citizen? These questions lie at the core of debates over the curriculum for geoscience majors. The wide variation in the design of geoscience majors demonstrates that geoscientists themselves have diverse opinions regarding the core knowledge of the discipline.

Skills

A geoscientist can do things that are atypical of nonexperts, such as making a geologic map or forecasting the weather. There are both general skills typical of most geoscientists (for example, the ability to make observations about Earth or the ability to interpret geospatial data) and specific skills that are typical of subspecialties (for example, the ability to determine the age of a rock or the composition of a water sample). The discussion of essential skills for a geoscience degree is less developed than that of essential knowledge. Furthermore, many Ph.D. geoscientists received their undergraduate degrees in other fields, introducing further diversity into what individuals perceive as optimal pathways to expertise. This situation contrasts with that in physics, where there is strong a strong consensus regarding foundational courses in the major.

Much of the work that has taken place to date in determining which skills are fundamental to geosciences has come from discussions of the undergraduate geoscience (Ormand, 2007b), geology (Drummond and Markin, 2008), and meteorology curricula (AMS, 1999). There is substantial overlap in the courses included in the major curriculum in geology at most institutions (Drummond and Markin, 2008). Field skills and quantitative skills have both been the topic of substantial discussion (Whitmeyer et al., 2009; Macdonald et al., 2000; Manduca et al., 2008), but implementation varies widely. Skill with geospatial data and representation has always been a central part of geology degree programs, and in modern times, this includes facility with geographic information systems and related digital tools. There is widespread agreement regarding the importance of high-level communication and problem-solving skills (AAC&U, 2011).

A variety of new programs has emerged to meet the needs of diversifying career options (e.g., Earth system science, environmental science, hydrogeology, biogeology; Ormand, 2007b). When a single major is offered, there are questions about its ability to simultaneously meet the needs of different employers, prepare future teachers, and prepare students for graduate school. These concerns reflect the tension between maintaining expertise within individuals and the rapid expansion of our field. Further, given the need to maintain the viability of a four-year program in the face of expanding knowledge and skills, there is concern that important skills (e.g., petrography, fossil identification) are being lost from our professional community.

It is not surprising that a field as broad as the geosciences, which does not share a single history, would find it difficult to establish a core. In our view, the tension between specialty and breadth is an important one that should be weighed repeatedly. As long as geoscientists maintain the ability to collaborate effectively, which we posit is supported by sharing the perspectives described previously herein, it seems appropriate, and in fact beneficial, to have diversity in the knowledge and skills selected as most critical in different departments. This diversity of training will develop students who are well suited to addressing different problems. Geoscience and the uses of geoscience are changing so rapidly that it is difficult to predict what will be needed in the lifetimes of our current students. We know from our studies of evolution that in an environment of unpredictable change, diversity fosters resiliency. Thus, diversity of preparation of future geoscientists is a strong strategy.

Guidance regarding central skills can be drawn from the preceding discussion of hypothesis testing in geoscience. There is little controversy that geoscience majors should graduate being able to do geoscience. Similarly, there is increasing emphasis placed on understanding the nature of science as a goal for K–12 and introductory undergraduate science curricula. A primary goal for geoscience education at these levels must be to understand how geoscience is a science—that is to expand students' understanding of the scientific method beyond single-variable experimentation to include testing of hypotheses against observations of Earth using multiple cases, converging lines of evidence, and model-based prediction. We posit that all geoscience majors should have skill in using these methods to address real problems, including experience in using models to understand complex systems.

Collaboration as a Central Feature

While there is no doubt that there are individual geoscientists with deep expertise in a single area or broad understanding of the geology of a region, a persuasive geoscience argument rests on its applicability across large numbers of cases, scales, and times, as well as the convergence of different lines of evidence often drawn from different specialties. Thus, the very nature of geoscience fosters collaboration. A geologist who knows all that is to be known about the Appalachians will benefit from collaboration with others who know all that is to be known about the Apennines, Andes, or Atlas Mountains. All will benefit from collaboration with a specialist in radiometric dating or geophysics. Similarly, those who specialize in a specific technique benefit from collaboration with those who understand the context of a specific location where that technique is used. A climate scientist who studies El Niño–Southern Oscillation will benefit from comparing notes with an expert on the North Atlantic Oscillation. Modern geoscience is fundamentally based on collaborative teams where each member brings a specialty, be it the holistic understanding of the specific area or a deep knowledge of a particular feature (e.g., shear zones) or technique (e.g., U-Pb dating).

Geoscientists often collaborate around the study of a particular place. These collaborations may be formal, brought together to create a competitive grant proposal to understand the processes operating in a particular time and place; or they may be informal, brought about to share information among researchers in a particular area. For example, oceanography has long been organized around seagoing expeditions, with the Deep Sea Drilling Project (1968–1975, marine geology) and the Geochemical Ocean Sections (Geosecs) project (1970–1979, chemical oceanography) establishing standards for data collection and collaborative authoring of results. Projects funded by the Earthscope, Continental Dynamics, and MARGINS/GeoPrisms programs of the National Science Foundation provide numerous modern examples of collaborations bringing together geoscientists with a wide variety of specialties to collaborate in the study of a particular case.

The role of the case in focusing collaboration among different types of geoscientists is important. Krohn's (2010) study of the ways in which interdisciplinary knowledge and research move forward emphasized the importance of cases in facilitating the ability of researchers with different expertise to collaborate. The individual expertise of the researchers allows them to collectively address the challenges of the case. At the same time, the individuals can then take their knowledge of this case, compare it to other cases in which their expertise has been important, and search for general principles. It is this back and forth between interdisciplinary work on specific cases, and the formation of general principles within a specific discipline or domain that moves thinking forward in the area of interest. This description of interdisciplinary learning is strikingly similar to strategies of hypothesis testing using cases described earlier in this paper, suggesting that the focus on the study of places facilitates collaboration in geosciences and provides experience with a mode of collaboration that is likely to be useful in broader interdisciplinary collaborations.

Geoscientists also collaborate for practical reasons, for example, to facilitate data collection or sharing, to reduce costs, and to allow use of specialized equipment. Unidata (a consortium of academic institutions that collaborates to collect and distribute atmospheric data) and the IRIS consortium (a well-established mechanism for seismologists to pool both equipment and resulting data) are large-scale, long-lived examples. Geochemists, paleontologists, climate scientists, and others are currently engaged in the creation of shared data repositories (PetDB, SedDB, Chronos, National Geophysical Data Center, National Snow and Ice Data Center). This type of collaboration facilitates less formal collaboration and reuse of data collected for one purpose as a line of evidence in another, which is essential in a discipline where convergence of multiple lines of evidence is a key factor in testing hypotheses.

Geoscientists must collaborate internationally in order to understand the global Earth system. The best place to study a particular process in either modern or ancient times is not constrained by national boundaries. An expert in any area of the geosciences must be comfortable with an international set of cases. From a practical point of view, the resources we need to sustain our civilization are globally distributed, and the hazards we face operate globally. Modern geoscience includes strong international collaborations to understand geologic hazards, to explore the global resource base, and to understand the impacts of human activity on the atmosphere and oceans.

In a field where collaboration is so fundamental, one would expect a culture to evolve that supports effective collaboration. Because collaborative teams play a fundamental role in economic, education, and military settings, they have been studied extensively (e.g., Hutchins, 1995; Salas and Fiore, 2004; Lattuca and Creamer, 2005; Hackman and Katz, 2010). From this work, we learn that collaborative problem solving is most effective if the members of the group can quickly grasp the problem at hand (Cooke et al., 2004), if they have a common understanding of how to approach the problem (Salas et al., 2005), and if they share an understanding of the ways in which different types of evidence are to be interpreted (Fransen et al., 2011). Further, collaborative problem solving is facilitated by a culture in which individuals acknowledge that certain members have special information or expertise, value this information or expertise, and make use of it (Wilson et al., 2007; Wooley et al., 2007). Shared vocabulary and expectations also facilitate effective collaborations (Salas et al., 2005; Weingart, 2010).

Viewed through this lens, the methods of hypothesis testing and the geoscience perspectives described in this paper provide an essential framework supporting geoscience collaboration. The methods of hypothesis testing, particularly the notion that testing against observation is the fundamental nature of proof, provide the essential shared understanding of the ways in which different types of evidence are to be interpreted. The geoscience perspectives provide both a framework in which the problem can be grasped and a common understanding of how to approach the problem. Geoscience vocabulary provides labels for cases formed by related processes, thus enabling easy alignment with other studies of similar features and quick communication of the starting expectations of the approach.

Collaboration in the geosciences is also supported by structures embedded in the practices of funding agencies. For example, funding for large programs like the International Ocean Drilling Program, RIDGE 2000, Earthscope, or the National Center for Atmospheric Research requires long-term vision documents laying out the major research questions for the program, as well as regular synthesis reports indicating the progress that has been made by the program as a whole. The creation of these documents supports broad discussion across the various subdisciplines engaged in study. From this discussion, there will emerge, if all goes well, a strong, detailed, shared understanding of the work to date, the priority problems, and promising approaches to address those problems. In addition, the development of these documents, and their use in creating subsequent requests for funding, leads to a shared language across subdisciplines, which supports collaboration. At the scale of a specific proposal, small groups of collaborating principal investigators are identified and engage in discourse to define the problem and specific approach. Project plans and time lines operationalize the way that the group will make use of the expertise of individuals and incorporate their contributions into the overall research study. For example, projects involving field study, geophysical sampling, and geochemical sampling may develop a plan that sequences research such that reconnaissance field work can inform siting for geophysical surveys and geochemical sampling. Geoscientists joining interdisciplinary collaborations bring with them both experience with and expectations of this type of process for establishing project goals, approaches, and plans.

Interestingly, studies show that problem-solving capacity is reduced if every member of the team has exactly the same understanding of the problem (Hutchins, 1995; Fransen et al., 2011). Thus, the most effective teams will have a balance of shared understanding and unique vantage points. Geoscience research teams composed of individuals with different specialties provide this type of balance. For example, in his account of the discovery of the Mediterranean salinity crisis event, Ken Hsü described the interplay between shared understanding of the problem and unique perception of the data at hand as a sedimentologist, a geophysicist, and a paleontologist worked toward understanding an initially inexplicable set of observations. He stated explicitly that without this diversity of approach, the discovery would not have been possible (Hsü, 1983).

It has been the tradition in science to discuss the importance of individuals. Einstein, Newton, and Richter are names of individuals associated with major breakthroughs in understanding. However, a careful reading of the history of science shows that it is rarely a lone individual who advances science. More often, multiple individuals discover ideas at the same time. They are "in the air" (Gladwell, 2008). The process of scientific discovery can more readily be understood as an emergent process where new knowledge emerges from the interactions among individuals (Hutchins, 1995). Studies of group cognition, the development of knowledge by groups, emphasize that groups have cognitive properties that are not predictable from the properties and knowledge of the individuals in the group (Hutchins, 1995). Group learning involves an individual learning a new area or skill, members of the group becoming aware of this, and emergence of a shared understanding of the group's overall store of skills (Hackman and Katz, 2010). In geoscience, as in most other modern science, this group learning takes place both at the level of the individual project, and at higher levels supporting the integration and synthesis of knowledge across the discipline. It is this group process of testing evidence and weighing conclusions that leads to the robustness of scientific knowledge and overcomes the errors introduced by individuals. The study of Earth's climate system over the past few decades provides an excellent example of science operating at the community level (Weart, 2011) and resulted in the awarding of the Nobel Prize to the International Panel on Climate Change.

Geoscience demands interdisciplinary and integrative thinking. As individuals and in groups, students must learn to combine multiple data types; weigh insights from multiple modes of inquiry; juggle multiple working hypotheses; and apply chemistry, physics, biology, and math in service of Earth-related questions and problems. Earth problems that could be solved and Earth questions that could be answered within the expertise of a single scientist were the low-hanging fruit. The major remaining problems and questions will require multiple brains. For geoscientists of the future, the ability to collaborate, communicate, and integrate both within and beyond the discipline will be at a premium (Savina, 2007; Bralower et al., 2008). Thus, we must attend carefully to developing this aspect of geoscience expertise as we move forward. Traditionally, students are inculcated into the culture of the discipline through interactions within their laboratory during graduate school. Projects such as GEOPrisms that explicitly engage graduate students and postdocs in the work of interdisciplinary collaboration provide models for new strategies in this area.

CONCLUSIONS

What is geoscience? What does it mean to be a geoscientist? Those are the key questions with which we began this essay. Upon reflection, we can move beyond the statement that geoscience is the study of the Earth system and geoscientists are people who do that work. Geoscience is a discipline based in making observations about Earth and testing hypotheses about Earth's history and processes against those observations. Geoscientists share a way of knowing that has developed to facilitate this goal and makes extensive use of comparisons between modern processes and those found in the rock record; comparison of cases to understand commonalities and differences attributable to process, history, and context; converging lines of evidence; and testing through prediction. This type of science is better described by modern discussions of the process of science than those that focus exclusively on experimentation. Geoscientists in aggregate have a wide variety of knowledge about Earth and a diversity of skills for obtaining new knowledge that are not typical of nongeoscientists. In specific, two geoscientists may have little in common in terms of knowledge or skills, but they are united in their discipline by shared perspectives, the fundamental role of observation and of a spatial and temporal organizational scheme in understanding Earth and its processes, and its nature as a long-lived, dynamic, complex system that has been shaped by a continuum of long-lived, low-impact processes and short-duration, high-impact processes. They are also united by a culture that values and actively supports collaboration as a strategy for effectively moving forward understanding of Earth and its processes.

Developing Geoscience Expertise in Students

We have argued that geoscientists have unique knowledge, skills, and methods. The specific knowledge, skills, and methods that they have vary with their specialty; however, they all include knowledge, skills, and methods that are not typical of nongeoscientists. As a community, it is important for us to preserve this breadth of knowledge, skills, and methods. If a portion of this expertise is lost from the community as a whole, our capability for solving problems that arise in the future is diminished. However, it is no longer either possible or desirable for each individual geoscientist to have all of this expertise. Rather, the problems we address require individuals to be free to develop the depth that can be used to address parts of a problem while the geoscience community as a whole continues to develop expertise in solving problems collaboratively. In this way, as a community working together, the geosciences bring more depth and expertise to a problem than a single individual scientist can provide.

This must be balanced, however, by concern that within the community as a whole, expertise is not lost. The history of geoscience is replete with examples where a subdiscipline in decline became essential as a new problem arose. For example, paleontology was rapidly being eliminated from the curriculum in the late 1980s, but now paleontology has become an essential aspect of paleoecology, a critical tool in understanding climate change. More recently, metamorphic petrology has lost the standing it enjoyed when mineral exploration was a central goal for many departments. However, new efforts at carbon sequestration depend on an understanding of the changes that minerals will undergo when CO_2 is introduced into an environment. A metamorphic petrologist is well equipped to address this question. Just as it is no longer possible for a single geoscientist to know all of geoscience, it is no longer possible for individual departments to teach all of geoscience. Thus, a new set of structures will be needed to support collaboration among departments in developing the next generation of geoscientists similar to those that support collaboration among individual scientists. Collectively geoscience departments must ensure not only an adequate supply of new types of geoscientists, but also that the breadth of our traditional approaches is preserved.

A fundamental factor to our ability to address Earth and planetary problems is the set of shared perspectives that are held in common by all geoscientists, as well as a culture of valuing collaborative approaches to studying Earth and its processes. We hold that the development of these perspectives and values in every geoscience student is fundamental to the health of the discipline. The core curriculum in geoscience, whatever the topics and skills that it chooses to teach, must develop these shared perspectives and values. Geoscience students, including undergraduates, must graduate understanding that geoscience is a collaborative science in which individuals share a perspective and approach but have different specific expertise. It is by drawing together the work of these individuals that we understand the processes and history of Earth. These values are supported by experience in collaboration. The development of experience with the planning and communication strategies that support the ability of geoscience professionals to work collaboratively on problems is as important in a strong undergraduate program as the development of geoscience knowledge and skill.

Geoscience is a practical science that can locate resources and identify hazards. Geoscience constrains our understanding of what happened in the past so that we may better understand what is likely to happen in the future. As such, modern geoscience is critical to our ability as a global community to live sustainably on Earth. Communicating the nature of geoscience and the distinct nature of geoscience expertise will create new opportunities to participate in solving important societal problems, from hazards and resources issues to environmental degradation. To this work geoscientists will bring their perspectives, a culture of valuing collaboration, strategies for testing hypotheses about Earth's history and processes, and skills and knowledge for locating resources, understanding Earth processes, and identifying hazards.

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