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The significance of geologic time: Cultural, educational, and economic frameworks

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ABSTRACT

The discovery of geologic time revolutionized scientific thinking and led to the development of the modern Earth sciences. Less appreciated, however, is the fact that geologic time has had far-reaching cultural and societal consequences that go well beyond its founding influence upon the geosciences. This essay summarizes the literature describing the difficulties students encounter in understanding deep time, provides an overview of the historical development and cultural relevance of deep time, and suggests ways to increase students' understanding of the significance of geologic time.

INTRODUCTION

What, then, is time? If no one asks me, I know what it is; but if I wish to explain to him who asks, I do not know. —St. Augustine

Only a small number of ideas deflect the path of history. Copernicus's shift from a geocentric to a heliocentric worldview was one. Hutton's (and Werner's) discovery of geologic time was another. Like Copernican space, the ramifications of Huttonian time have reverberated across culture—scientific, economic, political, and religious. Biological evolutionary theory is impossible without the spans of geologic time (Gould, 1987), nor can we begin to adequately understand our economic and environmental challenges—the end of the age of oil; the prospect of future climate change; the loss of biodiversity; the fatality of current rates of consumption—without the perspectives of deep time. Finally, geologic time presents a fundamental challenge to many in terms of its implications concerning the place of humanity in the greater scheme of things.

Geologic time—and the geosciences—occupies a central position in contemporary culture. It is thus ironic that teachers report that students have difficulties grasping the concept of geologic time. Some of the evidence for this claim is anecdotal, growing from a general sense that students lack a real "feel" for deep time, but there is also a fair amount of literature (e.g., Trend, 2001; Dodick and Orion, 2003a, 2003b, 2006; Libarkin et al., 2007) that shows that in-service and preservice teachers, as well as high-school and college students, misidentify events in geologic time by orders of magnitude, conflate events widely separated in time (e.g., humans and dinosaurs), and have a poor sense of rates of change. Moreover, students often do not seem much concerned with improving their sense of the span of geologic time. For them, little seems to be at stake.

As the opening quote from St. Augustine (354–430) indicates, the difficulty is not limited to students, or even to geologic lengths of time. The concept of time itself is notoriously elusive—but it is also of crucial importance. In one of the

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most important works of twentieth-century philosophy, *Being and Time* (1927; reprinted in 1962), Martin Heidegger builds his entire argument around the importance of time, claiming that our sense of the meaning of life depends on our sense of temporality. In the preface to his book, Heidegger announces: "our provisional hypothesis is that time is the horizon for any possible understanding of being whatsoever." His point—as we will discuss herein—is that both our sense of reality, and of what a culture counts as truth are crucially dependent on our conception of time.

In this essay, we seek to awaken a greater appreciation of geologic time by placing it within a wider societal context. Geologic time is one of the most culturally relevant ideas within the history of thought. While not easily grasped, the varied temporal spans of geologic time (e.g., the period since the Last Glacial Maximum, rates of evolution, or the length of time it takes to wear down a mountain or replace a lost species) offer perspectives of practical use to business people, politicians, and citizens. Moreover, even catching the merest hint of a geologic perspective—seeing our lives and our landscapes within the framework of a larger expanse of time—can fill our students with awe at the wonder that is life on Earth. This essay, then, seeks to help teachers better present the larger cultural significance of geologic spans of time to students across the curriculum. As central as the notion of geologic time is to the geosciences, and to the scientific enterprise in general, its implications are too far-reaching to be limited to the scientific community. A wider account of geologic time, ranging from the details of radiometrics to the perspectives of public policy, needs to be taught to *both* geoscience and nongeoscience students. These insights are crucial to inform and prepare nongeoscience students for their lives as citizens and consumers. Geoscience majors also need to understand these points, for they will live their lives as citizens and consumers as well as scientists. Moreover, in their professional careers, they will be the ones who will transmit these points to their fellow citizens, as well as to the next generation of students. Within this framework, we also briefly outline the literature in evolutionary and cognitive psychology on the known causes of humans' difficulties in grasping the concept of large expanses of time and incorporating a long view of time in their decision making.

Previous pedagogical literature on geologic time has focused on the understanding of scientific processes and phenomena constrained by geologic time. This essay provides a new perspective for contextualizing geologic time outside the traditional approaches. In what follows, we (1) summarize the state of the art within research on and teaching of geologic time, (2) provide the historical and philosophic background for the development of the concept of deep time, and (3) offer an account of its relevance in terms of three framing devices: geologic time as economic engine, as policy tool, and as cultural touchstone. Throughout, we offer suggestions for ways in which these points can be operationalized within the curriculum, research, and the public and private sectors.

In closing these introductory remarks, it is worthwhile to distinguish between "geologic" and "deep" time. Although often used as synonyms, the terms do point toward somewhat different aspects of time. "Deep time," the coinage of Thomas Carlyle (1832) and later popularized by the writer John McPhee (1981), emphasizes the dizzying stretch of the past beyond human culture (i.e., older than 8000 yr ago). In contrast, "geologic time" highlights the way geoscientists tell time—a coarse time scale in which millions of years are the most common coin of currency. On some occasions, paleontologists use deep time to distinguish their perspective on evolution from that of biologists. On still others, geoscientists use deep time as a synonym of pre-Quaternary time, a time when Earth did not resemble its modern appearance in terms of biota, continental distribution, and climate (Sadler, 2008, personal commun.). In this context, although historians, biologists, and archaeologists all make use of geologic time and scales, deep time becomes the exclusive realm of study of geoscientists.

TEACHING GEOLOGIC TIME

While geologic time is a fundamental concept across the geosciences, it may be most central to the field of stratigraphy. Within the stratigraphic community today, research focuses on the study of rates rather than dates, and on the construction of time lines of events rather than on the calibration of static, standardized time scales (see, e.g., Sadler and Cervato, 2011). Science groups like EARTHTIME (www.earth-time.org) sequence geologic time by integrating high-precision geochronology (the dates) and quantitative chronostratigraphy (the rates) with the goal of constraining ages of events that occurred hundreds of millions of years ago with precisions of the order of hundreds of thousands of years (approaching 0.1% of the age) instead of the millions of years of traditional methods.

Increased precision is a laudable research goal for the stratigraphic community, but it is unlikely to be of much interest to the uninitiated. Our central challenge is to find new ways to impart a broad and rich understanding of geologic time to students across the curriculum. While some of the evidence on the impediments to teaching geologic time is anecdotal, there is a growing body of research on the subject that ranges from the elementary to college level and to pre- and in-service teachers (e.g., Ault, 1982; Schoon, 1992; Trend, 2001; Dodick and Orion, 2003a, 2003b; Libarkin et al., 2005, 2007).

Work by Libarkin and colleagues supports the claim that college students have the same issues with deep time as do younger children (e.g., Friedman, 2005). Libarkin et al. (2007) found that college students in 43 different institutions in the United States hold a number of alternative conceptions about deep time and life on Earth. They point out that, while most students could place events like the origin of life, the extinction of dinosaurs, and the evolution of humans in the correct sequence, they had a poor understanding of the actual scale of time between these events.

Learning Goals

In the face of this, geoscience teachers have identified a number of useful conceptual tools, strategies, and benchmarks to deal with the challenge of teaching geologic time. For instance, National Science Education Standards recommend that beginning in grade 5, students should develop an understanding of Earth history and of the fundamental principles of stratigraphy, including a basic understanding of uniformitarianism and catastrophism. Students at this age can also be shown how fossils offer powerful evidence of environmental changes across time, and be introduced to scales and rates of Earth processes ranging from seconds (volcanic explosions) to tens of millions of years (the erosion of a mountain range) (National Research Council, 1996; Libarkin et al., 2007). Grasping the rates of geologic processes involves challenges both unique to the geosciences and of special societal significance. How long does it take to turn decaying organic matter into fossil fuels? How fast are tectonic plates moving, causing earthquakes and changes in the landscape? How frequent are large-scale floods?

Impediments and Misconceptions

We see three main impediments to students making sense of geologic time. First, deep time involves scales and events far removed from everyday human experience. Related to this, the rarity of catastrophic geologic events challenges students' imaginative capacities. Humans tend to "zero out" the likelihood of infrequent events like car accidents and life-threatening diseases (Tversky and Kahneman, 1974). To an even greater degree, earthquakes, floods, and volcanic eruptions fall prey to the same mental habit. It is a unique challenge for geoscience teachers to help students lengthen their temporal horizon to make geologic events relevant to them.

Second, deep time deals with exponential numbers and ratios that are notorious for challenging students. In an age where calculators are ubiquitous, one of the by-products of our technological culture has been the erosion of the "order of magnitude" thinking that geologic time embodies. Calculators and computers are wonderful for quickly coming to precise answers, but they discourage students from developing the orienting type of awareness that helps them tell whether an answer makes sense. Geologic time both requires and helps develop such a sense of knowledge as "reconnaissance" (Foltz, 2000), where students come to know their way around a problem.

The third and final impediment to the understanding of geologic time is caused by prominence of religious teachings that make some students resistant to the concept of an old Earth. In the United States, 45% of the population believes that humans were created by God in their present form sometime in the last 10,000 years (Gallup, 2004). We emphasize, however, that the attraction of creationism is not simply a matter of religious dogma. Humans are narrative beings (McIntyre, 1981); they seek a "sense of an ending" (Kermode, 1967); they want to place themselves within a narrative that gives a clear meaning and purpose to their lives. In contrast to the Christian story, modern geological and biological accounts describe a random, purposeless natural historical process (e.g., Gould, 1987; Frodeman, 1995, 2003). Educators should acknowledge—to themselves, and their students—that the seeming purposelessness of natural events across geologic time is deeply unsettling for many people.

The argument has also been made that humans' appreciation of deep time is impaired because we are predisposed by evolution to prefer short-term rewards versus longer-term rewards (e.g., Penn, 2003; McClure et al., 2004). In essence, the claim is that neural circuits in our brain were designed by natural selection to solve problems that our ancestors faced during our evolutionary history (Tooby and Cosmides, 1995). Neuro-economics has even attempted to quantify a "discount rate" of animals and humans that makes them choose between short- and longer-term options offered by life. We are dubious, however, about the efficacy of such socio-biological arguments.

Increasing Student Comprehension of Temporal Concepts

Textbooks commonly use 24 h or 1 yr analogies to help students comprehend the 4.6 billion year span of Earth history (e.g., comparing a year to the width of a penny, the expanse of geologic time would encircle the Earth more than 2 times, or to a pile of dollars, a stack 460 km high; www.kokogiak.com/megapenny/). Within this vast expanse of time, humans occupy only the tiniest amount, a daunting thought for students who find it more manageable to deal with the 6000 years of a young Earth. As widespread as these analogies are, it is unclear how effective they are at bridging the gap between our perception of human and geological time. This is an area ripe for research (e.g., Dodick, 2007).

Recent trends in elementary education in history deemphasize the idea of absolute chronology, instead focusing on relative time or the sequencing of events (e.g., Levstik and Barton, 2005). In geology, the earlier emphasis on large numbers (e.g., memorizing the whole time scale) and unfamiliar events explains some of the difficulties students have in grasping deep time. The general consensus now is that students are more comfortable placing events or fossils in a relative time sequence using spatial mental (or "logic-based") models of time (e.g., Trend, 2001; Dodick and Orion, 2003a, 2003b, 2006). Depending on the specific tasks and the age of the subjects, the concepts of absolute time and dating (or event-based time) are probably more challenging: Large numbers require more nuanced thinking in order to bridge the drastic differences in scale between the human experience with time and the various magnitudes of geologic time (e.g., Libarkin et al., 2007).

Cognitive scientists often utilize spatial metaphors in their studies of human conceptions of time, assuming that humans more easily understand space than time. So, for instance, Boroditsky (2000) distinguished between ego-moving metaphors, where the subject is actively involved in the time process, and time-moving metaphors, where humans experience time-related events as observers. Geoscientists (and students) experience time in both ways: Walking through outcrops or along sediment cores is an example of "ego-moving," while short-term events that occur on a human time scale like hurricanes and earthquakes are experienced as "time-moving." Cognitive scientists tend to represent time as one-dimensional, while most representations of events in geologic time scales are multidimensional (e.g., a spiral of time, the colors of a geologic time scale, logs of data and events placed along a time line, a time-scaled phylogenetic tree of life [Dodick, 2007]). An additional source of confusion is the common use of horizontal time lines in teaching young children about history and chronology, while geoscientists experience time vertically. The present in a geologic time line is always at the top, while a horizontal time line used in history can equally flow from left to right or vice versa. Finally, and arguably most confusing, in geologic time lines, time flows backward, while humans experience time in their daily lives as flowing forward (Dodick and Orion, 2006).

Increasing Student Motivation Concerning Geologic Time

The techniques summarized here offer important aid for instruction. However, rather than being primarily a matter of the mapping of cognitive abilities or the development of geo-pedagogical technique, we believe that achieving the goal of helping students better understand geologic time turns more on questions of context, motivation, and interest. Issues of motivation ("why should I care about deep time?") addressed by Zen (2001) and Frodeman (2003) point toward key elements of wider societal interest in the concept of geologic time.

Consider, for instance, Walther's law of facies—that the vertical succession of rock facies reflects lateral changes in environments. The insight that time units can cut across rock units helps students put Earth into motion: The outcrop's matched layers of black shale and chalky limestone become the sign of shifting seas across what is now a desert landscape. Rocks become pieces of petrified time, and a static entity becomes a dynamic scene in the student's mind. Similarly, understanding the ways in which geologic rates range from the very slow (the formation of mountains) to the instantaneous (an earthquake) places human activities within a geologic context relevant to larger social, economic, and political issues.

In what follows, we seek to place geologic time within such a larger humanistic and policy framework. Moreover, we believe that this adds to the logical rigor of teaching geologic time. To see how, consider the question of defining the appropriate degree of accuracy of an event in geologic time. There can be no purely scientific definition of what counts as a necessary degree of accuracy. The appropriate degree of accuracy is inevitably dependent on societal context (including, of course, the "society" formed by, e.g., a group of stratigraphers, funded to a given degree by industry or a state legislature).

Nonscience majors will have different—not better or worse—needs and interests compared with geoscience majors, just as Wall Street needs different degrees of accuracy for identifying the likely point of (say) peak oil compared with the timing of climate change. We should frame our discussions of geologic time within the framework of human context and interest, offering differing specific accounts of how differing temporal perspectives are relevant to different cohorts of students. The significance or "broader impact" of the events across geologic time is thereby woven into the fabric of geoscience education.

A BRIEF PHILOSOPHICAL HISTORY OF GEOLOGIC TIME

To grasp this broader impact, consider the historical development of the concept of geologic time. As Kant noted more 200 years ago in the *Critique of Pure Reason* (1881), space and time form part of the basic architecture of our thinking. A change in our understanding of these fundamental structures affects every aspect of our lives. However, even though the two are almost by definition of equal importance, the Copernican revolution in space has become an intellectual touchstone, while the Huttonian revolution passes, if not unnoticed, only partially as a cultural benchmark.

James Hutton's discovery of geologic time at the end of the eighteenth century—a length of time so expansive that he could imagine "no vestige of a beginning, no prospect of an end"—announced a scientific and cultural revolution. Geologic time represents much more than an arithmetic fact. It allows us to make sense of the outcrop, to see it as a snapshot of time, an environment preserved in stone. This is perhaps the greatest gift that the geologist can offer: to teach students how to revivify landscapes.

As powerful as this is, the geologic sense of time implies much more. By reorienting our sense of time, geology presents us with a new view of our basic sense of reality. As Heidegger argued, it is our sense of time—as ill-defined and un-self-conscious as it may be—that determines the type and manner of things that strike us as real or substantial.

An example will help make the point. Our current (i.e., standard scientific) definition of truth presupposes a specific understanding of time: we define reality as that which can be produced (and then reproduced) on demand. This makes anything that is caught up in time (historical geology, for instance) epistemologically suspect. Thus, the results of the experimental or laboratory sciences are considered the gold standard for truth. Those aspects of reality that deny exact repetition—the insights of the historical sciences, but also policy decisions, or a moment at the seashore when the light is just so—will be defined as "subjective" and not quite real. Similarly, if we define economic reality on one time scale—say, in terms of the profits turned last quarter—then the current price for a barrel of oil (~$100/barrel, December 2011) may be a realistic measure of its worth, but seen from a perspective informed by deep time, burning gas in a sports utility vehicle (SUV) becomes profligacy.

The earliest attempt to define the age of Earth was made by the seventeenth-century Irish Bishop James Ussher. Based on calculations taken from the Bible, Ussher identified the first day of Creation as beginning with the darkness that preceded Sunday, 23 October 4004 B.C. (Ussher, 1650). In 1669, Nicolas Steno described the stratigraphic laws of superposition, original horizontality, and crosscutting relationships from field observations he made in Tuscany. In the late eighteenth century, James Hutton's discovery of the immensity of geologic time was the product of more than 30 years of pondering the outcrops of his Berwickshire farm. Moreover, at the same time that Hutton was working in Scotland, in Saxony (Germany) Abraham Werner had realized the importance of distinguishing between lithostratigraphic and chronostratigraphic units. Werner realized that a given rock type traced across the landscape may record different moments in time, as depositional environments shift across a basin.

While generally taken as simply a point of stratigraphy, the cultural importance of Werner's insight has proven to be equal to Hutton's discovery of deep time. Werner's innovation was to see that it was possible to define entities by *time* rather than in terms of the character of the things (e.g., rocks) themselves. Of course, folk wisdom had always understood some things in terms of temporal categories—planting, harvest, and the cycles of human life—but formal conceptual thinking had long been guided by Plato and Aristotle's sense that the categories of thought needed to be held outside of the corrupting effects of time.

Werner's insight contributed to one of the most characteristic aspects of modern culture. Since the mid-nineteenth century, we have lived in a time-infused culture: Following Werner, we now define the truth of many claims in terms of time. For instance, with some noticeable exceptions (e.g., the experimental sciences; fundamentalist religions), our culture has embraced historicism, the belief that rather than there being invariant standards of truth, every claim can only be understood in relation to the historical period in which it is made. Historicism is commonly associated with anthropologists Franz Boaz and Ruth Benedict, but the roots of the historicizing of culture lie in Hutton, Werner, and the early nineteenth-century German philosopher Georg Hegel.[1]

In his *Phenomenology of Spirit* (1805; reprinted in 1977), Hegel analyzed the whole of human history culture in terms of the progressive evolution of culture. Hegel saw all of human history as unconsciously directed toward the end of self-knowledge (rationalism) and self-determination (democracy). In the early twentieth century, anthropology pluralized Hegel's point: Rather than seeing the historical development of human culture as pointing toward one common end, Benedict, a student of Boaz, argued that each particular culture presented a unique configuration that could not be judged by a universal standard. Each culture's moral imperatives formed a distinct whole; morality became relative to the values of the individual culture—a view today known as "cultural relativism."

At the risk of oversimplification, we can summarize these points with a table of the cultural changes caused by the Huttonian revolution in time (Table 1). Before the discovery of deep time, the study of Earth was limited to mineralogy; the age of Earth was thought to be 6000 years; the physical universe was seen as full of purpose; and ethics was understood to consist of a universal standard. All of these factors changed in the aftermath of the Huttonian revolution.

TABLE 1. CULTURAL CHANGES OF HUTTONIAN REVOLUTION

	Pre-Hutton	Post-Hutton
Discipline	Mineralogy	Geology
Length	6000 yr	4.5 billion yr
Meaning	Teleological	Nonteleological
Ethics	Universalist	Historicist

A THREE-PART FRAMEWORK

What is the practical upshot of this brief tour of the origins and cultural significance of geologic time? We identify three means by which student's motivation for learning about geologic time can be promoted. We propose the three categories of economics, politics, and culture to expand appreciation and understanding of geologic time.

Traditionally—that is, until the end of the nineteenth century—economics and politics formed a common subject known as political economy. In fact, all the spheres of society discussed here were intertwined: One of the distinctive aspects of late nineteenth- and twentieth-century Western society is the separation of the public of economy, politics, culture, and religion. The social sciences separated political economy into economics and political science, a division that is in many ways artificial, while ethics and religion were interpreted as subjective subjects unsuitable to rational adjudication. Thus, many of the following points could be placed in one or another section.

Time and the Private Realm

The economic implications of geologic time are widespread and inescapable. A wide range of financial factors can be better understood by placing them within the perspective of geologic time. Human society depends on a wide range of natural materials that have formed over geological time spans under conditions that are difficult or impossible to reproduce. These resources range from energy supplies (e.g., oil, coal), to construction materials (e.g., aggregates such as sand and gravel), to other basic necessities of life (e.g., topsoil, aquifers, and the very air we breathe).

[1]Now, if Heidegger is correct that our life is profoundly affected by changes in our understanding of time, then we should expect that other innovations, e.g., the development of chronometers, would have had wide cultural effects—and they have: The Western sense of time was deeply affected by the widespread adoption of clocks in the twelfth and thirteenth centuries within Muslim and Christian cultures. The net result of the clock, however, was to *mathematize* time—making it possible to put people on a regular schedule, and indeed to separate them from the ongoing flux of physical change. In the language of philosophy, clock time "Platonized" our experience by making mathematical units seem more real than lived reality.

Consider that an inch of topsoil forms over periods of time ranging from 100 to 10,000 years, yet the economics of farming practices in Iowa and elsewhere largely "externalize" this fact. Topsoil erosion occurs at rates that average 5 tons per acre each year (or one inch per 33 years, the thickness of a dime per year)—none of which is included within the cost of corn. Similarly, timing the point of "peak" oil, identifying changes in limited water resources (e.g., the Ogallala aquifer), and calculating the impact of severe weather events form only a small set of the examples where the perspective of deep time should (but sadly doesn't) affect the bottom line.

The economic implications of deep time raise questions concerning the common economic practice of discounting the future. Economics itself suffers from a severely foreshortened temporal horizon. As expressed in interest rates, each year in the future is discounted by 4%, 5%, or 7%. A 5% interest (or discount) rate means that every 14 years, the value of the substance—for instance, soil, or water—is cut by half. At this rate, the present-day value of a substance will decline by 99% in 100 yr, and 99.999% in 225 yr—numbers that barely qualify as being within the compass of geologic time.

Of course, society is not likely to begin calculating the cost of soil erosion or the depletion of an aquifer 100 or 1000 years into the future. However, this does raise an important point, highlighting the need to find ways to integrate the "long now" of geologic time into our economic planning, at least as a perspective that limits or regulates our economic habits. One can only wonder at the profound alteration of our economics if economists were introduced to geologic time as a matter of course.

Time and the Public Realm

By the public realm we mean the relation between deep time and public decision making. To be adequately framed, issues such as climate change, resource depletion, and the loss of biodiversity require the perspectives of geologic time. Moreover, geoscientists today find themselves caught up in the same forces that are affecting all of science: an increased emphasis on the public or societal relevance of basic science. The growing focus on the societal effects of science—codified in the National Science Foundation's required peer-review criteria of "broader impacts"—highlights the need for scientists to think about the larger consequences of their research. Scientists must make explicit connections between the research they are performing and its use to the society that funds that research.

This requires that we foster a greater awareness among our students of the public policy dimensions of geoscience. Consider the linked examples of our nation's energy policy and environmental policy. Each of these, and both together, depends on our ability to frame decision making in terms of the knowledge and perspectives uncovered by geoscientists. A sense of the broad sweep of time necessary for the creation of fossil fuels is crucial to policy making—for example, in setting Corporate Average Fuel Economy (CAFE) standards for automobile fuel efficiency. So is the fact that over the last 10,000 years, we have been in an interglacial period of relatively warm climate, which will eventually come to an end. Again, debates concerning future climate change must understand the residence time in the atmosphere for greenhouse gases (Archer, 2005). In sum, our decisions today must be placed within the framework of both the geologic past and the geologic future.

Time in the Realm of Culture

We have highlighted the importance of the greater societal aspects of geologic time in terms of the (often linked) points of economics and decision making. However, any account of the larger effects of understanding deep time must also acknowledge the power of a third dimension, what we call the cultural dimensions of geologic time.

One of the oldest debates within Western culture turns on identifying the core aspects of human nature. Since Adam Smith in the eighteenth century, Western culture has favored the definition of *Homo economicus*—which our fundamental nature turns on the production and acquisition of possessions. In the twentieth and now twenty-first century, this has led to the creation of mass consumer society, first in Europe and North America, and now around the world, and an overwhelming focus on material possessions. As resource economists and geologists have pointed out, it is unlikely that a global consumer society is at all possible—by some estimates, we would require the resources of another 4 or 5 Earths in order to allow China and India to have the standard of living of the United States.

Homo economicus, then, may be reaching the end of its useful life, causing a reevaluation of our sense of how we order our lives. It is quite possible that we will be forced to revisit more traditional accounts of what makes a life rich and fruitful, such as Aristotle's claim that our most basic source of pleasure is the simple experience of wonder at the nature of things. Within such a worldview, the geosciences, and particularly geologic time, will have much to offer.

Consider this small set of geologic wonders: the drying up and the subsequent reflooding of the Mediterranean Sea 6 m.y. ago (Hsü, 1983); the great floods resulting from the breaking of the ice dam at Glacial Lake Missoula in Montana (http://vulcan.wr.usgs.gov/Glossary/Glaciers/IceSheets/description_lake_missoula.html); the fact that where Chicago now sits was under 1 mile of ice 20,000 years ago; or that Yellowstone National Park is a bubbling caldera that has exploded three times over the last 2 m.y., and is slowly rising again. All of these are wondrous facts to ponder, highlighting the aesthetic aspects of geologic processes across time.

Nor should all the examples be in faraway places: Geologic time is always right under our feet. There are local examples: In central Iowa, students on their way to school each day drive by the remains of a 300-m.y.-old ocean that offers the opportunity to change their experience of everyday life.

BRINGING DEEP TIME INTO THE CLASSROOM

Some recommendations on ways in which to overcome these challenges can be found in the existing literature on geosciences education. Using time as a framework to tie together specific events by creating sequences using imagery without numbers has been shown to be successful (e.g., Dodick and Orion, 2003a, 2003b, 2006; Dodick, 2007). The physical experience of walking through a natural history museum and perusing displays of fossils arranged in a time sequence translates the experience of time into a lived phenomenon. Students can thus begin with something concrete before attaching their knowledge to the scaffolding provided by sets of numbers (e.g., Dodick, 2007). Shea (2001) described an elegant way to introduce college students to the mathematics of radiometric dating, using the raw amounts of parent and daughter isotopes and guiding the students stepwise through the calculations that lead to the age of the specimen. This approach gives a richer context to the technique than is usually given in introductory textbooks, where the process is "dumbed down" through tables and essentially becomes passive. (Animations of radioactive decay and rock dating can be found at http://serc.carleton.edu/NAGTWorkshops/visualization/collections/RadioDec.html.) However, additional research could help demonstrate that these metaphors are successful in providing students with a mental model of deep time and discover if students then apply this mental model when thinking about societal issues.

CONCLUSION

We have argued that it is crucial that all students—geoscientists or not—be exposed to wider economic, political, and cultural dimensions of deep time. We have also outlined some of the reasons why students have alternative conceptions of time, and sought to highlight why humans struggle to understand deep time and the importance of low-frequency events. We have framed our approach in terms of the importance of motivation, context, and interest. We conclude with two final examples showing how to bring these arguments into the classroom.

Consider the case of New Orleans and Hurricane Katrina. In the aftermath of the hurricane, the debate immediately turned to whether and how to rebuild the city. The debate, however, overwhelmingly focused on questions of cost, the possibility of adequately rebuilding the levees, and the likelihood of another category 3, 4, or 5 hurricane hitting New Orleans. If the discussants in the debate had been conversant with geologic time, and had worked it into their decision-making framework, they would have realized that the likelihood of another category 4 or 5 hurricane hitting New Orleans in the next few decades was nearly 100%.

Also, a factor almost entirely absent from the discussion was the question of the long-term viability of New Orleans from another source: the fate of the Mississippi River. Figure 1 shows a map of the Mississippi Delta where the path of the Mississippi River has varied over hundreds of miles over the course of several centuries. Moreover, the current path of the Mississippi is an

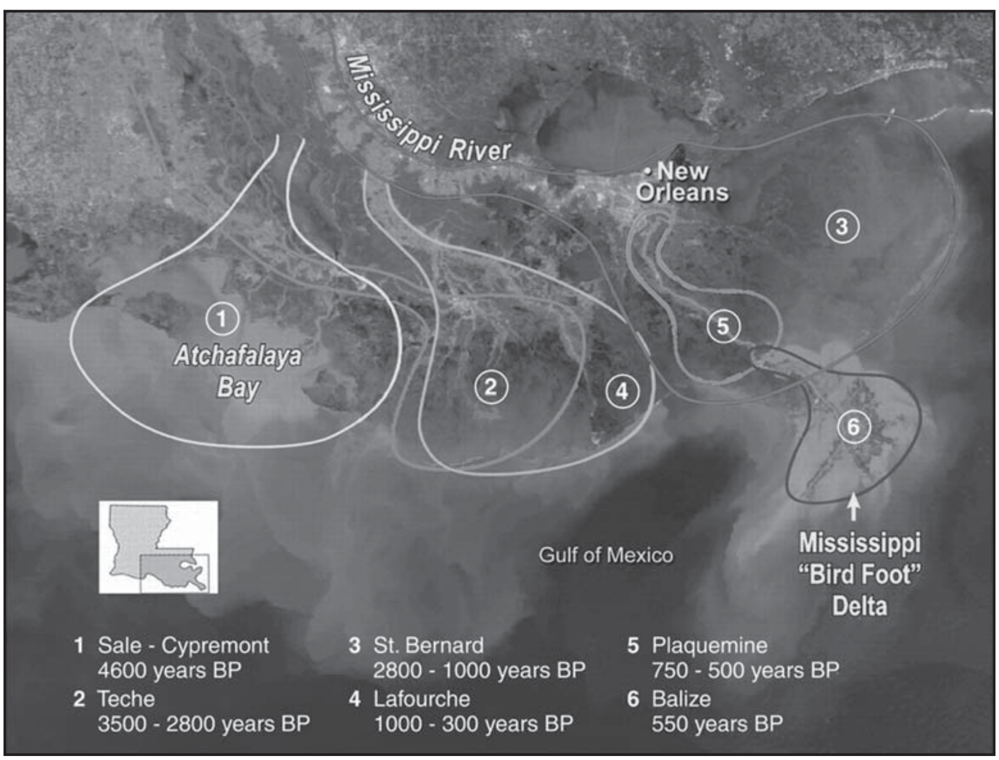

Figure 1. Holocene history of Mississippi River Delta lobes of river deposits, numbered in chronological order from oldest (1) to present (6) (after Day et al., 2007, which was modified from Kolb and Van Lopik, 1996; reprinted with permission of the American Association for the Advancement of Science). The Atchafalaya River is within lobe 1.

old one, destined to shift soon to the west, through the Atchafalaya channel. In fact, it is only through the continuing herculean efforts of the U.S. Army Corps of Engineers that the Mississippi River continues to flow past Baton Rouge and New Orleans. Without the continuing investment of money and labor (totaling more than $35 billion dollars to date), the Mississippi would have abandoned both cities by the 1950s (e.g., Coleman et al., 1998). It is a geologic certainty that eventually the river will flow through the Atchafalaya, leaving both cities as backwaters.

Nonetheless, the perspective offered by these facts of geology and hydrology made little or no contribution to public considerations of the future of New Orleans. Now, we do not mean to suggest that it would have been sufficient to hand the city council the geologic map of the Mississippi Delta shown in Figure 1. Rather, students and citizens, economists, and politicians must be walked through the experience of geologic time in a stepwise fashion.

Another example is provided by the Boxing Day Sumatra earthquake and ensuing tsunami that took almost 300,000 lives in the Indian Ocean on 26 December 2004. Many of those lives could have been saved if the Indian Ocean had a tsunami warning system in place similar to the one that exists for the Pacific Ocean. On the other hand, a detailed study and dating of ancient tsunami deposits along the coasts of northern Sumatra suggest that these large events occur every 600 years (Monecke et al., 2008). This infrequent recurrence may suggest that sustained tsunami hazard awareness informed by geological records of these events might be more effective in this region than large investments in large-scale warning systems.

Examples such as Katrina and New Orleans highlight what is at stake in framing geologic time within a context of economy, policy, and culture. Of course, we have always done some of this. Children learn very early on that the age of a tree can be found by counting the growth rings on a stump; we then can transfer this understanding to longer time scales by using the yearly layers in an ice core or the seasonal couplets in lacustrine varve deposits, but we need to give students what may be called a *humanistic* experience of deep time to help them to make the abstractions of geologic time more real, and more meaningful to their lives.

Placing deep time in a historical context offers another means for bridging the gap between human and geological perception of time. Using history to give context to science education has been shown to be successful at changing students' conception of the nature of science (e.g., Matthews, 1994; Heilbron, 2002). Work in progress at Iowa State University uses the historical perspective to humanize the science of deep time (Cervato et al., 2005). Preliminary results indicate that this approach is successful in increasing the comfort level of non-science, technology and engineering majors' with deep time. More ideas and resources on this approach can be found at http://serc.carleton.edu/introgeo/earthhistory/index.html.

Many before us (e.g., McPhee, 1981; Gould, 1987; see also Frodeman, 1995) have made the argument that the temporal perspective of geology is crucial for developing adequate models for the future sustainability of our planet. Our review of the methodologies being used to teach geologic time, and the assessment techniques used to assess students' understanding of geologic time, shows that few to none of these teaching and assessment techniques are explicitly oriented toward fostering students' perspective of geologic time and applying it to sustainability problems. Deep time provides the record of the frequency, magnitude, and recurrence of events like earthquakes, volcanoes, floods, and hurricanes that should inform risk assessment and inventory of resources. However, we see too few examples where the teachings of the geosciences have influenced economics or policy, and more research is needed to test the effectiveness of current teaching approaches. We hope that this paper can inaugurate a common research program among geoscientists, humanists, economists, and policy analysts to make full use of the significance of geologic time. We should spend less effort teaching students to think about the past and more effort teaching students to think about the future, using the geologic past as a guide.

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