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Mapping the domain of time in the geosciences

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INTRODUCTION TO PAPERS

There is perhaps nothing so distinctively associated with the geosciences as the concept of geologic time. In a science that unravels the long history of Earth, the vastness of geologic time, the sequence and duration of events, and the rates of geologic processes are central concepts. In the paper that follows, Cinzia Cervato, a stratigrapher and geoscience educator, and Robert Frodeman, a philosopher, remind us that geologic time is more than an important tool in the geosciences. Hutton's conceptualization of the length of geologic time was a revolution in thinking comparable to the Copernican revolution, changing humanity's understanding of their place in the history of the universe. Cervato and Frodeman make a compelling case that all citizens need a deep understanding and appreciation of geologic time to frame their personal and political choices, and to enrich their lives.

This point resonates through the commentaries that follow. Enrico Bonatti, a geochemist, elaborates the pathway from Hutton's observations to acceptance of an ancient Earth by the scientific community. This change in perspective required strong evidence from geoscience and physics, and it was confirmed by radiometric dating, a branch of chemistry. Bonatti reminds us that the concept of an Earth of very long duration, perhaps infinite, was already prevalent in ancient Greco-Roman culture. The competing visions of deep time and young Earth have been battling it out for many centuries, engaging the attention of intellectuals from Plato to Darwin. At the heart our conceptualization of time is a deeply philosophical issue. Geoscientists belong in a much broader conversation.

Accepting the importance of geologic time in the private, political, and cultural lives of citizens, commentary writers Malcolm Fenton, a science teacher and geologist, and Martha Monroe, a professor of environmental education, emphasize the importance of interdisciplinary collaborations in teaching about geologic time. Geoscientists, social scientists, and humanists all have potential roles to play in helping students explore the implications of geologic time in private and public decision-making. Fenton provides strong practical guidance based on his knowledge of the classroom. Monroe provides a theoretical frame and recommendations for moving from knowledge to action. However, she warns us that changing societal norms about the environment is not an easy process, and she makes the case that increasing knowledge alone does not necessarily lead to desired changes in behavior and decisions.

Understanding geologic time is no easy task. Conceptualizing the age of Earth, developing an intuition for the duration and rates of geologic events and processes, and mastering a history of Earth, even at a general level, are major cognitive undertakings. Cervato and Frodeman review the literature describing the overall difficulty and the specific challenges commonly encountered by students. Jeff Dodick, a geoscience education researcher, and Ilyse Resnick, Kinnari Atit, and Thomas Shipley, who are psychologists, look at the ways humans understand and work with time as a framework for designing teaching strategies. They emphasize the processes by which we reason from the present to the past, the way we conceive of and use events to create histories, and the difficulty we have moving from representations of space to those of time. Their commentaries clarify why teaching geologic time is challenging and offer strong suggestions for the design of new strategies.

Taken together, these papers inspire us to think more broadly about the importance of geologic time, not only for geosciences but for all of humanity. Not only is an understanding of the history of Earth central to geoscience and its contributions to solving the problems of living sustainably on the planet, it is central to the development of educated citizens prepared to participate in the private, political, and cultural aspects of the world.

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GUIDE TO THE CONCEPT MAP

Our concept map of Time in the Geosciences (Fig. 1) has four main nodes, which will be discussed in order of Big Ideas of Science, techniques, pedagogy, and temporal reasoning. In this and subsequent section introductions, nodes in the concept maps are called out in the text by means of Helvetica font.

Big Ideas of Science

A "Big Idea of Science" is a "concept, theme, or issue that gives meaning and connection to discrete facts and skills" (Wiggins and McTighe, 2006, p. 5). According to Wiggins and McTighe (2006), capital "B" Big Ideas are the hard-won results of scientists' inquiry, ways of thinking and perceiving that are the province of the expert, not obvious to the novice, and in some cases downright counterintuitive (p. 67). They generate new knowledge in a field while being helpful to novice learners (p. 69), and they apply to many other inquiries, both horizontally across subjects and vertically across the years of schooling. The concept of organizing teaching and learning around a relatively small number of Big Ideas, designing instruction to foster these ideas, and assessments to monitor mastery of them, is a prominent theme in contemporary science education reform.

By these criteria, the finding that the age of the Earth is vast is truly a Big Idea of Science. One of the central thrusts of Cervato and Frodeman's thematic paper is that mastery of this idea should be part of every young person's education, for both intellectual and practical reasons. Intellectually, understanding that humans have existed for only a small sliver of Earth's history was a milestone in humanity's understanding of our place in the cosmos; thus, the concept map shows a dashed line link outward from geoscience toward the arts and sciences of the human condition. On a practical level, understanding the vastness of geologic time enables understanding that slow processes can accumulate large effects, as in the case of evolution or erosion. Seen against the geological time scale, low-frequency but high-impact events such as floods, storms, bolide impacts, earthquakes, and ice ages are seen as part of Earth's business as usual, not anomalous "acts of God."

Techniques

The techniques branch of the time concept map encompasses all of the ingenious geo-thinking that has gone into inventing and refining (1) techniques for generating evidence about the past, and (2) techniques for generating insights about the future.

A traditional geology education is much concerned with the details of the myriad of techniques for generating evidence about the timing of events in the past and the age of entities in the geological record. The concept map branches into a bushy cluster of techniques for wresting temporal constraints from rocks and mud, using both relative dating and numerical dating. Geology students spend entire courses learning to think about dates, times, and ages, via fossils, via magnetic signatures of rocks and mud, via stable isotope ratios, via unstable isotope ratios, via geometry of crosscutting relationships, etc. Dozens or hundreds of geoscientist-lifetimes have been invested in developing these ingenious techniques, tapping into subtle and indirect time signals captured in the rock record, and building on human's cognitive capability to represent transformation over time ("diachronic thinking"; Dodick, this volume; Montagnero, 1992). Enrico Bonatti (this volume) recalls his high school science teacher, who told his students that "Time" is what can be measured with a clock. Comprehending how geologists think and learn about time requires a drastic expansion of one's concept of what constitutes a "clock."

Generating insights about the future requires a conceptually different toolkit than generating insights about the past. Generating insights about the future requires the use of models. The concept map shows three nodes: conceptual models (e.g., the water cycle), empirical models (e.g., simple weather forecasting techniques based on pattern matching), and process-based digital models (e.g., the Cane/Zebiak El Niño model; Cane and Zebiak, 1985). How do we teach students to use and create such models? Historically, it seems that humanity progressed from conceptual models to empirical models to process-based digital models around a given topic. Is there a natural learning progression for model-based reasoning that parallels this historical development?

Creative instructional designers are taking on the challenge of teaching the kind of model-based reasoning that enables geoscientists to generate insights about future Earth processes, for example, by giving students access to simplified versions of scientists' models (EdGCM, 2010) or by combining physical and digital model-building (Moore and Derry, 1995). However, we have few geospecific educational research studies to guide this instructional design. One early research thrust is documenting the nature of students' difficulties with model forecasts, including difficulty understanding the probabilistic nature of model outputs (Ishikawa, et al., 2005) and aversion to relying on model outputs for societally important decision making (Ishikawa et al., 2011). Understanding and improving how people think about the Earth of the future is a ripe field for research. Education research on model-based reasoning outside of geosciences (e.g., Lehrer and Schauble, 2005) and cognitive science research on how humans think about the future in everyday contexts (Shipley, 2008) provide some building blocks for this research agenda.

Pedagogy

There is a rich body of literature on the pedagogy of time in geosciences, based on both research studies and practitioners' wisdom. The concept map clusters these insights into impediments to learning, pedagogical motivators, and pedagogical strategies.

Cervato and Frodeman review some of the impediments to learning this material. The vast time scales of geological thinking are far outside of students' everyday experience, and much of the heavy lifting of shaping and reshaping Earth's surface

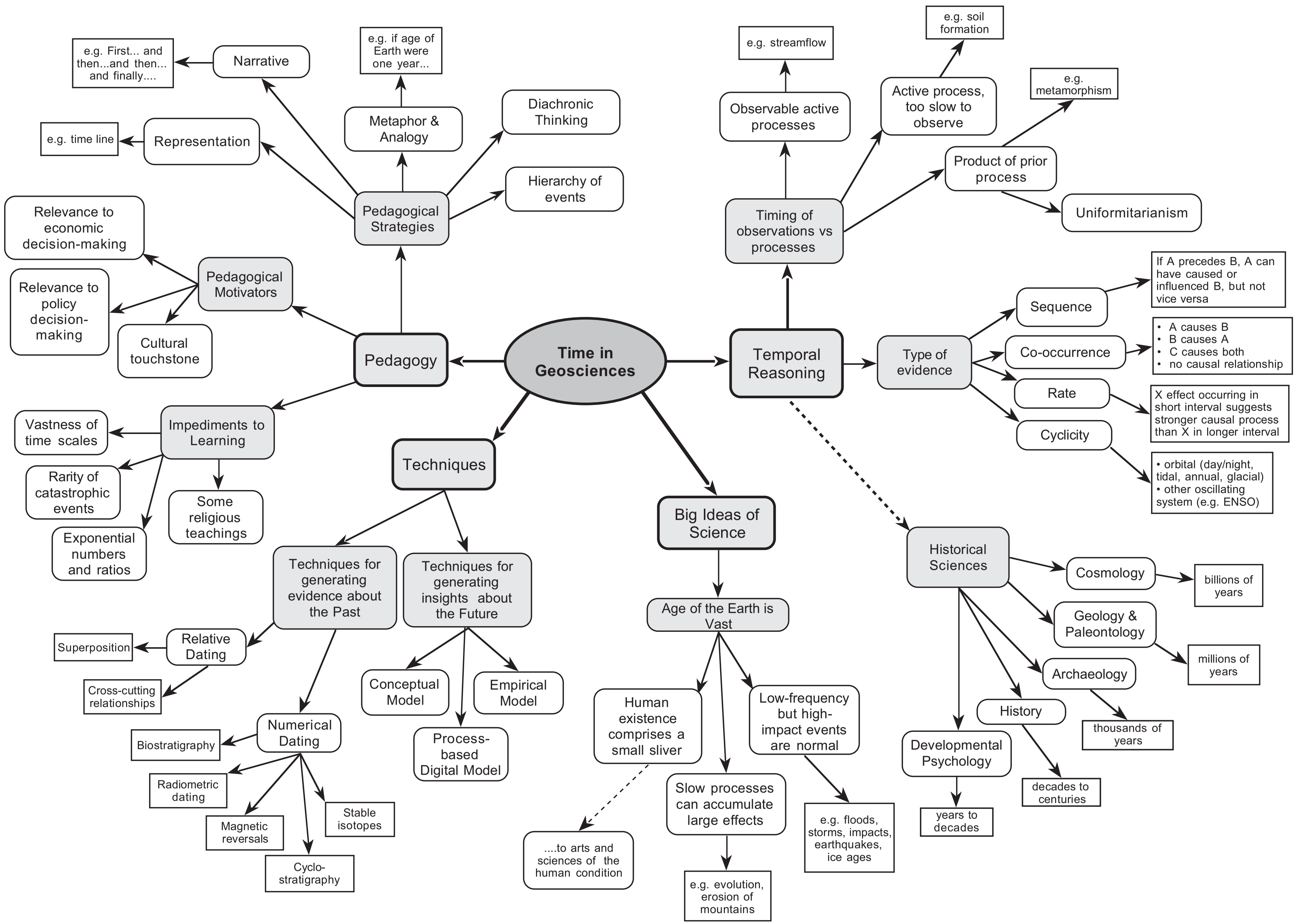

Figure 1. Concept map of Time in Geosciences. Nodes in the concept map are keyed to the text by Helvetica font.

is done by catastrophic events that are rare on the human time scale. Geoscientists take advantage of exponential numbers and ratios (e.g., isotope ratios) to scaffold their own thinking about geological time, but these quantitative skills are a stumbling block for many students. Finally, some religious traditions teach that Earth is young.

Set against these obstacles, Cervato and Frodeman propose three compelling pedagogical motivators or contexts in which the teaching and learning of geologic time can be situated; these are abbreviated on the concept map as relevance to economic decision making, relevance to policy decision making, and cultural touchstone. These motivators pertain to all students, not just future geologists, and they help geo-education avoid the pitfall of "provid[ing] uninteresting answers to questions we [students] never asked" (Osborne, 2006, quoted in Dodick, this volume). Fenton's commentary (this volume) points out that some of the ideas advanced by Cervato and Frodeman concerning the relevance of geologic time to the private, public, and cultural realm are more likely to appear in the curriculum under the canopy of environmental science rather than as earth science. Where administrative or cultural barriers separate "earth" from "environmental" science, geoscience educators would be well advised to join forces with, rather than fight against, our environmental science colleagues (Manduca, 2010).

A precursor volume to the present effort (Manduca et al., 2004) proposed three broad pedagogical strategies that can help students grasp the vastness and texture of geological time. These appear on the concept map as narrative, metaphor & analogy, and representation. Recounting the history of an area in narrative form uses natural language to order the sequence of geological events and leverages human experience that earlier events can influence later events but not vice versa. Analogies and metaphor bootstrap understanding of the unfamiliar by comparing it with the familiar; for example, the incomprehensibly slow deformation of rocks is explained by analogy to the not-quite-so-slow deformation of warming butter, or the vastness of geologic time is explained by analogy to a line of pennies twice circling the Earth (Cervato and Frodeman, this volume).

The classic representation for helping students grasp the sequence, subdivisions, and scope of geological time is the time line. Fenton's commentary (this volume) paints a vivid word picture of middle school students attempting to squeeze the duration of human civilization onto a 4.5-m-long paper strip on which each millimeter represents a million years of Earth history. Resnick et al. (this volume) caution us that asking students to use a space to represent time is cognitively challenging because temporal and spatial scales are psychologically segmented in different ways. To facilitate alignment of temporal and spatial scales, Resnick et al. recommend starting with smaller scales (e.g., one year to a meter) and progressively increasing the magnitude of the temporal scale (students' life span to a meter, human history to a meter, Earth history to a meter).

This Special Paper adds several new pedagogical strategies. Resnick et al. (this volume) review for the reader the cognitive science finding that the human mind tends to conceive of time as a sequence of "events," each characterized by a beginning, and an end, and an intervening interval of relatively constant or predictable phenomena. Moreover, humans tend to organize such psychological "events" in a multilevel hierarchy, with temporally shorter events nested inside longer events. Resnick et al. point out that the traditional geological time scale is organized in exactly this psychologically favorable structure: intervals of relatively predictable circumstances, bounded by beginnings and ends, across which change is rapid and conditions are unpredictable, nested into a hierarchy. They recommend leveraging this hierarchy of events in teaching, for example, by emphasizing how common characteristics hold together epochs within periods within eras within an eon.

The final pedagogical strategy in the concept map is diachronic thinking. We already encountered this idea in the techniques quadrant as the cognitive underpinning for relative dating. Dodick (this volume; Dodick and Orion, 2003b) shows that this idea can also be used to design instruction, as in the GeoTAT "Puzzles" (Dodick and Orion, 2006), which challenge students to interpret maps, cross sections, and block diagrams that have been purposely constructed to exercise diachronic principles.

Temporal Reasoning

The final region of the concept map has to do with the nature of temporal reasoning, explored in more detail in Kastens (2010b). In this quadrant, we have placed reasoning processes that geoscientists use to construct a chain of logic from evidence about time to claims about process. The reasoning by which earth scientists build the evidence about timing and sequence of events has already been covered in the techniques quadrant.

As shown by the dashed link to historical sciences, there is a continuum of historical disciplines (Frodeman, 1995; Dodick and Orion, 2003a) that range across time scales but share some common lines of reasoning. In order from longest to shortest time scales, these would include cosmology, geology & paleontology, archaeology, history, and developmental psychology. One characteristic that all of these disciplines have in common is that any specific observation or occurrence may be attributable to a combination of unchanging truths, plus the particular circumstances of the moment, plus the lingering effects of prior events.

The central cluster of temporal reasoning nodes depict four kinds of evidence that can lead to at least tentative or partial scientific claims: sequence, co-occurrence, rate, and cyclicity. Evidence about sequence constrains claims about causality: If A occurs before B, then A can cause or influence B, but B cannot cause or influence A. Evidence of co-occurrence suggests multiple working hypotheses about causality: If A and B occur at the same time, then A could cause B, or B could cause A, or C could cause both. These forms of reasoning are effective because, as explained by Resnick et al. (this volume), humans structure time into "events" (e.g., the aforementioned "A," "B," and "C") rather than as a seamless continuum of linear time.

Evidence about rate constrains claims about power. If a given phenomenon, for example, transport of a certain volume of sediment, occurred in an instant of geological time, it must have required more energy input per unit time, i.e., more power, than if the same phenomenon was spread across millions of years. As noted by Cervato and Frodeman (this volume), rates are a central research focus of the stratigraphic community today. Evidence of cyclicity favors a cyclic or repeating causal process; for example, the timing of Pleistocene glacial-interglacial cycles was a key constraint in developing a causal model based on small variations in the orbital parameters of Earth's rotation (Hays et al., 1976).

Another aspect of temporal reasoning has to do with the timing of observation versus the causative processes. One's position on this node constrains the types of reasoning that can be assembled to build the logical chain from evidence to claim. There seem to be three possibilities: In the first case, the causative processes are observable and active. The process that caused the product is active and functions on a fast enough time scale that formation or modification of the product can be observed, for example, sand ripples forming in an active tidal channel. In the second case, the causative processes are active, but too slow to observe in the field, for example, soil formation. The casual processes can be observed and measured, but accounting for the observations in their full magnitude requires a bold extrapolation across time. In the third case, the processes and circumstances that gave rise to the product or structure are no longer present or active, a situation noted on the concept map as product of prior processes. For example, a metamorphic rock at Earth's surface has been divorced from its formative temperature and pressure regime, and inferences about how it formed must be grounded in more indirect lines of reasoning.

A promising development in science education reform is an emphasis on the scientific practice of argumentation: fostering students' ability to articulate a claim about an aspect of the world, back up that claim with evidence, and construct a coherent line of reasoning to show that the evidence does indeed support the claim (e.g., Toulmin, 1958; Duschl, 2000; McNeill and Krajcik, 2007). A distinctive aspect of geoscience expertise (Manduca and Kastens, this volume) is facility with lines of reasoning that build from temporal evidence. Temporal evidence and temporal reasoning tend to suggest or favor a causal process, rather than pinpointing one and only one necessary and sufficient interpretation for a given observation. Thus, an important aspect of mastering the process of argumentation in geosciences requires learning to combine multiple sources of evidence and intertwine multiple lines of reasoning (Ault, 1998; Kastens, 2010a) to build a cumulative case for an interpretive model.

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