Building an Understanding of Geological Time: A Cognitive Synthesis of the "Macro" and "Micro" Scales of Time

Jeff Dodick Science Teaching Center, The Hebrew University of Jerusalem, Givat Ram, Jerusalem, Israel 91904

Nir Orion Department of Science Teaching, Weizmann Institute of Science, Rehovot, Israel, 76100

ABSTRACT

Few discoveries in geology are more important than geological time. However, for most people it is impossible to grasp because of its massive scale. In this chapter we offer a solution to this problem based on our research in cognition and education. Our strategy involves the decoupling of geological time between the macro-scale of "deep time which includes the major features of earth history, and whose research we call event-based studies, and the micro-scale of relative time represented by strata, whose research we term logic-based studies. Our event-based study focuses on the problem of learning about macroevolution within the massive time scale of the fossil record. We approached this problem by creating a four-stage learning model in which the students manipulate a series of increasingly complex visual representations of evolution in time. Post program results indicate that students had a better understanding of macroevolution as seen in the fossil record; moreover, they appreciated that different events in absolute time required different scales of time to occur. Our logic-based studies used Montagnero's diachronic thinking model as a basis for describing how students reconstruct geological systems in time. Using this model, we designed three specialized instruments to test a sample of middle and high school students. Our findings indicated that there were significant differences between grade 9–12 and grade 7–8 students in their ability to reconstruct geological systems. Moreover, grade 11-12 geology majors in Israel had a significant advantage over their non-geological counterparts in such reconstruction tasks.

Keywords: Geological Time, relative time, diachronic thinking, absolute time, scale.

INTRODUCTION

Geology has provided science with two paradigms which rival the revolutionary discoveries of the quanta in physics and the uncoiling of the DNA helix in biology-plate tectonics and geological time. The former, a discovery of the late 19^{th} and 20^{th} centuries, forever banished the picture of a static earth, replacing it with a vision of a world composed of drifting continents. It is discussed in detail in another chapter of this book. The second paradigm, the discovery of geological time has scientific roots which extend back to the 18^{th} century, in the work of James Hutton who discarded the "comforting" image of a world that was separated by a mere 6000 years from its creation (and creator) to one in which "we find no vestige of a beginning and no prospect of an end" (Hutton, 1788, p. 304).

The revolution of geological time is important to science because of its influence not only upon geology, but many scientific disciplines including paleontology, evolutionary biology, and cosmology, all of which are constrained by large-scale temporal processes. Thus, any student or practitioner that wants to build an understanding of such fields must do so within a framework of geological time.

Yet to grasp, what John McPhee (1980) has poetically termed "deep time" is no easy task. Human beings are limited to a lifetime that will allow them to see (with good health) the passage of three generations, not nearly the time needed to psychologically encompass 4.6 billion years of earth history. Thus, the question remains as to how it might be possible to understand (and accept) the vastness of geological time and the events which have shaped our planet. The purpose of this chapter, therefore is to offer solutions to this problem, based on our experiences as both scientists and researchers in science education. Using the tools of cognition and education, we will discuss a series of studies that we have completed which define the factors affecting students' ability to understand changes to the earth in the framework of "deep time", as well as possible directions for future research. By doing this, we hope to contribute to a better understanding about some of the reasoning processes used in geology, and thus, provide conceptual tools that might help geoscience educators improve their practice.

Previous Research on the understanding of Geological time

Despite, the critical importance of geological time, there has been relatively little attention given to it by researchers in the field of cognition or science education. The small amount of research that has been completed was previously reviewed by Dodick and Orion (2003a, 2003b, 2003c) and is updated here to provide structure to the ensuing discussion; it includes two types of research: event based studies and logic based studies.

Event based studies include research that surveys student understanding of the entirety of “deep time” (beginning with the formation of the earth or the universe) and usually involves sequencing a series of bio-geological events. This is done relatively, using card-sorting tasks, or lists of such events, and sometimes includes reference to absolute time, using questionnaires and / or interviews which rely on time lines or response time-scales divided into numerical intervals. Often in such sequencing tasks, the subject is asked to justify his reasons for his proposed temporal order. Using such responses, the subjects are often profiled into categories, which represent their knowledge, and misconceptions about relative and absolute time. The small number of event based studies can be classified according to their demographic breakdown and include:

Noonan and Good’s (1999) research on middle school students' understanding about the origins of earth and life; a similar study by Marques and Thompson (1997) with Portuguese students in elementary and middle schools; and Trends’ studies respectively on the conception of geological time amongst 10-11 year old children (Trend, 1997; 1998; 2001c; 2002), 17 year olds (Trend, 2001b; 2001c; 2002) as well as amongst primary teacher trainees (Trend, 2000; 2001c; 2002), and teachers (2001a; 2001c; 2002). Most recently, research has focused on university students and includes White’s (2004) time line study with 71 students in an entry level geoscience course, as well as the work of Libarkin and Kurdziel (2004) and Libarkin et. al. (2005) which classify college students’ ontological perspectives towards geological time.

Although it is difficult to compare such studies, as most used different research protocols, the findings do show that all of the samples tested had difficulties with sequence, assigning absolute dates, as well as scaling events on a time-line. Qualitatively, however, these difficulties do appear to lessen with the increasing age of the subjects who participated in these studies.

The second type of research, the logic based study is based on the logical decisions that students apply to the ordering of geological / biological events as seen in stratigraphic layers (using basic principles of relative dating). Two studies of this type are found in the literature: Chang and Barufaldi (1999) examined the effects of a problem-solving-based instructional model on their subjects’ (9th grade students in Taiwan) achievements and alternative frameworks. In their research, they used a questionnaire which contained visual problems testing the ability to reconstruct depositional environments. In contrast, Ault (1981) interviewed a group of students (grades K-6) using a series of puzzles testing how they reconstructed geological strata. Based on Zwart's (1976) suggestion that the development of temporal understanding lies in the "before and after" relationship, Ault (1981; 1982) theorized that young children organize geological time, relationally. Using these results, Ault (1981) claimed that the young child's concept of conventional time was no impediment towards his / her understanding of the geologic past. Nonetheless, although many of the children in Ault's (1981) study were successful at solving his interview problems, these same subjects had difficulties in solving similar problems in the field, indicating that there was little transfer from the classroom to authentic geological settings.

These difficulties can be traced to Ault's (1981) research design, which, influenced as it was by Piaget's (1969) previous work, included physics-based problems which associate time conception with the understanding of velocity, motion and distance. However, geology largely builds its knowledge of time through visual interpretation of **static** entities, such as strata (Frodeman, 1995; 1996), which represent previously dynamic systems. Ault's (1981) design multiplied the variables that he needed to explain, as he admitted in a later work (Ault, 1982). Further, it did not focus its efforts on the special qualities of geological time (such as its enormous scale) that might complicate a young child's thinking.

This argument is supported by research in psychology. Both Friedman (1978) and Harner (1982) note that it is not until around age 14 that children begin using time concepts such as century, generation and forefather. Thus, it is unlikely that the children studied by Ault (1981; 1982) would have had a deep understanding of absolute geological time.

Indeed, there is no reason to suggest that understanding the relationships amongst strata should necessarily allow one to conceptualize the massive scale of geological time. Thus, we argue that that the understanding of relative and absolute time can be studied, and taught, respectively, as separate entities (Dodick and Orion, 2003a; 2003c). In the earth sciences this is common, as geologists do not necessarily need to apply both relative and numerical dating methods to a given collection of strata in order to date them.

In addition to the studies noted above, we note the small body of research that catalogues general ideas about the earth, including problems related to geological time (Happs, 1982; Marques, 1988; Oversby, 1996; Schoon, 1989; Schoon 1992). The problem with such studies is that they do not provide a cognitive model of student understanding of geological time.

Finally, one might mention those works within geological education which have concentrated on the practical elements of teaching geological time (Everitt, Good and Pankiewicz, 1996; Hume, 1978; Metzger, 1992; Miller, 2005; Nieto-Obregon, 2005; Reuss, and Gardulski, 2001; Ritger and Cummins, 1991; Rowland, 1983; Spencer-Cervato and Day, 2000; Thomas, 2005). Unfortunately, most of these teaching models have never been formally evaluated, so it is difficult to attest to their effectiveness. Nonetheless, Ritger and Cummins' (1991) approach does show promise as it emphasizes a constructivistic approach in which the student builds a "personal metaphor" of geological time permitting him to structure this abstract concept based on his own criteria. Moreover, the interactive game approach designed by Reuss and Gardulski (2001) for their course in Historical Geology received very high ratings by the undergraduates who participated in this course.

In this chapter, we discuss our research (Dodick and Orion, 2003a; 2003b; 2003c) in which we define some of the problems faced by middle and high school students in understanding geological time. The goal of this work was to devise effective strategies for helping students interpret the fossil record. Thus, our research focused on the cognitive skills that are required for understanding evolution and environmental change over time. Rather than a concept in of itself, geological time is often referenced within the context of historical sciences such as paleontology, archeology, or geology, so it was felt that contextualizing geological time would provide a better indication of the students' understanding of this concept, while also permitting us to apply the results towards improving our curriculum development efforts. Indeed, much research supports such situated cognition.

This research follows the taxonomy of event-based and logic-based studies proposed above. In doing this, we hope to build a synthesis of the larger "macro" (event based studies) and smaller "micro" (logic based studies) scales of geological time.

PART 1: UNDERSTANDING EVOLUTIONARY CHANGE WITHIN THE FRAMEWORK OF "DEEP TIME"-AN EVENT BASED STUDY

Macroevolution, (i.e. evolution above the taxonomic level of species) takes place in geological time. However, as Dodick and Orion (2003b) have shown, most curricula, as well as education research connected to evolutionary biology ignore macroevolution, and have largely concentrated on the mechanisms of microevolution. Thus, in this study, we focused on a learning strategy that was designed to overcome students' difficulty in understanding the massive absolute scale of geological time, as it applies to macroevolution as witnessed in the fossil record. This strategy was employed in the Israeli high school program ***From Dinosaurs to Darwin: Evolution from the Perspective of Time*** (Dodick and Orion, 2000).

METHOD

To evaluate this learning strategy, we focused on an in-depth case study involving the implementation of this program amongst a single high school class, consisting of 22 earth sciences students, with little background in biology, in an urban high school in Israel. (Our intention is to expand this research with a larger sample of high school students). This class was chosen for implementation because the subject of this curriculum expanded on a required element of their earth sciences program, "History of the Earth" (focusing on the physical changes affecting the development of the earth over the vast span of geological time).

The subjects of this study were evaluated both prior to, and following the learning of the program with two questionnaires:

1. Geological Time Assessment Test (***GeoTAT***): a validated questionnaire containing a series of cognitive puzzles testing the students' ability to reconstruct depositional systems in time.
2. Macroevolution knowledge questionnaire which tested both the students' understanding of (macro) evolution, as well as absolute time. Thus, one of the tasks was for students to sequence major events in the fossil record on a numerical time line similar to the work of White (2004).

In addition, the first author was present at all sessions of this program to observe the students, and interview them as they proceeded through the activities.

EVALUATION

Briefly, the program ***From Dinosaurs to Darwin*** is divided into three units:

1. **Materials in time:** This unit deals with the basic materials of the fossil record and the principles of relative dating that permit scientists to understand their temporal relationships. This unit includes fieldwork in which the students reconstruct the depositional history of Mahktesh Hatira, a natural crater in the north-central Negev region of Israel.
2. **Evolution and the fossil record:** This unit is concerned with modelling the adaptive radiation of organisms in the context of absolute geological time.

3. **Independent project:** in which the students investigate evolutionary aspects of the fossil record (ex: the evolution of flight).

It is in the second unit that we employ the strategy of fusing evolution and the massive scale of geological time. This consists of four activities in which the guiding principle is to shape the students ability to manipulate multiple (iconographic) representations of evolution in time, while at the same time introducing the concept of absolute time. According to Kozma, Chin, Russell and Marx (2000) the ability to interpret (scientific) representations is critical to professional scientists, as it allows them to organize information into conceptually meaningful patterns. Further, they argue that if science students are to pursue inquiry-based problems, a fundamental goal of science education (American Association for the Advancement of Science, 1990, 1994; National Research Council, 1996, 2000) they must also obtain such interpretation skills. In their research, they have shown that chemists have a set of representational skills central to their research. These skills allow them to move flexibly between different types of representations so that they may better understand their domain. Similarly, paleontologists must mediate between different sets of representations, including phylogenetic trees, cross-sections, and anatomical figures to solve specific problems.

In the second unit, students experiment with some of these representations to learn how professional scientists transform concrete field-based information to a three dimensional picture of evolution. As the material is conceptually new, we have scaffolded the investigations into a four-stage model linked by a series of bridging questions. These questions were worded so that the students could critique the models that they design at each stage of the unit, while linking them to the next iconographic model. Thus, they build parallel conceptions of macroevolution which are nested within the scale of absolute time.

Stage 1: The "infamous ladder of progress" (Gould, 1989; 1995)

Although most biology and earth science textbooks deal with evolution, they sometimes unintentionally mislead students by using representations which treat evolution as a linear progression in time from prokaryotes to man, and thus, perpetuate the misconception that the history of life represents progress from primitive to complex. Moreover, because they isolate single groups of life (for example, fish which evolve prior to amphibians) in this temporal progression, students inadvertently construct a second misconception, that one form of life replaces another in time. (Indeed our research confirms this assertion).

Gould (1995, p. 252) in his essay "Evolution by Walking" notes a similar trend in the way fossils are displayed in many museums of natural history:

> In other words, temporal order is not construed as a set of representative samples for all animal groups through time, but as a sequential tale of most progressive at any moment, with superseded groups dropped forever once a new 'ruler' emerges even though the old groups may continue to flourish and diversify.

It is possible that this misconception is enhanced by the iconography of geology itself. A predominant representation in earth science textbooks is the cross-section. If fossils are illustrated within the section, they often show supposed progression from "primitive" (at the bottom) to "complex" (at the top) life forms. Moreover, many students who understand the principle of superposition will naturally assume this progressive trend. Thus, it was important that we design activities that would counteract this misunderstanding.

In the first activity of this unit, students participate in an activity titled, "Fossils and Rocks: A Detective Puzzle". This activity is a large-scale problem in biostratigraphic correlation, in which the students construct a cross-section consisting of 27 events representing the key evolutionary features of earth history (which were based on a survey of textbooks and interviews with earth scientists and biologists).

At the beginning of this investigation, they receive a set of nine cross-sections (representing geographically distinct sites) divided into five strata, each containing a different assemblage of fossils representing a key feature of the fossil record. After completing the correlation, the students list the key features of the fossil record (from oldest to youngest), based on their position relative to other key features, and place them into a table containing absolute dates for each of the key features.

After completing this unit, the students significantly improved their ability to correlate strata. Pre program they scored 67.8%; post program their scores improved to 81.1% indicating that they had grasped the mechanics of stratigraphic correlation. Note, that the student built cross-section indeed anticipates the misconception of "the ladder of progress". Thus, immediately after completing this activity, the students are confronted by two bridging-questions which challenge this misconception. The first asks for a critique of this representation as an "image of evolution in time", whereas the second asks them to suggest a better representation. To the former question, students noted many of the difficulties previously mentioned. In fact, some noticed these problems without being prompted. To the latter question, most suggested a branching tree-like icon, as it better represents evolutionary relationships, parallel development of different lineages and extinction. Post program, students recognized the superiority of this icon (pre scores = 22.2% and post scores = 55.6%); more importantly they could also cite reasons for its superiority (pre scores = 16.7% and post scores = 58.3%).

Stage 2: Evolutionary Relationships in Time

The second stage is connected to the first by requiring the students to build the preferred icon of evolution in time, the evolutionary tree. To complete this activity, the students completed group reports on a select number of key features of the fossil record (using MacDonald's (1989) method of small group oral presentations) in which the class builds a simple phylogenetic tree.

Our strategy is that while building their phylogenetic tree, the students construct an association between biological events and geological time periods. This strategy is based on research in psychology which indicates that one of the symbolic modes involved in representing conventional time systems (such as days of the week) is the associational network (Collins and Loftus, 1975). For example, Friedman (1982, p. 182) argues that individual months are recognized by their linkage with "numerous personal or shared propositions (e.g. my birthday, cold, Halloween, etc.)". So too, it might be possible to understand geological time by associating specific time periods with key evolutionary events.

Central to this learning strategy is that fossils are rich visual evidence for evolutionary change in time. In their studies of historical understanding amongst grade 5 children, Barton and Levstik (1996) and Levstik and Barton (1996) concluded that using visual images with a variety of chronological clues stimulated a greater depth of historical understanding than mere verbal description. So too, fossil materials, representing key events in life’s history, act as a concrete organizer to bridge over the abstract difficulties of evolutionary change in time.

Stage 3: The Scales of Time

A critical element in this unit was developing a sense of “deep time”, the understanding that man’s dominion is confined to the last microseconds of the metaphorical geologic clock. Previous efforts at teaching this concept have focused on constructing a single metaphor which might help the student build a perspective of the scale of geological time (Everitt, Good and Pankiewicz, 1996; Hume, 1978; Metzger, 1992; Nieto-Obregon, 2005; Ritger and Cummins, 1991; Rowland, 1983; Spencer-Cervato and Day, 2000).

The difficulty with these approaches is that by scaling all bio-geological events to the same timeline, students lose site of man's relation to geological time. Instead, we have the students compare six different time scales, geological time (4.6 Ba), biological time (3.8 Ba) fossil time (530 Ma), human evolution (2 Ma), civilization (5000 years), and personal time (75 years). The advantage is that students realize that different (historically constrained) disciplines, including the earth sciences, archaeology and history, by necessity, operate on different scales of absolute time, which at the same time often dwarf the human life span.

Post program, most students improved their ability to assign absolute dates to a variety of (well known) evolutionary events such as the beginning of life. More difficult, was plotting these events on a scaled time line, especially at its terminal end, as represented by events such as the appearance of dinosaurs or hominids. As with White's (2004) study of undergraduates, as well as Noonan and Good's (1999) work on middle school students, the tendency here was for the students to strongly overestimate the absolute age of these events on a timeline.

Nonetheless, although the students did not accurately date these events on the time line, they did get closer to the correct figures, post program; simply put, they reduced their overestimation. This suggests that the strategy of associating evolutionary events and their chronology is fundamentally sound. Moreover, students were more successful in understanding the chronology of events they had personally researched in their group projects.

Stage 4: The rates of evolution

Having completed the third stage, the students had a better understanding of the enormous scale of geological time, although problems remained. For this reason, we added a further representation of time. As this curriculum's focus is evolution, we thought it best to add another temporal criterion, that much of the development of life, as seen in the fossil record, has occurred in the last 530 million years of the geological time scale, beginning with the "Cambrian Explosion" (Gould, 1989). This represents a mere 11% of all geological time. (In fact, cellular life began 3.8 billion years ago; however the fossil record is biased towards post Cambrian events, because it was only then that hard skeletons evolved).

Thus, in this stage, students return to the phylogenetic tree completed in stage 2 and add a scale of absolute time. As a result, they see that much of evolution is squeezed into the upper reaches of their branching diagrams (Figures 1a and 1b). Moreover, they gain a new found perspective into the antiquity (and diversity) of unicellular life, echoing the sentiments of Gould (1995, p. 252): "bacteria continue to rule the world today, as they have since life's beginnings (and will until the sun explodes)". Finally, this activity demonstrates that different organisms evolve at different rates.

Insert Figure 1 about here

Our experience has shown that linking evolution with geological time is a sound method of building an understanding of absolute time. The key to this process is in exposing students to a variety of visual representations, each of which symbolizes a different aspect of evolution in time. In this way, students have the ability to critique the representations they see, as well as build a more sophisticated understanding of an abstract subject.

PART 2: RECONSTRUCTING GEOLOGICAL AND BIOLOGICAL PROCESSES IN TIME-LOGIC BASED STUDIES

Of the literature that does deal with geological time, most of it focuses on the difficulties associated with encompassing the vast scale of “deep time”. This is usually associated with the huge time spans provided by radiometric dating techniques in the geosciences. However, geology also builds its understanding of temporal changes through individual rock layers exposed on the earth's surface. Such layers can be logically ordered using relative dating principles, many of which were formulated in Europe between the 17th and 19th centuries. Thus, in this section we discuss the research we undertook to cognitively model the strategies that middle school and high school students use to reconstruct depositional sequences over time (Dodick and Orion, 2003a; 2003c).

BACKGROUND

Scientific skills are usually acquired after a long process of study and use of such skills that are situated in their natural environment. However, our research has shown that even students untutored in geology can apply some of its formal principles for reconstructing sequences of strata. They can do this because the structure of such principles is similar to Montangero’s (1992; 1996) model of ***diachronic thinking,*** the capacity to represent transformations over time. Montangero’s (1996) model defines the structural and functional entities that are activated when diachronic thinking is used. He tested this model by asking children aged 7-11 to reconstruct the time-based changes which affected phenomena they recognized from their daily lives, such as a tree’s life cycle. Based on these arguments, we suggest that students might also be able to transfer this natural talent in diachronic thinking to the more specialized scenarios of a depositional system (Dodick and Orion, 2003a; 2003c).

Montangero’s (1996) model consists of four schemes, which permit a subject to think diachronically. As part of our research, these schemes were translated into the specific principles that geologists use to reconstruct stratigraphic sequences. This correlation between Montangero's schemes and geologic principles was first presented in Dodick and Orion (2003a; 2003c) and is repeated here for clarity (Table 1).

Insert Table 1 about here

The factor limiting a subject’s ability to activate these schemes is his knowledge of the phenomenon; in his work, Montangero (1996) delineated three different types of knowledge which are important for activating the diachronic schemes. The following two knowledge factors are most important for understanding geological transformations:

1. Empirical knowledge: Knowledge of transformations derived from personal experience or from the influence of specific cultural representations. Thus, if students do not know that limestone is composed of reef dwelling organisms that lived in shallow water, they may not be able to reconstruct its full depositional history.
2. Organizational knowledge: Understanding of dimensions (numbers, space and time) as well as causal relations. Unlike novices, experienced geologists understand that the numbers of layers and outcrop size are not usually related to their absolute age.

METHOD

We used a combination of qualitative (interviews, observations in class and field) and quantitative (open questionnaires) methods to fully expose the strategies that our research sample used to temporally reconstruct depositional systems. The quantitative instruments included three questionnaires:

1. ***GeoTAT*** (Geological Time Aptitude Test):

The ***GeoTAT*** served a two fold purpose in this research: (i) to determine the factors which affect students' ability to temporally reconstruct a depositional system; (ii) to test how learning geology contributes to a student's ability in reconstructing depositional systems. The former study relied on a cross-sectional sample of 285 students in grades 7-12 none of whom had studied geology (designated **NGS**). The latter study compared two samples of grade 11-12 students: 54 who were studying geology (designated **GS**) and 98 **NGS**. (Note that in grades 11-12 in Israeli schools, students "major" in different subjects such as geology).

The ***GeoTAT*** can be divided into three sections. (Please see the Appendix for the ***GeoTAT***):

a. Puzzles (6a and 6b) which require the use of the single diachronic scheme of *transformation* (without reference to the other two diachronic schemes). This corresponds to the geologist's use of "actualism".
b. Puzzles (1a, 4, 5) which require the use of the single diachronic scheme of *temporal organization* (again, without reference to the other two diachronic schemes). These puzzles rely on the geological skills of superposition, correlation and bracketing.
c. Puzzles (1b, 2, 3a, 3b, 6c) which entail an integrated use of three diachronic schemes (*transformation, temporal organization and interstage linkage*). Geologically these puzzles required the use of a combination of skills including "actualism", superposition, and causal thinking.

2. ***TST*** (Temporal-Spatial Test):

This instrument combined four selected puzzles of the ***GeoTAT*** and seventeen selected puzzles from the ***MGMP*** (Middle Grades Mathematics Project) Spatial visualization test (Ben-Chaim, Lappan, and Houang, 1986; 1988). Its purpose was to determine if the ability to temporally order strata is influenced by spatial-visual ability. Product moment correlation coefficients were calculated for the entire ***GeoTAT*** and its individual puzzles against the ***MGMP***. It was distributed to 172 **NGS** in grades 10-11.

3. ***SFT*** (Stratigraphic Factors Test):

This test consists of three pairs of three-dimensional representations of outcrops that differed in overall size and / or numbers of layers. The test subjects were required to estimate which outcrop in a pair was older, while justifying their reasons. It was distributed to 52 **GS** in grades 11-12.

RESULTS AND DISCUSSION

Table 2 presents a cross-sectional comparison of the grade 7-12 **NGS** sample on the ***GeoTAT***. The numbers of the puzzles can be matched with the test which is presented in Appendix 1. Note that Table 2 lists the diachronic schemes, as well as the corresponding geological skill required to solve each puzzle. One-way ANOVA was used to determine if there was any difference whatsoever amongst any of the grade means scores for each ***GeoTAT*** puzzle. If such a difference did exist, then Duncan's new multiple range test was used to determine (post-priori) how each of the 6 grades (7-12) differed specifically for each of the puzzles (Huck, Cormier and Bounds, 1974). In other words Ducan's test checks all possible combinations of differences (whether significant or not) amongst the different grades. All differences in the Duncan's test were evaluated at a significance level of $p<0.05$. In reading

Duncan's new multiple range test in Table 2, the mean grade scores were arranged in order on the basis of the size of the means. Moreover, all grade levels that come before a "greater than sign" (>) achieved scores that were significantly larger than the scores achieved by the grades that come after this sign, whereas all grade levels separated by "commas" did not achieve scores that were significantly different.

Insert Table 2 about here

Generally, these data show an age trend in that 6 of 10 puzzles of the ***GeoTAT***, show a significant difference ($p<.05$) respectively, between grade 9-12 students and grade 7-8 students. In other words, the grade 9-12 students were significantly better at activating the diachronic schemes when confronted by problems in depositional history. Thus, to improve middle school students' abilities in reconstructing geological systems, programs in earth sciences should focus on enhancing their natural ability to think diachronically.

In addition, when comparing the Grade 11-12 **GS** against their **NGS** counterparts, we found that the former group held a significant advantage over the latter group in solving temporally constrained problems in stratigraphy (Dodick and Orion, 2003c). This advantage was strengthened in grade 12, by which time the **GS** had accumulated many hours in the field.

We will now present a more detailed analysis of the specific factors that were critical for students of differing grade (7-12) and skill (**GS** vs. **NGS**) level in solving the ***GeoTAT*** puzzles. The framework that was used to analyze the results of this research was rooted in Montangero's (1996) diachronic thinking model, which was modified by the authors (Dodick and Orion 2003a) for this research and is presented here to aid in this discussion (Figure 2).

Insert Figure 2 about here

Transformation Scheme

The transformation scheme was a key element for both **GS** and **NGS** in solving the ***GeoTAT*** puzzles. This is due to the fact that if the subject does not recognize that a change has taken place, such as the alteration of rock or fossil types in adjacent strata, he will not activate the other diachronic schemes. In turn, to activate the transformation scheme, the subject must be able to link his empirical knowledge of present-day phenomena with the past, based on the geological principle of "actualism" (see Table 1). Even the youngest subjects (grade 7) in our studies were able to use this principle, given the proper trigger (even if they could not articulate this principle). Thus, a question for future research is the age limit for applying actualistic thinking. This is significant for science education as this form of analogy is a basic reasoning pattern of many sciences.

Temporal Organization Scheme

The most easily applied diachronic scheme for all subjects (**GS** and **NGS**) in this research was temporal organization. This result is somewhat misleading, however, in that four of the five integrated diachronic puzzles in the ***GeoTAT*** contained undisturbed, horizontal strata that permitted temporal ordering using superposition. In fact, Ault (1981) demonstrated that young children in grade 2 could reliably order strata using this principle, so this result was not surprising.

The one integrated diachronic puzzle in the ***GeoTAT*** (1b) that contained folded layers, received the lowest scores amongst the **NGS** because many of the subjects could not apply a necessary second principle of geology, original horizontality (even when it was provided as a direct clue) which would have helped them solve this puzzle's depositional history. In other words, the students were unable to reconstruct how the originally horizontal layers became folded. This therefore inhibited their ability to solve the other diachronic schemes in this puzzle. The **GS** with their experience in both class and field had a clear advantage and did significantly better on this question than the **NGS** at both the grade 11 and 12 levels ($F = 15.43$, $df = 99$, $p < .001$) based on a two way ANOVA (Dodick and Orion, 2003c).

This leads to the question of the origin of a young student's understanding of geological superposition. Based on Zwart's (1976) argument that a child's temporal understanding is derived from the "before and after" relationship, Ault (1981) suggested that ordering geological layers via superposition is an advanced application of this relationship, serially applied to outcrops. Research has shown that children as young as three years in age verbally understand "before and after" (Stevenson and Pollitt, 1986; Harner, 1982); nonetheless, does this verbal understanding translate to a visual interpretation of strata?

A further question concerns students' ability to reconstruct tilted, folded, or crosscutting strata. Three lines of evidence suggest that this can be learned in the middle school years. Our research has shown that students in grade 9 with no background in geology could spontaneously order the fossil contents of folded strata. In other words they ignored the misleading clues of relative height of fossil contents and instead relied on the relationship of the strata itself. Moreover, observations on middle school children (grade 7-8) participating in the Israeli curriculum ***The Rock Cycle*** show that they could reconstruct tilted strata (although this ability has not been tested formally). Finally, Chang and Barufaldi (1999) indicate that grade 9 students in Taiwan (after completing a problem-solving unit in the earth sciences) could solve stratigraphic problems involving crosscutting relationships. However, the question remains whether even younger students could handle such material. Moreover, will such talent on written tests be transferred to the field?

Turning to stratigraphic correlation, we found that it was more difficult to do than superposition because it requires a three dimensional strategy incorporating both superposition and translation between different localities. This difference in difficulty is mirrored in history; the principle of superposition was elucidated by the Danish natural philosopher Steno in the 17th century, whereas English geological surveyor William Smith only established correlation in the 1790s. This enhanced level of complexity is reflected in the fact that the scores of all of the **NGS** (grade 9-12) were lower on the correlation puzzle (5) in comparison to scores obtained on the superposition puzzle (1a). Moreover, on this same puzzle, most of the grade 7-8 **NGS** failed to translate across outcrops and relied strictly on a strategy of superposition, and hence received lower scores.

Our research shows that it is possible to teach correlation effectively in both class and field in both middle and high schools. This is due to the fact that we found significant differences favoring the grade 12 **GS** over the grade 12 **NGS** ($t = 2.86$, $df = 152$, $p<.01$). Moreover, two grade 9 middle school classes saw their scores on the correlation puzzle increase significantly ($p<.05$) after completing the program ***From Dinosaurs to Darwin*** which included an in-depth activity in correlation.

Ault (1981) however, maintains that even younger subjects can correlate strata. In five of ten interviews with grade 6 students, the subjects were able to solve a simulated problem in correlation. However, this problem was easier than the example used in the ***GeoTAT***, and did not fully refer to geological correlation. Moreover, Ault (1981) noted that it was rare for students to be able to transfer such understanding to similar problems in the field.

Spatial Visual Thinking

As noted above, stratigraphic correlation employs a strategy mixing superposition and translation across different localities in search of matching fossils. This suggests that correlation places a heavier premium on spatial visual perception, as opposed to problems involving superposition alone (which only requires vertical ordering along a single outcrop).

This conjecture was tested with the ***TST*** in which Product moment correlations were calculated for four puzzles of the ***GeoTAT*** against puzzles of the ***MGMP*** spatial visualization test. The results indicated the strongest correlation between the stratigraphic correlation puzzle and the ***MGMP*** puzzles ($r = .41$, $p<.0001$) (Table 3). In other words, stratigraphic correlation seems to require the highest level of spatial visual thinking in order to temporally order its contents.

Insert Table 3 about here

This suggestion that there is a correlation between spatial visualization and temporal reasoning has a long history extending back to Kant's ***Critique of Pure Reason***. More recently, Friedman (1983, 1989, 1992) proposed that conventional time systems containing cycles, such as the days of the week are represented and manipulated by subjects older than 12 years in age, as three-dimensional positions in space. However, our research is the first to show this relationship in earth science. Nonetheless, this work has only scratched the surface of this complex connection between these two cognitive abilities; future research should investigate this effect with more complex depositional systems (such as those containing cross cutting relationships) as well as the effect of field conditions in which geological structures are often hidden. Such work could be conducted with novice geological students in high school and university, as well as with expert geoscientists.

Organizational Knowledge (layer size; rate of deposition)

A single puzzle (4) of the ***GeoTAT*** tested the students' ability to absolutely date a series of sedimentary rock exposures bracketed by horizontal layers of igneous rock. As noted in Table 2, 98% of the **NGS** failed this question, while even the majority of the **GS** had major difficulties, with only 33% of the grade 12 and 14.2% of the grade 11 **GS** successfully solving this puzzle. Surprisingly, the same mistake appeared amongst most of the incorrect solutions: the apportioning of equal amounts of time to each of the sedimentary layers. As each of the layers was equal in height on the ***GeoTAT*** puzzle, this led to the hypothesis that the students believed that the absolute age of the strata was connected to its proportional size. In turn, this suggests the additional hypothesis that students mistakenly see the process of sedimentary deposition as a linear process. These hypotheses were tested with the ***SFT*** (Stratigraphic Factors Test).

The ***SFT*** consists of three pairs of three-dimensional representations of outcrops that differ in overall size and / or numbers of layers. The task of the subjects was to estimate which outcrop in a pair was older, while providing their reasoning. The results showed that in general, the effect of size, both of the entire outcrop, and the individual layers, as well as the total number of layers strongly influenced the **GS**' understanding of absolute age. This is supported by the fact that no more than 35% of the students in any of the three ***SFT*** questions chose the correct answer for these puzzles, which is that it is (usually) impossible to estimate the age of an outcrop based on its size, or numbers of layers. Further, even when choosing this correct answer, it was rare (8%) for the subjects to give a correct reason, such as the fact that they were missing critical information, such as deposition rate.

When combined with the fact that in the ***GeoTAT***, many of the same students apportioned equal amounts of time to strata of the same height, this provides strong evidence that most students misunderstand the concept of rate in geological systems. At most, they see deposition as a process that occurs at a uniform or linear rate. In contrast, geologists know that different environmental conditions over time can significantly alter the rate of deposition. Moreover, sedimentation can cease, and erosional processes can take over leaving large temporal gaps (such as unconformities) in the rock record.

Obviously, varying rates of sedimentation complicate the understanding of deposition. However, it is a critical element that students should master if they are to have a complete understanding of deposition, and through it geological time. Rates of change are a basic concept of many scientific disciplines, both as a concrete methodological problem (measurement of rates) and as a more abstract philosophical concept (discrete vs. continuous rates of change). Thus, exposing students to rates within the earth sciences provides them with a chance to explore a scientifically universal concept.

To date, research on student understanding of rates has largely been associated with mathematics and physics education, with much of this research focused on the physical dynamics in real time of bodies in motion (Karpus, Pulos and Stage, 1983; Thompson, 1991; Thompson and Thompson, 1992). However historical sciences, such as geology, add another level of complexity, as noted in another chapter of this book by Dodick and Argamon (2005), in that its practitioners cannot directly manipulate the systems they study. Instead, the geological method permits one to reconstruct dynamic processes, such as deposition, by interpreting largely static clues, such as strata and fossils, from the past. Such clues are combined with evidence measured and observed from active earth systems today (providing that the present day conditions sufficiently match those that built the structures of the past); accordingly, geologists are then able to reconstruct geological history. This methodology differs tremendously with experimental sciences which rely on a real time strategy of manipulating independent variables and measuring such changes in dependent variables. Thus, any well thought out curriculum which teaches rates in earth systems should also include a discussion of the nature of the historical sciences.

SUMMARY: BUILDING A SYNTHESIS

Geological time is one of the foundational elements of the earth sciences as it provides a framework for organizing the events that have shaped our planet. Even the other most important paradigm in geology, plate tectonics, is only known through the changes that it has wrought upon our globe over the span of geological time. Indeed, many other fields in science are influenced by the massive temporal span provided by geological time. Nonetheless, geological time can be intimidating as it reduces man's personal (and even his own species') history to the metaphorical blink of an eye. How then is it possible to rationally accept this temporal framework that is so necessary to learning earth science?

Cognitively, our strategy involves the decoupling of geological time between the macro scale of "deep time", including as it does, the major events of earth history, and the micro scale of relative time represented by individual strata. Nonetheless, pedagogically, there is a commonality to our method, in that we try to reduce the abstract nature of these scales by contextualizing them within the concrete visual images of the earth sciences. Indeed, this method is common to many scientific concepts constrained by very large or very small scales.

In the case of the entirety of geological time, this is done via a series of increasingly complex iconographic representations of evolution in time. Using this method, students learn that different time scales are appropriate for representing different phenomena, from our planet's birth to man's evolution. Moreover, they also discover that different events develop at different rates. Such insight into differing scale and rate are not confined to geology alone; thus, investigating "deep time" serves as a starting point for discussing many other sciences, influenced by time spans of varying magnitudes.

Our strategy of reducing the abstract nature of “deep time” shows potential for helping students visualize the unseen. Nonetheless, research questions do remain, many associated with the age limits of the learner. Previous research indicates that it is unlikely that elementary school students could develop a strong understanding of "deep time". Both Friedman (1978) and Harner (1982) show that it is not until around age 14 that children develop the verbal concepts for dealing with long time spans. Thus, even when “deep time” is taught in middle school, caution must be exercised because of its enormous scale, and the numbers used to measure it. As we have noted, one way to avoid such problems is through the use of visual images containing a variety of chronological clues, as it permits students to relatively sequence such phenomena using their own knowledge, a task that is cognitively easier than simply relying on absolute dates; as we have seen, even university students when asked to provide absolute dates for events, such as the appearance of dinosaurs, on a geological timeline, greatly overestimate the age of such events (White, 2004).

A further solution is through basic research on students understanding of absolute or geochronological time. There have only been a limited number of studies concerning how students of different ages understand absolute geological time. Moreover, comparing studies is difficult because of differing research methodologies. Thus, a comprehensive survey of students from middle schools to university is required. At least one of the probes used in such research should be the student-generated timeline as used in Noonan and Good’s (1999) and White’s (2004) respective studies. Unlike verbal response scales, timelines have the advantage in that they represent sequence, scale and rate of geological time in one graphic package; thus, they more thoroughly expose underlying misconceptions. Such research can be combined with studies on students' worldview or ontological perspectives similar to those done by Noonan and Good (1999) and Libarkin et al. (2005). The purpose of such research is to classify students’ explanations about events in geological time, which can then be used to refine cognitive baselines for scaffolding learning materials.

A related problem connected to the timeline issue concerns student understanding of exponential numbers. The problem of greatly overestimating the absolute age of features in the fossil record maybe derived from the fact that massively large numbers simply have no meaning for students. Students in Israel first learn about exponents in grades 7-8, but this is no guarantee that they understand massively large exponential numbers, as seen in geological time. A survey of the research shows that there is very little research that is focused on this issue. Confrey (1991) interviewed a single undergraduate on her developing understanding of exponents using a geological time line. More recently, Tabach (pers. comm.) submitted a paper on the related issue of middle school students’ understanding of exponential growth. Thus, there is certainly room for research on the development of the understanding of exponents and their significance for geological time.

In the case of relative time, our learning strategy is to decompose the temporal complexity of geological structures via the use of diachronic schemes. Consequently, students acquire the ability to translate the static image of strata into their true nature-a transforming dynamic system. This methodology agrees with the vision of many earth science educators, who have emphasized the systemic nature of geology (Mayer et. al., 1992). An important component of systemic thinking is understanding how a system changes over time; in other words, systemic thinking demands an understanding of geological time, and diachronic thinking provides a cognitive skill that helps students reconstruct the unseen changes that affect such a system.

Diachronic thinking takes advantage of a general cognitive ability that seems to develop early in life. For this reason, this natural ability can reduce the cognitive load of students of all ages when learning about the transformation of geological systems. Moreover, since diachronic thinking is a general cognitive ability, it can be applied to a variety of time constrained systems; exposure to it within geology could better prepare students for learning about other systems in other science. Thus, again, the earth sciences can serve as an entry point to other sciences.

An important question for future research is the age limit for learning about relative geological time. Our work has shown that middle school students do develop some of the diachronic skills needed to understand some of the principles of relative dating (Dodick and Orion, 2003a; 2003c); but what about younger children in elementary school?

Montangero's (1992; 1996) studies suggest that children acquire the ability to understand transformations early in life (between ages 7-11). Moreover, Ault's (1981) research indicates that some young children (K-6) do understand principles of relative time, such as superposition. However, this question, concerning elementary students needs further study before it is validated. Ault's (1981) research was an important start, but it has methodological problems, complicating its results. Moreover, it is limited by a small sample size (40 interviews in total from a single school). To build a large statistical sample will require a quantitative instrument similar to the ***GeoTAT***, but with less complex puzzles.

This interest in younger students is not simply academic curiosity. Although a staple of many middle school curricula, the earth sciences are rarely taught in elementary schools. This is unfortunate as the earth sciences address some of the most pressing scientific problems that we face in the modern world, many of them connected to the environment. Fixing such problems can only come through an intelligent change in attitudes, and the sooner this process starts, the more likely that it will have impact. Giving students the conceptual tools to be able to interpret how the earth changes over time could lead to better environmental awareness.

Moreover, exposing young students to earth science and its historical methodology is important for broadening their understanding of science. Most young children, when surveyed about science, usually identify a scientist as "someone working in a laboratory who does experiments". Teaching about the historical, field based methods of the geosciences, including the basic principles of stratigraphy would counter this stereotype, while also providing children with an appreciation of their environment by participating in fieldwork.

Aside from age limits, another research question concerns the pedagogical effect of learning the earth sciences on students' understanding of geological time. Our research shows that experienced high school geology majors do have a significant advantage over their counterparts who lack such experience, in their ability to reconstruct geological systems (Dodick and Orion, 2003c). We suggest that the primary reason for this difference was the geological students' fieldwork experience. This is based on our observation that fieldwork provides students with a three dimensional understanding of how depositional systems change over time, in contrast to the static, flat images of textbooks. Moreover, fieldwork teaches a student about what types of evidence must be sought (and also ignored) in reconstructing a geological system. Such observations might be validated through an in-depth study of students as they solve problems in the field.

As Frodeman (1995; 2000) notes, geology has unfortunately been treated by many philosophers and scientists as a derivative science, whose methodology and logic are provided by the physical sciences. This is partly due to the fact that geology is considered by its critics to have theoretical limitations, such as the nature of geological time itself, which cannot be directly observed. This view is limited in that geological time provides a temporal framework that is critical for understanding many physical, chemical and biological processes. Moreover, many of the skills required for understanding geological time such as spatial visualization, reasoning with number, size and rate, and systems thinking, are general (cognitive) skills which can be mapped by a student onto other sciences, as well. Thus, ignoring geological time not only prevents students from appreciating the nature of the earth system, but could also impede their progress in learning other sciences as well.

REFERENCES CITED

American Association for the Advancement of Science, 1993, Benchmarks for science literacy: New York, Oxford University Press, 272 p.

American Association for the Advancement of Science. 1990, Science for all Americans: New York, Oxford University Press, 418 p.

Ault, C.R., 1981, Children's concepts about time no barrier to understanding the geologic past [Ph.D. Thesis]: Ithaca, Cornell University, 280 p.

Ault, C.R., 1982, Time in geological explanations as perceived by elementary school students: Journal of Geological Education, v. 30, p. 304-309.

Barton, K.C., and Levstik, L. S., 1996, "Back when God was around and everything": Elementary children's understanding of historical time: American Educational Research Journal, v. 33, p. 419-454.

Ben-Chaim, D., Lappan, G., and Houang, R.T., 1986, Development of a spatial visualizaton test for middle school boys and girls: Perceptual and Motor Skills, v. 63, p. 659-669.

Ben-Chaim, D., Lappan, G., and Houang, R.T., 1988, The effect on spatial visualization skills of Middle School boys and girls: American Educational Research Journal, v. 25, p. 51-71.

Chang, C.Y., and Barufaldi, J.P., 1999, The use of problem solving based instructional model in initiating change in students' achievement and alternative frameworks: International Journal of Science Education, v. 21, p. 373-388.

Collins, A.M., and Loftus, E.F., 1975, A spreading activation theory of semantic processing: Psychological Review, v. 82, p. 407-428.

Confrey, J. 1991. Learning to listen: A student's understanding of powers of ten, in von Glassesfeld, E., Radical constructivism in mathematics education: Amsterdam, Kluwer Academic Publishers, p. 111-138.

Dodick, J.T., and Argamon, S., 2005, Rediscovering the historical methodology of the Earth Sciences by understanding scientific communication styles. Submitted as a chapter for the book Cognition in Geology.

Dodick, J.T., and Orion, N. 2000, From dinosaurs to Darwin: Evolution from the perspective of "deep time": Rehovot, Israel, Weizmann Institute of Science, 128 p.

Dodick, J.T., and Orion, N., 2003a, Cognitive factors affecting student understanding of geological time: Journal of Research in Science Teaching, v. 40, p. 415-442.

Dodick, J.T., and Orion, N., 2003b, Introducing evolution to non-biology majors via the fossil record: A case study from the Israeli high school system: The American Biology Teacher, v. 65, p.185-190.

Dodick, J.T., and Orion, N., 2003c, Measuring student understanding of "deep time": Science Education, v. 87, p. 708-731.

Everitt, C.L., Good, S. C., and Pankiewicz, P. R., 1996, Conceptualizing the inconceivable by depicting the magnitude of geological time with a yearly planning calendar: Journal of Geoscience Education, v. 44, 290-293.

Friedman, W., 1978, Development of time concepts in children, *in* Reese, H., and L.P. Lipsett, L.P., eds., Advances in child development and behaviour, v. 12, New York, Academic Press, p. 267-298.

Friedman, W., 1982, Conventional time concepts and children's structuring of time, *in* Friedman, W., ed., The developmental psychology of Time, New York, Academic Press, p. 174-205.

Friedman, W., 1983, Image and verbal processes in reasoning about the months of the year. Journal of Experimental Psychology: Learning Memory and Cognition, 9, 650-666.

Friedman, W., 1989, The representation of temporal structure in children, adolescents, and adults. In Levin, I. and Zakay, D. Zakay, eds., Time and human cognition: A life span perspective: Amsterdam, North-Holland Publishing, p. 259-304.

Friedman, W., 1992, The development of children's representations of temporal structure. In Macar, F., ed., Time action and cognition: Amsterdam, Kluwer Academic Publishers, p. 67-75.

Frodeman, R.L., 1995, Geological reasoning: Geology as an interpretive and historical science: Geological Society of America Bulletin, v. 107, p. 960-968.

Frodeman, R.L., 1996, Envisioning the outcrop: Journal of Geoscience Education, v. 44, p. 417-427.

Frodeman, R.L., 2000, Shifting plates, in Frodeman, R.L., ed., Earth matters: The earth sciences, philosophy and the claims of the community: Upper Saddle River, NJ: Prentice Hall.

Gould, S.J., 1995, Dinosaur in a haystack: Reflections in natural history. New York, Harmony Books, 496 p.

Gould, S.J., 1989, Wonderful life: The Burgess Shale and the nature of history: London, W.W. Norton and Company, 256 p.

Happs, J.C., 1982, Some aspects of student understanding of two New Zealand landforms: New Zealand Science Teacher, v. 32, p. 4-12

Harner, L., 1982, Talking about the past and the future, in Friedman, W., ed., The developmental psychology of time: New York:, Academic Press, p. 141-169.

Huck, S.C., Cormier, W.H., and Bounds, W.G., 1974, Reading statistics and research: New York, Harper and Row, 377 p.

Hume, J.D., 1978, An understanding of geological time: Journal of Geological Education, v. 26, p. 141-143.

Hutton, J., 1788, Theory of the earth: Transactions of the Royal Society of Edinburgh, 1 (2), 209–304.

Karplus, R., Pulos, S., and Stage, E., 1983, Early adolescents' proportional reasoning on 'rate' problems: Educational Studies in Mathematics, v. 14, p. 219-234.

Kozma, R., Chin, E., Russell, J. and Marx, N., 2000, The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning: The Journal of the Learning Sciences, v. 9, p. 105-143.

Levstik, L.S., and Barton, K.C, 1996, 'They still use some of their past': Historical salience in elementary children's chronological thinking: Journal of Curriculum Studies, v. 28, p. 531-576.

Libarkin, J.C., Anderson, S.W., Science, J.D., Beilfuss, M, and Boone, W., 2005, Qualitative analysis of college students' ideas about the earth: Interviews and open-ended questionnaires: Journal of Geoscience Education, v. 53, p. 17-26.

Libarkin, J.C., and Kurdziel, J.P., 2004, Time is everything: Geologic time as a linchpin to a complete understanding of the earth, *in* Proceedings, National Association of Research in Science Teaching Annual Meeting, 77th, Vancouver, BC.

MacDonald, H., 1989, Small-group oral presentations in historical geology: Journal of Geoscience Education, v. 37, p. 49-52.

Marques, L. F., and Thompson, D. B., 1997, Portuguese students' understanding at age 10/11 and 14/15 of the origin and nature of the Earth and the development of life: Research in Science and Technology Education, v. 15, p. 29-51

Marques, L.F. 1988. Alternative frameworks for urban Portuguese pupils age 10/11 and 14/15 with respect to earth life and volcanoes. Unpublished masters dissertation, Keele University, U.K.

Mayer, V. et. al. 1992, The role of planet earth in the new science curriculum: Journal of Geological Education, v. 40, p. 66-73.

McPhee, J.A., 1980, Basin and Range: New York, Farrar, Straus, and Giroux, 216 p.

Metzger, E.P., 1992, The strategy column for pre-college science teachers. Lessons on time: Journal of Geological Education, v. 40, p. 261-264

Miller, M.G., 2005, Regional geology as a unifying theme and springboard to deep time: Journal of Geoscience Education, v. 49, p. 10-17.

Montangero, J., 1996, Understanding Changes in Time. Taylor and Francis: London.

Montangero, J., 1992, The development of the diachronic perspective in children, in Macar, F, ed., Time Action and Cognition: Amsterdam, Kluwer Academic Publishers, p. 55-65

National Research Council, 1996, The National Science Education Standards: Washington, D.C., National Academy, 262 p.

National Research Council, 2000, Inquiry and the National Science Education Standards: Washington, D.C., National Academy Press: Washington, 202 p.

Nieto-Obregon, J., 2005, Geologic time scales, maps and the chronoscalimeter: Journal of Geoscience Education, v. 49, p. 25-29.

Noonan, L. C., and Good, R. G., 1999, Deep time: Middle school students' ideas on the origins of earth and life on earth: Paper presented at the National Association for Research in Science Teaching Annual Meeting, Boston, MA.

Oversby, J., 1996, Knowledge of earth science and the potential for development. School Science Review, v. 78, p. 91-97.

Piaget, J., 1969, The child's conception of time: London, Routledge and Kegan Paul Publishing, 285 p.

Reuss, R.L., and Gardulski, A.F., 2001, An interactive game approach to learning in historical geology and paleontology: Journal of Geoscience Education, v. 49, p. 120-129.

Ritger, S.D., and Cummins, R.H., 1991, Using student created metaphors to comprehend geological time: Journal of Geological Education, v. 39, p. 9-11.

Rowland, S.M., 1983, Fingernail growth and time-distance rates in geology: Journal of Geological Education, v. 31, p. 176-178.

Schoon, K. J., 1989, Misconceptions in the earth sciences: A cross-age study, *in* Proceedings, National Association for Research in Science Teaching, 62nd, San Francisco, CA.

Schoon, K.J., 1992, Students' alternative conceptions of earth and space: Journal of Geological Education, v. 40, p. 209-214.

Spencer-Cervato, C., and Daly, J.F., 2000, Geological time: An interactive team-oriented introductory geology laboratory: Teaching Earth Sciences, v. 25, p. 19-22.

Stevenson, R.J., and Pollitt, C., 1986, The acquisition of temporal terms: Journal of Child Language, v. 14, p. 533-545.

Thomas, R.C., 2005, Learning geologic time in the field: Journal of Geoscience Education, v. 49, p. 18-21.

Thompson, P.W., and Thompson, A.G., 1992, Images of rate. Paper presented at the Annual Meeting of the American Educational Research Association, San Francisco, CA.

Thompson, P.W., 1991, The development of the concept of speed and its relationship to concepts of rate, in Harel G. and Confrey, J., eds., The development of multiplicative reasoning in the learning of mathematics: Albany, NY, SUNY Press.

Trend, R.D., 1997, An investigation into understanding of geological time among 10- and 11-year old children, with a discussion of implications for learning of other geological concepts, in Proceedings, Second International Conference on Geoscience Education and Training, Hilo, Hawaii.

Trend, R.D., 1998, An investigation into understanding of geological time among 10- and 11-year old children: International Journal of Science Education, v. 20, p. 973-988.

Trend, R.D., 2000, Conceptions of geological time among primary teacher trainees, with reference to their engagement with geosciences, history and science. International Journal of Science Education, v. 22, p. 539-555.

Trend, R.D., 2001a, Deep Time Framework: A preliminary study of UK primary teachers' conceptions of geological time and perceptions of geoscience: Journal of Research in Science Teaching, v. 38, p. 191-221.

Trend, R.D., 2001b, An investigation into the understanding of geological time among 17-year-old students, with implications for the subject matter knowledge of future teachers: International Research in Geographical and Environmental Education, v. 10, p. 298-321

Trend, R.D., 2001c, Perceptions of the planet: Deep time: Teaching Earth Science, v. 26, p. 30-38.

Trend, R.D., 2002, Developing the Concept of Deep Time, in Mayer, M.J., ed., Global science literacy: London, Kluwer Academic Publishers, p. 187-202

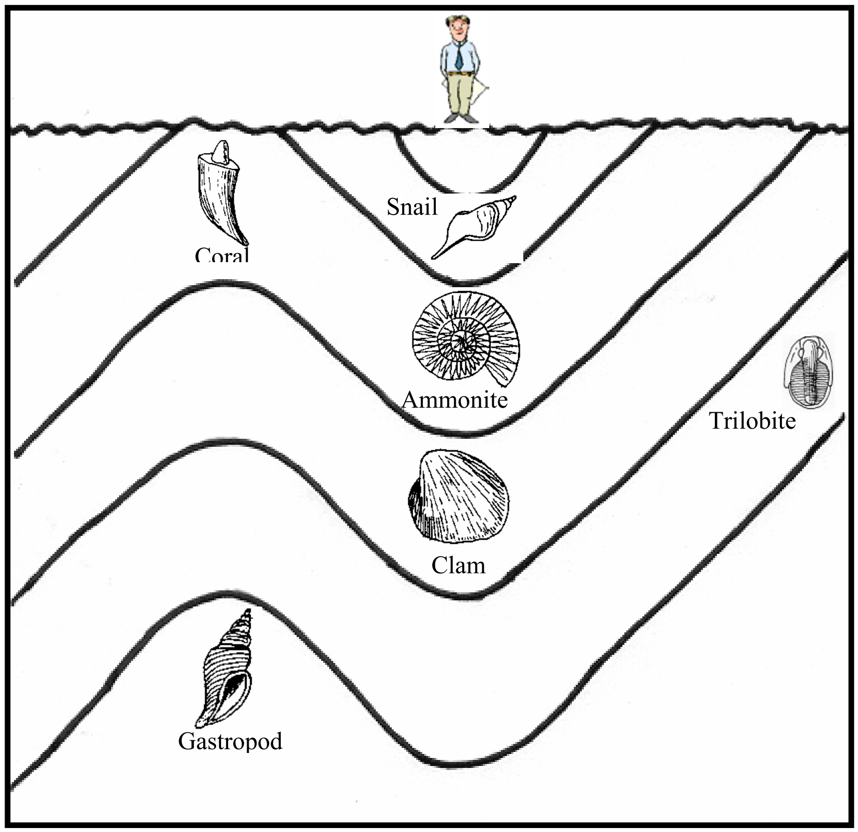
White, O.L., 2004, Analyzing college perceptions of geological time through the use of graphic timelines, *in* Proceedings, National Association of Research in Science Teaching Annual Meeting, 77th, Vancouver, BC.

Zwart, P.J., 1976, About time: A philosophical inquiry into the origin and nature of time: Amsterdam, North-Holland Publishing Company, 266 p.

Appendix

The appendix contains a complete copy of the ***GeoTAT*** questionnaire.

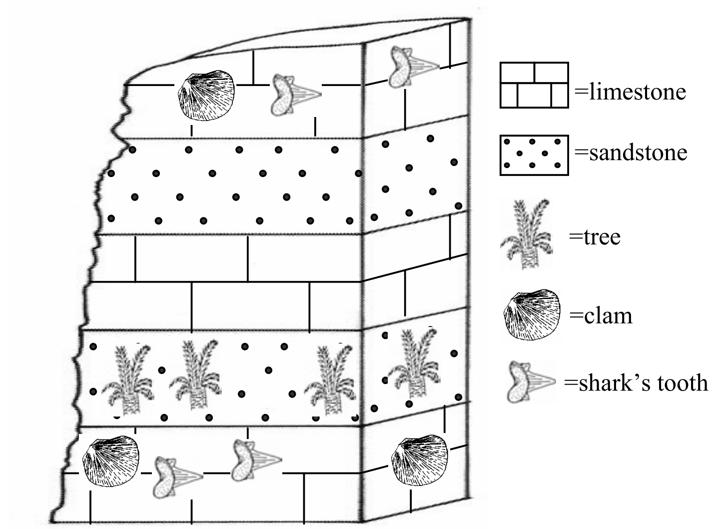
1.) The geologist in the diagram below is standing on a column of marine sedimentary rock containing fossils



*1a.) Attempt to order the fossils according to their age, from the oldest fossil to the youngest fossil. (**Clue:** marine sedimentary rock is originally deposited in horizontally lying layers).*

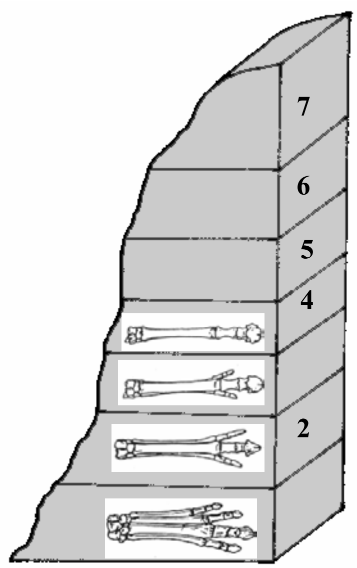
1b.) Try to reconstruct the processes, in order which lead to the creation of the rock exposure in the picture above.

2.) The illustration below represents a series of rock layers from a specific locality in the world.



Try to reconstruct the stages which created this sequence of layers based on their order of formation.

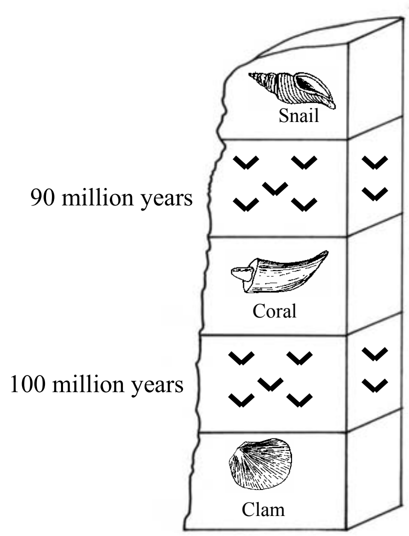
3.) The illustration below represents a fossil bearing rock exposure. The fossils are the remains of bones from the feet of unidentified species of mammals.



3a.) Try and describe the process that took place between rock layer 1 to rock layer 4.

3b.) Try to suggest 2 possible reasons for the absence of fossils after rock layer 4.

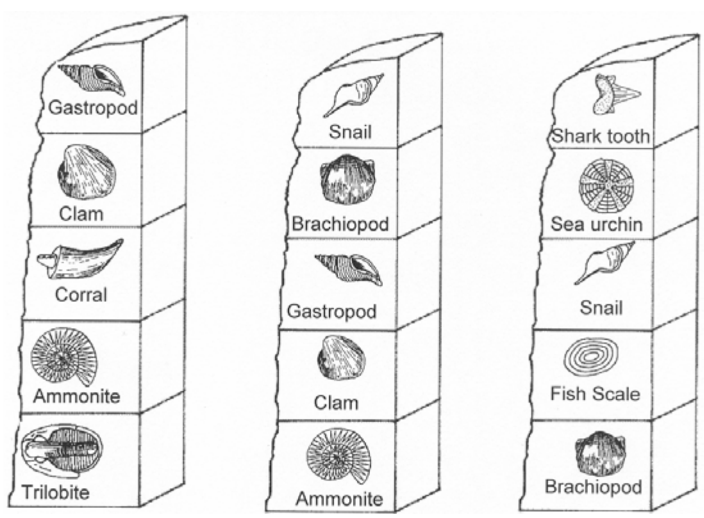
4.) The following picture represents a rock exposure that contains three types of fossils (snail, coral and clam). Two layers of igneous rocks (represented by the symbol ✓) lie between the layers containing the fossils. The age of the igneous rock layers have been determined in the lab by scientists.



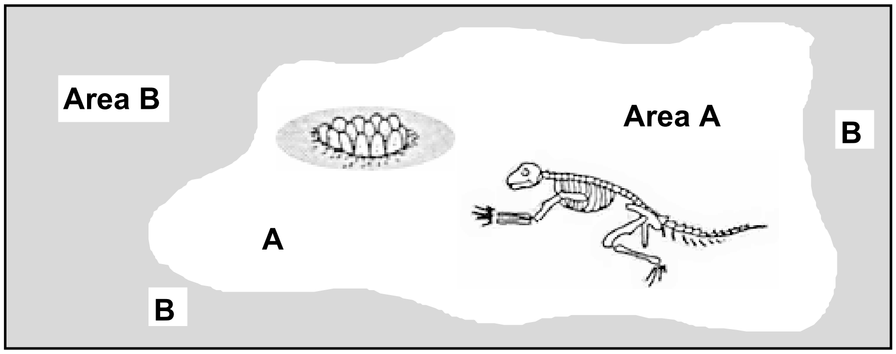
Try to determine the absolute age (in years) of the three different fossils (snail, coral and clam).

5.) The illustration below represents three rock exposures containing fossils.

Try to order the fossils according to their implied age, from the oldest fossil to the youngest fossil.



6.) The following illustration represents a dinosaur excavation site. This excavation can be broken down into two areas:



Area A:

This site is built of terrestrial sedimentary rock containing the skeletons of dinosaurs. Two important points can be noted about this area:

1. *The dinosaur skeletons excavated in this area range in size from very tiny to very large. This suggests that in this one area, the age range of the dinosaurs was broad, ranging from newly hatched babies to fully-grown adults.*
2. *In this site, a large series of nests containing fossilized eggs were discovered.*

Area B:

This area surrounds area B and is built of marine sedimentary rock containing fish.

6a.) Try to reconstruct how this looked when the dinosaurs were alive. What did areas A and B comprise?

6b.) What in your opinion might be the significance that in one single area scientists found a species of dinosaur ranging in size and age from egg to adult?

6c.) When scientists excavated this area deeply they found an alternating arrangement of layers consisting of marine sedimentary rock containing no fossils and terrestrial sedimentary rock containing fossils of dinosaurs (in the illustration below). What is the significance of this alternating arrangement of layers containing terrestrial sedimentary rock containing dinosaurs, and marine sedimentary rock without dinosaurs?

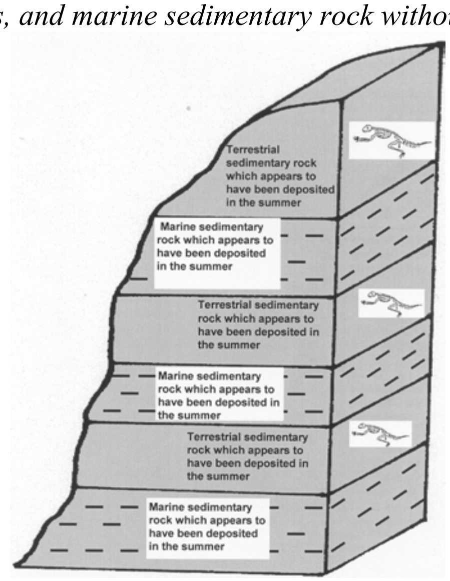


Figure 1. Illustrations of evolutionary relationships often do not add a scale of time (1a). By adding a temporal scale students see that much of the evolution of organisms with skeletons is compacted to the last 11% of time (1b). (These figures are schematic in nature and do not replicate any known phylogeny).

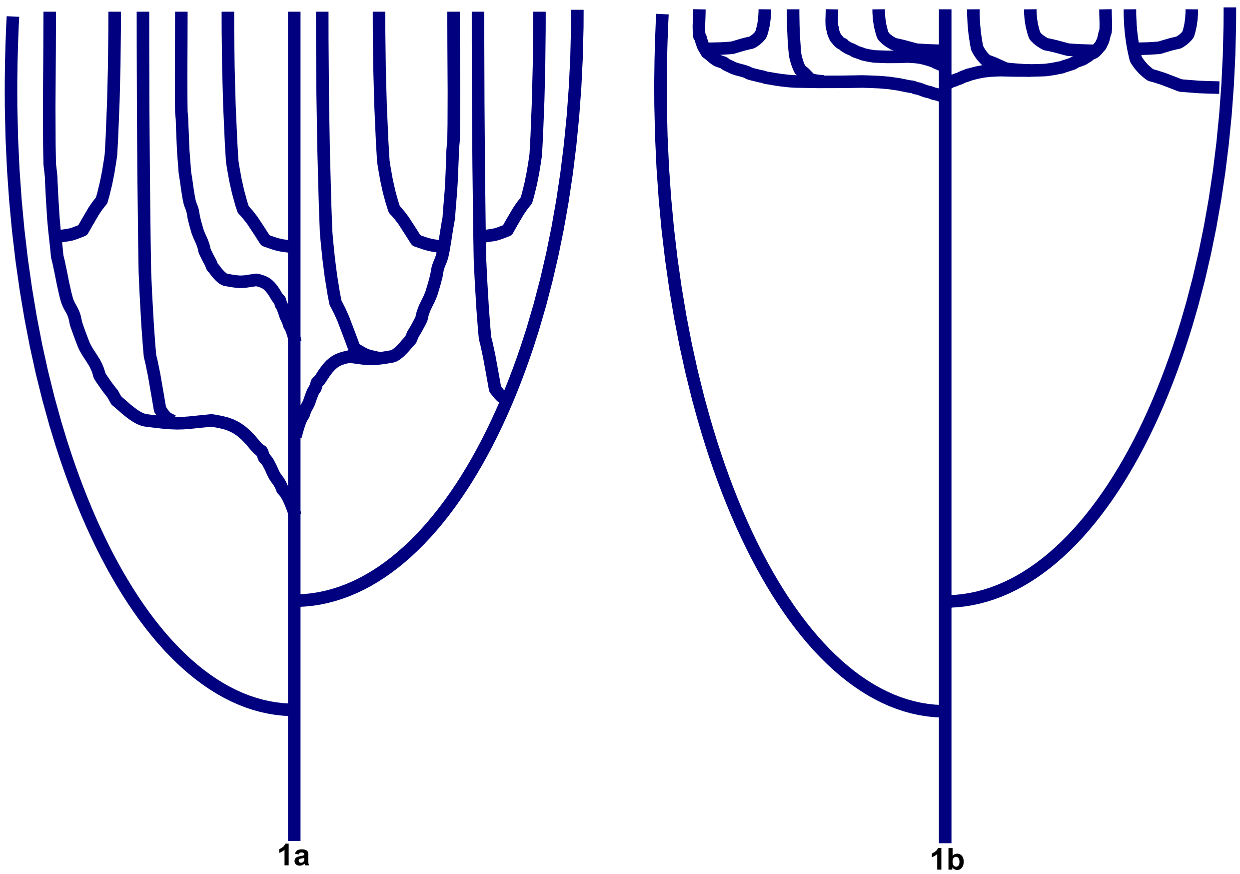


TABLE 1. DIACHRONIC SCHEMES AND THEIR GEOLOGICAL CORRELATES

Diachronic Schemes and their Explanation (Montangero, 1996)	Geological Correlate
Transformation: This scheme defines a principle of change, whether qualitative or quantitative. Quantitative transformation implies an increase or a decrease in the number of elements comprising an object, for example the changing number of a tree's leaves during different seasons. Qualitative transformations are concerned with the complexity of objects, such as the change in shape of a growing tree.	In geology, such **transformations** are understood through the principle of "actualism" ("the present as key to the past") in which geological or biological change is reconstructed through comparison with contemporary fossil and depositional environments.
Temporal Organization: This scheme defines the sequential order of stages in a transformational process, as well as the general form of the sequence of stages for example linear, cyclical etc.	In geology, principles, such as superposition, correlation, and original horizontality, all of which are based on the three dimensional relationship amongst strata are used as a means of determining **temporal organization**.
Interstage Linkage: The connections between the successive stages of transformational phenomena. Such connections are built in one of two ways: 1. Relations between necessary prerequisite and its sequel. 2. Cause and effect relationships.	In geology such stages of **interstage linkage** are reconstructed via the combination of actualism (as defined above), and (scientific) causal reasoning.
Dynamic Synthesis: Forming a whole from a set of successive stages which are thus conceived of as a manifestations of a single process of change	In geology such a **dynamic synthesis** is not a separate scheme but is rather a result of correctly activating the principles discussed previously. For this reason, this element was not emphasized in our study.

TABLE 2. CROSS-SECTIONAL COMPARISON OF THE NGS SAMPLE ON THE GEOTAT (N = 285).

Puzzle	Geological Skill(s) required	Diachronic Schemes required	Duncan (p <.05)
1a	Superposition, original horizontality	Isolated temporal Organization	11>10, 9, 12, 7, 8: 10, 9 > 8
1b	Superposition, actualistic thinking and causal thinking	Integrated use of diachronic schemes	11, 12 > 10, 9, 8, 7
2	Superposition, actualistic thinking and causal thinking	Integrated use of diachronic schemes	12, 10 > 8, 7
3a	Superposition, actualistic thinking and causal thinking	Integrated use of diachronic schemes	12, 9, 10, 11 > 7, 8
3b	Superposition, actualistic thinking and causal thinking	Integrated use of diachronic schemes	12, 11, 10, 9 > 8, 7
4	Superposition, bracketing	Isolated temporal Organization	N.A. (98% failure rate by **NGS**)
5	Superposition, correlation	Isolated temporal Organization	12, 9, 10, 11 > 8, 7
6a	Actualistic thinking	Isolated Transformation	12, 11, 9, 10 > 8, 7; 8 > 7
6b	Actualistic thinking	Isolated Transformation	11, 12, 9, 10 > 8, 7
6c	Superposition, actualistic thinking and causal thinking	Integrated use of diachronic schemes	12 > 9, 8, 7; 11, 10, 9 > 8, 7

Figure 2. A model of temporal logic in geology (based on Montangero, 1996)

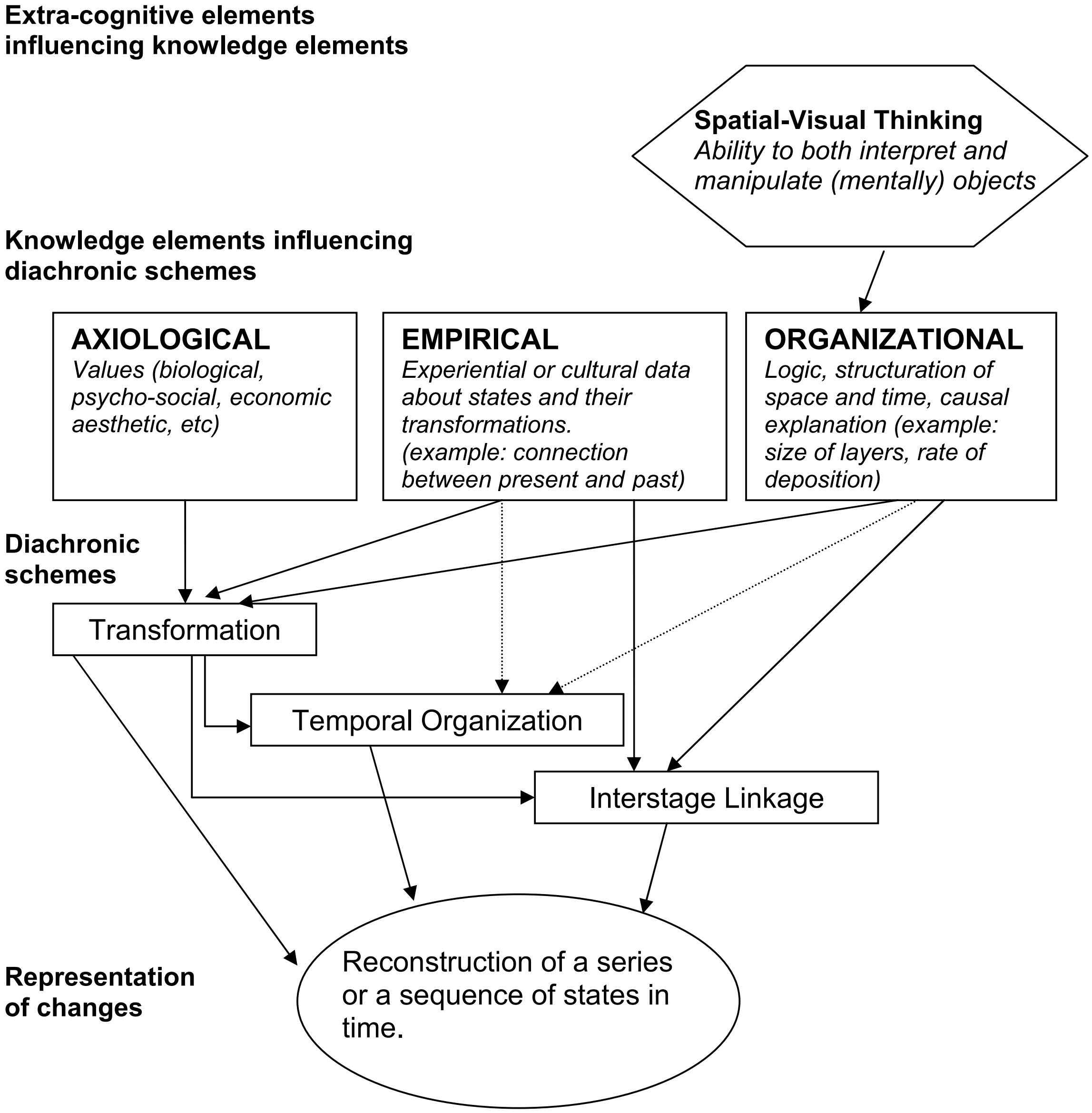


TABLE 3. PRODUCT MOMENT CORRELATIONS BETWEEN SELECT PUZZLES OF THE GEOTAT AND MGMP SPATIAL VISUALIZATION TEST WITH **NGS** (N = 172)

GeoTAT Puzzle	**Geological Skills**	**Correlation (r) with MGMP**	***p***
1a	Superposition, original horizontality	0.09	0.24
2	Superposition, actualistic thinking and causal thinking	0.14	0.13
6c	Superposition, actualistic thinking and causal thinking	0.21	0.02
5	Superposition, correlation	0.41	0.0001