UNDERSTANDING EVOLUTIONARY CHANGE WITHIN THE FRAMEWORK OF GEOLOGICAL TIME

JEFF DODICK *The Hebrew University of Jerusalem*

ABSTRACT. This paper focuses on a learning strategy designed to overcome students' difficulty in understanding evolutionary change within the framework of geological time. Incorporated into the learning program *From Dinosaurs to Darwin: Evolution from the Perspective of Time*, this strategy consists of four scaffolded investigations in which students manipulate and critique a series of (visual) representations of evolutionary change in geological time. These investigations include: (1) bio-stratigraphic correlation; (2) representing the development of life on earth through time; (3) comparing the magnitude of different time scales; (4) temporally scaling evolution. Using this format, students build an ever more sophisticated understanding of evolution in geological time. These activities were evaluated with a class of Israeli high school earth science students. Post-program results indicated that, although difficulties still remained, generally, the students had a better understanding of the scale of geological time and its connection to evolutionary change.

COMPRENDRE LE CHANGEMENT ÉVOLUTIF AU SEIN DE LA STRUCTURE DU TEMPS GÉOLOGIQUE

RÉSUMÉ. Cet essai met l'accent sur une stratégie d'apprentissage conçue pour surmonter les difficultés des étudiants à saisir les changements évolutifs au sein de la structure du temps géologique. Cette stratégie, intégrée au programme d'apprentissage *From Dinosaurs to Darwin: Evolution from the Perspective of Time*, se compose de quatre recherches avec appui pédagogique où les étudiants manipulent et critiquent une série de représentations visuelles des changements évolutifs dans le temps géologique. Ces recherches comprennent : (1) la corrélation biostratigraphique; (2) la représentation du développement de la vie sur la terre à travers le temps; (3) la comparaison de la magnitude des différentes échelles de temps et (4) la mise à l'échelle temporelle de l'évolution. À l'aide de ce format, les étudiants acquièrent une compréhension beaucoup plus parfaite de l'évolution dans le temps géologique. Ces activités ont été évaluées avec une classe d'étudiants en sciences de la terre d'une école secondaire israélienne. Les résultats, une fois les programmes terminés, ont montré que même si des difficultés persistaient, les étudiants avaient, en général, une meilleure compréhension de l'échelle du temps géologique et de son lien avec les changements évolutifs.

Introduction

By definition, evolutionary biology can be broken down into two subjects of study: *microevolution* and *macroevolution*. *Microevolution* is associated with evolutionary changes on the small scale, such as changes in gene frequencies within a population (Ridley, 1996); in contrast *macroevolution* is evolution on a grand scale, encompassing the origin of new taxonomic groups, evolutionary trends, adaptive radiation and mass extinction (Campbell and Reece, 2002). In terms of disciplinary boundaries microevolution and macroevolution also differ, with the former being the province of fields such as genetics and biochemistry and the latter the domain of paleontology. From an educational perspective, there are also differences between the two subjects in that microevolution often receives much of the pedagogic focus in most K-12 (biology) curricula (Dodick & Orion 2003b).

A possible reason for this bias is that for many biology educators the kernel of modern evolutionary theory is Natural Selection, and to fully understand how this evolutionary mechanism operates one must understand how variability is maintained in the population; this fits in well with microevolution's relationship with genetics (and specifically its connection to changing gene frequencies in natural populations). At the same time, most of the popular examples of evolution which have become part of the teaching literature, including industrial melanism in peppered moths, changing neck length in populations of giraffes, and antibiotic drug resistance in bacteria are examples of microevolution.

However, this strategy of starting a teaching unit in evolutionary biology with microevolution, and specifically Natural Selection, has difficulties. Much of the research on learning in evolutionary biology shows that even after instruction, students at both the high school and university levels often reject natural selection for a different understanding of "evolution," including Lamarck's theory of the "inheritance of acquired characteristics," anthropomorphism or teleology (see Dodick & Orion, 2003b for the references therein).

Natural selection is a difficult process to understand because it is dependent upon students understanding genetic processes, such as mutation, that are the ultimate sources of variation upon which Natural Selection acts. However, genetic processes such as mutation cannot be visualized directly within the cell and therefore remain abstract to many students. In this same vein, most students cannot visualize evolutionary change as a function of the changing proportion of individuals within a *population* over time, but rather see evolution as a gradual and progressive change in traits amongst *individuals* (Alters & Alters, 2001; Alters & Nelson, 2002; Brumby, 1984; Vincenzo Bizzo, 1994). In simple terms, it is much more difficult (and abstract) for students to generalize to a population which consists of many organisms, in comparison to visualizing change in an individual organism.

Dodick and Orion (2003b) have suggested that a solution to this problem is the use of the fossil record as a concrete visual representation of the abstract process of evolution. This suggestion is supported by research that shows that hands-on learning experiences, or simulations which concretize normally abstract, unseen processes in science by making them more visual can mediate some of the difficulties in learning such processes (Huppert, Lomask & Lazarowitz, 2002; Novak, 1976; Orion, 1993; Piaget, 1970, White & Frederickson, 2000).

An additional advantage to using the fossil record for illustrating evolution is that it establishes the concrete validity of the process (Dodick & Orion, 2003b). The abstract nature of Natural Selection as a mechanism of change does not establish for the student that such processes really can occur in nature. Thus, instead of beginning a curricular unit on evolution with Natural Selection, it might be better to start with the concrete evidence of the fossil record; this would then scaffold a student into an inquiry about the mechanisms that lead to differing fossil compositions in different strata of an outcrop. In other words, one should start with the (descriptive) evidence of the phenomena (the What?), which then creates curiosity amongst the student about the mechanism (the How? and Why?).

Indeed, this understanding resonates directly with Ernst Mayr's (1997) structuring of biology, and the questions it asks. According to him, biology (and all other sciences) start with a solid factual basis – the observations and findings upon which theories are based; in other words the answers to "What" questions. However, such "What" questions alone do not deal with all of the possible problems in biology. Hence, when dealing with functional questions (such as in physiology), we are asking about proximate causes, or "How" questions. Such "how" questions have also had an enormous impact on the physical sciences, as they have led to the discovery of natural laws. However, in biology we are also interested in ultimate causes, based on "why" questions and they are answered according to Mayr through evolutionary theory.

In fact, such a scaffolded sequence of questions has precedence in history. Many of the basic principles of biostratigraphy were determined before Darwin published *On the Origin of the Species* in 1859. Such principles permitted geologists to both identify and relatively date individual strata by their characteristic fossil contents. Geologists were able to accomplish this task precisely because of the process of evolution, as different organisms morphologically changed over time; preserved within sediments, such life forms create a stratigraphic ordering of fossils known as a faunal succession (Press & Siever, 1998). Such evidence as presented in works of 19th century geology (most importantly Lyell's *Principles of Geology*) had an important effect on the young Charles Darwin's eventual formulation of the mechanism of Natural Selection.

Finally, an advantage in using the fossil record as an introduction to evolution is that it emphasizes that this process occurs (for the most part) in geological time. Indeed, many educators and scientists list geological time as one of the most fundamental concepts in developing an understanding of evolution (Keown, 1988; Trowbridge, 1992; Wicander & Moore, 1993). Nonetheless, as a concept, geological time itself could serve as a cognitive stumbling block to understanding evolution, as most humans cannot psychologically relate in any meaningful way to 3.8 billion years of evolutionary history (that is, since the origin of the most primitive cells).

Thus, I endeavored to build a learning-experience that might help students to grasp evolutionary biology on the grand scale of what Thomas Carlyle (1832) first called "deep time" (www.oed.com). This term, which was later popularized by John McPhee (1980), poetically describes the human inability to represent the massive scale of geological time, in which the earth system and its biota evolved.

In this paper, I will be evaluating a learning strategy that was specifically designed to overcome students' learning difficulties in visualizing macroevolutionary change on the scale of "deep time." This strategy is employed in the Israeli high school program *From Dinosaurs to Darwin: Evolution from the Perspective of Time* (Dodick & Orion, 2000).

Previous research on the understanding of geological time

Despite the critical importance of geological time to a host of scientific fields including evolution, there has been relatively little attention given to it by researchers in the field of cognition or science education. The work that has been done is summarized by Dodick and Orion (2003a; 2003b; 2003c); preserving the taxonomy of such studies, I will discuss two types of research on student understanding of geological time: event-based studies and logic-based studies.

Logic-based studies investigate the logical decisions that students take in order to relative order geological/biological events as observed in stratigraphic layers. More specifically, such studies are interested in how, and at what age, students apply formal principles in geology, such as superposition (which states that a geological bed that overlies another bed is always younger, unless such beds are extremely deformed), which permit geologists to reconstruct the events that shape depositional environments over time. Such studies involve questionnaires and/or interviews that utilize three-dimensional puzzles that test students' abilities in thinking reconstructively.

Three 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' (grade 9 students in Taiwan) understanding of geological phenomena (including stratigraphy). In contrast, Ault (1981; 1982) interviewed a group of K-6 students using puzzles testing their ability to reconstruct sedimentary sequences using basic principles of stratigraphy. Finally, Dodick and Orion (2003a; 2003c) performed an extensive (comparative) study on the cognitive principles that guide Israeli middle (7-9) and high school (10-12) students (both with and without backgrounds in the earth sciences) when reconstructing geological strata.

Event-based studies entail research that surveys a subject's understanding of the entirety of "deep time" and usually involves relatively sequencing a series of bio-geological events, such as the creation of the earth, or the evolution of the dinosaurs. This is done using card-sorting tasks, or lists of such events, and usually 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 tasks, the subject is asked to justify his reasons for his proposed temporal order, as well as give absolute ages for each event. Using such responses, the subjects are often profiled into categories, which represent their knowledge and alternative frameworks about events in absolute time. Thus, event-based studies differ from logic-based studies in that the subject's responses are based on their knowledge of geobiological events learned both in formal and informal environments, rather than on their ability to use a logical principle from the earth sciences for reconstructing strata.

The small number of event-based studies can be subdivided by the age of the sample surveyed 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). More recently, research has focused on university students and includes Libarkin, Kurdziel, and Anderson's (2006) time line study, as well as the work of Libarkin and Kurdziel (2004) and Libarkin, Anderson, Science, Beilfuss and Boone (2005) which classify college students' ontological perspectives towards geological time.

As most of these studies used different research protocols, it is quite difficult to make comparisons. However the findings do show that university students generally placed the bio-geological events in correct relative order, in contrast with students in middle schools who had more difficulty with this task. All of the different samples mentioned above had difficulty both in scaling events in geological time as well as assigning absolute dates to said events. Amongst university students, there appears to be no major trend, with some of the subjects overestimating the age of such events, whereas others underestimated the age of the same events. In contrast, Noonan and Good (1999, p. 7) noted that most of their sample of middle-school students skewed the ages of many of the bio-geological events presented in their timeline questionnaire to “implausible high extremes of the timeline” (from 10 Ba to 20 Ba). This was a clear indication that geological time in general had little meaning for such students.

METHOD

To evaluate the learning model presented in *From Dinosaurs to Darwin: Evolution from the Perspective of Time*, I 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. (My intention is to expand this research in the future with a larger sample of high school students.) This class was chosen for implementation because the subject of this program expanded on a required element of their earth sciences curriculum, “History of the Earth” (focusing on the physical changes affecting the development of the earth).

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

1. Geological Time Assessment Test (GeoTAT): This questionnaire contains a series of cognitive puzzles testing the students’ ability to reconstruct changes in depositional systems over time. In other words its focus was on testing students’ understanding of relative time in geology. This questionnaire was thoroughly tested for content and construct validity (using factor analysis) as well as reliability (using Cronbach’s reliability coefficient). For details of this validity study, see Dodick and Orion (2003c).
2. Macroevolution knowledge questionnaire: This instrument, designed specifically for this research, tested both the students’ understanding of macroevolution, as well as absolute time. Thus, in one of its sections, the students were required to sequence major events in evolutionary history on a numerical time line similar to Noonan and Good (1999) and Libarkin, Kurdziel and Anderson (2006). The test itself was checked for content validity by 5 experts in biology and geoscience education.

In addition to surveying the students, the author was present during the implementation of the entire program in order to both observe and interview the students.

THE PROGRAM

Before I evaluate the learning strategy, I will provide a brief overview of the curriculum *From Dinosaurs to Darwin*. This program is divided into three units:

1. MATERIALS IN TIME: This unit deals with the basic principles of relative dating permitting scientists to relatively date fossils. It also includes a fieldwork project in which the students reconstruct the depositional history of Mahktesh Hatira, a "natural" crater (i.e., created by terrestrial, rather than extraterrestrial processes) in the north-central Negev region of Israel.
2. EVOLUTION AND THE FOSSIL RECORD: Armed with a basic understanding of relative time, the students tackle the more abstract problem of how to understand the adaptive radiation of organisms in the fossil record. Specific topics include the debate surrounding the thermo-physiology of the dinosaurs, the history of life on earth and macroevolution.
3. INDEPENDENT PROJECT: A continuation of elements studied in the second unit, these projects focus on macroevolutionary change as witnessed in the fossil record. Topics include: the evolution of flight, mass extinction, and hominid evolution.

It is in the second unit that I employ the strategy of connecting evolution with the massive scale of geological time. This consists of four in-depth activities in which the guiding principle is to shape the students ability to manipulate the 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 permits them to organize information into conceptually meaningful patterns. Further, they argue that if science students are to pursue inquiry-based problems, which is a fundamental goal of science education (American Association for the Advancement of Science, 1990; 1993; National Research Council, 1996; 2000), they must also obtain such interpretation skills. In their work, they have shown that chemists have a set of representational skills central to their research. These skills allow them to move flexibly between multiple representations so that they may better understand their domain. Similarly, paleontologists must mediate between multiple representations, including phylogenetic trees, anatomical illustrations, and stratigraphic profiles to solve specific problems in their field of study.

In the second unit, students experiment with some of these representations to learn how professional scientists transform concrete field-based information into a three-dimensional picture of evolution. As the material is conceptually new, I have scaffolded the activities into a *four-stage model* linked by a series of bridging questions. These questions were worded so that the students would be induced into evaluating the models they designed at each stage of the unit, while linking them to the next iconographic model in this unit. Briefly these 4 stages include:

1. The "infamous ladder of progress" in which students learn how to use the geological principle of biostratigraphic correlation.
2. Representing evolutionary relationships in time using different iconographic representations (most critically the phylogenetic tree).
3. Comparing the magnitude of different timelines in biological and earth history.
4. Understanding the rate and scale of evolution. (This involves proportionally scaling a phylogenetic tree on a geological time line.)

Data analysis

Stages 1-3 of the learning model were evaluated using select questions from the GeoTAT and Macroevolution Knowledge questionnaire. (As these instruments were designed to evaluate the entire unit of *From Dinosaurs to Darwin*, they also include questions that do not necessarily address the learning model presented in this paper; for this reason the results from these questions will not be discussed in this paper.)

Two questions were specifically chosen from the GeoTAT to evaluate stage 1 of the learning model (Table 1); the first evaluates the subject's ability to use the geological principle of superposition on distorted strata, whereas the second tested the understanding of biostratigraphic correlation. Stage 1 was also evaluated by 2 questions from the Macroevolution knowledge questionnaire which dealt specifically with the student's preferred representation of evolution ("phylogenetic tree" and "linear progression").

Three questions from the Macroevolution questionnaire evaluated stage 2 of the model; these questions focus on students' understanding of major evolutionary transitions in the history of life (such as the evolution of skeletons).

Finally, six questions addressed stage 3 of this model, which focuses on the understanding of absolute time, with students asked to correctly plot a major feature of evolution on a geological timeline, as well as provide the absolute date for this feature. The timeline was divided into nine units each representing 500 Myr of geological time. A separate section was provided beneath the timeline so that the students could enter the absolute date for each of the three features (first cells, age of the dinosaurs, and the origin of man). A correct answer on both the timeline and absolute date question is considered to be within ±10% of the scientifically accepted range for that event. Thus, for example the correct figure for the evolution of the dinosaurs was 65-225 Ma (±10% of that figure).

As all of the questions had a different score, they were standardized to a mark of 100% for easier comparison. The mean of all marks received at both the pre- and post-phases of implementation was calculated for each question. Due to the small size of the population, and the likely deviation from normality, the pre-post results were evaluated with the Wilcoxon Signed Rank test for paired differences.

Stage 4 of this learning model was evaluated through in-class observations as well as interviews in order to determine how it affected students' understanding of evolutionary change within the framework of geological time.

TABLE 1. Wilcoxon signed rank comparison of the pre-post results of the GeoTAT and macroeveolutionary knowledge questionnaire

Questionnaire Type	Research Stage	Question	Pre	Post	p
GeoTAT	1	Superposition (with distorted strata)	90.0	93.3	n.s
	1	Biostratigraphic Correlation	67.8	81.1	n.s
Macroevolution Knowledge	1	Which do you prefer as an evolutionary icon: Tree or Line?	22.2	54.5	n.s
	1	Explain why you prefer the Tree or Line as an evolutionary icon?[a]	16.7	58.3	.03
	2	Why did hard skeletons evolve amongst different groups of organisms?	0	50.0	.05
	2	Describe the changes in animal form when they moved from aquatic to terrestrial environments?	36.1	72.2	.03
	2	Describe why plants developed flowers?	33.3	72.2	.05
	3	Time line (dinosaurs)	0	22.2	n.s
	3	Time line (first cells)	33.33	77.9	n.s
	3	Time line (man)	11.11	44.4	n.s
	3	Absolute time (dinosaurs)	12.50	75.0	.05
	3	Absolute time (first cells)	22.2	22.2	n.s
	3	Absolute time (man)	33.3	88.9	.05

Note: The questions in this table refer specifically to those used to evaluate the 4-stage model that is presented in this paper. They are a subset of the total number of questions that are found in both the GeoTAT and the Macroevolutionary Knowledge questionnaire that were used to evaluate the entire program *From Dinosaurs to Darwin*.

[a] This question was only marked with the students that chose the correct answer on the previous question (i.e., Which do you prefer as an evolutionary icon? Tree or Line. The correct answer was tree).

RESULTS

Table 1 presents the analysis of the answers received on both the GeoTAT and Macroevolutionary knowledge questionnaire. Overall, the results were positive with post-program improvements on all of the questions asked, sometimes with large differences. Moreover, six of these results showed significant change. However, it is difficult to understand such raw scores and their changes without a detailed discussion of their connection to the (four) individual stages of the learning model. This will be done in the next sections of the paper.

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 visuals which treat this process as a linear progression from prokaryote to human, and thus, perpetuate the misconception that the history of life represents progress from primitive to complex. Further, because they isolate single groups of life (such as fish, which originate prior to amphibians) in this supposed progression, students inadvertently construct a second misconception, that one form of life inevitably replaces another in time (often through direct competition).

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 a supposed progression from "primitive" (at the bottom of the section) to "complex" life forms (at the top). Moreover, many students who (tacitly) understand superposition will naturally, but mistakenly, assume this supposed progressive trend. Thus, it was important to design activities that would counteract this misunderstanding.

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

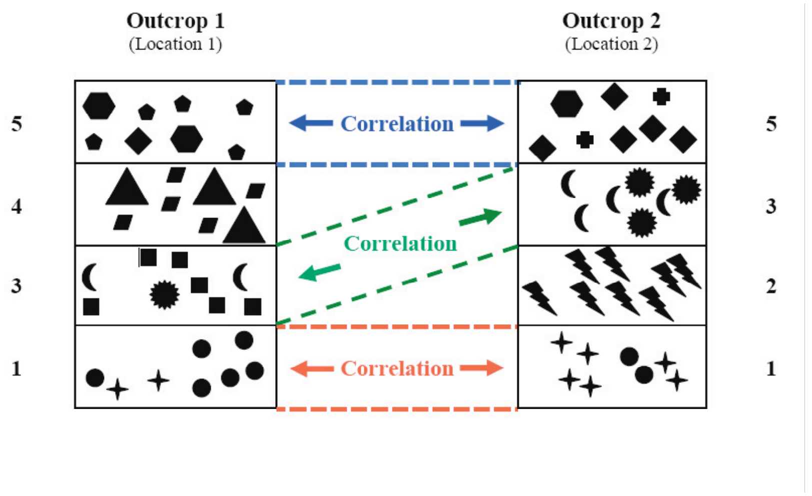

FIGURE 1. The logic of biostratigraphic correlation

Figure 1 is a schematic illustration of the logic behind biostratigraphic correlation. Correlation is performed by matching the fossil types, represented in this figure by the different symbols, found in each stratum (or bed) of geographically separated outcrops. Strata that contain the same fossil types are contemporaneous in age. The numbers on the sides of the schematic beds represent the relative ordering of the beds. Note that correlation allows one to complete this relative ordering by filling in fossiliferous strata that are missing from an outcrop due to processes such as erosion or lack of deposition.

At the beginning of this investigation, the subjects receive a set of nine cross-sections (representing geographically distinct sites) divided into five strata, each containing a picture of fossils representing a key feature of evolutionary history (such as the first terrestrial plants). The goal of this exercise is to create a single composite cross-section representing the correct relative ordering of these key evolutionary features. After completing the activity, the students list these features in a geological time scale which contains numerical dates indicating when each of the features originated.

After completing this unit, the students improved their ability to perform both superposition and correlation. In the case of the former, the improvement was slight, in part because they had previously learned this principle in their grade 11 earth science program (and so their pre-test scores were already high). In the case of correlation, the students' improvement was much greater; pre-program they scored 67.8%; post-program their scores improved to 81.1%, which was a shade under significance, indicating that the students were grasping the mechanics of correlation. It might be added that this particular activity has been tested with three other science classes (consisting of two grade 9 classes and one grade 11 class) and the difference in pre-post scores in all cases was significant.

Note that the single, composite cross-section built in this activity anticipates the misconception of "the ladder of progress." Thus, immediately after completing this activity, the students encounter 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 that were mentioned previously. In fact, some noticed these problems without being prompted by this question. 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, many of the students recognized the superiority of this icon (pre-scores = 22.2% and post-scores = 54.5%); more importantly they could also cite reasons for its superiority (pre-scores = 16.7% and post-scores = 58.3% which was a significant difference).

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. In 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, based on individual student reports.

The purpose of this activity was that in building their phylogenetic tree, the students construct an association between biological events and geological time (periods). This strategy is based on psychological research which indicates that one of the symbolic modes involved in representing conventional time systems (such as months or weeks) is the associational network (Collins & Loftus, 1975). For example, Friedman (1982, p. 182) argues that individual months are often 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 the fact that fossils are rich visual evidence for evolutionary change in time. In their research on history education 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 attached to dates. 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.

This activity was evaluated by three brief essay questions that asked the students to explain an important evolutionary event in the history of life (such as why animals developed hard skeletons). Overall the final results were very good as the difference between post- and pre-scores on all three questions was significant (Table 1).

Stage 3: Comparing the magnitude of different timelines in biological and earth history

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 better visualize the scale of geological time (Everitt, Good & Pankiewicz, 1996; Hume, 1978; Metzger, 1992; Nieto-Obregon, 2005; Ritger & Cummins, 1991; Rowland, 1983; Spencer-Cervato & Day, 2000).

The difficulty with these approaches is that by scaling all bio-geological events on the same timeline, students lose sight of man's relation to geological time. Instead, in this investigation, students compare four different types of timelines, each with a different representative range that corresponds to a critical facet of earth or biological history. These timelines (with their representative ranges presented in brackets) include: geological time (4.6 Byr), cellular evolution (3.8 Byr), skeletal evolution (542 Myr), and human evolution (2 Myr) (Figure 2). To make this investigation more relevant to the students, two other timelines have been added: the development of civilization (5000 years) and personal time (75 years).

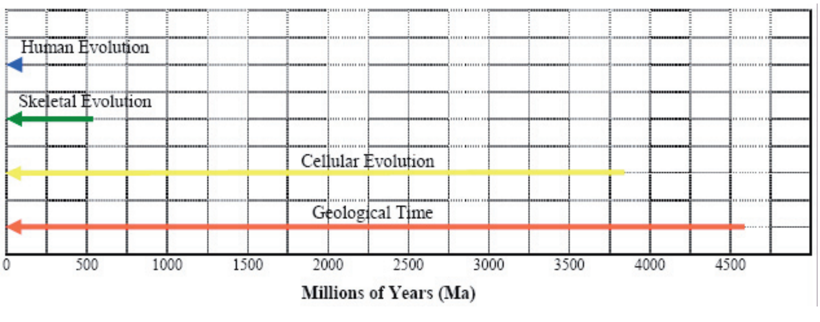

FIGURE 2. Comparison amongst different time lines in biological and geological history

The advantage of this method is that students realize that different temporally constrained disciplines, including evolutionary biology, archaeology, and history, by necessity, operate on different ranges of absolute time, which also often dwarf the human life span. Indeed, the arrow in Figure 2, which represents human evolution, extends far past its actual time range (approximately 2 Ma), because it is impossible to graphically represent this event on a temporal scale that also includes cellular and skeletal evolution. Thus, in completing this activity, students realize that the birth of civilization (approximately 5000 years ago), and a human's lifespan (75 years), cannot be modeled on a timeline which incorporates any of the major features of evolution.

The subjects were tested both prior to and following the program with a task that required them to plot selected events in the history of life (including the appearance of the first cells, evolution of the dinosaurs, and the origin of man) on a proportional timeline, as well as to provide absolute dates (within ±10% of the correct date) for these events.

Post-program, most students improved their ability to assign absolute dates, including significant changes associated with the evolution of dinosaurs and humans. More difficult was plotting these events on a scaled time line, especially at its terminal end, as represented by the evolution of the dinosaurs and the origin of man. Similar to Noonan and Good's (1999) work on middle school students, the tendency here was for the students to strongly overestimate the correct absolute age on the timeline. Thus, they did not realize that the dinosaurs evolved in the last 5% of geological time (approximately 225 Ma) and instead placed them much further along the timeline. This disconnect between absolute time and scaled time indicates that the students could learn dates as information but still had not fully internalized the implications of "deep time" (i.e., that most biological events are compressed into the last seconds of the geological time clock).

Nonetheless, although even post-program many of the students did not accurately plot these events on the time line, most got quantitatively closer to the correct figures (something which the data does not fully show); simply put, they reduced their overestimation. Moreover, students were much more successful in understanding the chronology of the specific events they had personally researched in their group projects. This suggests that the strategy of associating evolutionary events and their chronology is fundamentally sound.

Stage 4: The rates and scale of evolution

After completing the third stage, the students had a better understanding of the enormous scale of geological time, although problems remained. For this reason, I added a further representation of time to this unit. As this curriculum's focus is evolution, I 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 542 million years of geological time, beginning with the "Cambrian Explosion" (Gould, 1989); this represents (approximately) the last 12% of geological time. (In fact, cellular life began as much as 3.8 billion years ago, with the origin of the prokaryotes; still, the fossil record is biased towards the Cambrian and the periods that followed, because it was only from this period that most multicellular organisms with hard skeletons evolved, and it is such biological material which is best preserved in the fossil record.)

Thus, in this stage, students return to the phylogenetic tree completed in stage 2 of this unit (Figure 3a) and proportionally scale it along the geological timeline. As a result they see that much of the evolution of organisms with hard skeletons is indeed compressed to the upper 12% of geological time (3b). 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 have evolved at different rates. Such an understanding is good preparation for examining the debate about the gradualist and punctuated (equilibrium) theories of speciation. (And indeed, in the following chapter of *From Dinosaurs to Darwin,* students do investigate direct evidence for both theories of speciation.)

This graphic representation appears to be an effective means of characterizing the nature of evolutionary change as it occurs in the framework of geological time. In-class observations, as well as informal interviews that were held after completion of this activity, indicate that many of the students grasped the significance of the scaled phylogenetic tree. Many of the students especially noted that the branch representing hominid evolution had now been reduced to a minuscule twig on the "tree of life"; this elicited the (simple but poignant) comment from one student: "I am nothing" (in reference to his place in "deep time").

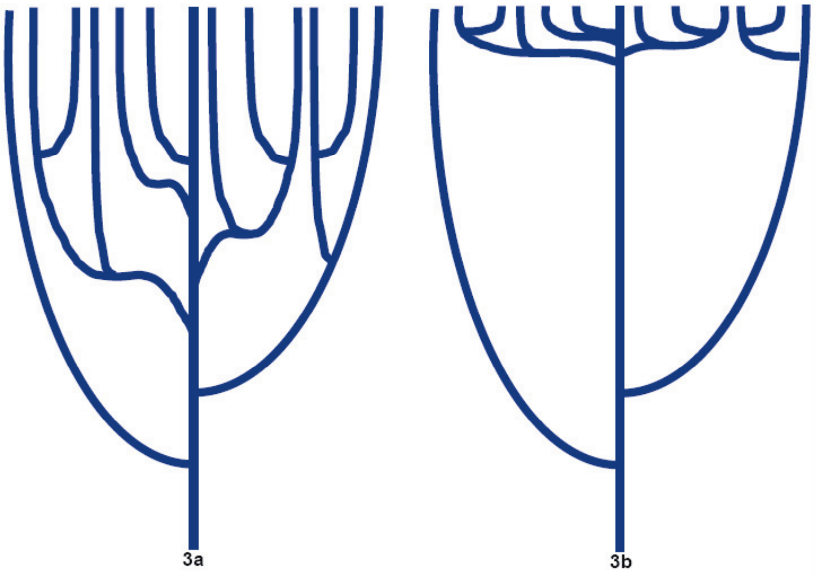

FIGURE 3. Illustrations of evolutionary relationships without (a) and with a scale of time (b). (Note that these figures are schematic and do not represent any known phylogeny)

CONCLUSIONS

Geological time is one of the foundational elements for understanding evolutionary biology, as it provides a framework for organizing the large-scale changes that have affected the world's biota. Even so, geological time can be intimidating, as it reduces human existence to the metaphorical blink of an eye. How then is it possible to gently inculcate this temporal framework that is so necessary to learning evolutionary biology?

Cognitively, my general approach towards teaching geological time involves breaking down this broad concept into the macro-scale of "deep time," including, as it does, the major features of evolutionary history, and the micro-scale of relative time represented by individual strata. To an extent this general approach parallels the earth science's division of geological time into *absolute* (or *numerical*) *time* and *relative time*, respectively. In this paper, I have focused on the former (absolute time), by illustrating a model for teaching evolutionary history within the framework of "deep time." (Readers who are interested in how students understand micro-scale transitions between strata should refer to Dodick and Orion [2003a; 2003c]).

In terms of evolutionary change in the framework of deep time, I have designed a model that uses a series of scaffolded, visual representations, each symbolizing a different aspect of evolution in time. In this way, students have the ability to both critically evaluate the representations they investigate, and construct a more sophisticated understanding of evolutionary change in time. Using this method, students learn that different time scales are appropriate for representing different phenomena, from our planet's birth to the evolution of the human species. Additionally, they also discover that different events develop at different rates. Such insight into differing scale and rate are not confined to evolutionary processes alone; thus, investigating evolutionary change within the framework of "deep time" serves as a starting point for discussing many other sciences, influenced by time spans of varying magnitudes.

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JEFF DODICK is an Assistant Professor of Science Education at the Science Teaching Centre of the Hebrew University of Jerusalem. He has a background in both Paleontology (M.Sc. from the University of Toronto) and Science Education (Ph.D. from the Weizmann Institute of Science). His current research focuses on how novice learners, as well as experts, solve problems and communicate findings in historical based sciences, including evolutionary biology, geology, and archeology.

JEFF DODICK est professeur adjoint en enseignement des sciences au Science Teaching Centre de la Hebrew University de Jérusalem. Il a des antécédents professionnels en paléontologie (maîtrise de la University of Toronto) et en enseignement des sciences (doctorat du Weizmann Institute of Science). Ses recherches actuelles portent sur la façon dont les étudiants novices, ainsi que les experts, résolvent les problèmes et communiquent les résultats en matière de sciences fondées sur l'histoire, y compris la biologie évolutionniste, la géologie, et l'archéologie.