Qualitative Analysis of College Students' Ideas about the Earth: Interviews and Open-Ended Questionnaires

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ABSTRACT

Student conceptual understanding and conceptual change is an active area of research in many science disciplines. In the geosciences, alternative conceptions held by students, particularly college students, are not well documented or understood. To further this body of research, students enrolled in introductory science courses at four institutions completed 265 open-ended questionnaires and participated in 105 interviews. Data were collected at a small private university, two large state schools, and one small public liberal arts college. Students were probed on a variety of topics related to the Earth's crust and interior, as well as geologic time. Analysis of questionnaire and interview responses indicates that students hold a number of non-scientific ideas about the Earth. Additionally, students apply a range of ontological categories to geologic phenomena, with significant implications for teaching geosciences from a systems perspective.

INTRODUCTION

The study of what students believe about science, how ideas about science can develop or change, and why some ideas are prevalent throughout society has been an active focus of research for many years (Gilbert and Watts, 1983; Driver et al., 1985; Lawson et al., 2000). The study of conceptual understanding and conceptual change in the Earth Sciences, however, has typically been limited to issues related to space science or the environment. Additionally, the few existing studies are almost exclusively limited to K-12 students, with very little examination of ideas held by college students. We report here on a multi-institution study of the ideas held by college students about a variety of geoscience topics. This research is part of a larger project aimed at developing an assessment instrument for entry-level geoscience courses (Libarkin et al., 2002).

We have chosen to focus our initial efforts on three aspects of geoscience: Earth's crust, Earth's interior, and geologic time. Findings reported here are limited to topics covered in questionnaires administered during the 2001-2002 academic year and student interviews conducted during Spring 2002, although study of additional topics is ongoing. We find that a range of student ideas exists, and many of these are common across institutions, regardless of the demographics of the student population. Additionally, students' views of the world around them can be categorized ontologically (e.g. Chi and Slotta, 1993; Chi, 1997), and we have found similarities in ontological perspectives within the entire population studied. The term "ontology" refers to a hierarchical structuring of knowledge, and allows us to describe the ways in which people understand geologic processes (Table 1). We separate our discussion into two components: a reporting of existing student ideas, and an analysis of the implications of student ontologies on current reform efforts.

Student Ideas - Student ideas about the Earth that have not previously been reported are documented here. A few of the most prevalent ideas are discussed in detail, and some suggestions for their origin and ties to existing literature are reported. Additionally, commonalities in non-scientific ideas that exist across institutions, as well as differences, are considered. For instance, most students at all four institutions believed some form of life existed when the Earth first formed as a planet. However, the form that this life took varied significantly across institutions. Similarly, most students subdivided the Earth's interior into spherical layers, although few students were able to explain the reasons behind these divisions.

Student Ontologies - The focus of Earth Science education at both the K-12 and collegiate levels has shifted over the past decade from a focus on sub-disciplines to a focus on the Earth as an integrated system. National organizations have published a number of documents encouraging faculty to teach undergraduates from an Earth Systems Science perspective (Ireton et al., 1997) and national K-12 standards are similarly reflecting this change in emphasis (AAAS, 1993; NRC, 1995). Although geoscientists, and indeed scientists from all disciplines, would agree that study of the Earth requires the integration of a wide range of scientific perspectives, it is not clear how well students understand this aspect of the nature of Earth Science (e.g., Fig.1; Table 1).

PREVIOUS RESEARCH

Student Ideas - Conceptual understanding, and especially the pre-instruction notions held by students, is widely addressed in science, especially in physics and chemistry (e.g., Lewis and Linn, 1994, and references therein), with research in biology primarily focusing on subdisciplines, such as evolutionary biology. Similar

Student Responses	Interpretation
It is a… ummm, something that you would… something that is leftover from like…some type of thing, like a creature or an animal that we found in the rock. The rock, or the sand, or what ever is formed around it Well, um, after they died, the fossils remain and then I would assume some kind of, uh, archeology or researcher would preserve them, and study them.	MATTER: Fossils are remains after death or leftovers. No identification of any change occurring to organism, or mechanism for preservation.
I would explain a fossil as just…what we think as all the bones of a part of an animal that has been buried underneath the ground, that we have discovered and dug up and put together.	TRANSFORMATION: Fossils are parts of animal that have undergone burial. No discussion of burial or fossilization processes.
Uh, I don't know much about like how the plants or tree or that kind of stuff have fossilized. I'm not sure about that. But, I know that they find fossils of dinosaurs and they can date them back to when they first came…that's how they can do that...	PROTO-PROCESS: Material must become fossilized, but no clear explanation of process. Fossils can be dated, but again no explanation of specific process for dating.
I'd probably explain it as like the skeletal remains, like if they'd seen a skeleton before it'd be like skeleton but it's rock. The bones have been replaced by mineral deposits...	PROCESS: Mechanism for fossilization is explained

Table 1. Example of interview coding based on ontologies: Fossils. Note: Interviewer asked variant on these questions: "What is a fossil?", "How are fossils formed?", and "What can fossils tell us?"

studies in the Earth Sciences are more limited than in other disciplines, especially at the undergraduate level. Existing studies of student conceptions in physical geology focus primarily upon demographic variables such as gender and age, or target participant attitude rather than conceptual understanding. Very few studies involving college-aged students exist (Schoon, 1989; Schoon, 1992; DeLaughter et al., 1998), however, four key content areas are addressed in the literature: 1) Definitional issues, primarily with regards to terms that are part of vernacular speech such as "fossil", "mineral", and "rock" (Oversby, 1996; Finley, 1982); 2) Soil and water, including soil development (Happs, 1984), the water cycle (Bar, 1989), groundwater (Meyer, 1987), and marine knowledge (Brody, 1996; Fortner and Teates, 1980); 3) Tectonics, with particular emphasis on earthquakes (Schoon, 1989; Schoon, 1992) and mountain building, including origin and mechanisms (Chang and Barufaldi, 1999; Marques and Thompson, 1997; Muthukrishna et al., 1993). Some mention is also made of student ideas about volcanoes (Bezzi and Happs, 1994), the Earth's interior (Lillo, 1994; DeLaughter et al., 1998), and the Earth's magnetic field (Oversby, 1996); and 4) Geologic time, both with respect to absolute time (Marques and Thompson, 1997; Trend, 1998) and relative time, especially with reference to stratigraphy (Ault, 1982; Chang and Barufaldi, 1999) and the sequence of geological events, such as the appearance of organisms in the fossil record (Trend, 2000; Trend, 1998; Schoon, 1992). Understanding geologic time is necessary for understanding those geologic concepts that cannot be directly observed on human time scales, such as mountain building. Lawson et al. (2000) have termed concepts that are dependent upon an understanding of geologic time "hypothetical", and provide an interesting framework from which all concepts can be viewed. Finally, the Journal of Geoscience Education recently devoted most of the January 2001 issue to teaching geologic time.

Student Ontologies - Chi and others (1994; Chi, 1997) have applied a scheme for understanding how students perceive the nature of phenomena to education, and this scheme has proven very useful in our analysis of student interviews. Specifically, they begin by placing aspects of the world into three ontological categories: Matter, Processes, and Mental States. Matter refers to things, such as tectonic plates. Processes refers to events, procedures, or interactions, such as the erosion of a mountain. Mental States refers to intangibles, such as dreams or thoughts. For this study, only the first two ontological categories were addressed, with the addition of subcategories that are important for understanding how students view the Earth around them, as well as how they interpret material taught in the geoscience classroom (Figure 1).

METHODS

Students from four institutions, a small elite private university (Harvard University=HU), two large state universities (Indiana University-Bloomington= IU; University of Arizona=UA), and one small public liberal arts college (Black Hills State University=BH), participated in this study. Several different recruitment strategies were used to collect data (Table 2). In all, 265 written student responses to open-ended questionnaires were collected and 105 separate student interviews were conducted. Questionnaires were completed at the beginning of the semester and interviews were conducted from mid- to end of semester. Data were thus collected from students before, during, and after completion of entry-level geoscience courses. Interviewees and questionnaire respondents were enrolled in introductory or general education courses in the geosciences at HU, IU and BH; students at UA were enrolled in comparable bioscience courses. Interviewees ranged in age from 18-50, although the bulk of the students were freshmen and sophomores in college. The interviewee population was 56% female, typically Caucasian, and not planning to major in science. Finally, almost all students participating in interviews reported taking an Earth Science course in middle or high school. Demographic data were not collected from students completing the questionnaire.

Design and Procedure - A short, open-ended questionnaire eliciting student ideas about earthquakes, the Earth's interior, and geologic time was administered in Fall 2001 and Spring 2002 (Figure 2). This questionnaire was designed to cover one topic in each of

Data Type	School	Date	Number of Students	Recruitment
Questionnaires	HU	Fall 2001	18	V-in class
	HU	Spring 2002	36	V-in class
	UA	Spring 2002	30	V-in class
	UA	Spring 2002	32	EC
	BH	Fall 2001	65	V-in class
	BH	Spring 2002	84	V-in class
Interviews	HU	Spring 2002	5	V
	IU	Spring 2002	82	ED
	UA	Spring 2002	2	V
	BH	Spring 2002	16	V

Table 2. Sample size, recruitment, and institutional setting. School: Harvard University=HU, Indiana University-Bloomington= IU, University of Arizona=UA, Black Hills State University=BH. Recruitment: V=Voluntary; EC=Extra credit; in class refers to completion of questionnaires during class time.

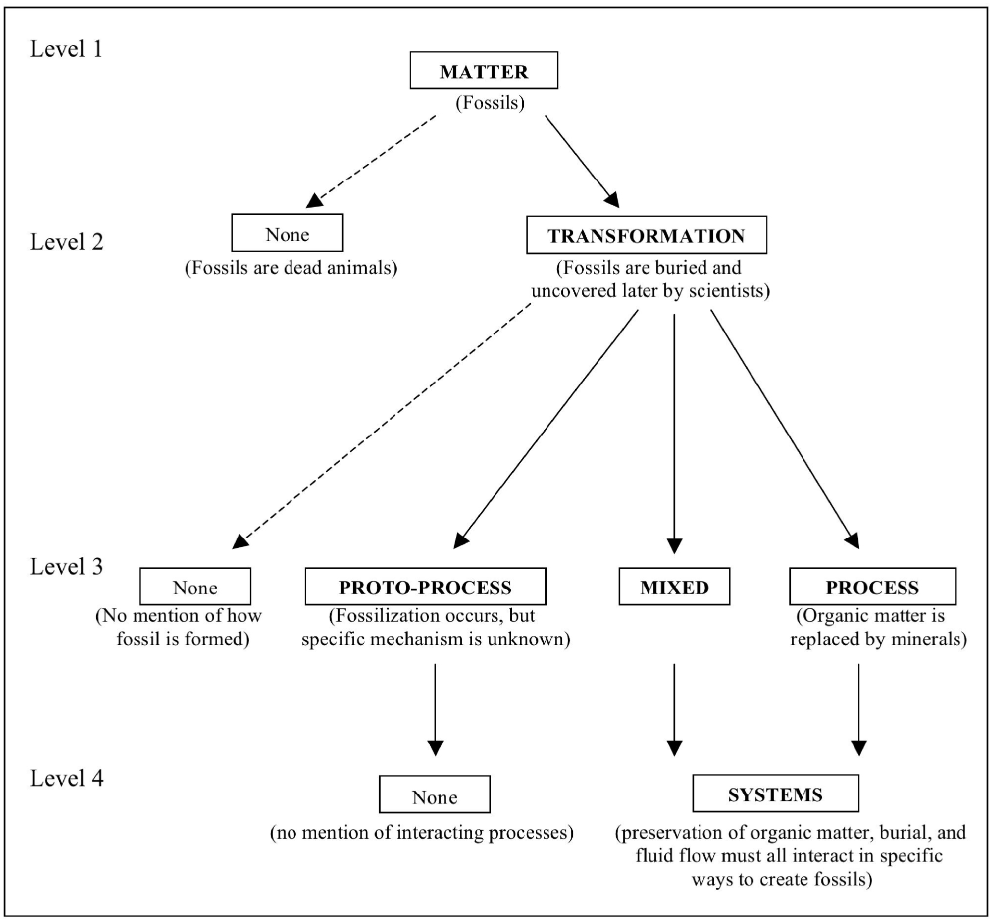


Figure 1. Model for ontologies. This model was used to code twenty of the interviews in the study to determine the ontologies about Earth phenomena students bring to introductory classrooms. Examples of ontologies related to fossils are given, as in Table 1. Model is modified from Chi and others (1994, 1997).

the three content areas targeted in this study. Analysis of the initial questionnaire results guided the development of an interview protocol, with multiple, pre-interview revisions based upon within group review. Interview questions were developed from a review of topics typically included in introductory and general education geoscience textbooks, and several questions were added to the protocol after the first twenty interviews to help clarify student thinking. Four interviewers, each based at a study site, conducted semi-structured interviews; protocol questions guided the initial discussion, and probing questions (probes) were used to encourage students to explain responses. Suggested probes were included in the protocol, although interviewers were

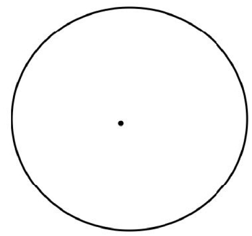
Please answer the following questions as completely as possible, using pictures if necessary.

1. If you had to explain the word "earthquake" to a friend, what would you say?

2. Please explain the event or events that you think might cause an earthquake to occur.

3. If you could take a giant knife and cut the Earth in half, what do you think the inside of the Earth would look like?

4. Draw a picture of the Earth's interior. The circle represents the Earth's surface, and the dot is the very center of the Earth.



5. If you had a time machine and could travel back to when the Earth was formed:
a. What do you think the Earth would look like? *(correct answers include references to gases, particles, magma, molten, and volcanic)*
b. How many years back in time would you have traveled? *? (correct answer is any response between 4 and 5 billion years ago)*
c. Would there be any living things? If so, which organisms do you think you might encounter? *? (correct answer is no.)*

Figure 2. Final version of the open-ended questionnaire completed by 265 students at three institutions (Table 2). Correct responses to the questions about the Earth's formation are provided; these questions were analyzed quantitatively (see text and Figure 5).

given the freedom to develop their own probes as needed. Interviews typically consisted of one to four questions, and lasted between 0.5 and 1 hour.

Data Analysis - Open-ended questionnaires and interview data were analyzed via thematic content analysis (see Libarkin and Kurdziel, 2002 for a review of relevant literature). Content analysis focuses on searching for patterns in text; in this study, themes were identified inductively such that they emerged naturally from the data. All 265 questionnaires and 105 interviews were analyzed with reference to student ideas, and twenty interviews were used to assess student mental perspectives related to the Earth. Thematic content analysis related to specific topics, such as earthquakes, was simply a matter of determining which ideas were exhibited by students on questionnaires and in interviews.

In addition to the content analysis, three time-related questions from the open-ended questionnaire were quantitatively evaluated. In this evaluation an attempt was made to differentiate misconceptions about the Earth's formation from random guessing. Responses were binned into common categories, and these categories were used to determine the likelihood of a student guessing a correct response (Figure 2). These data were used to construct a curve representing the spread of correct responses that would be expected if students were randomly guessing responses (Figure 3). Comparison of this random curve with response curves at other institutions indicates whether or not the student body is likely to have misconceptions about the Earth's formation. Specifically, institutional response curves with fewer correct responses than predicted by random guessing indicate that the student body most likely carries misconceptions.

We found it useful to further break down ontological processes into three sub-categories: 1) Proto-process, wherein the student mentions an understanding that a process must exist to cause the transformation, but no further explanation of a specific mechanism is given. This includes mention of a process-related word, such as evolution, but without a clear explanation of what evolution actually is; 2) Full process, such that students provide a complete explanation of the underlying causes or mechanisms for transformations, even if these causes are not scientifically correct; and 3) Mixed process, where the student sometimes exhibits full process understanding, and at other times only demonstrates proto-process understanding. Ontologies demonstrated in in-depth analysis of twenty interviews were analyzed by two researchers based on five main categories: matter, transformation, proto-process, mixed process, and process (Figure 1). The mention of an object or phenomenon is coded as matter; changes occurring to an object or event are transformations; and processes are the underlying causes related to transformations. Systems are made up of interacting processes, although none of the students interviewed demonstrated a systems perspective. We chose an occurrence level of 30% as indicative of a mental perspective; e.g., if the matter category was mentioned in an interview 90 times, we

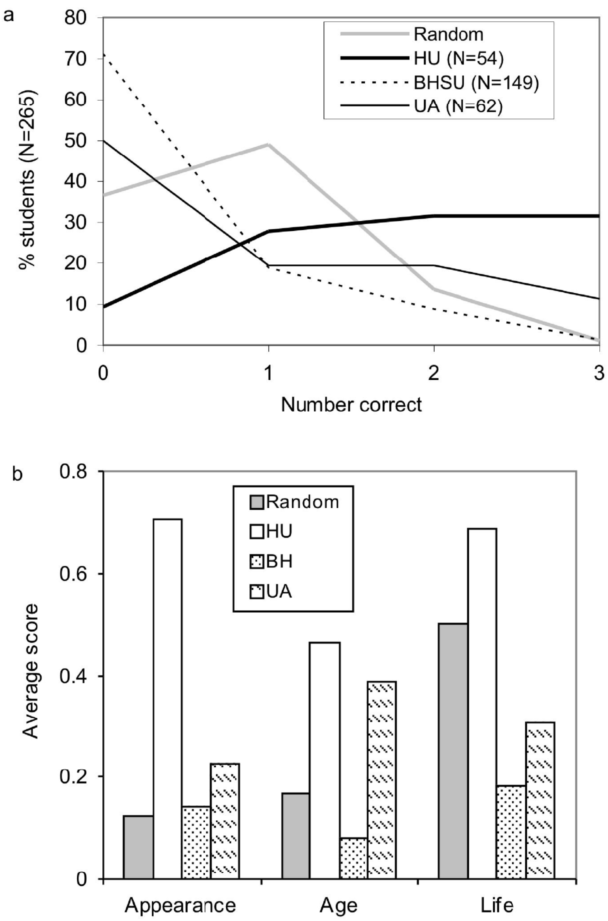


Figure 3. Response histograms for question 5 of Figure 2. Random represents the distribution of scores expected for random guessing. a) Number of correct answers out of a possible total of three. Students at HU are entering the course with scientific conceptions, while students at BH and UA are mostly entering with misconceptions. b) Average normalized score for each institution on each of the three time related questions (Figure 2).

would expect to see a discussion of changes occurring to that matter at least 30 times before we could apply the transformation code. Similarly, underlying mechanisms for changes would need to be mentioned at least 10 times before the process code could be used. We chose a level of 30% as only about 30% of interview questions required a discussion of complex perspectives, and this level clearly allowed us to differentiate between students. Finally, all twenty interviews were coded by both researchers with an initial coding agreement of 90%; discrepancies occurred between transformation and proto-process levels only. After a review and discussion of the coding, agreement was brought to 100%.

RESULTS AND DISCUSSION

This data set provides a rich perspective into the mindset of students enrolled in introductory and general education geoscience courses. The written questions collected from students provide a window into the prevalence of ideas about the Earth, although without the deeper contextual understanding afforded by interviews. Together, these data have allowed us to document both the range of ideas held by students and the mental perspectives from which they view the Earth.

Student Ideas - The complex range of student ideas about scientific phenomena is well-documented across scientific disciplines. In this study, a wide variety of non-scientific views about geoscience concepts were revealed at all four of the participating institutions. The scope of this paper prohibits detailed discussion of each interview question, although important aspects of student views of the Earth's crust, Earth's interior, and geologic time are discussed in detail. Many of the ideas about the Earth's crust and interior are tied into ideas about time, although we have attempted to distinguish between spatial and temporal concepts.

Geologic Time - Previous research has found that students have difficulty comprehending geologic time scales (sometimes referred to as "deep time") and placing geologic events in logical sequence (Ault, 1982; Schoon, 1992; Trend, 2000). Our data indicate that fewer than 50% of all students in this study, and at some institutions less than 10%, believe that the Earth is 4-5 b.y. old. Students hold a number of misconceptions about the Earth's formation and the appearance of life, and these ideas are remarkably consistent across institutions. However, the frequency of occurrence of non-scientific ideas differs between institutions and is worth discussing. Student ideas about the formation of the Earth were collected on the open-ended questionnaire (question 5 of Figure 2) and these responses were used to analyze whether students held scientific ideas, alternative non-scientific ideas, or were randomly responding to questions (Figure 3a). Scores that can be distinguished from random guessing provide insight into the ideas held by a student population. Our analysis indicates that most students (~70%) at HU are entering introductory geoscience with time-related conceptions that are aligned with scientific thought, while students at BH and UA are entering predominantly with misconceptions. 75% of students at HU are entering with scientific ideas about the way the Earth formed, specifically what it may have looked like at formation, and the appearance of life on Earth. Slightly fewer students knew the scientifically accepted age of the Earth, but we primarily view this question as a means of diagnosing major misconceptions or alternative ideas about deep time. Specifically, only 9% of HU students believed the Earth was less than 3 b.y. old, with 46% of the HU students answering the question correctly. In contrast, 38% of BH and 16% of UA students believed the Earth was less than one b.y. old, with 11-13% indicating that the Earth was less than 100,000 years old. Only 8% and 39% of BH and UA students, respectively, believed the Earth was 4-5 b.y. old. A significant number of students from all three institutions either did not respond to this question, or provided non-numerical answers such as "a long time ago", "when we were cavemen", "to dinosaur age", "at the beginning of time", and "to when man had first migrated to the American continents".

Another misconception revealed in both written responses and interviews involved the timing of the appearance of life on Earth (Figure 3b). Although students at HU were more likely to believe that life did not exist until sometime after the Earth formed, more than 30% believed some form of life did exist at the Earth's formation. Students at both BH and UA were more likely to believe life existed at the Earth's formation,

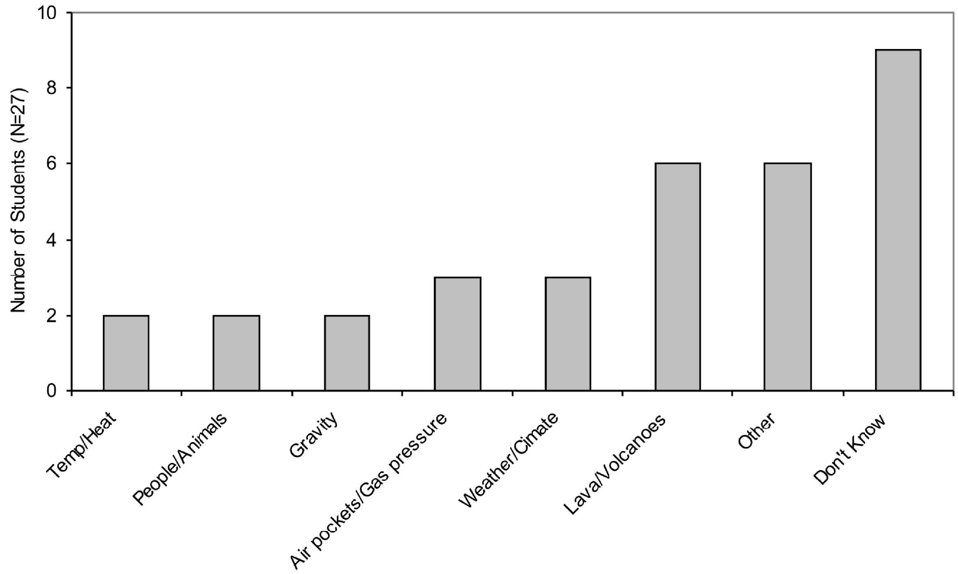


Figure 4. Alternative views regarding factors that may cause earthquakes, as revealed by student responses to the open-ended questionnaire (question 2 of Figure 2). Of 235 students responding to this question on the open-ended questionnaire, only 27 did not mention plate tectonics or faulting in written responses, although very few students were able to explain these terms when probed during interviews.

with more frequency than would be expected with simple guessing (Figure 3b). The types of life that students expected to encounter varied significantly. Three forms of life at formation dominated: a) simple or single-celled organisms (e.g., "Yep. Tiny microscopic Algee [sic] and microscopic organisms"); b) life in water (e.g., "sea type creatures/water animals Ex: fish/squid/alligator" and "huge sea creatures with no bones, therefore no fossils") and; c) all life observed today.

A number of other ideas about the type of life that existed when the Earth first formed were observed. A few examples that represent the range of ideas encountered in this study are presented here. According to students, in addition to the ideas of simple or single-celled life, life in water, and all life, other life that might have existed when the Earth first formed includes:

1) Dinosaurs: "yes. dinosaurs", "yes, different creatures-dinosaurs, reptiles, large fish, humans", "Bugs/dinosaurs", "Sure, dinosaurs, reptiles, amphibians. Because more dominant species would be in abundance", "Dinosaurs, b/c they were alive then", "Yes, everything that does today as well as dinosaurs", and "fish, dinosaurs?...". This view was not correlated to any other ideas, including the age of the Earth and its appearance at formation.
2) Insects: "I'm sure there were organisms probably small bugs", "yes bugs, bacteria", "I would encounter insects and fish in the ocean and some type of land animal", "plants..bugs maybe..", "yes, mostly small insects", and "yes, flies, bugs, pets [sic]".
3) Trilobites, which most likely stems from earlier instruction: "...trilobites...", "yes, trilobites", "Don't know what they're called [picture of a trilobite]", "Supposably [sic] some little things Like this [picture of a trilobite]", and "trilobytes [sic], ants and insects, dinosaurs, reptiles, crocodiles, etc.".
4) Plants as the only life form other than microorganisms: "plants, tress, grass", "Yes. Any plants or micro organisms", "plants", and "you would see plants".
5) Humans: "Yes, Egyptians, cats", "yes, different creatures-dinosaurs, reptiles, large fish, humans", "Adam and Eve", and "yes all that are here today". This idea was always linked to a religious reference or a young Earth, typically less than 100,000 years.

The ideas that single-celled or water-borne life existed when the Earth first formed may result from curricula or popular media used to teach concepts about life, specifically evolution. Students are taught that single-celled organisms were the first life to evolve, and that life most likely first evolved in water. For instance, one student wrote, "I think there would be living things but probably less and not like the ones today. I think the organisms I'd encounter would be things like fish, cockroaches…I would expect to see a fish like the coelcanth because they have been on Earth for such a long time. Also they are quite primitive". Another dominant alternative concept, that all life existed when the Earth was formed, most likely stems from religious teachings, as is demonstrated by the words of the students: "adam and eve?", "Yes, all according to Bible", "Yes-humans believe it or not-created on day six-all types of animals", and "Yes, in Genesis it says that God created all living things-plants, animals, and humans. There were probably Dinosaurs which became extinct". One student held the scientifically accepted idea, with a religious explanation, demonstrating this by writing, "No living thing for at least a week".

The open-ended questionnaire did not probe student ideas about the Earth's future. However, student interviews revealed a difficulty in extrapolating scientific concepts into a future context. For example, during interviews most students correctly showed the movement of continents from the past to the present, but many showed no change in position when queried about the appearance of the Earth's surface well into the future. Most students believed the Earth would maintain its

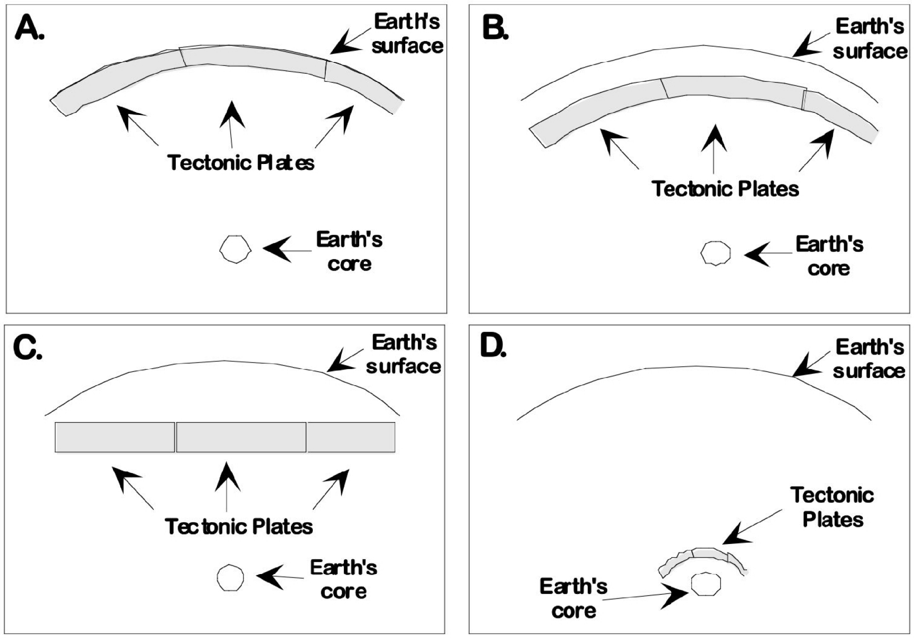


Figure 5. Schematic representing student ideas about the location of the Earth's tectonic plates as revealed during interviews. The scientific perspective (A) was rarely described by students; most believed there exists a discontinuity between tectonic plates and the Earth's surface (B). Other ideas relate to the planar versus spherical nature of tectonic plates within the Earth (C), as well as tectonic plates that are interacting with the Earth's core or atmosphere (D).

shape and size, although a few believed that the Earth was expanding or shrinking over time. The idea of an expanding Earth also appeared when discussing earthquakes (see below). Although students' understanding of the Earth's past has been an active focus of previous research, little work into students' ideas about the Earth's future has been conducted.

Earth's Crust - Student responses to questions in interviews and on the questionnaire regarding earthquakes, volcanoes, and the formation of the Earth's surface features provide a window into typical ideas about the Earth's crust. 235 students provided a written response on the open-ended questionnaire to the questions about earthquakes and their causes (Figure 2). A written response that included reference to plates, tectonics, faults, or released energy, and without significant reference to alternative mechanisms such as weather, was scored as a "correct" response. Interestingly, only 27 students gave written answers that we considered to be "incorrect" (Figure 4). These incorrect responses provided insight into alternative, non-scientific ideas held by students about earthquakes and plate tectonics in general, and many of these ideas were subsequently revealed in interviews. Alternative explanations for the primary causes of earthquakes included the influence of heat, temperature, climate, weather, people, and animals (Figure 4). Gas pressure, gravity, the rotation of the Earth and processes in the Earth's core, "exploding soil", and volcanoes as the only source of earthquakes were also called upon to explain earthquake occurrence. Finally, one student believed that the Earth was expanding, and this expansion resulted in earthquakes. Probing during interviews revealed that many students hold both scientific and non-scientific ideas about phenomena at the same time. While most students believed that plate tectonics was the primary mechanism responsible for earthquakes, interviews revealed that many students believed secondary causes were also important. A student possessing multiple ideas at once has been described in most areas of science (e.g., Taber, 2001).

During interviews, probing revealed that some students were unsure about the location of the Earth's tectonic plates, believing them to be somewhere below the Earth's surface, with empty or dirt-filled space between the tectonic plate and the Earth's surface. The motion of these plates was decoupled from the surface; in this view, tectonic plates move relative to the Earth's surface and the observer. A few students place tectonic plates at the Earth's core or in the atmosphere, effectively removing them from any possible contact with human-occupied space (Figure 5). This perspective-related misconception is similar to the ideas held by many elementary-aged students about the spherical Earth. Some children believe that the spherical Earth and the Earth that we live on are not the same object (Nussbaum, 1985), implying an inability to relate personal space to the larger space occupied by the Earth. Similarly, many students in this study were unable to conceive of tectonic plates relative to their own space, and most preferred to disconnect tectonic plates and their movement from the Earth's surface. This misconception may be a function of our inability to directly observe tectonic plates on a personal scale, and is analogous to the "hypothetical" misconceptions described by Lawson et al. (2000) with relation to time.

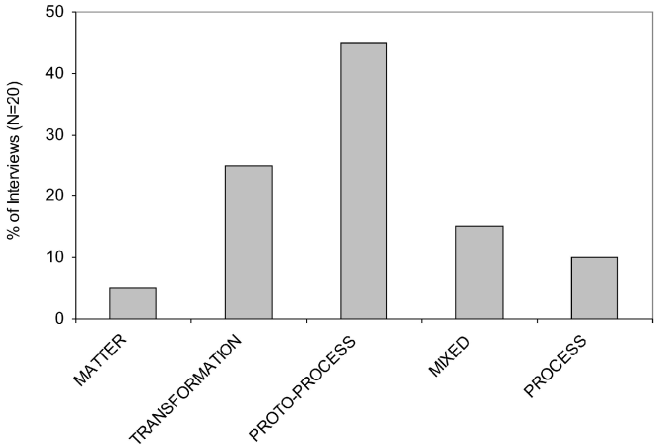


Figure 6. Distribution of ontologies observed in twenty coded interviews. Results indicate that few students are viewing the Earth from a process perspective, as would be required for complete understanding of Earth processes.

An interesting disconnect between the location of earthquakes and volcanoes on the Earth's surface was also observed during interviews. Although many students were able to identify a correlation between large earthquake occurrence and tectonic plate boundaries, few connected volcanoes with plate tectonics. Students believed that volcanoes only occur on islands, that they are associated with warm climates, and that volcanoes only occur along the equator, among other ideas. For instance, one student indicated correctly "This is the big plate. I think it is called the Pacific plate. And it is called the Pacific ring of fire because there is [sic] earthquakes and volcanoes all around this because this is the most active plate I believe." Another student indicated only a passing knowledge of volcanoes, "I guess that there is some down in Hawaii…I don't know, I guess, maybe somewhere along the borders of continents or somewhere along …along borders of…different countries, states…or mountain ranges…There's supposed to be…Hawaii, that's about it." Finally, several students felt volcanoes were associated with warm temperature, as demonstrated by this comment: "a lot of volcanoes are so hot you would think that they would have to occur in a warm area where it would allow it".

Earth's Interior - Most responses to the written question about the Earth's interior involved a drawing or description of spherical layers. A few students conceived of flat layers, similar to the findings of Lillo (1994) and Delaughter et al. (1998). However, we found student descriptions of the Earth's interior to be most telling. Specifically, many responses were based on analogies. The prevalence of analogies, such as "like a dartboard", "like a jawbreaker", and "like a baseball", may be reflective of methods used to teach these ideas in textbooks and K-12 curricula. Many students also used scientific terms, such as magma, mantle, and core, although most students were unable to explain these terms, or why spherical boundaries were drawn. Finally, almost all students mixed physical state (lithosphere, asthenosphere, mesosphere, inner core, outer core) and chemical boundary (crust, mantle, core) terms, indicating a lack of understanding of the basis for subdividing the Earth's interior. Student ideas about how we study the interior of the Earth were similar to those of Delaughter et al. (1998), although some students believed it was not possible to study the interior.

MENTAL PERSPECTIVES

In-depth analyses of twenty interviews indicate that most students have simplistic mental perspectives about geoscience subjects (Figure 6). Specifically, the majority of students interviewed do not actively view the Earth as a series of processes that result in changes to Earth materials, much less as integrated processes that form the basis of an Earth Systems Science perspective. Rather, most students view the Earth as a set of objects (matter) that experience changes (transformation), but not necessarily for specific reasons; if students acknowledge underlying causes, these causes are typically not clearly understood (proto-process). These findings are not, however, unique to the geosciences. Researchers in other fields have similarly found that students uniformly view the world as consisting of matter, and it is quite difficult for students to grasp concepts at the process level (Chi et al., 1994). Although we have added an intermediate category between matter and process, this similarity of worldview across disciplines may indicate that students are unlikely to develop a process perspective through traditional instruction alone. Further research into the cognitive differences between students with different mental perspectives may illuminate how all students can be taught to consider the underlying processes that shape the Earth and the Earth's surficial features.

CONCLUSION AND IMPLICATIONS

What implications does this study have for classroom instruction? Every student interviewed for this study reported previous exposure to geoscience concepts, typically in the early high school years. Students used scientific terminology in both written responses and during interviews, although most demonstrated an inability to explain this terminology or offered competing ideas that were logically at odds with the terms used. Intriguingly, this pattern repeats itself across most of the subjects probed in interviews, wherein students demonstrate exposure to ideas, but incomplete understanding. For example, ~97% of students used the terms "plate" or "plate tectonics" when responding to the open-ended questions about earthquakes (Figure 2). However, upon probing during interviews, few students were able to provide a scientifically appropriate explanation of the term "tectonic plate" (Figure 5). A similar phenomenon is observed when students are asked to describe their views of the Earth at its formation. Although many students correctly state the age of the Earth, these same students exhibit non-scientific ideas about how the Earth's age is determined, including scientifically incorrect views about carbon dating and radioactivity. These findings suggest that the incorporation of scientific terminology into an explanation does not necessarily imply understanding. Based upon the frequent use of scientific terminology by students, and their inability to adequately explain these terms, we propose that the use of scientific phrasing in introductory courses may be more harmful than helpful. Faculty may find it useful to refrain from using specific scientific words, such as "plate tectonics" or "radiometric dating", until after students have demonstrated a clear understanding of the concepts underlying the terminology. Finally, initial results suggest that analogies, particularly those used to describe the Earth's interior (e.g., "like a baseball"), may sometimes interfere with acquisition of scientific ideas. Similar findings have been reported in other geoscience content areas (Blake, 2001), as well as in physics (Duit et al., 2001).

Other scientific disciplines, especially physics, have linked student misconceptions to direct experience with the physical world. For instance, the prevalent idea that large objects fall faster in gravity than small objects most likely derives from the influence of air friction on real world phenomena (e.g., Osbourne, 1984). Although many geologic phenomena cannot be directly observed on human time scales, student misconceptions may be derived through experiences with books, secondary school curricula, religious instruction, film, and TV. Schoon (1992) points out that students who believe dinosaurs and people coexisted likely obtained this idea from the media, and our study suggests that religious instruction may also play a role in reinforcing this idea. Finally, these data revealed a number of ideas that may be derived from scientific ideas, such as the view that a supercontinent (Pangea) existed when the Earth first formed, that the Earth was covered with water or ice at its formation, and that algae or single-celled organisms have been present since the Earth formed. Faculty should be aware of the prevalence of these ideas since misconceptions will be in direct competition with the scientific ideas presented in the classroom. Faculty may inadvertently reinforce misconceptions that are based upon or similar to scientific concepts, and should be careful to place scientific facts and theories in an appropriate context.

This study may also have implications for current educational reform efforts in the geosciences. In particular, college faculty and K-12 teachers are being called upon to teach Earth Science from a systems perspective. As written in the National Science Education Standards (NRC, 1995), "A major goal of science in middle grades [5-8] is for students to develop an understanding of earth and the solar system as a set of closely coupled systems...systems provide a framework in which students can investigate the four major interacting components of the earth system..." Specific concepts identified for mastery by middle school students include clear understanding of the change in landforms resulting from constructive and destructive forces, of plate tectonics, and Earth's history, including the Principle of Uniformitarianism. Similarly, a report from a workshop convened specifically to discuss the inclusion of Earth Systems Science into undergraduate education states that (Ireton et al., 1997): "Earth system science conveys the complexities, ambiguities, and uncertainties of the processes that control and shape the planet...The Earth system approach allows students to understand not only the interconnected nature of the system but also how these connections add uncertainties to predictions." The report suggests that college-level geoscience courses should thus include a discussion of subsystems that make up the Earth system, interaction of these subsystems on both a temporal and spatial scale, and the interaction of people and the environment. Mastery of the ideas set forth in these documents requires a mental perspective amenable to viewing the world from more than a matter perspective. In particular, a view that objects will transform, and that there are clear mechanisms underlying these transformations, are necessary for full comprehension of these concepts. Our data suggest that college students are primarily situated at the transformation and proto-process levels; this suggests that instruction in Earth Systems Science at all levels may need to first address the general modification of students' ontologies prior to topic-specific instruction. Certainly, further research is needed to study the ideas and ontologies held by students at all grade levels, how students acquire a specific perspective, and how these perspectives can be modified to align with scientific views. Curricular reform efforts should acknowledge the influence of mental perspectives, especially when addressing conceptual change.

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