Barriers to College Students Learning How Rocks Form

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ABSTRACT

Students do not have a good understanding of how rocks form. Instead, they have many non-scientific alternative conceptions to explain different aspects of rock formation. Using 10 interviews and nearly 200 questionnaires filled out by students at four different colleges, we identified many alternative conceptions students have about rock formation. We then used themes within those alternative conceptions to identify the underlying conceptual barriers that cause them. Conceptual barriers are deeply-held conceptions that prevent students from understanding scientific explanations. One conceptual barrier can cause many alternative conceptions, and alternative conceptions can be the result of more than one conceptual barrier. The seven conceptual barriers identified in the study that prevent students from understanding rock formation are Deep Time, Changing Earth, Large Spatial Scale, Bedrock, Materials, Atomic Scale, and Pressure. Because of these conceptual barriers, students cannot form scientifically correct mental models of how rocks form, resulting in alternative conceptions, so the conceptual barriers need to be overcome before students truly learn the scientific explanations of how rocks form. The results of this study can be applied to other areas of geology in addition to rock formation.

INTRODUCTION

Rocks and how they form are among the fundamental topics in geology because we need to understand them in order to understand Earth's history and processes. The three rock types and the rock cycle are essential topics students should learn in college-level introductory geoscience classes (Kelso et al., 2000). Although rocks are a key element in most introductory classes in lectures, labs, and/or field trips, there is scant research on college students' conceptions (or alternative conceptions) of rock formation (Kusnick, 2002; Kortz, 2009).

To being able to effectively teach students scientific material, it is important to know if they are entering the classroom with alternative conceptions and what those alternative conceptions are. Students are not blank slates, and they use their prior knowledge to construct ideas about the Earth (e.g. Chang and Barufaldi, 1999; Kusnick, 2002; Taber, 2003). Although this prior knowledge may be non-scientific, students may still use it as a base for new knowledge taught in the classroom. As a result, they construct an inappropriate mental model, or representation of the phenomena. Therefore, students cannot learn the scientific perspective if they have their alternative conceptions still in place (e.g. Committee on Undergraduate Science Education, 1997; Clement, 2000; Gobert, 2000; National Resource Council, 2000; Taber, 2003; Chi, 2008). By knowing what those potentially non-scientific ideas are, instructors, researchers, and curriculum developers are better able to achieve an understanding of students' learning difficulties and help them appropriately.

Previous research on students' conceptions of rocks has focused mostly on children and how they describe and classify rocks (e.g. Happs, 1982; Blake, 2001; Blake, 2004; Blake, 2005; Ford, 2005; Dal 2006). However, Kusnick (2002) investigated pre-service elementary school teachers on their conceptions of rock formation based on writing assignments the students completed during the semester. She described many common alternative conceptions of those students and noted deeply-held beliefs of students that lead to those alternative conceptions. Similarly, Kortz (2009) found that college students in introductory geology classes do not view rocks as part of processes but instead as individual objects that often do not change. Notably, because many students view rocks as static objects, they may not intuitively understand that rocks form and change over time. Moreover, students often mix up the three rock types and do not discriminate between the distinct formation processes that distinguish them (Kortz, 2009).

Several investigators have examined in greater depth the underlying factors behind many of the alternative conceptions students have science in general, and about rocks in particular. We present a synopsis of their work as it pertains to the difficulties students have in understanding the rock cycle, that is organized around the terminology those investigators have introduced into the geoscience literature.

Critical Barriers – Hawkins (1978) identified "critical barriers" that prevent students from fully understanding scientific phenomena, and Ault (1984) applied them to rock formation. They define a critical barrier as "exceedingly unobvious" ideas that are difficult to overcome, since patient explanation rarely immediately cures it (Hawkins, 1978; Ault, 1984). Although grasping critical barriers is necessary to understanding in a discipline, they are often mastered relatively late in the learning of a science, despite their "elementary" nature. They often result from the conflict between common sense, intuitive, everyday notions about phenomena and the structure of scientific thoughts. Critical barriers are typically fundamental or basic concepts in a discipline, with the intimation that they should be easy to grasp. To the contrary, they are usually complex and subtle ideas, which are the end product of years of scientific research and controversy. They also presume significant prior knowledge about the topic, a point that becomes immediately evident when you attempt to "unwrap" a critical barrier. This occurs when developing STEM curricula that address grade span expectations (i.e.,

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standards) for K-12, as they often unwittingly list critical barriers as standards. Examples of specific critical barriers we have encountered in geoscience courses include the rock cycle, strike and dip, cladograms, and earthquake prediction. Of relevance to this paper is the classification of Ault (1982, 1984). He identified four broadly defined barriers to understanding the formation of rocks:

1. Bedrock – its existence, its scale, the pattern of layering, and other inferences about unobserved events
2. Large-scale physical patterns and the physical changes they represent
3. Geologic time
4. Scale (spatial)

Conceptual Prisms – Although the concept of critical barriers gives us a convenient framework for describing and categorizing ideas that students find difficult to grasp, it provides little insight into the reasons why these barriers occur. The work of Kusnick (2002) is germane, as she demonstrated that students have deeply held beliefs about the world, termed "conceptual prisms," that distort their understanding of how rocks form. Conceptual prisms result from the interaction of the student's world view and personal experience with what they were taught about rocks. They are deeply held but largely unexamined beliefs that refract geologic instruction, resulting in a spectrum of ideas about geology. The four conceptual prisms suggested by Kusnick are:

1. What is a rock? (common language vs. scientific language)
2. Scales of space and time
3. Stable Earth (landscapes are forever)
4. Human dominance (humans play a role in rock formation)

Clearly Ault's critical barriers to understanding rocks share much in common with Kusnick's conceptual prisms. However, the latter classification attempts to identify a deeper and more general set of barriers to learning that apply not only to understanding the rock cycle, but also to many other scientific ideas. This issue is the subject of an extensive literature that addresses the reasons why humans find seemingly "simple" scientific and mathematical concepts so difficult to grasp. It draws heavily from cognitive science and evolutionary psychology, and implies that there are universal constraints on how we process information, and that these constraints are "hard-wired". A review of this work is beyond the scope of this paper, and the reader is referred to Pinker (1997) and Marcus (2008) for entrées to the literature.

Threshold Concepts – Most recently, "threshold concepts" have been invoked to explain difficulties that students have in learning many topics over a wide range of disciplines (Meyer and Land, 2003; Stokes et al., 2007). Threshold concepts are a "mental blockage" that when cleared results in understanding or 'insight' opening up a whole new way of thinking or practicing in a discipline. They represent a transformed way of understanding, something without which the learner finds difficult to progress within the curriculum. Although little research has been performed to identify threshold concepts in geology, an extensive list was created of possible threshold concepts at a workshop on threshold concepts in geography, earth, and environmental sciences (Geography, Earth and Environmental Sciences Subject Centre (GEES), 2006). The workshop participants (GEES, 2006) and other researchers (e.g. Truscott et al., 2006) include the following possible threshold concepts relating to rocks and their formation:

1. Time - deep/geological time, absolute time
2. Scale e.g. time, distance, space
3. Rates of activity
4. Metamorphic processes
5. Crystallography
6. Chemical reactions
7. Bonding interactions of atoms
8. Rock cycle
9. Tectonic plate

The "mental blockage" of Meyer and Land is the same as Ault's critical barrier. However, unlike Ault, Meyer and Land are focused on the transformative process by which the barrier is removed.

Conceptual Barriers – In this study, we identify common alternative conceptions of college students' understanding of rocks and their formation. Our goal is to use patterns in these alternative conceptions to find their underlying conceptual causes which pose barriers to students' comprehension. As Libarkin and others wrote (2003), "Understanding the common thought processes applied to different content matter is a powerful method for understanding how students view the world around them."

The findings of previous studies regarding barriers to learning are used as an initial platform to aid in our investigation of the underlying conceptual causes. Although they are not completely analogous, critical barriers, conceptual prisms, and threshold concepts all are concerned with the barriers to learning, and the ways in which they may eliminated. We will use the term **conceptual barrier** in this paper to describe this idea. As used in this paper, a conceptual barrier is an underlying, deeply held conception that prevents students from understanding the scientific explanation. Here, the term also refers to the underlying causes of the barrier, and the ways in which they can be eliminated.

METHODS

Methodological Approach – We used a qualitative approach to identify alternative conceptions of students and analyze them for underlying conceptual barriers. Specifically, we relied on in-depth interviews of students' views of rocks and their formation and questionnaires about rocks and interpretations made from rocks. We chose a qualitative approach in order to gather rich sources of information to best answer our exploratory research question. There are no quantitative tools currently available to gather the necessary data.

Research Population – The conceptions of 196 students enrolled in 12 introductory geology classes taught by 6 different instructors at 4 schools were investigated through questionnaires distributed over two semesters in this study. Table 1 gives information about the participating schools and classes. The variety of institutions and instructors helps to reduce the possible influence of individual instructors' emphases and teaching styles. Previous studies on rocks have mostly focused on a smaller diversity of students (e.g. Happs, 1982; Blake, 2001; Blake, 2004; Blake, 2005; Ford, 2005; Dal 2006).

In addition, at the end of the second semester of data collection, 10 students taking introductory geology courses from the large community college on the East Coast were interviewed by the first author. In this study, the interviewed students will be referred to by a pseudonym. This name is used so the students remain anonymous, and other than gender, it does not represent any personal information about the student.

The interviewed students were purposefully selected and represent a spectrum of academic abilities in geology classes. Four students were female (Beth, Elizabeth, Grace, and Harriet), one considered himself a minority (Carlos), their ages ranged from 20 to 27, and none of the students were science majors. Three students (David, Felipe, and Grace) remembered taking a class in high school in which they learned about rocks. In general, these students represent the broad make up of students who take geology classes at this community college.

The interviewed students had been taught by 3 different instructors at the large community college on the east coast. All students took one introductory geology class where they learned about rocks, except Beth and Elizabeth, who had taken two. The classes were all fairly "typical" introductory geology classes where students learned about rocks in both lecture and lab. The information that follows about each class is self-reported information by the professors.

Beth and Carlos took introductory geology from one professor. This professor taught about rocks during 10 to 15 50-minute classes throughout the semester, frequently revisiting the topic. Approximately 85-95% of the class was spent lecturing, with the remaining time devoted to answering student questions (which sometimes lead to group discussions), looking at rocks, and showing videos. In lecture, rock identification and the relationship between features within rocks and their formation were emphasized. There were 4 labs devoted to rocks (including a field trip to learn about building stones), and the labs emphasized identification of rocks and minerals, rock chemistry, and formation.

Harriet and James took introductory geology from another professor. This professor lectured for seven 50-minute classes about rocks, sometimes bringing in samples for the students to observe. Lecture focused on rock identification, the three rock types and how they form, the rock cycle, and how the rock cycle relates to plate tectonics. There were three labs on rocks emphasizing observing, describing, identifying, and classifying them. Two additional labs used maps to relate rock type and deformation in order to read the geological history of certain areas.

Andrew, Beth, David, Elizabeth, Felipe, Grace, and Ian took introductory geology from the final professor at the community college on the East Coast. This professor has taught over 20 introductory geoscience classes and has been recognized with a teaching award. Rocks were taught during approximately seven 50-minute classes throughout the semester. Roughly one-half to two-thirds of class was spent lecturing, with the remaining time used for students to complete worksheets (such as Lecture Tutorials, see Kortz et al., 2008), answer Conceptest questions (see McConnell et al., 2006), have small group student discussions, and watch videos. Lectures emphasized general rock formation and the information that can be learned from rocks. There were three or four labs on rocks (depending on the section), where students identified rocks, classified them in categories reflecting information about formation, and related rocks to geologic maps, making interpretations about the history of the area. This professor also included an optional field trip in the class.

Research Tools – Questionnaires were distributed to all participating students (see Appendix A for a list of

TABLE 1. STUDY POPULATION[1]

School Type	Location in U.S.	Size	Ethnicity (percentages)[2]					Intro Geology Course Information		
			African American	Asian/Pac. Islander	Hispanic	Caucasian	Other[3]	Class Size	Lab?	Field Trip?
Comm. College	East coast	Large	7	3	12	65	13	15-28	Yes	Opt.
Comm. College	South	Large	25	2	31	22	11	20-30	Yes	Unk.
Comm. College	West Coast	Med.	9	24	32	19	9	45-53	Opt.	Yes
State Univ.	East Coast	Med.	5	2	4	75	14	34	Yes	Opt.

[1]Information about the schools and courses in which the students who completed the questionnaires were enrolled.
[2]Ethnicity may not add to 100% due to rounding and students not reporting their ethnicity.
[3]"Other" includes Native American, non-resident alien, and unknown.

questions on the questionnaires). The questionnaires asked questions probing several different aspects of rocks and what can be learned from them. For example, there were several questions that asked the students to "Tell me about the rock [basalt / limestone / schist or gneiss / granite]." The questionnaires are further discussed in Kortz (2009).

In the interviews, students were given hand samples of rocks (Figures 1 and 2), and they were asked questions about the rocks, their appearance, formation, history, and future. Between one and three rocks were examined in detail during each interview. The interviews were semi-structured, and probing questions were guided by students' responses. Example questions asked during the interviews are given in Appendix B. Example probing questions include "How would that happen?", "Then what happens?", and "How long would that take?" During the interview, the interviewer would occasionally summarize the students' statements back to them in their own language to verify that her understanding matched what the students meant. The interviews ranged between 20 and 60 minutes long and were transcribed verbatim, resulting in 192 pages of double-spaced transcripts.

Analysis – We began our analysis by examining the subset of the questionnaire questions that asked students to "Tell me about the rock." These questions were initially coded for underlying themes of alternative conceptions using constant comparative analysis (Glaser and Strauss, 1967; Lincoln and Guba, 1985) following the methods described by Erlandson and others (1993).

Student answers were broken down into segments representing discreet alternative conceptions. These segments ranged in size from phrases to several sentences. We formed categories of related alternative conceptions, and as we analyzed more students' answers, we compared the categories and modified them to incorporate the new information. As more answers were analyzed, the categories morphed, splitting into separate categories as they became too heterogeneous, or merging into single categories. Once the categories captured all the variations in the students' ideas, a final list of alternative conception themes was generated. In this way, the themes emerge from the data and are a reflection of the students' answers.

FIGURE 1. The granite used during the interviews. This is a pink granite, measuring 13 cm across.

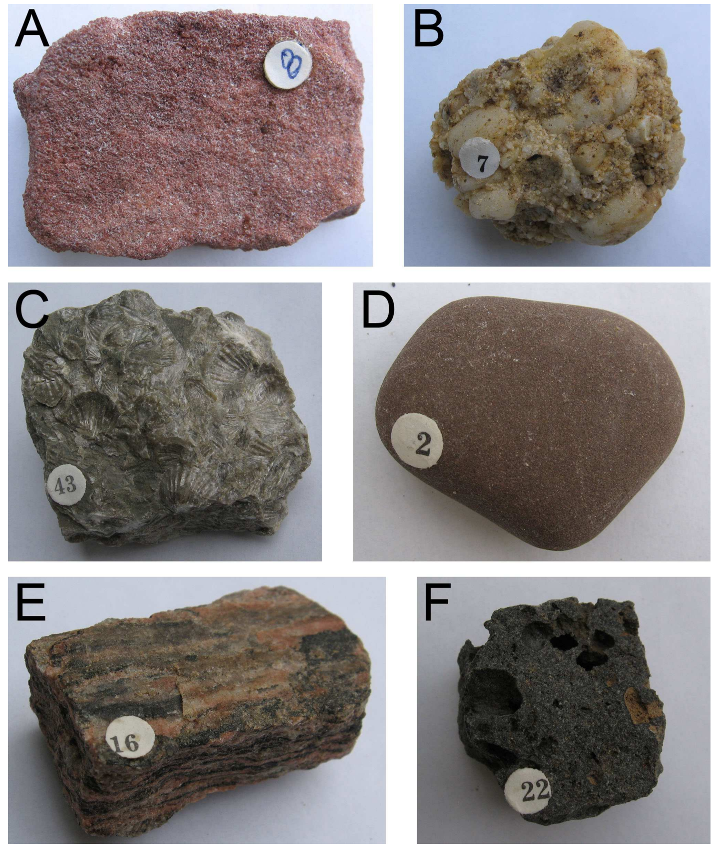

FIGURE 2. The optional rocks used during the interviews. Students were directed to pick a rock of their choosing to talk about. The rocks range from 3.5 to 5 cm across. The rocks are: (A) red sandstone, (B) conglomerate, (C) limestone with shells, (D) siltstone, (E) gneiss, and (F) scoria basalt.

For example, the student who completed Questionnaire 8F wrote about basalt: "Bottom of the ocean from sediments and magma. Hardened by pressure from the water. It is subducted and melted to form new rocks." We divided this answer into four segments, two of which contained alternative conceptions: "from sediments and magma" and "hardened by pressure from the water." Our initial categories in which we placed these alternative conceptions were "Igneous rocks contain sediments" and "Igneous rocks form from pressure, reactions, or drying out," respectively. These two categories were eventually reconfigured into the single category "Igneous rocks are not the result of magma crystallizing."

To help identify underlying causes of student alternative conceptions, we grouped the alternative conception themes uncovered in the questionnaire under larger-scale themes. We tried to identify what might cause students to have a particular alternative conception, resulting in the identification of conceptual barriers. Published barriers to learning, such as conceptual prisms (Kusnick, 2002), critical barriers (Ault, 1984), and threshold concepts (GEES, 2006), were used to help create these overarching themes. We established four initial themes from the initial analysis of the questionnaires. These themes were: rocks = handsamples not bedrock; scales of space (atomic to kilometers) and time; stable Earth; and recycling of materials. We interpreted the alternative conception described in the example above, "Igneous rocks are not the result of magma crystallizing," to be a result of the students not understanding the atomic processes involved with magma crystallizing into minerals forming a solid rock, so it could be explained by the "scales of space and time" overarching theme.

Once the initial overarching themes were established from the questionnaires, the interviews were analyzed with those themes. During the interviews, the students explained their thoughts in much greater detail than on the questionnaire and gave explanations of their thinking resulting in some of the alternative conceptions. With this additional information, we adjusted and refined the themes using the constant comparative method to best reflect the thinking of the students. For example, we found that the initial theme combining the scales of a range of distances and time was too heterogeneous to properly reflect students' thoughts and difficulties with understanding geologic concepts, so we divided it into the separate categories of microscopic distances, immense distances, and long periods of time.

Finally, the student answers on all questions on the questionnaires were analyzed with the newly adjusted themes, to reclassify the alternative conceptions and verify that the themes truly represent the student data. At this point, no major changes were made to the themes, and we felt satisfied that we had captured the essence of the conceptual barriers to students' understanding with our themes. We discussed the themes with colleagues to get additional perspectives.

Building Trustworthiness – Trustworthiness in qualitative research is what validity and reliability are in quantitative research. Erlandson and others (1993) wrote (based on the paradigm established by Guba and Lincoln, e.g. Lincoln and Guba, 1985) that trustworthiness "demonstrate[s] its truth value, provide[s] basis for applying it, and allow[s] for external judgments to be made about the consistency of its procedures and the neutrality of its findings or decisions" (page 29). The four aspects of trustworthiness are credibility, transferability, dependability, and confirmability. Each of these, as it applies to this study, is described in Table 2.

Study Limitations – In this study, there were ten students who were interviewed, all from the same East Coast community college, and they were purposefully selected to get the most information from the interviews. Because these students were not randomly selected, we cannot say they are a representative sample of the overall population of geology students, even at the one community college. Although nearly 200 students filled out the questionnaires, from a diversity of institutions across the United States, the questionnaires did not probe students' beliefs so they represent a minimum of alternative conceptions. As a result, although the themes identified describe the students in our population with a high rate of consistency, they may not be fully representative of the overall population of geology students. Further research is needed to determine how widespread and deeply held the barriers are across populations.

CONCEPTUAL BARRIERS TO LEARNING

Many of the alternative conceptions that students have will still give them correct answers on many questions about rock formation. Therefore, it is often difficult to know if the students truly understand the processes that form rocks. Table 3 lists quotes from students during interviews that give the impression that

TABLE 2. TRUSTWORTHINESS AND HOW IT IS APPROACHED IN THIS STUDY

Aspect of Trustworthiness	What It Measures	Comparison to Quantitative Research	How It Is Approached in This Study
Credibility (whether the research conclusions match what the participants thought)	Truth Value	Internal Validity	• Triangulation (collection of information from different points of view) with interviews and questionnaires • Triangulation with questions on different topics to collect student views from different perspectives • Interviewer summarized student descriptions back to students • Colleagues provided feedback after reading portions of interviews • Use of student quotes to demonstrate link between students' words and interpretations
Transferability (the extent the findings can be applied outside of the study)	Applicability	External Validity	• Description of classes and students from which data were collected • Purposive sampling to maximize the range of information from the interviews
Dependability (whether the findings would be repeated under similar conditions)	Consistency	Reliability	• Triangulation (described above) • Code-recode procedure of analysis • Peer review by colleagues
Confirmability (whether conclusions can be tracked to the source)	Neutrality	Objectivity	• Triangulation (described above) • Student quotes used to illustrate link between source and interpretations

they understand the rock forming process. However, upon further probing during the interviews, the students reveal some alternative conceptions (also given in Table 3), indicating that the students do not truly understand how the rocks formed.

The alternative conceptions illustrated in Table 3 are a just a few examples of the vast array of alternative conceptions students possess about rocks and their formation. In the following section, we explain our theory that many of these alternative conceptions exist because there are underlying conceptual barriers to student learning. Because students do not have a good understanding of these underlying conceptual barriers, they cannot have an accurate picture of how rocks form, resulting in alternative conceptions.

Table 4 summarizes the seven conceptual barriers to learning how rocks form that were identified in this study as well as alternative conceptions that result from the conceptual barriers. These conceptual barriers are described in detail below. Example alternative conceptions that are caused by each barrier are also described, as well as some possible explanations that these beliefs exist. The frequency with which the students displayed the conceptual barriers and alternative conceptions in the interviews and questionnaires is also given in Table 4. The alternative conceptions listed are selected because they were expressed by at least three students in this study. In addition, some of the alternative conceptions were previously described by other researchers as well, and we note where this is the case.

Many of the students' alternative conceptions are related to more than one barrier. For example, this study found that the idea that granite forms from magma is an extremely difficult concept for students to grasp because there are many conceptual barriers that need to be overcome to succeed in learning this concept. As a result, students have many alternative conceptions to explain the formation of granite.

Deep Time – Because most geological processes take a very long time to happen, students need to have a grasp of the concept of geologic time to truly understand how rocks form. In order to make sense of the rock cycle, students also need to realize that it takes many millions of years for rocks to cycle through. However, students do not have a good grasp of deep time (Trend, 2000; Trend, 2001a; Trend, 2001b; Dodick and Orion, 2003a; Dodick and Orion, 2003b; Hidalgo and Otero, 2004; Libarkin et al., 2007) and try to put the formation of rocks into scales with which they are familiar.

Examples of alternative conceptions that are caused by this conceptual barrier are:

1. ***A "long time" is at most thousands of years***. When students hear that rocks take a "long time" to form, they think in terms of their own lives, and most place the time scale to be hundreds to thousands of years. This time scale makes it impossible for students to understand slow processes such as metamorphism or the formation of thick layers of sedimentary rock. For example, when David was asked how long it took for a rock to change to the way it looks now, he responded, "It would take a great deal of time. It's not something that just happens, maybe a couple

TABLE 3. CORRECT-SOUNDING STUDENT QUOTES UNTIL THEY ARE EXPLAINED

It Sounds Good (Student Quote)	But…(Further Explanation by Student)
Andrew: "The lava comes up through hotspots and it forms basalt when it cools."	Basalt is made from sediments. Sediments form in the core, are brought to the surface by hotspots, then mold together to form the rock basalt.
James: "This is the extrusive rock… Extruded from some kind of volcano."	The rock came from the magma chamber wall or the volcano. It came out of the volcano, possibly carried by the magma, but it can not stay in the magma because it would melt.
Elizabeth: "Maybe if the magma was still inside of the Earth and it didn't come up, parts of that magma could become granite."	Basalt picks up crystals from a rock layer as it rises to the surface. Under pressure beneath the surface, the crystals combine to get bigger and form granite.
Carlos: "But when that rock [granite] starts cooling down, … the formation stops."	In beach sand, minerals pack together, and the compression is from volcanic heat or hot weather. The rocks become bigger over time, but stop growing when the compression from heat stops.
James: "This rock [granite] probably formed in some underground magma chamber that cooled."	Minerals are added to magma from the chamber walls or from other rocks in the magma. The minerals migrate to each other, fuse, and cool slowly to form rock.
Andrew: "One of those softer rocks like silt or shale… can be formed by the different sediments that are like, almost like mud or something that it will come together."	Streams carry sediments, which then clump together. The clumps are deposited at the sides or end of the river, and they dry to form rocks. The drier the rock gets, the weaker it gets.
Elizabeth: "[Sand] would somehow need to get deposited into the earth. … It becomes layered, so the deepest layers gets the most heat and pressure and becomes sandstone."	The layers are several centimeters thick, so the rock is forming less than a meter below the surface.
Grace: "When … the limestone becomes – comes together and becomes a solid form, maybe it encaptures some of the life that was in the ocean."	Limestone is sticky and soft, attracting shells to it. It slowly hardens over time because it dries and the calcium in it hardens.
David: "Metamorphic is like changing rock, I believe. It changes over time."	Metamorphism includes weathering of the rock's surface and imprints from fossils.
Elizabeth: "I think it was broken off of a bigger piece… It would be a layer of the Earth."	The layers of the Earth about a meter long and several centimeters thick.

hundred years."

2. ***People play a role in moving sediments and rocks***. People are naturally anthrocentric, so they place humans into roles of moving ancient sediments and rocks (Kusnick, 2002). This belief likely stems from students' personal experience of the human influence in city landscapes, such as seeing excavations and noticing sediments on roads. In addition, some students may have heard humans are currently Earth's principal geomorphic agent (e.g. Hooke, 2000 and Wilkinson, 2005), but did not consider the different time scales involved between human activities and the formation and deformation of rocks. Students also describe animals, usually birds and fish, as often playing a role in moving sediments and rocks. For example, Harriet described fossils in a sedimentary rock as forming because

> "the fish dropped the empty shells down and then another deposit of the ocean floor bed came over, you know, just by, like, currents or whatever moving the ocean floor around depositing more clay on top of the shells and then more little fish drop more shells."

Students do not picture enough time to be able to see significant changes from slow geologic processes.

3. ***Rocks come to the surface through volcanoes or earthquakes***. Because students cannot picture the wearing away of thick layers of rock, they describe a much quicker process of bringing deeply-formed rocks to the surface where we can see them. These catastrophic events quickly move rocks to the surface.

Changing Earth – Students view the Earth as static, so they do not think of things as forming. Because rocks form and are a result of changes to the Earth, this view inhibits students from truly understanding how rocks form (or that rocks form!) and what they can tell us about the Earth in the past. This barrier is tied to the Deep Time barrier, because if students do not understand the enormous lengths of time available for geological processes to act, they will not believe that things on Earth can change. David is an example of a student who does not have a complete grasp on the idea of a changing Earth, illustrated by the following quote:

Int: If it [a rock] started off underground…, how did it

TABLE 4. CRITICAL BARRIERS AND RESULTING ALTERNATIVE CONCEPTIONS

	n interview[2]	% questionnaire[3]
Deep Time[1]	**9**	**5%**
A "long time" is at most thousands of years.	5	0
People play a role in moving sediments and rock.	5	1
Rocks come to the surface through volcanoes or earthquakes.	4	2
Changing Earth	**9**	**15**
Features on the Earth do not appear or disappear.	1	10
Rocks pre-exist in magma.	2	2
Sedimentary rocks are located in the environment in which they are formed.	4	1
Igneous and metamorphic rocks need exotic conditions to form.	3	1
Large Spatial Scale	**10**	**5**
Sedimentary rocks form at or just beneath the Earth's surface.	3	1
Layers in rocks are the same as layers in the Earth.	4	0
Volcanism is needed to provide the heat for rock formation.	4	0
Rocks move down into the Earth through earthquakes, divergent boundaries, cracks, or by burying themselves.	3	2
Magma and rocks come from the core.	4	1
Bedrock	**9**	**22**
A rock forms as a hand sample.	7	16
Pieces purposely gather to form rocks.	4	1
Granite is made from sediments.	5	2
The ground is not made of rock.	2	4
Materials	**7**	**5**
Magma turns into a black rock and black rocks were magma (i.e. black = igneous).	4	1
Rocks can change color.	2	1
Rocks can change into any other rock.	2	2
Atomic Scale	**10**	**9**
Igneous rocks are not the result of magma crystallizing.	8	5
Sedimentary rocks form by wet sediments drying.	3	0
Minerals form separately, then come together to form rocks.	3	1
Metamorphic rocks melt.	2	2
Pressure	**7**	**1**
Pressure to form rocks is caused by things like heat, water, faults, and air.	6	1

[1]Critical barriers to learning (in **bold**) and example alternative conceptions that result
[2]n interview is the number of interviewed students (out of 10 students) expressing misconceptions explained by this barrier or expressing the given misconceptions
[3]% questionnaire is the percentage of students who completed questionnaires expressing misconceptions explained by this barrier or expressing the given misconceptions.

get there?
David: How did it get underground?
Int: Mmhmm.
David: I just thought that's how the world was made.

Examples of alternative conceptions that are caused by this conceptual barrier are:

1. ***Features on the Earth do not appear or disappear***. Students view features on the Earth, such as mountains or seas, as permanent features. For example, on the questionnaire, students were asked how we would know if there was an ancient mountain range in an area if it had eroded completely away. Many students responded that you would look for hills, not believing that the mountains could disappear completely. Similarly, in response to a question on the questionnaire about how we know that some dinosaurs lived next to water, some students responded that the area would still be low-lying or full of sediments today. For example, the student who filled out Questionnaire 9BB wrote "because of the plants … and maybe theirs [sic] mud."

2. ***Rocks pre-exist in magma***. Students have a difficult time believing that rocks can form, especially from a liquid (see the Atomic Scale conceptual barrier), so they picture the liquid magma moving rocks that already exist. For example, James was asked about rocks and their relationship to magma and responded,

> "They could have been rocks that broke away from the chamber wall. They could have been already formed rocks that were introduced into the magma… It could have been that exact size that just never broke down or never grew. So it's hard to say if that was created on the walls and broke away or in the middle… There could have been absolutely nothing there and was introduced from another vein that intruded the magma chamber."

Students picture the magma chamber walls and volcano as always being there and not forming from magma. The idea that pieces of basalt come out, solid and intact, from a volcano is also documented in other research (Dal, 2006). This view that rocks pre-exist in magma also ties to the conceptual barrier of Bedrock, since the students do not view igneous rocks as forming extensive bodies.

3. ***Sedimentary rocks are located in the environment in which they are formed***. Kusnick (2002) also described this alternative conception. Students describe most limestone as being found in the ocean and conglomerate as being found in a river, and if you want to find sandstone, you would look in a desert. They do not picture features and environments of the Earth changing. Again, this ties to Deep Time since students do not think about the fact that there is ample time available for things to change. Also, this alternative conception links to the conceptual barrier of Large Spatial Scale because students picture sedimentary rocks as forming at or right below the surface.

4. ***Igneous and metamorphic rocks need exotic conditions to form***. Students do not view the formation of rocks to be a "normal" event of the changing Earth, so they require an unusual process to form the rocks. Extreme heat is often correctly described as necessary to form igneous and metamorphic rocks. However, the extreme heat is usually described as coming from the core of the Earth, volcanoes, or asteroid impacts. One student wrote on Questionnaire 8B that "Schist and gneiss are metamorphic rocks that form in instances of extreme pressure and heat, not in typical locations, so there was most likely a fault there in the past." This student does not realize that the conditions necessary to form metamorphic rocks are actually quite widespread in the Earth.

Large Spatial Scale – Most rocks form deep underground and must somehow be brought to the surface in order for people to see them. However, although the rock formation happens deep underground, it still occurs in the outer skin of the Earth. Within the outer skin of the Earth are many large-scale beds or layers of rocks. Students are unfamiliar with this view of the structure of the Earth, and the relationship between the different aspects of the interior.

Examples of alternative conceptions that are caused by this barrier are:

1. ***Sedimentary rocks form at or just beneath the Earth's surface***. When asked how deep sedimentary rocks (such as sandstone) form, most students during the interviews described a depth that could be dug to with a shovel. They do not have a sense of the enormous depths at which most sedimentary rocks are formed. Tied with this belief of shallow burial, students, understandably, believe that sedimentary rocks form in the environment in which you find them (see Changing Earth), and they do not realize the immense times necessary to form the rocks (see Deep Time).

2. ***Layers in rocks are the same as layers in the Earth***. Students mix up geologists' use of the term layers and take it to mean layers within a handsample, layers in an outcrop, and layers within the earth. For example, the following is Felipe's discussion of gneiss (Figure 2f):

Felipe: This rock, I think it's a piece from a bigger rock, so it's just a section.
Interviewer: How big was that bigger rock?
Felipe: I'd say a layer of the Earth, uh plate, a really big layer, probably kind of thick. Actually a few layers because of the stripes [in the handsample]. It's probably its own separate layer, so I'd say this came from a few sections, a chip off a few sections.
Int: Could you give me an approximate estimate of how big that would be?
Felipe: How big? Hmm, each layer looks like it's a few millimeters, so a rock, sandstone, maybe I'm trying to picture, maybe a few hundred feet tall.

Some students also expressed that the bottom of a hand sample was significantly older than the top, again mixing up scale of layers. Without a view of the large scale of the layering of bedrock, students cannot have a complete picture of an area. Ault (1984) also described students having difficulties picturing extensive layers of bedrock.

In addition, some students view there to be layers of different minerals within the Earth's crust and mantle. This belief appears to stem from a misapplication of Bowen's reaction series and layered magma chambers, but this connection needs to be investigated further.

3. ***Volcanism is needed to provide the heat for rock formation***. Because students do not picture rocks as forming kilometers beneath the surface, they cannot understand the heat source to form these rocks. As a result, they turn to a geologic source they know is hot, and require volcanoes or magma to provide any heat necessary to form rocks. This alternative conception also implies that they have little concept of the thermal structure of the Earth.

4. ***Rocks move deep into the Earth through earthquakes, divergent boundaries, cracks, or by burying themselves.*** Students have a difficult time picturing rocks moving to great depths by gradual burial by layers upon layers of sediments. So, they ascribe a process to bury rocks beneath the surface, although usually not far beneath the surface. Students described rocks falling into cracks at divergent boundaries and as a result of earthquakes. Also, Ian described a rock moving down away from the surface because it "buries itself in the ground" and James said that "every time you step on dirt, you compact it into a certain level. You're pushing minerals down." These students do not understand the scale of the depth needed to form or transform rocks.

5. ***Magma and rocks come from the core.*** Because the core is molten and hot, many students think that either magma or rocks and minerals in magma came up to the surface from the core, usually through hotspots. This disconnect between the scale of the Earth and the scale of magma sources of volcanoes has also been seen by other researchers (Kortz et al., 2008; Libarkin and Anderson, 2005).

Bedrock – The subsurface of the Earth is made up of bedrock. The bedrock is extensive and made up of solid, continuous rock and rock layers. When a geologist sees a handsample of rock, they know that it came from a much, much larger body. If a student does not understand the nature of bedrock, they will tend to view rocks as small pieces. This is how they normally see rocks around them, both in class or lab and in their daily lives.

Examples of alternative conceptions that are caused by this barrier are:

1. ***A rock forms as a handsample***. When students describe how rocks form and change, they describe how handsamples of the rocks form and change (also described by Happs, 1982 and Kusnick, 2002). Even when they describe a handsample as breaking off of a much large piece, that "much large piece" will typically be a small enough size where it will fit onto a table. Students do not apply the processes of rock formation to something that creates bedrock. This view is likely a result of the students almost exclusively seeing handsamples of rock, both in a geology lecture and lab as well as in their everyday lives. In the following example, Carlos understands that a granite handsample comes from a much larger piece, but the size of that piece is dictated by what he has seen in his personal experiences:

> Int: And how big was it [granite handsample] before?
> Carlos: Before, it could have been, maybe around 4 feet, maybe more.
> Int: And how did you come up with that?
> Carlos: I came up with that number because usually when you go to places and try to buy granite, they usually have really long [slabs]. They're like maybe 6 feet high, 4 feet…

2. ***Pieces purposely gather to form rocks***. Students view pieces of rock, such as sediments or minerals, as migrating together to form handsamples of rocks. They do not think of vast layers of sediments turning, as a whole, into a rock. Rocks are formed with a purpose. For example, when asked what creates granite, James responded "Well the quartz. You have your micas, the different blends that just attract chemically. You know, they migrate towards each other… I mean the time and energy the earth put into just creating this rock is, I can't even explain it." This belief relates to Kusnick's (2002) growing pebbles (also described by Ault, 1984; Blake 2005; and Dal, 2007) where students describe rocks existing in streams because they slowly grow over time as sediments accumulate. Andrew sums up this perspective,

> "The sediments would come down the river, and I think that eventually, I think they pick up different pieces or whatever along the way, kind of clump together to form maybe different types of rocks…. Once they reach the end, wherever the river dumps out into the sides of the shore, and once they dry up, they can form into rocks."

A corollary to this alternative conception is that not everything is part of the rock cycle. There are some materials, such as dirt, that do not ever form rocks. The rock cycle is thought to take specific particles or sediments, and move them around, through everything else, in order to form the new rocks. Students often do not picture everything taking part. The top layer of the Earth especially (what students can see) is not thought to participate in the rock cycle. For example, Ian describes rocks and minerals combining to form new rocks, but ignores any material that might be between them as not taking part in rock formation:

> Int: How close would they [rocks] have to be [to combine]?
> Ian: Well I would just assume that they would have to be almost pushed within, to each other. I mean pressurized so they need to compact so they would have to be very close. Because obviously they can't just be, an arm's length away or what not, because that's not going to push it together. You have to be touching each other."

3. ***Granite is made from sediments***. Students do not picture granite as a vast, solidified magma body that underlies huge areas. Because granite is made up of

different minerals of different colors, shapes, and sizes, students picture those minerals coming together to form granite as an accumulation of sediments. Some students described granite as sand accumulating and then compressing together. Students picture granite forming as a small rock that might form as large as a countertop (see previous student discussion under "A rock is a handsample"). Carlos describes a sedimentary process for forming granite in the following quote:

> "A lot of beaches, they have different color sand… You basically take… some of the black, some of the white, some of the mix that we have here, and you end up crush it together, you end up forming a new type of rock or a certain type of rock, like granite…. Maybe Connecticut might have certain type of granite, and maybe in like California they might have a different type of granite, because it's a different area with different sediment coves."

4. ***The ground is not made of rock***. Students see mountains and volcanoes as being made out of particles, such as boulders, smaller rocks, and dirt, instead of solid rock. When asked what mountains are made of, Beth responded, "The actual particles that make up the mountains? Because that's sand and some little rock pieces, like the big sand and gravel pieces." Ault (1984) also identified this alternative conception. This view furthermore results in students not realizing that volcanoes are formed from the build-up of lava. Carlos describes a volcano being there before it started erupting lava, "It starts building up kind of like… a mountain and when the volcano starts to become active…" This alternative conception was also documented by Dal (2006), and relates to the conceptual barrier of Changing Earth.

Materials – To know what a rock is and how it formed, you need to know the materials that make up that rock. Minerals and the elements that make them are key factors in rocks. Not understanding the relationship between rocks, sediments, minerals, and atoms poses large barriers to learning how rocks form.

Examples of alternative conceptions that are caused by this conceptual barrier are:

1. ***Magma turns into a black rock and black rocks were magma (i.e. black equals igneous)***. If students see a black rock or black pieces in a rock, they automatically think igneous. On the flip side, when students think of igneous rocks, they picture the rock as black. This alternative conception results from the everyday experience of hot, burnt material being black. Also, when students see pictures of volcanoes erupting, the resulting rock is typically black. As a result, although students understand basalt is igneous, they cannot picture granite as being an igneous rock. Andrew describes a granite handsample, explaining that it could not have been magma,

> "I think it was solid rock because I think if it was lava it would be more just black, more solid black. It may have been partly lava because there is some black in here… But I think it was not originally lava because I think it would be a darker color than what it is."

2. ***Rocks can change color***. Although weathering may change the color on the surface of a rock, students believe that the color of the entire rock can change. One of the most common factors that students attribute to changing rock color is heat, which they feel can make a rock redder or black. Grace describes this perspective, "I would have thought that heat would have made it darker just because, kind of when you think about volcanic rock, it's black and you kind of just associate blackness with heat." Students who view that rocks can change color will have a difficult time understanding the information geologists gather from rock color, such as composition of igneous rocks and organic content in shale.

3. ***Rocks can change into any other rock***. Because many students do not understand the chemical and mineral make-up of rocks, they picture that any rock can change into any other rock. For example, on the questionnaire, students described granite metamorphosing into marble, sandstone melting into granite, and basalt turning into limestone. Sibley and others (2007) also described students' use of nonsensical transitions of rock types.

Atomic Scale – The formation of most rocks results from atoms crystallizing into minerals. If students do not understand the very basics of atoms and especially the processes of how they react with each other, they will have a difficult time grasping the formation of rocks, especially igneous and metamorphic.

Examples of alternative conceptions that are caused by this critical barrier are:

1. ***Igneous rocks are not the result of magma crystallizing.*** Students have a difficult time accepting that minerals grow from "nothing," although they acknowledge that rocks can change and minerals in them can grow larger. Students cannot picture how a homogeneous liquid can turn into a heterogeneous solid, such as granite. An example of a student (Elizabeth) with this alternative conception is, "I don't know what rock it would have been before granite. Because it would have to have at least some evidence of small crystals I would say." Since many students view minerals as being added to the rock, or the rock originally starting with small crystals already in it, students view magma as allowing the minerals to combine and grow. They do not see the magma itself crystallizing. Therefore, the belief that magma does not crystallize results in some students thinking that lava does not turn into a rock. For example, one student answered on Questionnaire 7E that "Basalt is found near lava/magma," illustrating that basalt and lava are separate entities.

2. ***Sedimentary rocks form by wet sediments drying.*** Students have seen mud (a sediment) or cement dry to form a solid mass, and translate this process to the formation of sedimentary rocks without considering the differences between sediments and rocks at the atomic level. This alternative conception (observed as well by

Kusnick, 2002) also ties to students not understanding the immense time scales involved in forming rocks. This belief may also be enforced by students learning that many sedimentary rocks form in the absence of water, such as limestone forming when oceans evaporate, sandstone forming from dry desert sand, and conglomerate forming after flooding. As a corollary, students believe that sediments in a sedimentary rock are held together by dried mud, something cement-like (in the sense of concrete), or something sticky. Students do not view the sediments as being attached at the atomic level.

3. ***Minerals form separately, then come together to form rocks***. Students do not always describe a rock forming in place. They often describe minerals forming in one place, and then being transported to form a rock. Andrew expresses this perspective when talking about granite, a rock with obvious minerals, "They [sediments] form together from coming up to the surface of the Earth and then they come to the top of the crust to form, they basically cool together to form different parts of the rock." Notice that this student correctly describes granite as forming when minerals cool, although he has a very different process pictured than geologists do. This view of minerals forming separately from rocks leads to students having difficulties distinguishing how the three different rock types form, since this view would have all rocks forming in the same general way.

4. ***Metamorphic rocks melt***. Students do not understand the atomic changes involved in metamorphosing rocks. Because metamorphism is often described as involving heat and pressure, students often assume that the heat means the rocks melt. They have little experience with things changing in the solid state, so they cannot picture it happening.

Pressure – Most rocks, as they are changing or forming, are compressed by immense pressures. These pressures are outside the normal experiences of students, and are therefore difficult to grasp and understand their cause.

An example of an alternative conception that is caused by this conceptual barrier is:

1. ***Pressure to form rocks is caused by things like heat, water, faults, and air***. Although students realize that most rocks require pressure to form, they do not have a firm grasp of what causes pressure. Because many rocks require both heat and pressure to form, many students link the two in a causal relationship, with heat causing the pressure. Also, many students underestimate the amount of pressure necessary to compress sediments together and think that air and water (such as at the bottom of a stream) could cause enough pressure. Carlos describes several causes of pressure for the formation of granite in the following quote:

> "I believe it needs water because it needs to get basically compressed together. You can do it by heat, like volcanoes do if they melt. You can do it by water, cause if you take sand and put it together, and say you leave it there in a hot, hot place, it'll get harder and harder, and all the different things that are in there basically it'll decrease the water in the sediment, and it'll get all compressed together by the weather again."

DISCUSSION

Pervasiveness of Conceptual Barriers – The conceptual barriers are widespread among students. All ten of the interviewed students held alternative conceptions that can be explained by the seven conceptual barriers. One student (Felipe) was identified as having only three of the seven barriers, one student (Harriet) had five barriers, three students (Andrew, Carlos, and Ian) had six barriers, and the remaining 5 students describe alternative conceptions explained by all seven of the barriers (see Table 4 for the distribution by conceptual barrier). Nearly half of students filling out the questionnaire (93 of 196) wrote at least one alternative conception that can be explained by the seven conceptual barriers (see Table 4 for the distribution by conceptual barrier). No obvious pattern was observed between the barriers students had with the introductory course in which they were enrolled or their achieving level in the introductory geology courses. The students also expressed many additional alternative conceptions and incorrect statements that were at a more "shallow" level, such as "granite is extrusive" and "basalt is shiny." Many of these appear to be based on the students incorrectly remembering the features of a particular rock. Because the students filling out the questionnaires mostly did not go into depth in their answers, and because they were not probed for more information, the number of students answering the questionnaire holding alternative conceptions explained by the conceptual barriers is likely much higher.

Many of the alternative conceptions explained by the conceptual barriers and the conceptual barriers themselves have been described by researchers examining students' conceptions on geologic topics other than rocks and rock formation. For example, Dickerson and others (2005) described students' difficulties with scale as an impediment for understanding groundwater. Many of the geoscience alternative conceptions listed by Kirkby (2008) can also be explained by the conceptual barriers described in this study. For example, the conceptual barrier of Deep Time explains the alternative conception, "Plate motion is rapid enough that continent collision can cause financial and political chaos, while rifting can divide families or separate a species from its food source." Students do not realize that continents collide or divide over millions of years. Another example, "Rivers do not carve valleys, but only passively flow down them," can be explained by the conceptual barrier of Changing Earth, since students view the valleys as always existing. Therefore, the conceptual barriers to rock formation as described in this study likely also apply to many other areas of geology.

The conceptual barriers of geologic time (Deep Time as well as Changing Earth) and spatial literacy (Large Spatial Scale as well as Bedrock and Atomic Scale) identified in this study have been described by other researchers when discussing problems to learning geology in general. For example, Manduca and Mogk (2006) describe "three of the most fundamental characteristics of geoscience thinking [as] space, time, and complex systems" (page 51). Kastens and Ishikawa (2006) and Dodick and Orion (2006) discuss the spatial realm and geologic time, respectively, in detailed terms of how geoscientists think and learn about the Earth.

Some of the barriers described in this study are unique to geology, while some are likely shared with other sciences. Alternative conceptions explained by the conceptual barriers of Atomic Scale and Pressure have been described in other sciences (e.g. Ben-Zvi et al., 1986; Henriques, 2000). However, because geology is a historical science that deals with immense time and distance scales, it has many unique aspects that make it different than other sciences. In particular, the barriers described in this study of Deep Time, Changing Earth, Large Spatial Scale, Bedrock, and Materials (in rocks) are all barriers that make geology uniquely difficult for students to understand. As a result of its uniqueness, geology needs to be taught differently than many other sciences. In particular, going out in the field is an integral aspect of learning geology and may help in reducing conceptual barriers (see below).

Mental Models – Mental models, or cognitive models, are "an individual's representation of a phenomenon, and are used to explain that phenomenon and predict outcomes" (Libarkin et al., 2003). For example, a student would create a mental model of how granite forms, and that student would use that mental model to answer questions and make predictions about granite. Since individual students have many of the conceptual barriers identified in this study, they cannot construct an appropriate mental model of rocks and how they form and change. In the example of granite, if a student does not have a correct conception of the conceptual barriers of Changing Earth, Large Spatial Scale, Bedrock, Materials, and/or Atomic Scale, they cannot form a scientifically-correct mental model of granite formation. Therefore, because the conceptual barriers exist in the students' understanding, they cannot develop scientifically-correct mental models, so alternative conceptions result.

A student's prior conceptions of the Earth, such as the conceptual barriers identified in this study, dictate how new knowledge is perceived and organized within mental models. If a student does not realize that bedrock exists, they will not perceive rock formation as occurring in vast areas. If they do not consider that events can occur over millions of years, they will not understand the slow processes of metamorphism or uplift. Table 5 gives examples of typical statements an instructor (or geology textbook) may make and how it may be interpreted by students. The table was created by summarizing views expressed by students during the interviews. This potential interpretation by students is a result of them having scientifically incorrect mental models (resulting from the conceptual barriers) which cause them to integrate the instructor's statement into non-scientific interpretations, creating alternative conceptions.

Implications for Teaching – The results of this study have several implications for teaching geology. First, the instructor needs to be aware of the conceptual barriers. If the instructor does not know where students have difficulties in understanding rock formation, then they will not be able to effectively help students. Instructors may not initially find this necessary, since students may be answer exam questions relating to rock. However, Table 3 illustrates that reasonable statements made by students may actually be hiding incorrect mental models. Table 5 lists students' possible interpretations to statements that the instructor may think are extremely clear and obvious. However, because of the underlying conceptual barriers carried by the students, these statements are often misinterpreted. If the instructor is not aware of this possibility, they will not be able to teach effectively.

Second, it is important to make students aware of the barriers by directly talking about them. Learning should not be like a mystery novel, where students need to discover the barriers for themselves (because most will not!). Instead, present the students with some of the difficulties they may encounter when trying to learn geologic concepts.

Third, even if students are aware of the conceptual barriers, it still may be very difficult for them to get past them. Not all the conceptual barriers are likely at the same difficulty level to learn, and some might be easier for students to get past. An example in geology where research has been performed is on the subject of deep time. Although research shows that it is extremely difficult for students to understand deep time, one way to help get the idea across is to use relative times (Trend,

TABLE 5. STUDENT INTERPRETATIONS OF INSTRUCTION

What the Instructor Says[1]	What Students May Interpret
Granite is igneous.	Granite is made up of sediments that are igneous. Pieces of granite come together in magma. Magma causes heat which fuses sediments to form granite.
Metamorphic rocks form from heat and pressure.	Heat is from the Earth's core or volcanoes. Pressure is from heat or water. The heat melts the rock. Metamorphism can occur at the Earth's surface, if the conditions are right.
Sandstone forms in deserts.	Desert sand can combine (often by drying) into rocks, at or right below the surface. Sandstone is found in the desert.
It takes a long time for rocks to form.	Rocks take 10 to 1000 years to form.
Basalt erupts from a volcano.	Solid basalt pieces come out of a volcano, sometimes in the lava.
Sediments are often formed in mountains.	Earthquakes and plate motion grinds rocks in mountains to form sediments.

[1]Among other explanations during lecture

2000; Trend, 2001a; Hidalgo and Otero, 2004). For example, students view the Ice Age as being a long time ago, so it might be useful to describe a rock as starting to form before the Ice Age. Visual representations of temporal scales may also help students to better grasp the immense time involved.

Student-centered learning environments often increase student learning more than lecture alone (e.g. Hake, 1998; National Research Council, 2000; Crouch and Mazur, 2001; Chiu et al., 2002; Meltzer and Manivannan, 2002; McConnell et al., 2003; Steer et al., 2005). In this active learning environment, students are at the center of their own learning, and the instructor helps to guide them in their cognitive development. McConnell and others (2005) reported that students intellectually developed more quickly and consistently in a course where inquiry based learning and group work was used. Because students in an inquiry-based, student-centered environment learned to think more abstractly, they would have an easier time understanding the conceptual barriers, as many of the conceptual barriers require an element of abstract thinking.

However, student-centered learning environments are not a silver bullet. The activities need to be well-designed with proper scaffolding to guide the student learning process, because using alternatives to lecture may not automatically increase student learning (Hake, 1998; Libarkin and Anderson, 2005; Kirschner et al., 2006) and, decrease, as a result, the conceptual barriers. Labs are often active learning environments, but students must be required to do more than classify and identify rocks in order to help reduce conceptual barriers. In addition, although one of the instructors of the interviewed students used active learning methods frequently during instruction, these methods were not developed with knowledge of the conceptual barriers. Developing activities (both for lecture and lab) that specifically and repeated focus on the conceptual barriers would likely have a significant positive effect on reducing them.

A technique described by Ault (1984) for overcoming barriers to learning is to make everyday experiences meaningful in terms of scientific notions. Because students use their everyday experiences to try to understand geology, a good way to help them understand geology is to tie the difficult geologic concepts back to their everyday experiences (Ault, 1984; National Resource Council, 2000; McConnell et al., 2005). For example, Ault (1982) uses the analogy of a compost pile with layers of different ages to help students understand relative time and bedrock layers.

Finally, it is very important to expose students to geology in the field. Geology is different from most other sciences, and field work is integral to our understanding. Fieldtrips are one of the best ways for students to see bedrock, examine the materials, view the slow processes involved, and interpret past environments, all of which will help them overcome the conceptual barriers. Orion (1993) writes that field trips provide a "direct experience with concrete phenomena and materials." These concrete experiences link hands-on experiences with the theoretical information learned in class, allowing a transition between concrete and abstract levels of cognition (Orion, 1993; Orion 2007). The implications of this use of field trips is that field trips should focus on the interaction between students and the environment with a focus on process instead of content, and there should be significant devotion to a summary that includes more "complex concepts which demand a higher abstraction ability" (Orion, 1993). The summary periods after the field trips are ideal for students to better understand geologic ideas to help reduce their conceptual barriers. For example, Elkins and Elkins (2007) found that students in a field based introductory geology course had better conceptual understanding of geology topics than students in a similar classroom-based course.

CONCLUSION

Many students do not have a grasp on the fundamental aspects of rock formation, and, as a result, they have many alternative conceptions explaining how rocks form. It is our hypothesis that there are themes connecting these alternative conceptions, and these themes are deeply-held conceptual barriers that prevent students from understanding many aspects of rock formation. The conceptual barriers identified in this study are Deep Time, Changing Earth, Large Spatial Scale, Bedrock, Materials, Atomic Scale, and Pressure. As a result of these conceptual barriers, students cannot form scientifically-correct mental models of rock formation. Information learned instead is applied incorrectly, and alternative conceptions result. The conceptual barriers identified during students' explanations of rock formation also can likely explain other alternative conceptions in geology as well.

Although this research answers questions about student learning, many more are raised. For future work, it would be good to document how widespread these conceptual barriers are across the larger populations, from novice geology students to geology majors to graduate students to practicing geologists. It would be useful to investigate when in their education geologists overcome these conceptual barriers, and how they get past them. Are there best practices in the classroom (such as making students aware of the conceptual barriers or targeting them with specific assignment and labs) or are fieldtrips and field work necessary? It would also be helpful to relate these findings in conceptual barriers of rock formation to the different fields within geology as well as the different sciences. Do students across the sciences have similar barriers to learning? And finally, research is needed to find out more about causes of conceptual barriers, which may help us better overcome them.

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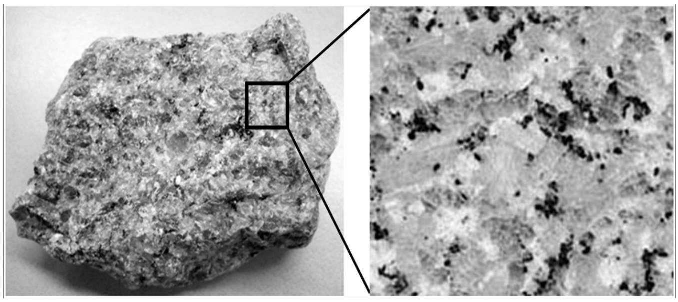
APPENDIX A: QUESTIONNAIRES

There were 6 versions of the questionnaire, with each version containing overlapping, but slightly different questions than the other versions. The first table contains Questions 1, 2, and 6 on the questionnaire, divided by version into columns. The second table contains Questions 3, 4, and 5 on the questionnaire, also divided by version. Not all questions on the questionnaire were analyzed in this study.

VERSIONS 1 AND 4	**VERSIONS 2 AND 5**	**VERSIONS 3 AND 6**
A person on TV says the area in which they are standing was the location of a volcano that erupted many millions of years ago, long before people saw the area. The volcano is no longer there. How did they figure that out?	You find out that a particular area was once an ancient mountain range that has since eroded away. What would you expect to see?	A paleontologist determines that a group of dinosaurs once lived next to a shallow sea. How did the paleontologist figure out that there was a shallow sea?
A group of friends goes on a hike, and the occasionally pick up rocks along the way. All the rocks they pick up are gneiss and schist. What can they figure out about the area in which they hiked?	A new planet is discovered, and there is limestone covering the surface. What can you figure out about this planet?	You and a friend are examining a picture of a person holding a rock. You notice that the rock is basalt and the entire background in the picture is also basalt. What can you tell your friend about the area where the picture was taken?
Tell me about the rock limestone.	Tell me about the rock basalt.	Tell me about the rocks schist or gneiss.

VERSIONS 1, 2, AND 3

Tell me about this rock:

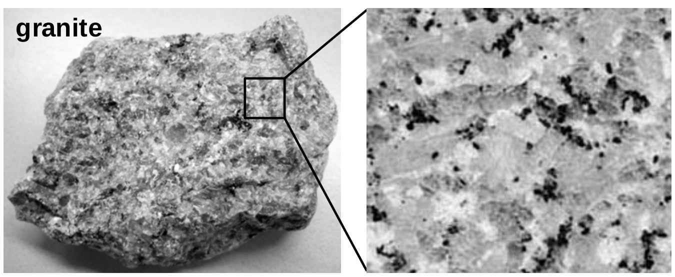


How do rocks change over extremely long periods of time? If possible, give examples.

Why do you think you learn about rocks in this class?

VERSIONS 4, 5, AND 6

Tell me about this rock:



If you had to explain the rock cycle to a friend, what would you say?

What can a rock tell you about its history?

APPENDIX B: INTERVIEW QUESTIONS

The following questions were used as guides for the semi-structured interviews to learn about students' conceptions of rocks. These questions were asked in no particular order, and not all questions were asked during each interview. These questions were used to frame interviews, but most questions asked were based on the respondents' answers to previous questions.

What is a rock?
Tell me about this rock. [discussing a hand sample]
How has the shape of this rock changed over time?
What was this rock like before…?
Where?
When?
What will this rock be like in the future? The past?
If you wanted to go find rock like this, where could you find it?
Where did this rock come from?
How does this rock fit into what geologist call igneous, sedimentary, and metamorphic rocks? *(note: Try not to use these words before the student does, but try to get at this idea. By the end of the interview, if it doesn't come up, may ask a question such as: Some people say that this rock is an igneous rock…)*
Why do geologists study rocks?