Research Methodologies in Science Education
Assessing Students' Alternative Conceptions

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Faculty often have a variety of unique expectations for student learning. At the introductory and non-major levels, goals for geosciences courses can vary widely, although they typically include several of the following: deep conceptual understanding of fundamental principles, improved understanding of the processes of science, improved attitudes toward science, and skills development (critical thinking, synthesis, and communication). Apart from attitudinal shifts, many faculty would agree that beginning geosciences courses should provide students with the knowledge and skills necessary for complex decision-making about their own interactions with the Earth. For students to achieve deep conceptual understanding, they must be familiar with fundamental content knowledge and be able to apply it to complex questions. What are some barriers to achieving this level of understanding? Which instructional strategies will help students achieve conceptual understanding of fundamental geoscience concepts? How do we know if students have reached a deep conceptual understanding? This column will explore these issues.

WHAT ARE ALTERNATIVE CONCEPTIONS?

New faculty members who are teaching introductory geoscience courses for the first time are often eager to impart their knowledge and love of geology to their students. New instructors often envision teaching as inscribing "blank slates" with a breadth of geology knowledge. If students really were "blank slates", perhaps teaching and learning would be effortless. In reality, students come to formal education with a large range of knowledge, skills, experiences, and beliefs that influence how they perceive the natural world, and how they categorize and interpret it (National Research Council, 2000). This prior knowledge and experience affects students' abilities to remember, reason, and acquire new knowledge. Contemporary views of learning postulate that people construct new knowledge and understanding based on what they already know and believe (Piaget, 1978; Vygotsky, 1978; National Research Council, 2000). Because new knowledge is built from existing knowledge, many educators contend that instructors should pay attention to these incomplete understandings of concepts (called "misconceptions" in older education literature, now commonly referred to as "alternative conceptions" or "preconceptions") that students bring with them.

HOW DO ALTERNATIVE CONCEPTIONS INFLUENCE STUDENT LEARNING?

College students often hold alternative conceptions about physical and biological phenomena that fit their experiences but do not fit scientific accounts of the natural world. Consequently, students' personal understanding of Earth systems can impact the way in which they understand and retain the formal geoscience teaching they are exposed to. A number of researchers have suggested that students' alternative conceptions can be as important to conceptual understanding as pedagogy (National Research Council, 2000). Many education researchers contend that these alternative conceptions must be addressed in order for them to change to scientific conceptions (Posner et al., 1982; Driver & Odham, 1986; Minstrell, 1989). If students' alternative conceptions are not engaged, they may fail to grasp the new concepts that are taught, or they may memorize them for the purposes of the test, but revert to their alternative conceptions outside the classroom. Numerous studies demonstrate that alternative conceptions often persist after instruction (Schneps, 1987; National Research Council, 2000).

Some researchers contend that alternative conceptions need not be addressed directly; rather, what is needed is a focus on key concepts coupled with clear explanations and extensive applications (Muthukrishna et al., 1993). This type of instruction helps students build a new conceptual framework that is independent of previously held beliefs. Research on problem solving has revealed that experts utilize different strategies than novices when faced with new information (National Research Council, 2000). Experts possess a deep foundation of factual knowledge that is carefully organized into a conceptual framework. This extensive, discipline-based know-ledge affects how experts make observations and how they organize and interpret information and this, in turn, increases their abilities to remember, reason, and solve discipline-specific problems. Once students are able to organize information into a conceptual framework, they are better able to apply what was learned to new situations and to learn related information more quickly. Our role, as educators, is to help students build this conceptual framework. Confronting alternative conceptions directly is one way to help students gain conceptual understanding, but researchers disagree on whether it is the best or only viable strategy.

Parts of the Earth are flat and other parts have mountains:

- How would you describe a mountain to someone who has never seen one?
- How long do you think mountains have existed? Are they as old as the Earth, or did they form before or after the Earth?
- Where do mountains come from?
- What causes them to occur in some places, but not others?

Figure 1. Open-ended questionnaire about mountain formation.

HOW CAN WE IDENTIFY THESE ALTERNATIVE CONCEPTIONS?

One way to identify alternative conceptions is to develop short questionnaires to probe students' prior knowledge. We should begin with a literature search via GEOREF *and* ERIC (education reference database) using a phrase such as "student and conceptions and geology". In addition, we should check references that index publications on alternative conceptions. A large research base on alternative conceptions in science exists (references in Wandersee et al.1994, bibliography by Pfundt and Duit 1994), but the majority of published papers pertain to physics; fewer studies target students' alternative conceptions in earth science, astronomy, biology, and chemistry. Many of the classic papers in misconceptions research deal with students younger than those in universities; however, this research is not immaterial to undergraduate education. Many college students hold similar alternative conceptions about the workings of the natural world.

Suppose you are interested in students' views of the dynamic changes that can occur to the Earth's crust but your literature search *does not reveal* any studies on this topic. If your goal is to quickly identify students' views before you begin this unit of the course, you may want to compose your own questionnaire. For example, if you wanted to probe student understanding of mountain formation, you could create a targeted questionnaire which probes foundational beliefs about mountains and their evolution (Fig. 1). This questionnaire would be administered during class and your students should be told why you need their input, with assurances that their responses will not be graded. You could quickly read through their responses to get an idea of the range of student views on mountain formation, and instruction could be modified accordingly. You might also administer the same questionnaire after completing the unit to see if/how students' views had changed after instruction.

In the case of mountain formation, a literature search would have revealed two research papers that address students' conceptual understanding (Muthukrishna et al. 1993, Chang and Barufaldi 1999). After reading these papers, you could compose a question about mountain formation that includes a wide array of possible answers that act as *distractors*. Distractors are response options that coincide with commonly held alternative conceptions, usually identified through extensive interviews with students. The resulting questionnaire might resemble Fig. 2. Each of the responses in the questionnaire is derived from the available literature and represents an idea students have suggested for the mechanism(s) that result in mountain formation (E is the "correct" response). The questionnaire also asks students to explain their choice, thereby giving the instructor additional information about students' thinking. Administration of this questionnaire prior to instruction would enable you to quickly identify the most common preconceptions held by your students. The questionnaire could also be used as a post-test to assess instruction-related progression from non-scientific beliefs to scientific understanding.

An alternative method for identifying alternative conceptions is to have students construct *concept maps*. A concept map is a diagram showing the mental connections that students make between a major concept and other concepts that they have learned. A concept map consists of nodes, each containing concept labels, which are linked together with directional lines, also labeled, that describe the relationship between concepts. The concept nodes are arranged in hierarchical levels that move from general to specific concepts. For example, a concept map of mountain formation would be ordered from the general concept of Plate Tectonics, through more specific ideas related to uplift and specific types of faults (Fig. 3). Step by step instructions on constructing and using concept maps (as well as many other useful classroom assessment techniques) are available in Angelo & Cross (1993) and also on the web site - Field-tested Learning Assessment Guide for

Complete this sentence:

Mountains are______________________________.

Which of the following do you believe might cause mountains to form?

Mark as many choices as you think apply:

- A. Wind blowing pieces of rock and sand into a pile
- B. Gravitational attraction of the Moon causing rocks to bend
- C. Minerals pushing up from beneath the Earth's surface
- D. Landslides creating piles of rock
- E. Continents pushing against each other
- F. Pressure under the surface pushing rocks up
- G. Oceans receding and leaving rocks behind
- H. Ocean water evaporating and leaving mineral deposits behind

Please explain why you have made this choice(s).

Figure 2. Multiple-choice questionnaire with distractors. Each of the responses in the questionnaire is derived from the available literature

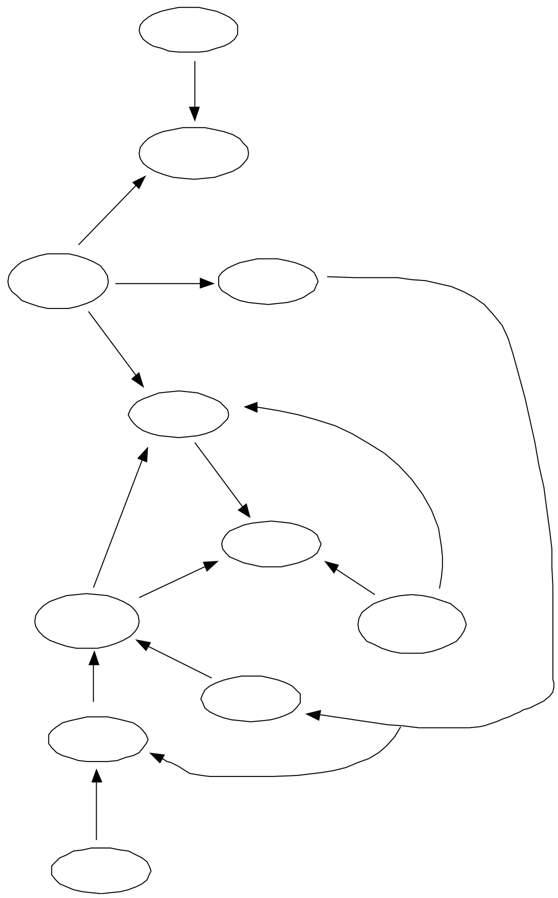

Figure 3. Concept map of mountain building.

Science, Math, Engineering, and Technology Instructors. By reading a concept map from top to bottom, an instructor can gain insight into the way students view a scientific topic and examine the valid understandings and misconceptions students hold. After students have mastered concept mapping, some instructors will generate concept maps and leave certain nodes blank (often called "select and fill-in concept maps'). The instructors usually provide a list of concepts and ask students to work in collaborative groups to fill in the missing concepts. This can be a very effective way of getting students to discuss their thinking and expose understanding as well as confusion.

Compared to targeted questionnaires, this approach will initially require more instructor and classroom time. Most undergraduates will never have seen a concept map before, and many will not have the learning skills needed to construct one. As a result, the instructor will need class time to work with students. However, this initial investment is worthwhile, as concept maps are also useful for helping students see the "big picture" and organize their knowledge into a conceptual framework.

WHICH TEACHING STRATEGIES HAVE THE POTENTIAL TO TRANSFORM STUDENTS' ALTERNATIVE CONCEPTIONS INTO SCIENTIFIC UNDERSTANDING?

So now that you have a handle on your students' alternative conceptions, how do you proceed? Simply pointing out that students' misconceptions do not match scientific conceptions will have little effect. Although there is no magic bullet, some teaching techniques (pedagogies) do appear to facilitate the development of scientific understanding.

There are many different theories of learning and each has implications for teaching. Posner and colleagues (1982) argue that conceptual change can occur *only* when students are dissatisfied with their current understanding and have ready access to a better idea (the scientific conception). Additionally, the new idea/conception *must* be understandable, reasonable, and useful to the student in order for conceptual change to occur. Posner and colleagues (1982) make the analogy between conceptual change and paradigm shifts. For example, scientists once thought that the continents of the earth were held rigidly in place, and most scoffed at the theory of continental drift when it was originally developed. However, when sufficient evidence was accumulated that contradicted this view, and the theory of plate tectonics was developed, scientists abandoned the old ideas in favor of the new theory, simply because plate tectonics had more explanatory power.

Instructors who are guided by conceptual change theory typically use the following instructional sequence to catalogue and target students' alternative conceptions:

1) identify students' views/preconceptions;

2) create opportunities for students to explore their preconceptions and test their ability to explain phenomena and make predictions;

3) provide stimuli that make the limitations of student's preconceptions apparent to the student, leading to dissatisfaction with the preconception;

4) provide many contexts where scientific conception has much more explanatory and predictive power than alternative conception(s).

In essence, according to conceptual change theory, the instructor's task is to lower the status of alternative conceptions and raise the status of the scientific conception. Classroom research confirms that this approach can be effective (National Research Council 2000). However, this technique is not always successful; for example, this approach did not help some college students develop a scientific understanding of evolution (Demastes et al. 1995).

Not all researchers agree that alternative conceptions need to be explicitly addressed in instruction. Muthukrishna and colleagues (1993) contend that well-designed science curricula will help students develop conceptual frameworks. They contend that curricula that present concepts coherently and unambiguously and provide lots of opportunities for students to apply the concept will eliminate alternative conceptions. Few researchers have taken the specific approach advocated by Muthukrishna and colleagues (1993). However, many instructors teach science as inquiry. The inquiry approach can be characterized as encouraging students to practice and implement the processes and thinking skills associated with the work of professional scientists. These skills include forming, testing, and evaluating hypotheses, and predicting, observing, and synthesizing new information. This approach differs from the conceptual change ap-

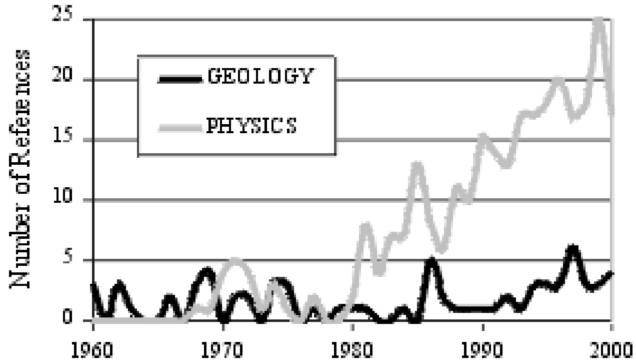

Figure 4. Number of papers published which discuss students' conceptions of physics and geology, 1960-2000. The education reference database ERIC was searched using the phrase "student and (conception or conceptions or conceptual)", and then subdivided using the phrases "physics" and "geology or geoscience or geosciences or Earth". INSPEC and GEOREF, the most comprehensive physics and geology reference databases, respectively, were also searched. The numbers presented here are sums of the ERIC, INSPEC, and GEOREF searches, and include journal articles and papers prepared and presented at conferences, but not abstracts. Studies of geological conceptions have remained at a baseline level (0-5 papers) for the past 40 years, while studies of physics conceptions began to increase in number in the early 1980s. Notice that this increase coincides with the publication of one of the first studies of college student preconceptions in physics originating from within the physics community (Halloun and Hestenes, 1985a; 1985b).

proach (i.e. Posner et al. 1982) in that there is no formal elicitation of students' alternative conceptions. This instructional approach has been shown to be effective in many disciplines (National Research Council 2000). For example, seventh grade students in an urban school who were given inquiry-based physics instruction were shown to do better on conceptual physics problems than eleventh and twelfth grade suburban students who were taught by conventional methods (White and Frederickson 1998).

As instructors in introductory and advanced courses, we are in a unique position to collect data on our teaching and our students' learning. The data we collect can help reveal which instructional strategies are most effective at helping students to develop coherent scientific understandings of geological processes.

DEVELOPING A GEOSCIENCES CONCEPT TEST

Classroom research on students' alternative conceptions of geological processes can ultimately lead to the development of a diagnostic assessment tool in the geosciences. There is a need for a geosciences concept test and such a test would have multiple uses. Tests offer individual instructors a way to quickly analyze the views of their students. They allow instructors to determine if instruction has had any effect on students' conceptual understanding at the end of a unit or course. Finally, tests can be used as a means for evaluating gains in students' conceptual understanding of geological processes across a variety of teaching methodologies, curriculums, and course structures and between instructors and universities.

The development of such a diagnostic assessment tool in physics has had a dramatic impact on the physics education community. Hestenes and others (1992) developed the Force Concept Inventory (FCI) after extensive study of student "commonsense beliefs" (Halloun and Hestenes, 1985a; Halloun and Hestenes, 1985b). The FCI is now a widely used instrument and has affected physics education in three very significant ways. First, the use of distractors as alternative test responses means that faculty can quickly analyze the views of their students, and modify their instruction. Additionally, physics faculty are routinely surprised by the generally low scores achieved by students on the FCI; this has resulted in a dramatic rethinking within the physics community of how and why concepts are taught (Redish and Steinberg, 1999). Finally, the dissemination of this tool has resulted in a dramatic increase in the number of studies dealing with student alternative conceptions in physics. Indeed, while the physics community has seen a 5-fold increase in published papers related to conceptual understanding, there are few publications associated with conceptual understanding in geology (Fig. 4; Appendix A).

Although other science disciplines (e.g., Zeilik et al., 1999) are beginning to embrace students' conceptual understanding as an important component of course outcomes, as yet there exists no measure of conceptual gain in the geosciences. Interestingly, the development of the FCI for physics education had impact in other science disciplines, as evidenced by increased interest in, for instance, astronomy and biology. It seems that these types of assessment efforts have the potential to change the culture of science education, not just the mechanism.

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Demastes, S.S., Settlage, J., and Good, R.G., 1995, Students' conceptions of natural selection and its role in evolution: Cases of replication and comparison: Journal of Research in Science Teaching 32, p. 535-550.

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Halloun, I.A., and Hestenes, D., 1985b, Common sense concepts about motion. American Journal of Physics 53, p. 56-1065.

Hestenes, D., Wells, M., and Swackhamer, G., 1992, Force Concept Inventory: The Physics Teacher 30, p. 141-158.

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Posner, G., Strike, K., Hewson,P., and Gertzog, W., 1982, Accommodation of a scientific conception: Towards a theory of conceptual change: Science Education 66, p. 221-227.

Redish, E.F., and Steinberg, R.N., 1999, Teaching physics: Figuring out what works: Physics Today 52, p. 24-30.

Schneps, M.H. (Producer), 1987, A private universe. (Film): Boston, Harvard University and Smithsonian Institute.

Vygotsky, L.S., 1978, Mind in society: The development of the higher psychological processes: Cambridge, MA: Harvard University Press, 159 p.

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White, B.Y. and Fredrickson, J.R., 1998, Inquiry, modeling, and metacognition: Making science accessible to all students: Cognition and Science 16, p. 90-91.

Zeilik, M., Schau, C., and Mattern, N., 1999, Conceptual astronomy II: Replicating conceptual gain, probing attitude changes across three semesters: American Journal of Physics 67, p. 923-927.

APPENDIX A: Bibliography of papers related to alternative conceptions about geology. This list covers most, but not all, existing studies related to students' alternative ideas about geologic concepts.

Earth and space

Nussbaum, J., 1997, Children's conceptions of the Earth as a cosmic body: a cross age study: Science Education, v. 63, p. 83-93.

Nussbaum, J., and Novak, J.D., 1976, An assessment of children's concepts of the Earth utilizing structured interviews: Science Education, v. 60, p. 535-550.

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

Alternative conceptions about seasons, phases of the Moon, other planets as seen from Earth. Discusses college-aged student

Zeilik, M., Schau, C., and Mattern, N., 1999, Conceptual astronomy. II. Replicating conceptual gain, probing attitude changes across three semesters: American Journal of Physics, v. 67, p. 923-927.

Alternative conceptions about phases of the Moon and the position of the Sun in the sky:

Earth's oceans and atmosphere

Bar, V., 1989, Children's views about the water cycle, Science Education 73: 481-500.

Ideas about precipitation and phase changes.

Brody, M.J., 199, An assessment of 4th-, 8th-, and 11th-grade students' environmental science knowledge related to Oregon's marine resources: Journal of Environmental Education, v. 27, p. 21-27.

Content knowledge of marine resources appears to increase as students age, but not their ability to interpret this knowledge.

Fortner, R.W., and Teates, T.G., 1980, Baseline studies for marine education: Experiences related to marine knowledge and attitudes: Journal of Environmental Education, v. 11, p. 11-19.

Student knowledge of the ocean's natural properties and impact on society.

Geologic definitions

Finley, F.N., 1982, An empirical determination of concepts contributing to successful performance of a science process: a study of mineral classification: Journal of Research in Science Teaching, v. 19, p. 689-696.

Ability of students to classify minerals based on their knowledge of mineral properties.

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

Geologic terms, such as fossil, mineral, and rock.

Soil and water issues
Happs, J.C., 1984, Soil generation and development: view held by New Zealand students: Journal of Geography, v. 83, p. 177-180.
Alternative views about definition, creation, and age of soils, including geologic change. Working papers on student understanding of mountains, glaciers, and rocks produced by J.C. Happs (1982) while at the Science Education Unit of the University of Waikato are also referenced by some authors.

Bar, V., 1988, Children's views about the water cycle: Science Education, v. 73, p. 481-500.
Orders student explanations of the water cycle into age-related stages of understanding.

Meyer, W.B., 1987, Vernacular American theories of earth science: Journal of Geological Education, v. 35, p. 193-196.
Popular ideas about groundwater, especially the analogy many people make with surface water.

Plate tectonics
Bezzi, A., and Happs, J.C., Belief systems as barriers to learning in geological education: Journal of Geological Education , v. 42, p. 134-140.
Locality-specific volcanism and sources of ideas held by students.

Chang, C., and Barufaldi, J.P., 1999, The use of problem-solving-based instructional model in initiating change in students' achievement and alternative frameworks: International Journal of Science Education, v. 21, p. 373-388.
Create a rubric for scoring student ideas about mountain building on a scale from Understanding to No Conception.

Marques, L., and, Thompson, D., 1997, Misconceptions and conceptual changes concerning continental drift and plate tectonics among Portuguese students aged 16-17: Research in Science and Technological Education, v. 15, p. 195-222.
Alternative conceptions related to plate tectonics and plate motion.

Muthukrishna, N., Carnine, D., Grossen, B., Miller, S., 1999, Children's alternative frameworks: Should they be directly addressed in science instruction?, Journal of Research in Science Teaching, v. 30,p. 233-248.
Misconceptions related to mountain building and convection. Discuss need to directly address alternative frameworks in instruction.

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

Geologic time (Journal of Geoscience Education recently devoted most of the 1/ 2001 issue to teaching geologic time.)
Ault Jr., C.R., 1982, Time in geological explanations as perceived by elementary-school students: Journal of Geological Education, v. 30, p. 304-309.
Ability of students to understand relative time.

Chang, C., and Barufaldi, J.P., 199, The use of problem-solving-based instructional model in initiating change in students' achievement and alternative frameworks: International Journal of Science Education, v. 21, p. 373-388.
Discuss achievement test item related to stratigraphy.

Schoon, K.J., 1992. Students' alternative conceptions of Earth and space, Journal of Geological Education , v. 40, p. 209-214.
Coexistence of dinosaurs and men.

Trend, R., 1998. An investigation into understanding of geological time among 10- and 11-year-old children, International Journal of Science Education, v. 20, p. 973-988.
Children's understanding of relative time, especially with reference to ordering geologic events.

Trend, R., 2000. Conceptions of geological time among primary teacher trainees, with reference to their engagement with geoscience, history, and science: International Journal of Science Education, v. 2, p. 539-555.
Primary teachers' understanding of relative and absolute time.

Evolution (Has been studied by a number of researchers. Selected papers of interest to geologists are listed here.)
Bishop, B. and Anderson, C. W., 1990, Student conceptions of natural selection and its role in evolution: Journal of Research in Science Teaching, v. 27, p. 412-427.

Brem, S. K., Ranney, M. and Schindel, J., in press, What does it mean to evolve? The perceived personal and social impact of evolutionary theory on a college:Journal of Research in Science Teaching.