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Using Students' Sketches to Recognize Alternative Conceptions About Plate Tectonics Persisting From Prior Instruction

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ABSTRACT

Should instructors assume that students possess conceptual knowledge of plate tectonics when they reach a second college geoscience course? Five cohorts in a historical geology course over 5 y—a total of 149 students—completed an in-class assignment in which they drew sketches of plate boundaries with required annotations. Analysis of the sketches revealed that most students lack an explanatory mental model that links the locations of earthquakes, volcanoes, and magma generation to plate-boundary processes and hold a pervasive alternative conception of Earth's interior structure that does not distinguish between compositional and rheological boundaries. Students who drew sketches that illustrated the most alternative conceptions also scored lower on a beginning-of-the-course administration of the Geoscience Concept Inventory, showing that conceptual understanding of plate tectonics correlates with overall conceptual geoscience knowledge obtained during previous course experiences. In addition, students tracking to the historical geology course via an introductory physical geology course showed stronger conceptual understanding of plate tectonics than those choosing an Earth-system science prerequisite, with those students previously enrolled in both courses illustrating the fewest alternative conceptions. © *2012 National Association of Geoscience Teachers*. [DOI: 10.5408/11-251.1]

Key words: plate tectonics, misconceptions

INTRODUCTION

Presuming cumulative knowledge acquisition and skill development, faculty commonly assume that students achieved basic conceptual understanding of a subject in an introductory course that can be expanded on in subsequent courses. Competing with this assumption is the well-known observation from cognitive psychology that students persistently retain alternative conceptions (or misconceptions) regarding key ideas that are resistant to many forms of instruction (e.g., Posner et al., 1982; Bransford et al., 2000; Chi, 2008).

This paper summarizes an ongoing classroom-action research project (Mettetal, 2001) focused on an assignment in a historical geology course that assesses students' basic understanding of causal and dynamic aspects of plate tectonics following a previous introductory course. Our report serves three purposes: (1) to elaborate on the utility of students' sketches to assess mental models of fundamental geological processes (Gobert and Clement, 1999; Gobert, 2005; Libarkin and Anderson, 2005b; Sibley, 2005; Steer et al., 2005; Johnson and Reynolds, 2006) and thus quickly recognize and refute alternative conceptions; (2) to integrate our results with previous research on alternative conceptions regarding plate tectonics (e.g., King, 2000; Sibley, 2005; Clark et al., 2011) and thus generalize implications for instruction; and (3) to illustrate correlations between level of conceptual understanding of plate tectonics and independent measures of previous-course learning.

As the underpinning theory that explains many aspects of ongoing and past processes on Earth, plate tectonics is commonly viewed (e.g., typical textbook statements; Earth Science Literacy Initiative, 2010) as one of the most important concepts that students should understand as an outcome of an introductory college geoscience course, whether it be a terminal general-education course for nonmajors or the foundational course for pursuing a disciplinary major. Learners are typically exposed to elements of the theory in middle-school (typically ages 12–14) science (e.g., National Committee on Science Education Standards and Assessment, 1996; Gobert, 2005; Ford and Taylor, 2006) with subsequent informal learning experiences through prominent presentation of elements of the theory in museum exhibits and television programs. Given that science literacy among the public is strongly correlated to courses completed in college (Miller, 2004), it is likely that most comprehension of the fundamental concepts and applications of plate tectonics is achieved in introductory college-level physical geology or Earth-system science courses. In our experience, instructors presume that students possess sufficient mastery of the causal and dynamic aspects of plate tectonics to grasp new applications and extensions of the theory when pursuing geoscience coursework beyond these initial introductory classes.

Our study examines an ongoing assessment of students' conceptual understanding of plate tectonics in a historical geology course taught by the senior author Smith. Students reach this course after completion of a physical geology course, an Earth-system science course, or both. Students enrolled in the Earth History course apply conceptual understanding of plate tectonics to reconstructing ever-changing global and regional geographies, biogeography, climate, and oceanographic conditions, as well as the formation and distribution of rock types that are definitive of tectonic processes throughout the history of the planet. Therefore, prior to developing these applications of plate tectonics, a simple sketching exercise was designed and employed over a period of 5 y (one semester each year) to

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identify deficiencies in foundational understanding of plate tectonics and to correct misunderstandings that could inhibit effective learning in the Earth History course.

Beyond reporting the results of this exercise, we explore how the depth of correct conceptual understanding of plate tectonics relates to the nature of students' prior overall geoscience learning. This objective entails the testing of two hypotheses. The first proposes that conceptual understanding of plate tectonics, as illustrated through this exercise, correlates to overall geoscience conceptual knowledge as measured by the Geoscience Concept Inventory (GCI; Libarkin and Anderson, 2005a). The second hypothesis proposes that students progressing to the historical geology course following completion of a physical geology course have fewer misunderstandings regarding plate tectonics than do students completing an Earth-system science course and that those students who completed both courses prior to Earth History have the fewest alternative conceptions. The premise of the second hypothesis is that for students completing only one prior introductory course, the physical geology course is likely to provide a firmer conceptual understanding of plate dynamics than the wider-ranging, interdisciplinary Earth-system science course—but with strongest understanding likely for students who benefited from learning about the theory twice.

METHODS

The Course and the Exercise

Earth History at the University of New Mexico is a second-semester course that follows successful completion of an introductory course in physical geology or Earth-system science; some students complete both of these introductory courses prior to enrollment in Earth History. The two introductory courses and Earth History fulfill both natural-science general-education requirements and requirements for bachelor degrees in Earth and Planetary Sciences (geology) and Environmental Science. During the time of interest to this study (fall 2006 through fall 2010); 26% of the Earth History students were Earth and Planetary Sciences majors; 24% were Environmental Science majors; 22% were majors in other science, technology, engineering, and mathematics disciplines; 12% were education majors (primarily in secondary-school science programs); and the remaining 16% were pursuing degrees in other fields. Exercises completed by 149 students were used in this study, with 74 previously completing the physical geology course, 38 completing the Earth-system science course, 14 completing both introductory courses, and 23 entering Earth History having applied their transfer credit or score on the Advanced Placement Environmental Science Examination to meet the prerequisite requirement. Both the physical geology and the Earth-system science courses are taught by faculty in the Department of Earth and Planetary Sciences. The content covered in sections of either course varies with instructor. However, syllabi comparisons show that consideration of plate-tectonics theory occupies more course time in the physical geology course than in the Earth-system science course. In addition the theory is typically integrated throughout other course topics in the physical geology course that are not included in the Earth-system science course, such as igneous processes, metamorphism, mantle convection, earthquakes, and geological structures.

Four weeks into the semester, Earth History students were assigned to read an eight-page text that reviews fundamental plate-tectonics concepts, including the definition of a plate within the context of Earth's internal structure and the dynamic processes at the three types of plate boundaries. This text includes diagrams that illustrate the attributes that students are asked to sketch later in class. The reading assignment introduces a section of the course that focuses on methods of tectonic and paleogeographic reconstructions and application of those methods to understanding the Neoproterozoic-to-present tectonic history of North America.

Following the reading assignment, students were asked in class to construct cross-sectional sketches of a convergent and a divergent plate boundary (exercise prompt provided in Appendix 1). Students were provided with a checklist of features and processes to label on their sketches; the checklist is as follows: crust, lithosphere, asthenosphere, arrows indicating plate motion, where earthquakes occur, where volcanoes are present, and where magma is generated within Earth's interior in association with plate-boundary processes. At this stage, students were instructed to construct their own drawing without consulting reading materials or peers. After completing their sketch, students were encouraged to compare their results with one or more peers and then, if deemed necessary, draw a second set of sketches that reflected knowledge gained during the peer discussion. The sketches were collected and assessed for common errors, which were then addressed during the next class period using a refutational approach (e.g., Tippett, 2010). A week later, the students were given the opportunity to make new cross-sectional sketches for a low-stakes grade. For this study, we examined only the original sketch, which represented the students' conceptual understanding based on previous course experience and their reading of the short topical-review text prior to peer interaction and new instruction.

Data Collection and Analysis

Copies of the initial sketches drawn by 149 students between fall 2006 and fall 2010 are the basis of the study (examples shown in Fig. 1). We identified and defined alternative conceptions represented in student sketches by recognizing repeated patterns in the sketches, establishing criteria for consistently identifying a conceptual error, and then applying these criteria to tally alternative conceptions on all papers. This effort was initially undertaken by the second author Bermea, who was an undergraduate student completing an Earth and Planetary Sciences minor and who had not taken the Earth History course from Smith. Therefore, Bermea brought no biases from having completed this assignment. In addition, as a student, we feel that she was more likely to focus on unambiguous and fundamental conceptual errors and less likely to interpret more nuanced or advanced-level comprehension errors compared to the disciplinary-expert professor for the course. For example, most sketches did not illustrate the thickening of the lithosphere with distance from midocean ridges, but we did not identify that omission as an alternative conception.

Bermea identified eight persistent and widespread conceptual misunderstandings, which are summarized in Table I. One alternative conception is general to sketches of both plate boundaries (G) and reflects a fundamental misunderstanding of terminology and characteristics of Earth's interior layers. Three alternative conceptions were repeatedly expressed on the convergent-plate-boundary sketches, and four were common on the divergent-plate-boundary sketches. After Bermea established criteria for recognizing these alternative conceptions (Table I), Smith examined a subset of the sketches to test the reliability of cross-rater consistency in identifying the alternative conceptions. Smith's and Bermea's assessments of the alternative conceptions in the subset of sketches were identical for six of the alternative conceptions, with small variations in evaluating alternative conceptions 2 and 4 on the divergent-boundary sketches, leading to new tallies for those categories.

Additional analyses were undertaken to explore hypothesized relationships between the number of alternative conceptions and the students' overall geoscience understanding or previously completed introductory course. Smith's Earth History students complete a 15-question GCI (v. 1.0; Libarkin and Anderson, 2005a) assessment at the beginning and at the end of the course. The 15-question inventory followed rules provided by Libarkin and Anderson (2008) for GCI subtest construction with a focus, where possible within the subtest construction protocol, on topics that are included in the Earth History course. There were no questions specifically about plate-boundary processes. The pretest (beginning of the semester) scores were used in the analysis for this study. Some students were absent when the GCI was administered, so alternative conceptions tallied on only 144 of the 149 sketches were used for comparing alternative conceptions to GCI score. In addition, students completed a voluntary survey at the beginning of the course that queried information about the introductory class completed as the prerequisite to the current class. Only students who took their introductory course at the University of New Mexico were included, which excluded 23 sketches by students with advanced placement or transfer credit from the stage of the study that compared alternative conceptions to prior-course experience (i.e., 126 sketches used in this analysis). For each of the eight alternative conceptions, the Student's *t*-test was used to compare the GCI-score distributions of students who did or did not represent the conceptual error in their sketches. Chi-square tests were employed to compare the frequency of each alternative conception among three subpopulations: those students previously completing only introductory physical geology, those previously completing only introductory Earth-system science, and those previously completing both courses.

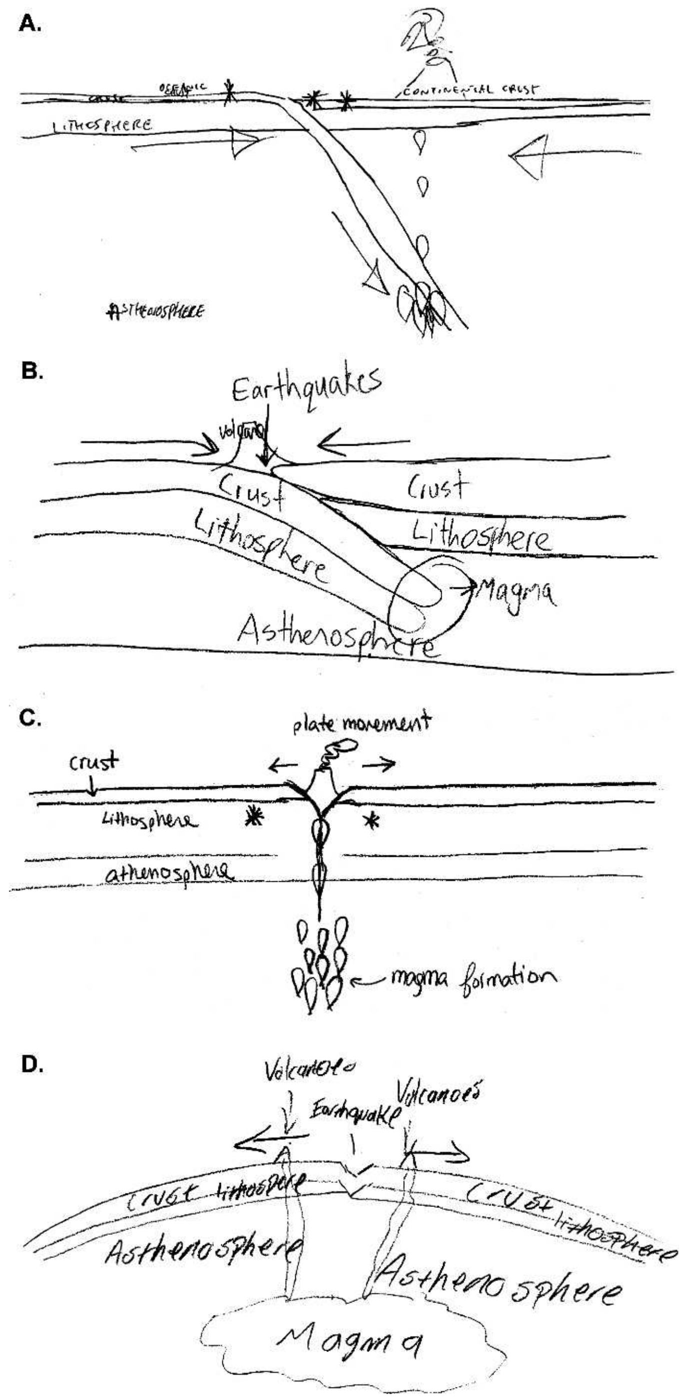

FIGURE 1: Student sketches illustrating the alternative conceptions listed in Table I. Authors of sketches A and C followed a suggested legend, whereby asterisks represent earthquake locations and balloons represent the generation and rise of magma. Sketches A–C illustrate the general alternative conception (G, see Table 1 for abbreviations) that depicts the crust as being separate from the lithosphere. Sketch A also illustrates alternative conceptions about earthquake locations (Con1) and magma generation (Con2) at convergent boundaries. Sketch B also reflects Con1 and Con2 and places volcanoes in the trench at the plate boundary, rather than on the over-riding plate (Con3). Sketch C illustrates earthquakes deep within the lithosphere and on either side of, rather than at, the divergent boundary (Div1) and shows magma originating below the asthenosphere (Div2). Sketch D depicts a trough rather than a ridge at the divergent boundary (Div4) and shows magma rising from deep in the asthenosphere (Div2) to supply volcanoes located on either side of, but not at, the divergent boundary (Div3). All sketches reproduced with the written permission of the student authors.

TABLE I: Alternative conceptions (misconceptions) regarding plate tectonics.

Alternative Conception (Abbreviation)	Description	Representation	Student Sketches Demonstrating Alternative Conception
General alternative conception (G)	Compositional and rheological layering of Earth's interior are not distinguished.	Students show the crust as being on top of, rather than part of, the lithosphere. In many cases plates are illustrated as consisting of only the crust, but in some cases they also contain the asthenosphere.	79%
Convergent-boundary alternative conception 1 (Con1)	Earthquakes only occur at the surface trace of the boundary of the converging plates.	Students fail to show deep earthquakes occurring within the inclined subducting plate (Wadati-Benioff zone).	74%
Convergent-boundary alternative conception 2 (Con2)	Magma forms from melting plates or comes from beneath the subducting plate.	Magma is drawn as forming at the termination of a subducting plate, because the plate is melting, or is shown to form below the subducting plate, rather than above it.	65%
Convergent-boundary alternative conception 3 (Con3)	Volcanoes are not directly related to melting above the subducting plate.	Volcanoes are drawn directly at the convergent plate boundary, or volcanoes are drawn on the subducting plate.	31%
Divergent-boundary alternative conception 1 (Div1)	Earthquakes are not related to the boundary of lithospheric plate separation.	Earthquakes are not drawn at the plate boundary but instead are located either away from the boundary or, less commonly, in the asthenosphere or lower lithosphere.	76%
Divergent-boundary alternative conception 2 (Div2)	Magma forms deep in the asthenosphere rather than in the upper mantle.	Magma is shown rising from deep in the asthenosphere or from below the base of the diagram; magma formation may be omitted from the diagram.	51%
Divergent-boundary alternative conception 3 (Div3)	Volcanoes are not related to the divergence of plates at the boundary.	Volcanoes are sketched as forming away from the boundary, instead of at the boundary, or volcanoes not shown.	31%
Divergent-boundary alternative conception 4 (Div4)	Divergent boundaries are marked by depressions on the ocean floor.	Students draw deep "valleys" where midocean ridges actually exist.	16%

RESULTS

Frequency of Alternative Conceptions

The last column of Table I summarizes the frequency of each alternative conception among the 149 examined sketches. In sketches of both boundary types, an overwhelming number (79%) of students represented the crust as existing above the lithosphere rather than being part of the lithosphere (Figs. 1A–C) and in some cases (Fig. 1A) explicitly show plates as consisting only of the crust. Therefore, it is unclear that most students understand how the "plate" in "plate tectonics" is defined.

Three persistent alternative conceptions were recognized in the convergent-boundary sketches. Convergent-boundary alternative conception 1 (Con1) refers to the failure to depict earthquakes along the Wadati-Benioff zone (Figs. 1A and B); 74% of the sketches only showed earthquakes occurring near the surface in the vicinity of the plate boundary. Sixty-five percent of sketches did not show the location of magma generation above the subducting plate; instead, sketches illustrating convergent-boundary alternative conception 2 (Con2) emphasized melting of the plate at a down-dip termination (Fig. 1B) or depicted magma forming in the mantle below the subducting plate (Fig. 1A). Nearly one-third of the drawings illustrated convergent-boundary alternative conception 3 (Con3) by placing volcanoes in the trench at the plate boundary (Fig. 1B) or on the subducting plate at a distance from the boundary.

Four alternative conceptions were identified in the divergent-boundary sketches (Table I). About three-quarters of the drawings depicted earthquakes as occurring within the plates at some distance from the boundary, rather than at the locus of plate separation (Div1). Roughly half of the drawings display examples of the second alternative conception, which shows magma generation deep in the asthenosphere (Fig 1D), below the asthenosphere (Fig. 1C), or even rising from some unknown location below the drawing (Div2). Divergent-boundary alternative conception 3 (Div3) is reflected in 31% of the drawings by either, in most cases, misplacing volcanoes on either side of the plate boundary to account for the elevation of midocean ridges (Fig. 1D) or, in fewer cases, not depicting or labeling any volcanism at the site of plate divergence. The fourth divergent-boundary alternative conception (Div4), represented in about one-sixth of the drawings, is shown by a tendency to omit the existence of midocean ridges and, instead, present a trough at the divergent boundary between plates that are flat on either side of the boundary or, less commonly, slope downward toward the boundary (Fig. 1D).

Taken as a whole, the sketches show poor conceptual understanding of the explanatory power of plate tectonics to

TABLE II: Comparison of GCI scores for students whose sketches did or did not illustrate alternative conceptions (see Table 1 for alternative conception abbreviations).

Alternative Conception	GCI Score, Sketches Without Alternative Conception		GCI Score, Sketches With Alternative Conception		Statistical Significance Based on *t*-Test
	n	Mean (SD)	*n*	Mean (SD)	*p* Value
G	30	10.30 (2.12)	114	9.29 (2.88)	0.0749
Con1	37	10.38 (2.39)	107	9.20 (2.83)	0.0245
Con2	50	10.56 (2.49)	94	8.95 (2.75)	0.0007
Con3	100	10.20 (2.39)	44	7.91 (2.92)	<0.0001
Div1	34	9.62 (2.97)	110	9.46 (2.72)	0.7777
Div2	70	10.09 (2.56)	74	8.95 (2.86)	0.0129
Div3	99	9.91 (2.65)	45	8.60 (2.83)	0.0080
Div4	121	9.66 (2.76)	23	8.68 (2.71)	0.1090

explain the distribution of earthquakes and volcanoes and the processes of melting that supply magma to volcanoes (Table I). Although criteria for recognition of alternative conceptions differ among the boundary sketches, the data suggest that the most prevalent misunderstandings (excluding Div4) fall into four categories: (1) the relationship of plates to the terms describing Earth's internal structure (G), (2) the relationship of earthquake hypocenter locations to plate-boundary stresses (Con1 and Div1), (3) the formation of magma by wet melting and decompression as a consequence of plate dynamics (Con2 and Div2), and (4) the relationship of volcano distribution to magma generation and plate boundary processes (Con3 and Div3).

Relationship of Alternative Conceptions and Overall Geoscience Conceptual Knowledge

Table II compares the mean GCI scores (maximum possible score is 15) for students whose sketches are consistent with an alternative erroneous understanding and those whose sketches are consistent with correct conceptual understanding for each alternative conception described in Table I. Average GCI scores are uniformly higher, in all cases, for students who drew correct cross-sectional sketches. For five of the eight alternative conceptions, students whose sketches were incorrect also had statistically significantly lower pretest GCI scores, based on the *t*-test (p score less than 0.05), than did the students whose sketches were correct with regard to the particular concept. Therefore, the data support the hypothesis that students who hold alternative conceptions about features and processes at plate boundaries also show overall lower mastery of geoscience concepts.

Relationship of Alternative Conceptions and Introductory-Course Experience

Table III summarizes the pretest GCI scores and unpaired-comparison *t*-tests for the Earth History students, divided into categories based on introductory-course experience. Veterans of the physical geology course showed significantly better geoscience conceptual knowledge than students who previously enrolled in the Earth-system science course. The mean GCI score for students who completed both introductory courses prior to enrolling in Earth History was slightly lower than for those who only took the physical geology course. However, because of the wide distribution of GCI scores among students in all three categories and the relatively small sample ($n = 14$, or 11%) of students who took both courses, it is not possible to confidently distinguish the scores for these latter students from those in the other two groups.

More significant differences among students with different prior-course backgrounds are also illustrated in Table III, which compares the three subsamples in terms of the average number of total alternative conceptions. As proposed by the second hypothesis, students who completed both introductory courses prior to Earth History demonstrated the fewest alternative conceptions in their sketches, followed by those who only completed physical geology; students who had only completed the Earth-system science course represented the most errors in their sketches.

These course-related differences are less clear when considering each alternative conception separately (Table IV). A chi-square test was used to test the significance of these differences because, rather than having a range of scores as when evaluating differences in GCI achievement or

TABLE III: Variation in GCI score and total number of plate-tectonics alternative conceptions compared to prerequisite-course experience.

	Prior-Course Completion			Unpaired *t*-Test, *p* value		
	Physical Geology ($n = 74$) Mean (SD)	Earth-System Science ($n = 38$) Mean (SD)	Both Courses ($n = 14$) Mean (SD)	Physical Geology/ Earth-System Science	Physical Geology/Both Courses	Earth-System Science/Both Courses
GCI score	9.97 (2.68)	8.61 (2.79)	9.79 (2.72)	0.0139	0.8135	0.1788
Total alternative conceptions	4.20 (1.70)	4.92 (1.44)	3.29 (1.77)	0.0289	0.0710	0.0013

average number of alternative conceptions, there is simply a tabulation of incorrect and correct when comparing number of alternative conceptions. Although the veterans of the Earth-system science course who had not completed physical geology showed the highest percentage of alternative views for each recognized alternative conception, these differences are only statistically significant for two of the convergent-boundary examples.

DISCUSSION

Summary of Alternative Conceptions

A classroom-action research project utilizing a student-sketch exercise demonstrates that roughly three-quarters of students in a second-semester historical geology course hold erroneous alternative conceptions of fundamental aspects of plate tectonics that persist despite prior instruction. The existence of these erroneous understandings was not surprising in light of research showing the persistence of alternative conceptions (summarized by Bransford et al., 2000); however, the widespread misunderstanding of the causal explanations provided by plate-tectonics theory was unanticipated. This result is particularly surprising given that understanding of plate tectonics by the public is viewed more positively in science-literacy studies than for other scientific concepts (Miller, 2000). We interpret these misunderstandings as alternative conceptions rather than incomplete knowledge (Chi, 2008), because the nature of the content assessed on the sketches is common to introductory college texts and the middle-school national science standards (National Committee on Science Education Standards and Assessment, 1996). We view these alternative conceptions as flawed mental models, because such models represent how people organize their conceptual understanding and retrieve knowledge for the purpose of problem solving (Nersessian, 2008).

The persistent alternative conception that the crust overlies the lithosphere rather than being part of the lithosphere is likely related to a misunderstanding of Earth's internal structure that has been recognized in other studies (Libarkin et al., 2005; Sibley, 2005; Steer et al., 2005; Clark et al., 2011; Kortz et al., 2011). We suggest that a mental model of compositional layering (crust, mantle, and core) developed in schoolwork at an early age impedes subsequent accommodation of learning of the rheological distinction between lithosphere and asthenosphere. As a result, most students in our study apparently assimilate new learning with their existing model by assigning the lithosphere and asthenosphere to layers wholly within the mantle (see Posner et al., 1982, for discussion of Piaget's concepts of accommodation and assimilation in the conceptual change process). Although not rigorously pursued, work by Libarkin et al. (2005) and anecdotal conversations with the students in this study suggest that most do not know the defined meanings of any of these layer terms (crust, mantle, core, lithosphere, and asthenosphere), so when they are asked to sketch their mental model of Earth's interior, they focus on putting the terms into some particular order with little regard to compositional or rheological meaning (cf. Steer et al., 2005). Ambiguous or inconsistent labeling of crust and lithosphere in some textbook drawings (King, 2010) could reinforce these views. We might consider this alternative conception as simply a matter of incomplete mastery of terminology; however, rheology is critical to basic conceptual, rather than simply descriptive, knowledge of plate tectonics and suggests that students do not know what properties define a plate. Similar concerns were raised by Kortz et al. (2011) regarding students' inability to identify where plate boundaries exist on nonannotated perspective cross-sectional and plan views of ocean basins, continents, and island arcs that show midocean ridges and subducted plates.

The inability of most students in this study to correctly locate earthquakes, volcanoes, regions of magma generation, or a combination of these implies weak conceptual understanding of plate-tectonics theory to explain concrete phenomena, as also noted in other studies (Barrow and Haskins, 1996; Ford and Taylor, 2006; Libarkin and Baker, 2007; Libarkin and Clark, 2008). A goal of general-education science instruction is to build conceptual understanding of scientific methodology and epistemology (Posner et al., 1982). In this framework, students should learn that theories in the natural sciences are formulated to explain, not to describe, natural phenomena. The students in our study correctly drew arrows at the plate boundaries and, with two exceptions (out of 149 sketches), showed subduction at convergent boundaries. We hypothesize that these correct elements of sketches demonstrate a solid descriptive mental

TABLE IV: Percentage of student sketches illustrating alternative conceptions compared to prerequisite-course experience (see Table 1 for alternative conception abbreviations).

Alternative Conception	Prior-Course Completion			χ^2-Test, p Values		
	Physical Geology (n = 74) Mean (SD)	Earth-System Science (n = 38) Mean (SD)	Both Courses (n = 14) Mean (SD)	Physical Geology/Earth-System Science	Physical Geology/Both Courses	Earth-System Science/Both Courses
G	77	84	71	0.3910	0.6233	0.2996
Con1	73	89	43	0.0475	0.0242	0.0004
Con2	61	87	36	0.0052	0.0752	0.0002
Con3	32	39	14	0.4298	0.1801	0.0859
Div1	77	82	64	0.6021	0.2989	0.1892
Div2	47	58	57	0.2594	0.4715	0.9612
Div3	31	32	29	0.9211	0.8756	0.8349
Div4	16	21	14	0.5061	0.8715	0.5829

model for plate tectonics but that students do not have a firm dynamic explanatory mental model. Many geoscience instructors with whom we have discussed this result have suggested that plate tectonics is difficult for novice learners to conceptualize because the scale of plates is so large, the rates of plate motion are so slow, and many critical pieces of evidence are inferred within Earth's interior rather than directly observed; this opinion is consistent with research on middle-school students (Ford and Taylor, 2006). However, we feel that earthquakes and volcanic eruptions are among the most concrete phenomena that students should be able to explain through understanding of plate tectonics.

Even if students have not witnessed earthquakes or volcanic eruptions, they have strong, curious interests in these geological phenomena because of the spectacular, sometimes devastating, and commonly newsworthy results (Barrow and Haskins, 1996). The inclined Wadati-Benioff earthquake zone is critical evidence for the existence of subducted plates, but nearly three-quarters of the students in this study failed to include that evidence in their sketches. In most cases, earthquake locations seemed to be almost randomly distributed in the surface zone of students' sketches. King (2000) noted that 52% of precollege teachers in a study were unable to connect earthquake-depth relationships to plate-boundary processes. Class discussions over the 5-y period of our study consistently show that most of these students do not understand the relationship of earthquakes, plate motions, stress, and strain and that this lack of understanding impedes their ability to relate earthquakes to the dynamics of plate motions. They also have not come to deeply understand that most earthquake energy release occurs below the surface. Anecdotal conversations with students who harbor the earthquake-location alternative conceptions suggest a hypothesis that despite having experienced instruction regarding the difference between hypocenter and epicenter and illustration of the deep earthquakes along the Wadati-Benioff zone, students have not discarded a prior belief, supported by textbook and media maps of epicenter locations and building damage, that earthquakes happen at Earth's surface rather than being generated beneath the surface.

Although errors in volcano placement are less common than for earthquake locations (Table I), the vague and commonly incorrect representations of magma generation imply that most students in this study do not understand why volcanoes exist at these locations. Similarly, Clark et al. (2011) found that few students mention decompression or wet melting in annotations of plate-boundary diagrams, and Libarkin and Clark (2008) found that interviewed students are not confident of their understanding of melting processes. Stern (1998) drew attention to textbook descriptions of convergent boundaries that erroneously show magma generation by melting of the subducting plate, a mistaken view held by many students in this study (Con2). The use of orange and red hues in textbook colors of Earth's interior are commonly misinterpreted by students as representing magma (Hall-Wallace, 2002; Clark et al., 2011) rather than high-temperature solids. If students retain a long-held alternative conception of a mostly molten mantle (e.g., schoolteachers, King, 2000; middle-school students, Ford and Taylor, 2006), then they likely have not developed a mental model of plate tectonics that explains the unusual circumstances that cause partial melting in the mantle and therefore explains the distribution of most volcanoes in relation to plate boundaries, including the reasons volcanoes form at divergent boundaries but form at a distance from convergent boundaries. The inability of nearly one-third of the students to correctly locate volcanic eruptions at divergent boundaries (Div3) implies weak mental models of the role of igneous processes to form oceanic lithosphere.

Alternative Conceptions and Prior Geoscience Learning

The correlation between higher pretest GCI scores and fewer alternative conceptions (Table II) supports our hypothesis that stronger conceptual understanding of plate tectonics would correlate with overall greater geoscience conceptual knowledge. We also view this correlation as supporting the validity of the alternative-conception-recognition criteria developed for assessing the students' sketches.

To at least some degree, the level of conceptual geoscience knowledge assessed on the GCI subtest and alternative concepts about plate tectonics relate to prior course work (Tables III and IV). We did not develop our hypothesis regarding conceptual understanding of plate tectonics and course-taking pattern to judge the value of physical geology versus Earth-system science courses. Rather, we wanted to see whether there are implications for encouraging further geoscience course taking by students who initiated their interest in Earth sciences through either of these general-education courses. Most geoscience curricula were developed decades ago around the premise that students will pass through a traditional physical geology course en route to additional courses in the field. As introductory courses are redesigned to be more integrative and interdisciplinary, there are tradeoffs in content that may leave some traditional physical geology topics for emphasis in later courses. In addition, although students who completed physical geology had higher GCI pretest scores and fewer alternative conceptions about plate tectonics than their peers rising from the Earth-system science course, both populations (and those who completed both courses) possessed similar alternative conceptions in large numbers (Table III).

To complete our discussion of this alternative-conception-identification assessment, there are also useful insights from the sketches, not analyzed here, that students draw after peer consultation and again a week later. The students' second sketches, following peer discussion, typically contain most of the same errors as in the first sketches, although these alternative conceptions are rarely reflected in the third sketches drawn a week later. The limited improvement during peer comparison is likely a consequence of the most common alternative conceptions being held by a substantial majority of the students, although additional refutational instruction promotes conceptual change by the time the final sketches are made.

Limitations

Although student sketches represent powerful, unbiased artifacts of learners' mental models, they are more difficult to code than assessments based on student annotation of existing diagrams (e.g., Clark and Libarkin, 2011). In addition, we are largely inferring the rationale behind students' alternative conceptions from their drawings and anecdotal notations from classroom discussion without a rigorous qualitative study involving student interviews (e.g., Sibley, 2005; Clark and Libarkin, 2011; Kortz et al., 2011).

Nonetheless, several observations support the overall validity of our approach. First, inter-rater agreement on alternative-conception recognition was high. Second, the conceptual errors noted in this study have been recognized by previous workers. Third, the strong relationships between students' GCI scores and conceptual understanding of plate tectonics interpreted from their sketches (Table II) correlates our coding criteria with a validated assessment instrument.

CONCLUSIONS

Student sketches are an effective artifact for assessing learners' mental models of geoscience concepts and can form a basis for quickly identifying level of mastery of concepts presumptively learned during prior courses. This classroom-action research project illustrates the ability to use such sketches to consistently identify widespread alternative conceptions about plate tectonics that persisted from prior instruction. The similarity of these alternative conceptions with those identified in previous studies and correlations to independent measures of students' prior learning should encourage instructors to use student sketches as a valid measure of assessing understanding of geoscience concepts. Identifying alternative conceptions and confronting them explicitly during instruction is essential for learner conceptual change (Posner et al., 1982; Chi, 2008).

Combining our observations with those of previous researchers leads us to suggest several implications for teaching and learning the theory of plate tectonics. We suggest that existing information provided by studies at a variety of institutions implies that students exit their introductory geology course with descriptive factual knowledge of plate tectonics but weaker conceptual explanatory knowledge that relates the dynamics of plate motions to the evidence that the theory explains. This conclusion suggests the importance of using evidence and dynamic connections between plate motions and observable processes to support the learning of the theory in introductory courses (e.g., Marques and Thompson, 1997). Explanatory models are at the core of meaning for scientific theories and are the center of sense making by learners (Clement, 2008); therefore, solidifying explanations rather than only descriptions within students' mental models is important for their scientific literacy and as a tool for correcting alternative conceptions. In addition, as shown in this study, instructors of subsequent courses should be aware of these weak links between plate motions and other geological processes within students' largely descriptive mental models of plate tectonics.

The consistency of our results with those of other researchers (Barrow and Haskins, 1996; King, 2000; Libarkin et al., 2005; Sibley, 2005; Steer et al., 2005; Clark et al., 2011; Kortz et al., 2011) suggests that instructors should be aware of several widely recognized alternative conceptions that linger after the introductory course and bring these topics into their instruction, rather than assuming prior mastery. Key among these alternative conceptions are (1) confusion between compositional and rheological layering of Earth's interior; (2) the definition of a plate and criteria for recognizing plate boundaries; (3) the locations of earthquake hypocenters and the ability of plate tectonics to explain the stresses and strains revealed in the distribution of earthquakes, not only in plan view but also in three dimensions; and (4) the processes that cause melting in overwhelmingly solid mantle and how those processes of lithosphere formation relate to plate tectonics and therefore to the locations of volcanoes in relation to plate boundaries.

In addition, alternative conceptions that have persisted to the second course, or beyond, in the geoscience curriculum will not likely be corrected by simply lecturing over the material again. Conceptual change depends on developing some level of cognitive conflict that requires discarding incorrect beliefs to accept new ones (Posner et al., 1982; Bransford et al., 2000; Chi, 2008; Clement, 2008). Although not elaborated in this paper, Smith has had success in correcting the erroneous conceptual understanding of plate tectonics by his Earth History students by use of refutational techniques (Kowalski and Taylor, 2009; Broughton et al., 2010; Tippett, 2010), which are advocated as an effective way to revise beliefs (Chi, 2008). Revision of multiple beliefs is critical to conceptual change via transformation of mental models (Chi, 2008). Instruction that is initiated by statements such as "Many students incorrectly assume that..." or "Many of your plate boundary sketches incorrectly show..." alerts students to the shortcomings in their understanding (Broughton et al., 2010). Other related approaches can involve having students compare their sketches to textbook versions or drawings that instructors construct and then not only redraw their sketch but also list the errors they made and write explanations for their misunderstandings. In short, recognizing the alternative conceptions that persist in learners' mental models of critical-to-understand concepts is only half the instructor's task; the other half is to produce the conceptual change that stops the persistence of erroneous or insufficient understanding. Further research is needed into instructional strategies that confront and remove these erroneous conceptions during initial college-level (or earlier) instruction of the most fundamental theory in the geosciences.

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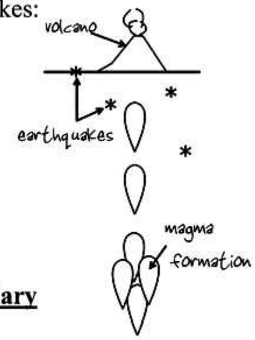
InClass Exercise: Plate Boundary Processes

FOR THE FIRST DRAWINGS: PLEASE WORK BY YOURSELF AND DO NOT CONSULT ANY READING OR NOTE RESOURCES.

All of your drawings *must* include the items in this checklist:

- ☐ Crust
- ☐ Lithosphere
- ☐ Asthenosphere
- ☐ Arrows showing directions of plate movement
- ☐ Where magma forms
- ☐ Volcanoes
- ☐ Earthquakes (mark locations with *s)

Suggested method for noting volcanoes, magma, and earthquakes:



1. *Draw* and *label* a cross-section through a **divergent plate boundary** within an ocean basin.

First drawing:

Second drawing:

1. *Draw* and *label* a cross-section through a **convergent plate boundary**

First drawing:

Second drawing:

APPENDIX 1: Example of student worksheet.