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Alternative Conceptions of Plate Tectonics Held by Nonscience Undergraduates

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ABSTRACT

The theory of plate tectonics is the conceptual model through which most dynamic processes on Earth are understood. A solid understanding of the basic tenets of this theory is crucial in developing a scientifically literate public and future geoscientists. The size of plates and scale of tectonic processes are inherently unobservable, necessitating the use of images and models in instruction. To explore plate tectonics conceptions held by undergraduates, we designed and administered a postinstruction survey instrument centered on a common schematic representation of plate tectonics. We report results from a sample of n = 60 nongeoscience majors enrolled in five different introductory Earth-science courses taught at a major research university and a community college. Students held a number of alternative conceptions associated with terminology, plate motion, and plate-related subsurface melting. We also note that some aspects of figures commonly used to teach plate tectonics are problematic for students and may actually result in reinforcement of alternative conceptions. Further work at both the K–12 and college levels directed at innovative approaches to address student conceptions regarding plate tectonics, including designing images that support key scientific messages, is needed. This research can inform curriculum development for entry-level geoscience courses as well as the use of images to convey complex science.
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INTRODUCTION

The theory of plate tectonics, which describes the large-scale movements and interactions of Earth's fragmented lithosphere, is arguably the most fundamental concept in the geosciences. Studies of the sea floor in the 1950s and 1960s (Dietz, 1961; Hess, 1962; Vine and Matthews, 1963; Morley and Larochelle, 1964) elucidated a mechanism to explain Wegener's drifting continents (Wegener, 1966), paving the way for the scientific revolution that rocked the geological community. The theory of plate tectonics has become so fundamental to understanding Earth that, like the theory of evolution, it is an essential theory for the development of a scientifically literate populace. This importance is reflected in the prevalence of plate tectonics and related processes within K–12 and general literacy standards (AAAS, American Association for the Advancement of Science, 1993; Earth Science Literacy Initiative, 2009). Similarly, chapter headings in introductory-level geoscience textbooks, such as: "Plate Tectonics: A Unifying Theory" (Monroe *et al.*, 2007), "The Way the Earth Works: Plate Tectonics" (Marshak, 2008), and "Plate Tectonics: The Unifying Theory" (Grotzinger and Jordan, 2010) are indicative of the importance of teaching this theory to students enrolled in entry-level geoscience courses.

Earth science courses for nonscience majors or beginning geoscientists generally provide broad overviews of significant scientific concepts, models, and theories. Students who may be taking their only college-level science course will have few, if any, future opportunities to correct their alternative conceptions about scientific models. At the same time, science instruction in introductory courses lays the foundation upon which budding geoscientists will build conceptual models in subsequent courses.

Alternative conceptions have been documented in a number of previous studies on student understanding of plate tectonics and related aspects of Earth. Added to this, concerns have been raised regarding the perpetuation of alternative concepts in Earth science textbooks (Stern, 1998; King, 2010). An understanding of the fundamental nature of Earth's interior is an important prerequisite to grasping plate tectonic processes and their relation to the solid Earth. For example, DeLaughter *et al.* (1998) reported that, prior to instruction, university students enrolled in an introductory-level Earth science course held the alternative conception that a magma layer exists inside Earth. King (2000) documented a range of alternative conceptions regarding the states of matter in Earth's interior held by science teachers in the United Kingdom. Notably, only 16% of 61 surveyed teachers correctly labeled the mantle below the asthenosphere as solid. When asked to describe Earth's interior, 10% of the 5th grade students studied by Gobert (2000) sketched a layered cross-section with the core as the lowermost layer in the circle, the mantle as a layer above that, and the crust as the top layer in the circle. This same alternative conception has been observed in drawings by 10–15 yr old students in Spain (Lillo, 1994), and by college students (Steer *et al.*, 2005; Wunderle, 2007). In addition, Libarkin *et al.* (2005) reported that undergraduate students confuse terms that define chemical zonations, such as crust and mantle, with the rheological zones of lithosphere and asthenosphere.

Confusion regarding what a tectonic plate is and where it is relative to Earth's surface has been documented in high school students in Portugal and college students in the United States. After lessons on plate tectonics, 64% of

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16- and 17-yr old Portuguese students stated the alternative conception that tectonic plates are arranged like a stack of layers (Marques and Thompson, 1997). Libarkin (2006) similarly reported that college students in the United States represent plates and magma as layers within Earth. In addition, some college students enrolled in introductory or general education geoscience courses were unsure about the location of tectonic plates, describing them as existing below Earth's surface, at the core, or even in the atmosphere (Libarkin *et al.*, 2005). Similarly, Dahl *et al*. (2005) found that a majority of the in-service teachers in their study were likewise unsure about tectonic plate locations.

The work of Sibley (2005) raises concerns regarding the conceptual models of plate tectonics that some geoscience undergraduates may be carrying into the workforce or graduate school. During interviews, nearly one-half of upper-class geoscience majors and beginning graduate students represented mountains formed at a continent–continent convergent boundary either as cones sitting on a flat surface or as two sheets of hard rubber that had been pushed together. Sibley's (2005) findings indicate that some geoscience students do not understand the isostatic compensation provided by a low-density root underneath mountains.

In an attempt to expand upon this knowledge base of alternative conceptions related to plate tectonics and to consider the role of images in learning, we designed a plate tectonics conceptions survey instrument (Clark and Libarkin, 2011). In this paper, we address a subset of data collected with this instrument, and consider the following question: Which alternative conceptions about plate tectonics do undergraduate students retain after completing an entry-level geoscience course that explicitly covers the topic of plate tectonics?

THEORETICAL FRAMEWORK

The current study follows research into alternative conceptions in the Earth sciences that has been occurring since at least the early 1980s (e.g., Ault, 1982; Happs, 1982; Schoon, 1995; DeLaughter *et al.*, 1998; Dove, 1998; Trend, 1998; Dodick and Orion, 2003; Libarkin and Anderson, 2005; Cudaback, 2006; Petcovic and Ruhf, 2008; Kortz and Murray, 2009). Our work is grounded in the notion that prior knowledge is important for learning, and that recognizing the presence of alternative conceptions can help instructors appropriately assist students in the process of conceptual change that will lead to the adoption of scientific models (e.g., Posner *et al.*, 1982; Hewson and Hewson, 1983; Driver *et al.*, 1994; Guzzetti, 2000).

Locating the Research

Researcher background and philosophical perspective affect the researcher's interpretation of data and are, therefore, important aspects in assessing the research design (Patton, 2002; Maxwell, 2005; Marshall and Rossman, 2006; Feig, 2011). The lead author is a geoscientist with a research background in isotope geochemistry and geocognition, which is the study of how people perceive and understand Earth and Earth processes. The second and third authors are also geoscientists with research backgrounds in geocognition, as well as geodynamics and planetary geology, respectively. The fourth author is an undergraduate with a double major in environmental geoscience and environmental economics. Our philosophical perspective would be considered post-positivist. That is, we perceive that what is currently considered to be knowledge is subject to change as new evidence becomes available (cf. Phillips and Burbules, 2000).

METHODS

To better understand the postinstruction alternative and scientific conceptions held by nonscience majors, we designed a multiquestion, mixed-methods survey instrument based on a common schematic cross-section of Earth (Fig. 1). The survey instrument consisted of a demographic survey and a set of five to six research questions:

(1) Identify by name any features related to plate tectonics.
(2) Circle areas below the surface where you think melting is occurring.
(3) Use arrows to indicate the relative direction tectonic plates are moving.
(4) Explain what the colors below the surface represent.
(5) Explain why melting occurs in the places you indicated in the figure.
(6) Estimate the percentage of the mantle that is liquid (magma). (Note: This question was added to the survey instrument after data had been collected from all but one of the five courses involved in this study.)

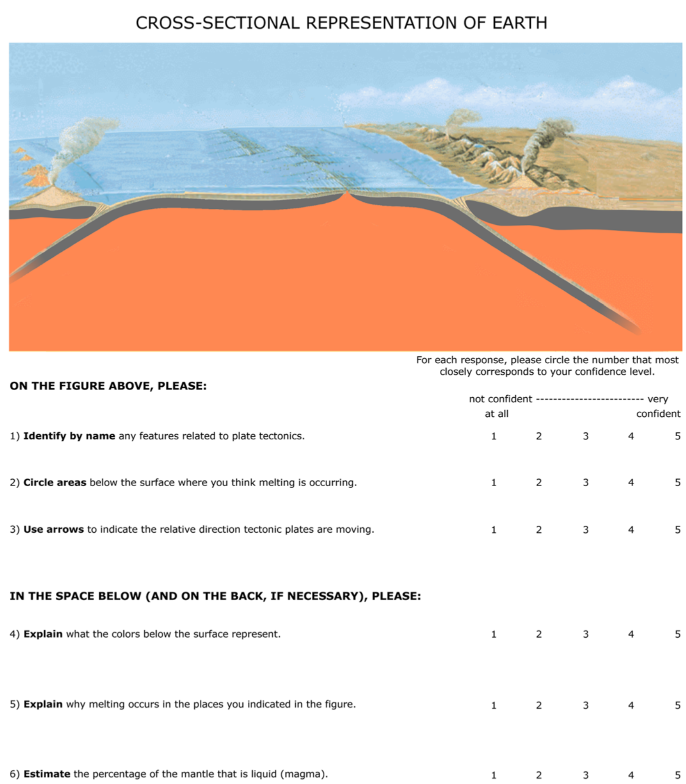

FIGURE 1: (Color online) Survey instrument. Image is modified from Vigil in Simkin *et al.* (1994) and Vigil and Tilling in Simkin *et al.* (2006).

For the first three questions, students were asked to write their responses on the cross-section image because student-augmentation of drawings can provide insight into students' concepts (Libarkin, 2006). Unlike free-form drawings, augmented drawings constrain the nature of student responses and limit the number of potential coding categories in qualitative studies. Students responded with short written responses to the last three questions. Open-ended responses provide more insight into a student's thinking than would fixed responses, such as Likert-scale or multiple-choice questions. Analysis of written responses allows researchers to record not only students' answers but may also allow for interpretation of underlying reasoning.

Clark and Libarkin (2011) document the development of this survey from initial modification of a cross section available in the public-domain (Vigil in Simkin *et al*., 1994) with additional modifications based on the updated, online version of the same image (Vigil and Tilling in Simkin *et al*., 2006). Modifications involved removing all text and reducing the complexity of the image: The hot spot, continental rift, arrows indicating relative motion of the plates, and aspects that indicated melting were removed. These modifications allowed us to ask questions about terminology, relative plate motion, and melting.

Design of Survey Questions

A complete description of the instrument design process is provided in Clark and Libarkin (2011); we provide a brief overview of this process here. Survey questions were developed through an iterative process that included discussions between the first two authors; discussions within the Geocognition Research Lab group at Michigan State University (MSU); a review by members of the Center for Research on College Science Teaching and Learning (CRCSTL) at MSU; and, consideration of solicited feedback that we received by posting the survey instrument on the Geoscience Education Research listserv. The survey instrument was then disseminated to nonscience majors and was used as the protocol in an interview with a geoscience graduate student. Wording of some of the questions was modified based on our analysis of the data collected from the first course and the interview. For example, the first question on the survey instrument requested students to: "Label anything related to plate tectonics". In response, some students wrote "PT" over features that are associated with plate tectonics. While we interpreted those responses to indicate that the students were labeling plate tectonic features as, "plate tectonics", the intended objective was to probe participants' abilities at identifying those features by name. To minimize generic responses, question 1 was modified to read: "Identify anything related to plate tectonics." Similarly, question 2 was modified from, "Show where you think melting could be occurring" to "Circle areas below the surface where you think melting is occurring." The image was also slightly modified after initial data collection. Although most features related to a hot spot in the original image had been removed, one island was visible in the version of the image that had been validated by experts and disseminated to students in the first course. This island created an unintended distraction for at least one student, and was removed prior to dissemination of the survey instrument to subsequent courses. These modifications improved our ability to accurately code responses.

Data Collection

The survey instrument was administered, post instruction, to undergraduate students enrolled at a large research university in the Midwest (n = 172) and a community college in the Northeast (n = 8). The students in the Midwestern university were enrolled in one of three physical science for nonmajors courses: two sections of Global Change (n = 24 and 68), and one section of Natural Hazards and the Environment (n = 80). Community college students were enrolled in Historical Geology (n = 4) and an Oceanography Laboratory course (n = 4). This instrument was one of several distributed simultaneously; each student completed only one of the surveys, and the numbers reported here are not representative of course enrollments. We do not have data on the number of students who were present but chose not to return a survey. The first author, who was not involved in the teaching of any of the courses, disseminated the surveys at the Midwestern University. The second author taught one of the Global Change courses and the third author taught both of the courses at the community college. She also disseminated the surveys to her courses. Students in all courses were informed that this survey was not graded, their participation was voluntary, and that choosing to participate or sit out would not affect any grades in the course. This research has received Institutional Review Board approval and all students were provided with a consent form. Nonidentifying demographic data related to age, gender, ethnicity, and educational background were collected, and responses were anonymous.

Study Population

Out of 180 completed surveys, 60 were selected randomly for analysis. Analysis of questions 1–5 was performed on this sample of 60 surveys. Question 6 was only asked in one course at the four-year university, and we report on all responses received for that question (n = 50). The sampled students consisted of nonscience majors (96.6%). Most reported previous enrollment in an Earth Science course in the 8th or 9th grade (71.2%), but had no other college-level geoscience experience (80.2%). Demographically, the studied population had an average age of 20 ± 1 yr (1 s.d.), consisted of 53% females, and was predominantly non-Hispanic Caucasian (72.4%). Students who identified themselves as Asian (9.2%) were the largest minority, followed by multi-ethnic (5.4%), other (4.9%), black (4.3%), and Hispanic (3.8%).

Scoring of the Survey Instrument

A detailed discussion of the iterative approach we undertook in developing the scoring rubric is presented in Clark and Libarkin (2011); we provide an overview here. Survey data were analyzed using a scoring rubric that was developed via an iterative thematic content analysis (cf. Denzin and Lincoln, 1998; Patton, 2002). The initial rubric was created by the first author based on an analysis of data from the first course. The rubric was subsequently refined through discussions between the authors and as new data were included in the study. In the end, data for each question were analyzed using the final rubric. Responses to question 1 were recorded and grouped into categories. For example, "subducting plate/slab", "subduction zone", and "subduction" were all categorized as subduction. Responses were also scored as correct, incorrect, or partially correct. For example, responses were coded as (1) correct, (2) partially correct, and (3) incorrect, respectively for labeling of the following features as lithosphere: (1) the lithosphere (i.e., crust plus mantle lithosphere; (2) only the mantle lithosphere; and (3) the asthenosphere. The protocol for coding question 2 (Fig. 2) required multiple iterations, including researcher discussions, before a final version was completed and agreed upon (Clark and Libarkin, 2011). In question 3, students were prompted to indicate plate motion by drawing arrows. These arrows were coded in terms of (1) direction and (2) location within the diagram. For questions 4 and 5, general categories were initially created based on common responses. These categories evolved iteratively into a final rubric with which two raters independently coded each response.

Each of the first five questions was coded by at least two researchers. The sixth question was a simple recording of percent melt and did not require coding. Initial inter-rater agreement of independently obtained codes was 81.5, 83.5, 90.0, and 83.3%, respectively, for questions 1–4. Subsequently, researchers discussed discrepancies between their codings and attained 100% agreement. For question 5, the first author created the initial coding categories based on student responses. The second author made suggestions for combining categories and adding a new category. Together, the two coders simplified the categories, reconciled any differences in coding, and reached 100% agreement as they collaboratively coded all responses. One key factor in attaining a high inter-rater reliability was the development of a very explicit protocol (cf. Ambrose *et al.*, 2004; Bresciani *et al.*, 2009; and references therein). For example, the diagonal lines in the scoring rubric for question 2 [Fig. 2(a)] that are perpendicular to the subducting plates were added as a guide for determining whether a specific circle was to be coded as category "4" (trench) or category "5" (descending plate). If the center of a circle was above the line, then it was coded as a "4"; if the center of the circle was below the line, then it was coded as a "5".

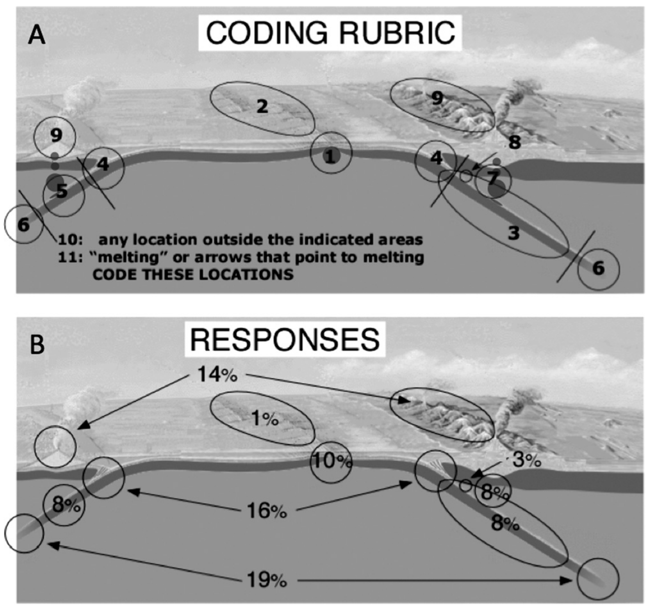

FIGURE 2: (a) Coding rubric for question 2 based on locations where students commonly indicated melting. Coded areas are symmetric. For example, if a student placed a circle on top of either the right or left descending plate directly below the volcano, then that circle was coded as area 5. Gray circled areas near codes 1, 5, and 7 show scientifically acceptable areas of melting. (b) Distribution of responses. Random areas within the subsurface were selected in 13% of responses.

Rigor and Trustworthiness

It is important to assess the research design, data collection, analytical methods, and findings of any research project. In a mixed-methods study such as this one, where both qualitative data (i.e., answers written on the image and open-ended responses) and quantitative data (e.g., answers that estimate the percentage of liquid in the mantle) are collected and analyzed, the rigor (i.e., validity and reliability; Litwin, 1995; Morse *et al.*, 2002) and the trustworthiness (credibility, transferability, and dependability; Lincoln and Guba, 1985) of the instrument and findings must be assessed. A synopsis of our approach to evaluating rigor and trustworthiness is provided in Table I. A more detailed discussion is presented in Clark and Libarkin (2011).

RESULTS

Terminology

In responding to question 1, 43 students (72%) labeled at least one feature on the diagram. Students who answered question 1 labeled 4.2 ± 2.9 (1 s.d.) features on average, with an overall range of 1–15 features labeled per student. In all, 181 labels were coded. Of these labeled features, 65% of responses were coded as correct; 13% partially correct; and, 22% incorrect. Students labeled both plate tectonic features and processes on the image (Table 1). Interestingly, a process, "subduction", was the most common label, although as a whole, feature-related terms were much more dominant. "Volcano", "crust", and "mid-ocean ridge" were the most frequently labeled features, with each used by approximately 25% of students. "Volcano" was used correctly 100% of the time, and "mid-ocean ridge" was used correctly 86% of the time. In contrast, "crust" was used correctly in only 47% of the submitted responses. Responses for other common plate tectonic features such as "mantle", "lithosphere", "melting", and "plate" were correctly applied less than one-half of the time, as well. Although the image did not include hot-spot volcanism, seven students labeled a feature as such; two students labeled the divergent boundary as a hot spot and five labeled the foremost island-arc volcano as such.

Terms that are directly related to the rheological divisions of Earth, such as lithosphere ($n = 5$) and asthenosphere ($n = 4$) were used less than half as often as terms related to chemical properties: crust ($n = 15$) and mantle ($n = 7$). The term "plate" was misapplied to the asthenosphere, mantle lithosphere, and plate boundaries. Of the eight students who labeled the "mantle", seven labeled

TABLE 1: Rigor and trustworthiness.

Criteria	Description and approaches	Plate tectonics conceptions survey instrument
Content validity	A measure of whether or not items actually measure the latent trait that they are intended to measure. This is often evaluated through expert review of items and revision in response to expert opinion.	Comments from five geoscientists from the GRL[1] and GeoEd-Research listserv[2] and two science educators from the CRCSTL[3] group led to revisions prior to disseminating the survey instrument to students. Further revisions came after analyzing student responses from the first class and from an interview with a geoscience graduate student.
Communication Validity	Researchers develop surveys in order to generate an understanding of a study population. While researchers often assume that participants will interpret questions as intended, explicitly considering this aspect of instrument validity can generate important insights (cf. Lopez, 1996).	Communication validity was improved in questions 1 and 2 as we modified the wording until nearly everyone who answered the questions was providing meaningful responses.
Conclusion validity/ Credibility	Conclusion Validity is the measure of one's ability to determine the relationship, or lack thereof, between the variables being studied. In general, researchers need to ensure that they are not biasing study findings through personal expectations, their own actions, or failure to consider study limitations. For qualitative work, *credibility* also addresses researcher bias, and in particular the degree to which study participants agree with findings and the broader implications of the work (cf. Lewis, 2009).	We found this to be the most difficult metric of validity and reliability to evaluate. Experts exposed to our research findings during presentations at professional meetings have generally agreed with the study findings. Ultimately, we view credibility as final step in the study validation process.
Transferability	A measure of the extent to which results can be generalized to populations outside of the study. This validation is difficult to achieve, although the power of survey research lies in its ability to sample many populations, and hence generate measures of external validity.	This survey instrument was collected from 180 students enrolled in five different courses at two institutions in the Midwest and Northeast United States. The students represent typical undergraduate nonscience majors who are fulfilling a science requirement.
Dependability	A measure of the extent to which other researchers would be able to replicate the study findings.	Clark and Libarkin (2011) describe the development of this survey instrument and rubric. That description serves as an audit trail, providing details for others to evaluate the instrument's design and our findings.
Inter-rater reliability	Inter-rater reliability helps ensure that findings are reproducible. Often, this is established through an iterative process whereby multiple researchers code identical data and establish consistency in analytical results.	Prediscussion inter-rater agreement was $\geq$ 80% for all questions and 100% post-discussion; see text for details.

Notes:
[1]GRL—Geocognition Research Laboratory at Michigan State University.
[2]GeoEd-Research listserv —an online resource for persons interested in geoeducation research.
[3]CRCSTL—Center for Research on College Science Teaching and Learning.This table is modified after Clark and Libarkin (2011). Except where noted, concepts of rigor and trustworthiness are adapted from Lincoln and Guba (1985), Litwin (1995), and Trochim and Donnelly (2007).

only the orange part of the image (i.e., the asthenosphere), and the eighth labeled only the dark gray layer representing the mantle lithosphere. No one correctly identified both the orange (asthenosphere) and dark gray (mantle lithosphere) as the mantle.

As mentioned above, process-related labels were dominated by "subduction" and related phrases (e.g., "sinking plate"; Table 2). Terms related to convergent plate boundaries (i.e., subduction and convergent) were used more frequently (n = 42), than terms related to the divergent boundary (i.e., divergent and mid-ocean ridge; n = 24). The degree of correct term usage was similar for both of the boundaries (79 and 83% correct, respectively). No students correctly labeled the transform boundaries along the mid-ocean ridge.

Plate Motion

Students were prompted to place arrows on the diagram to represent plate motion. In all, 83 paired and 39 single arrows were coded. Nearly one-half of the students (n = 28; 46.7%) indicated motion related to the divergent boundary and at both convergent boundaries. Thirty percent (n = 18) indicated motion near two of the boundaries, 11.7% (n = 7) indicated motion near only one boundary, and 11.7% (n = 7) did not answer the question. Only one student indicated motion related to the transform

TABLE 2: Partial list of terms used to identify features (responses to question 1).

Response	Total labeled	Correct	Partially correct	Incorrect	Percent correct (%)
Subduction[1]	30	28	1	1	93
Volcano ± eruption	16	16	0	0	100
Crust (incl. continental and oceanic crust)	15	7	3	5	47
Mid-ocean ridge/ rift	14	12	0	2	86
Convergent ± boundary	12	5	3	4	42
Melting	11	3	1	7	27
Divergent ± boundary	10	8	0	2	80
Mountain ± range	9	7	0	2	78
Hot spot	7	0	0	7	0
Mantle	7	0	7	0	0
Trench	7	7	0	0	100
Lithosphere	5	1	2	2	20
Asthenosphere	4	4	0	0	100
Plate	4	0	2	2	0

Twenty other terms were used less than 4× each. Mantle responses included six that identified only the orange zone, and one that identified only the dark gray zone.
[1]Includes subduction, subducted or sinking plate.

boundaries along the mid-ocean ridge. Students who indicated motion near only two boundaries tended to do so near the two convergent boundaries (n = 14 of 18; 77.8%), and most of responses that indicated motion near only one boundary did so near the divergent boundary (n = 6 of 7; 85.7%).

Eighty-two percent (n = 32) of the students who indicated motion at the divergent boundary recognized that both plates are moving. Interestingly, 25% (n = 8) of these responses indicated convergence, rather than divergence (e.g., Fig. 3). Ten percent of the responses at the divergent boundary indicated motion of only one of the plates, and the remaining 8% of students indicated anomalous plate motions (e.g., arrows that were parallel to the divergent boundary).

Of those students who indicated motion at one or both of the convergent zones, movement was indicated on both plates at the ocean–ocean and ocean-continent convergent zones in 52% and 59% of responses, respectively (n = 24 and 26). Thirty-nine percent of the other coded responses indicated movement of only one plate (n = 18 and n = 17 at the ocean–ocean and ocean-continent convergent zones, respectively). Of the 18 students who indicated movement of only one plate at the ocean–ocean convergent zone, most (n = 16) indicated downward motion on the subducting plate, and one indicated upward motion on this plate. Similarly, most students (n = 13 of 17) who indicated motion of only one plate at the ocean-continent boundary indicated subduction of the plate. All but one of these students were part of the cohort who also indicated downward motion at the ocean–ocean convergent boundary.

Several other interesting student ideas about plate motion were noted. One student indicated that overriding plates move toward convergent boundaries without also indicating a downward motion of the descending plate. Four students presented the opposing, and scientifically inaccurate, view that the relative motion of the continental plate is directed away from the ocean-continent subduction boundary. Additional responses coded at the convergent boundaries include four students who indicated convergence within the overriding plates by drawing pairs of arrows pointing toward each other on the sides of volcanoes. One student held an opposing view and drew arrows pointing away from each other on the sides of the island-arc volcanoes. Finally, the one student who indicated motion along the transform boundary suggested motion that is inconsistent with the correct sense of motion along transforms.

Sub-Surface Melting

Students were prompted to indicate where and why melting occurs below the Earth's surface (questions 2 and 5). Students in the last course that was assessed were also asked to estimate the percentage of melt beneath Earth's surface (question 6). The frequencies of responses related to the location of melting reported here represent the percentage of responses that fell within a specific area (Fig. 2). Fifty-nine students responded to "Circle areas below the surface where you think melting is occurring", circling a total of 77 places on the image. The most frequently selected locations were where the subducting plates appear to fade away in the image [19%; Figs. 2(a) and 2(b)]. The next most frequently indicated area was at the trenches where the plates subduct into the asthenosphere (16%). Eight percent of responses indicated that the entire subducting plate is melting, and another 8% indicated melting of the plate directly below the volcanoes. Volcanoes were identified as places of melting in 14% of responses. Thirteen percent of responses pointed to seemingly random places in the asthenosphere. As to the scientifically correct areas of melting, only 10% of the students circled the area directly below the divergent boundary and 8% indicated melting in the mantle wedge above the

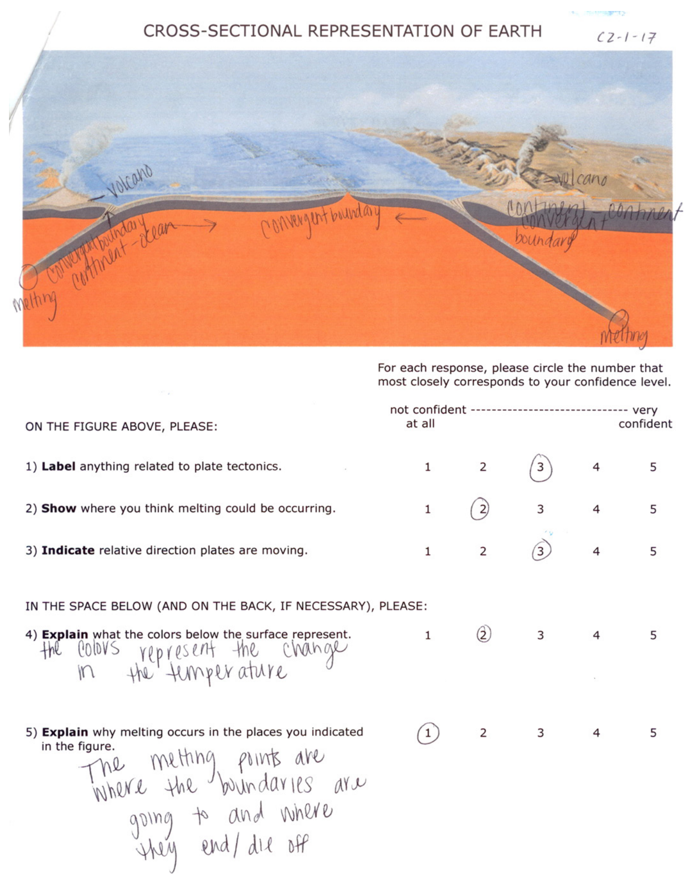

FIGURE 3: (Color online) Example of a student's responses. The responses include a number of alternative conceptions discussed in the text, including (1) "convergent boundary" and arrows indicating convergence at the divergent boundary; (2) confusion about what constitutes a continent; and, (3) indicating melting at the ends of the descending plates.

subducting plate. Interestingly, 67% of the students who indicated melting where the plates fade away did not indicate melting at any other location in the image.

Student rationale for the underlying processes responsible for melting varied dramatically. Forty-nine students responded to "Explain why melting occurs in the places you indicated in the figure", providing a total of 72 explanations for melting. The most commonly cited reason for why melting occurs was temperature [or] heat (31%), followed by rocks [or] plates crashing together [or] moving past each other (14%), pressure (13%), friction (10%), and magma melts rock (6%). Of those students who identified pressure as a cause of melting, only one student wrote, "release of pressure", which would be interpreted as a correct response. However, this student stated that both an increase and a decrease in pressure cause melting, "Intense pressure, release of pressure, water, heat, and rising magma". Only 4% of students mentioned water, and another 4% cited magma carrying heat as a mechanism for melting. Other responses included: volcanoes (4%), rising heat from the core (3%), climate (1%), and ambiguous answers or "I do not know" (11%; Table 3).

We report on all (n = 50) responses from students who were asked about the percent of melt in the mantle

TABLE 3: Responses explaining why melting occurs in the subsurface (responses to question 5).

Response	Percent (%)
Temperature [or] heat	31
Rocks [or] plates crashing together [or] moving past each other	14
Pressure	13
Friction	10
Magma melts rock	6
Water	4
Volcanoes	4
Rising magma carries heat	4
Heat from the core	3
Climate	1
Ambiguous or student said they did not know	11

(question 6). Responses ranged from ≤5% to 90% of the mantle being liquid. On average, students estimated a liquid content of 57% ± 26% (1 s.d.) with a mode of 80% (Fig. 4).

Color in the Image

Only half (29 out of n = 60) of students provided rationale for the presence of color in the image. Overall, students provided a range of explanations for what the differing colors in the image represent. Students typically attributed meaning to the orange, gray, and tan layers. We focus our analysis on the responses related to the orange layer (Fig. 1). Thirty-eight percent of students who answered this question identified the orange color as magma or a related term. This contrasts with the 28% of students who identified the orange layer as representing the mantle. The orange layer was also attributed to the rheological terms of lithosphere and asthenosphere. More students identified the orange as representing the lithosphere (14%) than the asthenosphere (7%; Table 4).

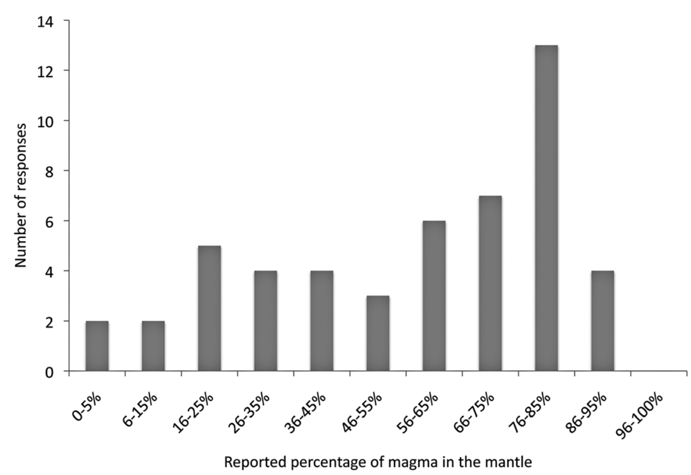

FIGURE 4: Responses (n = 50) from students in the one course who were asked to estimate the percentage of the mantle that is liquid.

TABLE 4: Students' interpretation of the orange colored area of the image (responses to question 4).

Response	Percent (%)
Magma, melted rock, or liquid	38
Mantle	28
Lithosphere	14
Asthenosphere	7
Other comments	13

DISCUSSION

Our survey results suggest that students have difficulties with a wide variety of scientific concepts related to plate tectonics. Post-instruction, students retain some familiarity with the terminology of plate tectonics, although they commonly misapply or conflate chemical and rheological categories. Other difficulties include not recognizing where and why melting occurs below Earth's surface, misinterpreting the state of matter in the mantle, and applying internally inconsistent models for plate motion. We note that terminology, plate tectonic representations, and prior experience all appear to play a role in building and maintaining students' alternative conceptions about plate tectonics.

Terminology

As has been noted in other disciplines (e.g., Pushkin, 1997; Sigal, 2002), novel terminology can pose a barrier to students' conceptual understanding. Student labeling of tectonic features reveals their confusion related to novel geoscience terms. We documented significant misuse of object-oriented terminology, such as "lithosphere", as well as conflation of rheological and chemical terms. These findings agree with those of Libarkin *et al*. (2005).

Volcanoes and subducting plates are obvious aspects of the image, and these were the two most commonly identified features. Terms used to identify chemical and rheological zones of Earth were also common, with chemical terms being preferentially used. "Crust" and "mantle" were used nearly two and one-half times more frequently than "lithosphere" and "asthenosphere", which suggests that the students were more comfortable with the chemical terms than they are with the tectonically relevant rheological terms.

Although the image included representations of all three major plate boundaries, process-related labeling primarily focused on subduction zones and secondarily on divergent boundaries. This focus on subduction may result from the presence of two subduction zones and only one divergent boundary in the image, or from students finding subduction to be a more obvious process. The transform boundaries in the image dissect the divergent boundary, as is common in nature. Consequently, transform boundaries are not obviously distinct from the divergent boundaries. This may have affected why no students used the term, "transform" and only one attempted, albeit incorrectly, to indicate motion along the largest transform segment.

Plate Motion

Topographic features, such as volcanoes and trenches, are an important key to understanding the relationship between subsurface plate tectonic processes and surface manifestations. The surface expression of tectonic processes was integral to the formation of the theory plate tectonics and is ubiquitous in plate tectonics exercises (e.g., Sawyer *et al*., 2005). Unfortunately, recognition of features by students does not necessarily imply an understanding of underlying processes.

One out of every four students who indicated motion of both plates at the mid-ocean ridge indicated convergence instead of divergence. This suggests either a misinterpretation of plate tectonic processes or of the image itself. The most likely explanation is that students who indicated that the plates are coming together at the mid-ocean ridge misunderstood why the ridge is topographically higher than the surrounding ocean floor. As noted earlier, Sibley (2005) reported that nearly half of upper-class geoscience majors and beginning graduate students in his study misunderstand the nature of mountain formation at continent–continent convergent boundaries. Students in that study represented mountains either as cones sitting on a flat surface or as two sheets of hard rubber that had been pushed together. Similarly, we interpret student representation of convergence at divergent boundaries as indicative of their interpreting the elevated topography at that boundary to be caused by plates coming together. This interpretation may also explain why several students placed converging arrows on the sides of the subduction-related volcanoes. Alternatively, students may have thought the subduction-zone volcanoes were on the plate boundary rather than adjacent to it (Kortz *et al*., 2011). Interestingly, four respondents indicated convergence at both of the subduction zones and at the mid-ocean ridge. This creates an internally inconsistent model requiring plates to forgo extension.

Subsurface Melting and Color

Analysis of student responses about melting suggests that students were either not exposed to or are not retaining scientifically appropriate ideas about the state of matter in Earth's subsurface. As has been previously documented in studies of science teachers and students from elementary school through college (e.g., DeLaughter *et al*., 1998; Gobert, 2000; King, 2000), some participants in our study held the alternative conception that the mantle is liquid. The mantle is unambiguously greater than 99% solid. Clearly, partial melting occurs in the mantle below spreading axes, above subduction zones, and at isolated hot spots. However, away from these unique environments, the asthenosphere is solid (Karato and Jung, 1998) or possibly up to about 1% melt (Kawakatsu *et al*., 2009). The only other part of the mantle where a small fraction of molten rock may exist is the ultralow velocity zone just above the core-mantle boundary (Garnero *et al*., 1998). The solid nature of the mantle is not getting conveyed to many students and educators.

In our data set, an increase in temperature was the most commonly cited reason for why melting occurs. However, the vast majority of melting in the mantle is due to depressurization of the asthenosphere where plates spread apart, and hydration of the mantle wedge resulting from dehydration reactions occurring in the descending plates. Neither of these processes requires the addition of heat to generate melts. That the two processes that actually lead to the vast majority of melting accounted for only 5%

of postinstruction responses points to a need to focus more instructional effort on these topics.

Alternative conceptions related to the state of matter of the mantle and the reasons for melting may be associated with how the mantle and descending plates are commonly represented in images used for teaching. Following existing images, we retained an orange color to represent the asthenosphere in our survey image, and we showed the descending plates fading away in the deeper mantle (Fig. 1). Students' preference for labeling the orange part of the image as magma, melted rock, or liquid (Table 4) suggests that the orange coloration contributes to students' confusion of both the physical state of the asthenosphere and the location of molten rock beneath Earth's surface. An interpretation that the descending plates melt as they fade away in the deeper mantle is unsurprising when considered in light of the student conceptual lens of a molten mantle (Fig. 3). Depicting descending plates fading into the deeper mantle may be prompting students to develop new alternative conception or reinforcing an existing idea that melting occurs at depth in the mantle.

The second most commonly chosen locations for melting were at the trenches. If a student thinks the orange represents magma and that magma melts rock (Table 4), then this might explain part of why the trenches were selected as a melting location. However, the color choice in the image may not be the dominant influence on this alternative conception. Many students stated that friction, rocks clashing, or plates moving past one another are the causes of melting, and these processes occur at the trenches where two plates destructively interact. It may be that students are utilizing underlying misconceptions about the causes of melting to determine locations of melt.

The issue of how images represent plate tectonic processes has been discussed previously when, for example, Stern (1998, p. 223) wrote, "The unfortunate tendency of introductory geology texts to show the subducted crust being melted beneath the arc volcano is a lamentable misrepresentation of our science's understanding of this fundamental and distinctive earth process." The alternative conception that the descending plate is the main source material for subduction-related magmas is clearly seen in our dataset. As noted, only 8% of responses correctly indicated melting within the mantle wedge, compared to 16% of responses that indicated melting of the subducting plate (categories 3 and 5, respectively, Fig. 2). If we include those responses that indicated melting where the plate disappears, the fraction of responses indicating melting of the descending plate jumps to 35%.

Beyond the potential of images to mislead, textbooks (King, 2010) and science benchmarks have described the asthenosphere and mantle as "partially molten". For example, the AAAS benchmarks state that, "The earth's plates sit on a dense, hot, somewhat melted layer of the earth." (AAAS, 2009). If students learn that tectonic plates sit on a "somewhat melted layer" and also see images with the asthenosphere being represented by orange or red colors, colors which are widely considered to represent the concept of hot (Madden *et al.*, 2000), it would take only a small cognitive misstep to form the alternative conception that the mantle is liquid.

Addressing Alternative Conceptions

Students can have difficulty transitioning from alternative to scientifically correct conceptions. Research indicates that successful conceptual change often requires active learning during which students can directly confront discrepancies between their own ideas and tangible evidence (e.g., Posner *et al.*, 1982; Hewson and Hewson, 1988; Chan *et al.*, 1997; Guzzetti, 2000). The students who participated in this study received 1 to 2 weeks of plate tectonics instruction. The instructional techniques ranged from traditional lecture to inquiry. Examples of active learning methods used in some classrooms included a jigsaw activity wherein students become "specialists" in one aspect of identifying plate boundaries and then teach their peers (Sawyer *et al.*, 2005) as well as preliminary versions of Lecture Tutorials for plate tectonics (Kortz *et al.*, 2008). Although we did not specifically investigate instructional strategies, we suspect that many of the fundamental concepts discussed here were not directly addressed or emphasized by instructors. Our discussions with experts suggest that many faculty who teach introductory-level courses perceive these fundamental concepts to be quite easy to understand. This may explain why these concepts are not emphasized in instruction. However, as shown in this study, these fundamental concepts are still not clear to the students despite instruction.

College-level science courses may have the most significant impact on the scientific literacy of the American public (Miller, 2010). Many nonscience majors at universities nationwide take only one physical science course to satisfy general education science requirements. If alternative conceptions are not adequately addressed during that course, students are likely to become part of a general public that has a limited grasp of fundamental scientific concepts. As some geoscience concepts are extremely entrenched and hard to change by either traditional or alternative teaching approaches (Libarkin and Anderson, 2005), the sooner and more frequently alternative conceptions are addressed, the more likely the success of the intervention.

Study Limitations

Although this study has documented the extent of numerous alternative conceptions related to plate tectonics, it was conducted using only one image and a limited set of questions. The number of students who completed the survey (n = 180) and the number analyzed (n = 60) allowed us to see overall response patterns, but collecting data from students enrolled in courses at multiple colleges and universities would have strengthened the transferability of our findings as well as allowed us to analyze the data for inter-course differences in alternative conceptions. Two other limitations are that surveys do not provide for an in-depth understanding of the respondents' underlying thinking that led them to their responses, and this dataset did not measure the potential alternative conceptions that may be held by geoscience instructors. On-going work using in-depth interviews with individuals who span the continuum of geoscience novices to experts will provide more insights into the sources and durability of alternative conceptions.

RECOMMENDATIONS AND CONCLUSIONS

This study furthers our understanding of what undergraduates take away from the entry-level geoscience classroom, in particular ideas about plate tectonic features, processes, and concepts. Our data suggest that even after instruction many students retain, or have created, a significant number of alternative conceptions about plate tectonics. Several key take-home messages are important from this work. First, postinstruction students are comfortable with only a few of the terms prevalent in plate tectonics discourse. In addition, students are unable to apply many common terms correctly. Faculty should be aware that use of scientific terminology that is comfortable to experts might inhibit student learning even if this terminology is used repeatedly during instruction. Second, we identified common alternative conceptions about plate tectonic processes. Overall, students commonly misidentify where melting occurs, and misunderstand plate motion and the state of matter in the mantle. Finally, student responses suggest that aspects of the image used in the survey may create conceptual hurdles for students. The image, an adaptation of images commonly used in instruction, supported by national geological organizations, and widely reproduced in textbooks and online, may be causing or reinforcing alternative conceptions, such as the mantle being molten or descending plates that melt deep in the mantle.

Three main recommendations about instruction arise from this study. First, we encourage the consideration of the effectiveness of multiple instructional strategies, from traditional to inquiry-based, for plate tectonics learning. The increasing use of nontraditional approaches, such as Lecture Tutorials (Kortz and Smay, 2010) and ConcepTests (McConnell *et al*., 2006) in teaching plate tectonics provides an opportunity to carefully examine the relationship between plate tectonics learning and instruction. Second, we recommend that figures used to teach plate tectonics be carefully analyzed and revised in light of our findings. In particular, some aspects of plate tectonic images, such as the fading slab tips and orange mantle, may induce or reinforce alternative conceptions. Third, we note that although this study did not look at alternative conceptions of K–12 students, we echo calls for improving the teaching of science in the K–12 system, including efforts specifically directed at pre-service teachers (e.g., Schoon, 1995; Posnanski, 2007). In this way, alternative conceptions will be addressed, or perhaps not created, earlier in the students' educational experiences, leading to fewer alternative conceptions being carried into college and adulthood. We also encourage efforts at the college level that are directed specifically towards journalism majors, because journalists act as important sources of scientific information for the general public.

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