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Students' mental model development during historically contextualized inquiry: how the 'Tectonic Plate' metaphor impeded the process

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ABSTRACT

At present, quality earth science education in grade school is rare, increasing the importance of post-secondary courses. Observations of post-secondary geoscience indicate students often maintain errant ideas about the earth, even after direct instruction. This qualitative case study documents model-building activities of students as they experienced classroom instruction that braids history, inquiry, and model-based-learning within the context of earth dynamics. Transcripts of students' conversations, and their written work indicate students primarily employed model accretion to enhance their mental models. Instances of accretion were descriptive, pertaining to *what* their model consisted of, as opposed to how it explained the target phenomenon. Participants also conflated "continent" with "tectonic plate" and had difficulty attributing elastic properties – the mechanism for earthquakes – to rocks or "plates". We assert that the documented learning difficulties resulted from use of the metaphor "tectonic *plate*", reinforced by other everyday experiences and meanings. We suggest students need time with new models or concepts to develop strong descriptions before developing explanations. They need concrete experiences and explicit discussions concerning mapping those experiences to concepts. Lastly, because students often apply common meanings to scientific terms, we should not ask *if* they understand, but ask *how* they understand the concept.

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Introduction

The recent decade has seen multiple calls for enhanced earth science education (Barstow & Geary, 2002; Hoffman & Barstow, 2007; IUGS Strategic Planning Committee, 2012). In response, earth scientists and earth science educators have developed literacy targets: what people should know in order to understand earth science issues and make informed decisions. The Earth Science Literacy Principles (Wysession et al., 2012) is an example of such a document. Globally, the importance of earth science literacy is reflected in various

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standards documents (Asia-Pacific Economic Cooperation, 2008, 2012; Eurydice Network, 2011; InterAmerican Network of the Academies of Sciences, 2011; National Research Council, 2012). Despite this emphasis, K-12 earth science education in most of the world is not high quality (IUGS Strategic Planning Committee, 2012; King, 2008, 2013). Since many problems facing Earth's inhabitants are earth science-related—climate change, clean water supply, geologic hazards, resource extraction, etc.—it is important to make sure that students' higher education exposure to earth science is highly effective.

There is a need to study conceptual development in the earth sciences. Cheek (2010) found only 79 articles on geoscience conceptual development published within the 27 years prior to her review. She also indicated that most were anecdotal reports about the types of strategies that seemed to work. Libarkin (2005), Marques and Thompson (1997), and Wandersee, Clary, Anderson, and Libarkin (2003) demonstrated that students entering a course with conceptions outside the consensus view often finish the course with little change to those conceptions. The goal of this paper is to supplement the earth science conceptual development literature by illustrating examples of mental model building in the context of earthquakes and plate tectonics. We also give a couple of examples of where learning did not happen as intended and propose a framework for explaining why students are not meeting desired learning outcomes. We hope this will begin a dialogue about the words we use when teaching novices and what we as instructors might take for granted in terms of their interpretation of our words. Do they really hear what we say?

Literature review

The following section reviews literature regarding students' learning, to be used as a framework for developing a curriculum that enhances student learning. This curriculum essentially 'braids' strategies of inquiry, history, and model-based learning (MBL) into a single case study focusing on earthquakes and plate tectonics.

The problem: student conceptual development

Students come to school with understandings of phenomena derived from their own experiences in the world. These understandings often differ from scientific explanations, and are resistant to change (Posner, Strike, Hewson, & Gertzog, 1982; Strike & Posner, 1992), especially from traditional, lecture-style instruction. Students have difficulty developing geologic explanations for many reasons: conflation of scientific terminology with common usage (Clark, Libarkin, Kortz, & Jordan, 2011; Libarkin & Anderson, 2005), geologic processes often happen on scales of time and space beyond everyday experiences, making understanding of such processes difficult (Blake, 2005; Orion & Ault, 2007), and students also have the tendency to project their common, everyday experiences onto geologic phenomena (Clark et al., 2011; Marques & Thompson, 1997; Sibley, 2005). Instructors can contribute to this issue when they take for granted that novices understand vocabulary as it is spoken in lecture (Bransford, 2000). We will highlight three strategies for mitigating learning difficulties.

Strategy 1: inquiry. Traditionally, *inquiry* has been defined in terms of the scientific method (making observations, asking a question, formulating hypotheses, testing through experimentation, collecting and analyzing data, repeat) (AAAS, 1993; National Research Council, 1996). Deng, Chen, Tsai, and Chai (2011) suggested that inquiry also incorporates argumentation. Inquiry is important because it gives students 'the opportunity to experience a process similar to the process by which a given piece of [knowledge] was invented' (Gravemeijer, 2004, p. 114). We refer to Bybee's (2006) interpretation; engaging in scientifically oriented questions, prioritizing evidence in the creation of an explanation, connecting explanations to other scientific knowledge, and communicating/arguing the explanation to others. Our cases compel students to answer questions (either historic or current, of their making, or ones created for them) using actual data. The students have freedom to direct the inquiry, but the trajectory is structured by the history.

Strategy 2: historical case studies. The second strategy is the use of case studies. Recent discussions of case study use in science classes (Herreid, 2007) have highlighted benefits such as enhancing relevance of science content (Dinan, 2005; Dunnivant, Moore, Alfano, Buckley, & Newman, 2000), students' critical thinking skills (Dori, Tal, & Tsaushu, 2003; Herreid, 2004; Hodges, 2005; Yadav & Beckerman, 2009), and students' active participation (Camill, 2006; Dinan, 2005). Cases can promote useful understandings of nature of science (NoS) by exposing students to the *processes and the stories* behind the facts (Herreid, 2007). Conant (1947) incorporated history of science to teach the 'tactics and strategy' of science. Later attempts were modest, at best (Matthews, 1994). Recently, the use of history (Argentieri et al., 2014), and more specifically, historical case studies has been gaining momentum in North America and Europe (Allchin, 2011; Höttecke, Henke, & Rieß, 2012). Historical cases have the added advantage of the science already being worked out (Allchin, 2014). Students having worked on a solution, can look to the history for how and why certain ideas developed (Dolphin, 2009). By braiding inquiry activities with historic case studies, students experience *science-in-the-making* (Latour, 1987); the inquiry is open-ended, though bounded within the context of history (Allchin, 2014).

Strategy 3: MBL. For a novice to generate new knowledge (mental model) or expand explanatory coherence (Thagard, 2012) of previous ideas, (s)he must build that new knowledge iteratively (Nersessian, 2008). This often comes about by applying knowledge from concrete experiences to more abstract concepts (Harre, 2004; Lakoff & Johnson, 1980, 1999). Like 'bootstrapping' in computer science, a learner utilizes pieces of knowledge from different and possibly unrelated domains and puts them together (Carey, 2009) by way of analogy, modeling, visualization (Gilbert, 2008), or thought experimentation. Duschl (1990) referred to the process of knowledge creation as a 'rational feedback loop' (p. 49). Visualization, induction (Buckley & Boulter, 2000), or mapping onto analogues—using concrete experiences as a proxy for a more abstract concept—are key processes in mental model development (Else, Clement, & Rae-Ramirez, 2008; Nersessian, 2008).

After model generation, learners reconcile the model with observations of the phenomenon. Learners adapt (Nersessian, 2008), or modify (Núñez-Oviedo, Clement, & Rae-Ramirez, 2008) their model to align with observations. This includes adding (accretion mode), subtracting (reduction mode), or amending (evolution mode) the model during repeated cycles of testing and refining. This takes a great deal of effort and many communicative exchanges.

We have developed a series of case studies, which historically contextualize inquiry activities centered on model development within the domain of earthquakes and plate tectonics. With these cases, we investigate these two questions:

(1) How do students construct or modify their conceptions about plate tectonics using instruction that braids history, inquiry, and MBL strategies?
(2) How do students utilize their personal and classroom experiences when building their mental models of earthquakes and plate tectonics that differ from the consensus view?

Methods

Research design

This qualitative case study focuses on a group of five women. Though the qualitative nature of the investigation limits our ability to generalize about student learning, 'Studies that explore student thinking in depth … go further than just identifying alternative conceptions or preferred mental models, but rather … inform teachers about the learning process itself' (Taber, 2003, p. 752). Our rich data recordings allow us to dissect the meaning-making processes of the participants (Won, Yoon, & Treagust, 2014), identify where mental model building seemed hampered, and then work to mitigate possible barriers created by prior experiences (Cheek, 2010; Francek, 2013) or the pedagogy used during instruction (Libarkin, 2005; Niebert, Marsch, & Treagust, 2012; Taber, 2003).

The course and instructor. The physical science course used to implement this study was presented mainly to education majors as a science requirement for receiving a teaching certificate, and maintained a blend of lecturing and in-class activities connected to out-of-class readings from a textbook. During class, students explored questions in small informal groups and wrote individual responses to end-of-activity questions. Students earned credit for completing in-class activities (15%), two exams (50%), and a term project (35%). The class had approximately 40 students, about 95% female. The instructor (second author), a chemistry department member, has taught this course for two years. She had a general understanding of the geologic content, but the history and models were new to her. We spent several hours preparing for the implementation of the case, including three meetings prior to and after each class, lasting about one hour.

The participants. The first author solicited participants a few weeks prior to case implementation. Five women volunteered and became the study group. They agreed to let me observe them and audio record their conversations during instruction. Some chose to keep their real name for the report, others offered a pseudonym. The participants were:

- Jane, 19, was pursuing degrees in general education and sociology. She was a second-year student.
- Carrie, 19, was a general education and sociology major, also in her second year.
- Lucie, 21, was from France and in her third year at university, majoring in biology.
- Danielle, 20, was a second-year education major, minoring in sociology.
- Julie, 18, was a first-year university student majoring in math but seeking a degree in science.

The curriculum. The first author designed and refined the curriculum in two prior undergraduate geology courses. Instruction began with comparisons among four different historical models explaining the origin of continents and ocean basins. These included text and diagrams of the porous earth model (Şengör, 2003), contracting earth model (Dana, 1847; Suess, Sollas, & Sollas, 1904) with land bridges (Malaise, 1972; Schuchert, 1932; Willis, 1932) corollary, horizontal displacement (Wegener & Skerl, 1924), and expanding earth (Carey, 1976; Jordan, 1971). The instructor described each of the models briefly, and then gave students written descriptions and diagrams of the models. She asked students to determine implications of each model and how they might go about testing the explanatory power of each. The essential questions (Wiggins & McTighe, 2006) that guided the activity were: How can there be multiple possible explanations for the same data? What is the benefit of approaching a problem with multiple working hypotheses?

The second class began with the idea of earthquakes as one phenomenon that could occur in each of the models used the previous day. Wendy introduced the 1906 San Francisco earthquake, and students read personal accounts of the event (James, 1911; London, 1906), as well as portions of the commissioned report investigating its cause (Reid, 1910). These activities contextualized the ensuing inquiry into elastic rebound theory utilizing the earthquake machine (Hubenthal, Braile, & Taber, 2008). This concrete, functional model (Boulter & Buckley, 2000) consists of pulling wood blocks wrapped with a rubber band along a meter long strip of sandpaper to create a 'stick-slip' motion (Figure 1). We asked students to discern the forces operating in the model, then to map the model to the real world. By first developing an empirical understanding *of* the model, students develop a better understanding of the target concept *with* the model (Kuorikoski & Ylikoski, 2014). The essential questions driving this portion of instruction were: What is an earthquake? Where do they get their energy? Why is it important to study them?

The third class was primarily lecture with some demonstrations exploring the nature of seismic waves using visualizations,[1] to refine understandings about the earthquake machine inquiry. Essential questions were: How are seismic data expressed? What can they tell us about Earth's interior? The fourth class was an inquiry utilizing seafloor data (seismicity, volcanicity, bathymetry, geochronology, and sediment thickness), after Sawyer (2002), to discern patterns among them. Based on the data, students attempted to discern plate boundaries. The essential question was: How can we describe and explain the patterns of global seismicity? See Figure 2 for case structure.

Historical *interludes* set the stage for the inquiry and mental model-building activities, and contextualized the activities afterwards; history situates inquiry. This gives advantage to historical cases over contemporary cases or problem-based learning because history has a guiding effect on the problem and possible solutions (Allchin, 2014). Contemporary

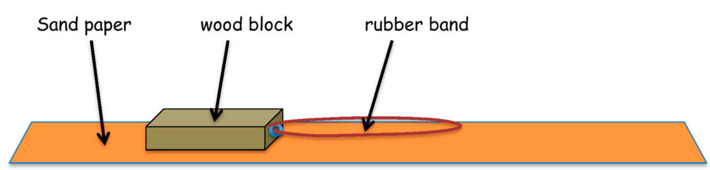

Figure 1. The earthquake machine.

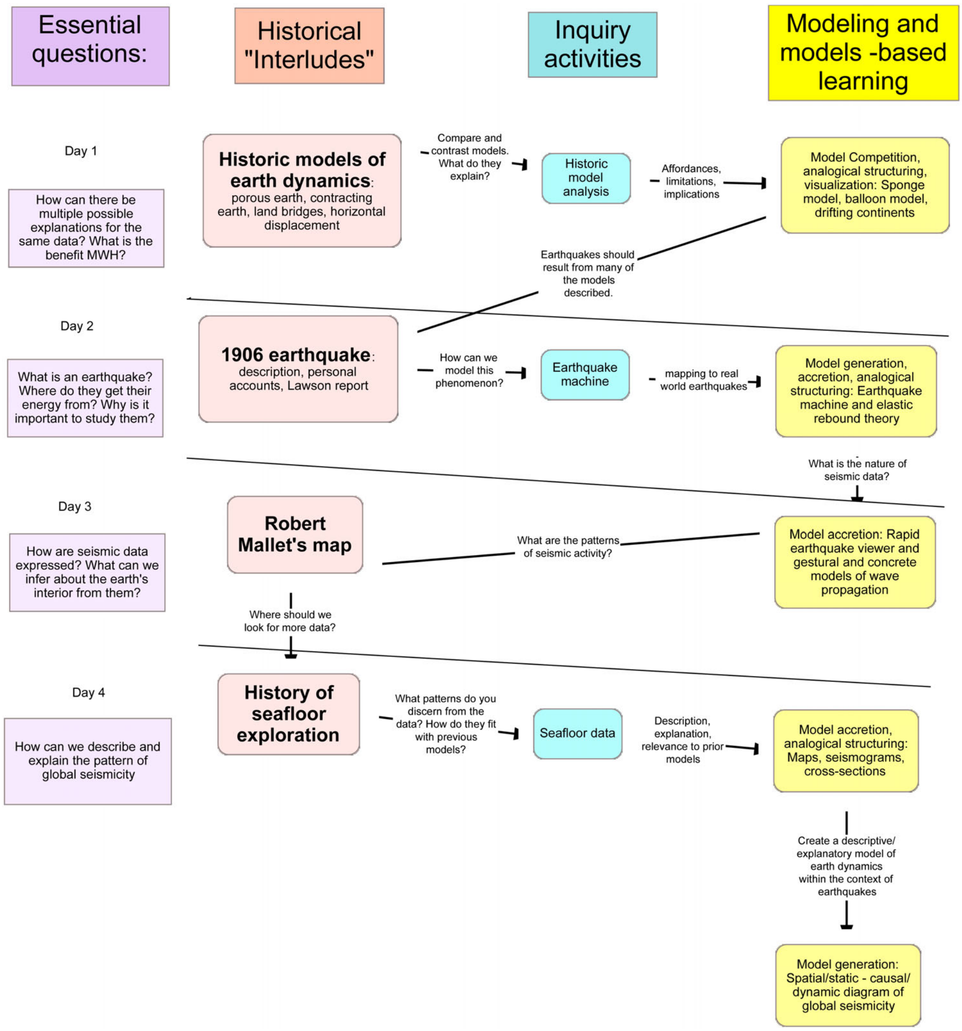

Figure 2. A graphical representation of the 'braiding' of historical interludes with inquiry and model-building activities, with arrows giving the general direction of instruction, and two-headed arrows representing instances for iterations in model building and refinement.

cases may be more relevant to students; however, unlike the settled science of historical cases, contemporary cases leave students wanting some kind of closure. Our curricular design brings together inquiry and mental model building within the structure of a historic case study, defining the end product of the inquiry. Students experience *science-in-the-making* (Latour, 1987) through open-ended inquiry, but also learn how similar past inquiries worked out, and why. Though we built NoS learning goals into the case, our primary goal was to teach geology content, for it is the content piece that is most relevant to other potential users of the case in other classes (Höttecke & Silva, 2011).

Data collection. The instructor implemented the case. The first author acted as participant observer, interacting with the students on a limited basis, taking field notes and audio recording their conversations focusing on evidence of MBL, including gestures, drawings,

Table 1. Examples of data coding within the MBL framework.

Mode	Descriptive	Explanatory
Generation	*Use a labeled diagram to show the forces that are actually involved in the working of the machine.* (Directions from activity handout)	*So, what are your thoughts on that?* (Asked by instructor in reference to the purpose of rubber bands (elastics) in the model)
Accretion	*And if the earth was shrinking don't you think the continents would be moving closer together?*	*But that's why we still have earthquakes, right? Maybe, because the tectonic plates are continuously moving, that's why we have earthquakes.*
Reduction	Carrie: *I know. Except, they're not as strong as, like, under here and in through, sort of Asia, right?* Lucie: *It's not the intensity …* Carrie: *Isn't that what the color indicates?* Lucie: *No, it's the depth, the depth. So here, it's at the surface …*	No examples in data.
Competition	*I think this one explains really well how come there's different, like, fossils found on different continents, of the same organisms. The other ones don't do that at all. This one has evidence for …*	*The other problem is that is like our forces we pulled it using three elastic bands instead of just a string. You know, because there was elastic energy, in this case, for the model; the elastic energy when we are pulling it. So, we should use string.*

and language indicating mental model-building processes. Data also existed as samples of written work such as reflections and exams.

Data analysis. To discern patterns in the participants' MBL, we utilized a framework similar to that outlined in Clement (2008a). This framework allowed us to analyze 'medium sized … interaction patterns' (Núñez-Oviedo et al., 2008, p. 118), specifically multiple exchanges among students, while focusing particularly where mental model building differed from learning goals. We coded passages in the transcripts as model *generation*, *accretion*, *reduction*, and *competition*, noting whether actions were descriptive or explanatory. We coded, based on the following criteria (Table 1):

- *Generation mode*—instances where students initiated a mental model.
- *Accretion mode*—incremental addition (new generalizations or facts) to the current mental model.
- *Reduction mode*—mental model aspects removed because they are not useful.
- *Competition mode*—actively comparing two models for the same phenomenon.

During coding, we determined two modes of mental model building; *descriptive* (tells *what*), and *explanatory* (tells *why*) knowledge. We highlight them here as a possible measure of cognitive investment. Where descriptive knowledge relies on direct observations (some coasts have deeper earthquakes), explanatory knowledge relies more on reasoning, prior knowledge, and phenomena that are not necessarily directly observable (deeper earthquakes result from subduction). Thagard (2012) identified explanation as the most sophisticated kind of thinking in science.

We also coded examples indicating student dissonance, due to either a perceived gap or inconsistencies in their knowledge. We noted comments of reflection on prior knowledge, affirmation of others' statements, active modeling (e.g. visualizations, gestures, analogies (Nersessian, 2008)), questioning, and expressions indicating metacognition. Though our analysis is similar to what Clement (2008a) reported, it also differs in a fundamental respect. Clement (2008b), Else et al. (2008), Khan (2008a), and Núñez-Oviedo et al. (2008) looked mainly at conversational exchanges between instructor and students. Our data reflect prolonged exchanges between and among students, with little interaction from the instructor.

The lead author developed the coding scheme based on the cited literature and described it to the second author. We coded transcripts independently and compared results. We agreed with our coding designations just over 94% of the time, and were able to reconcile all differences through subsequent discussion.

Findings

The following sections present our findings. In this particular paper, we give only brief treatment to our first research question, the nature of mental model building that the students invoked during instruction. We give greater attention to our second research question, times where students struggled or developed mental models inconsistent with learning goals. In the *Discussion* portion of the paper, we propose an explanation for our claims and highlight implications for developing more effective instruction.

Model building based mainly on accretion and description

We found that the vast majority of mental model building by students happened as model *accretion*, and was mainly *descriptive*. We coded 2.5% model generation, 86% of accretion, 0.5% of reduction, and 11% of competition. Also, descriptive claims outnumbered explanatory by 4.7 to 1. Danielle demonstrated descriptive accretion during her work with the earthquake machine. 'So, with one elastic and two rocks, it goes like this.' (She pulls the earthquake machine across the sandpaper) (20140320:711–713). As was common with all the participants, Danielle built her understanding of this model through direct manipulation and observations.

This result is not surprising. The participants made incidental comments relaying that though they had some previous exposure to the concepts of earthquakes and plate tectonics, it was in Grade 7 and mainly lecture based. Therefore, the present activities were brand new to the participants. Their current mental models for these geological concepts were also incomplete compared to the consensus models. Accretion to these incomplete mental models would be the natural trajectory as they gained experiences. Also, explanation requires more than a description of variables, but rather a projection of what would happen *if* a certain variable or variables changed (Kuorikoski & Ylikoski, 2014; Woodward, 2003). Looking at the history of science, determination of the existence of a phenomenon always preceded—sometimes by decades—the explanation of that phenomenon (Rudwick, 2014). Thagard (2012) stated that explanation is the most sophisticated kind of thinking, requiring high cognitive demands. Novices to a topic have difficulty getting past descriptive thinking about representations to develop more sophisticated understandings (Seufert, 2003), like 'interpreting, connecting, and translating various representations' (Won et al., 2014, p. 841).

Struggles with, or inconsistent model building

The following sections document three instances where mental model building was not coherent with learning goals. The first instance shows participants struggling to distinguish between earthquake depth and magnitude. The second shows difficulties distinguishing tectonic plate from continent. Finally, participants demonstrated difficulties attributing elastic properties to rocks.

Are deeper earthquakes stronger? During the maps activity on the fourth day, while students were looking at various maps of seafloor data, some appeared to have difficulty interpreting the map of global seismicity. The map plotted earthquake epicenters for events happening from 1990 to 1996. Epicenters were also color-coded for depth. Wendy mentioned this at the beginning of the class. Throughout the activity, participants showed signs of either conflating earthquake depth with magnitude, or associating depth with magnitude.

Julie: Do the colors mean different magnitudes?
Lucie: Color indicates depth.
Danielle: So, blue is the deepest, green, then orange, then red. So there's very little blue and mostly there's red. So red is the least; 0 to 33 km.
Jane: And where the- Would that still have to do with magnitude, though? That the deeper it is in the earth, the more dangerous the earthquake, or the more destructive? (20140327:230–247)
Carrie: I know. Except, they're not as strong as, like, under here and in through, sort of Asia, right?
Lucie: It's not the intensity …
Carrie: Isn't that what the color indicates?
Lucie: No, it's the depth, the depth. So here, it's at the surface …
Danielle: The depth, yes, but that means it's less intense. This is the least here, zero to 300 km, I mean zero to 33 km. And then green is 70 to 300 km's. So, they're still less intense. (20140327:396–419)
Danielle: Is depth same thing as magnitude? They're probably related. (20140327:539–540)

Both Jane and Carrie associated depth of earthquake with magnitude; the deeper the earthquake, the greater its magnitude. Danielle also seemed to equate them. Especially, having no personal experience relating to either earthquake depth or magnitude, these two concepts would be very abstract.

Defining tectonic plate. From the data, we discerned that participants did not maintain a scientific understanding of tectonic plate. They often conflated the concept of tectonic plates with that of continents. Note the following discussion of Wegener's theory of continental drift.

Carrie: I've never considered them [plates] continuing to move, before.
Danielle: Right. But that's why we still have earthquakes, right? Maybe, because the tectonic plates are continuously moving, that's why we have earthquakes.
Carrie: Right. (She moves her hands in front of her face in opposite directions to create a horizontal circle) Yeah, like in my mind, it's like the continents are still moving and all of a sudden they're going to come back together, and like, come in a circle and crash on the other side (giggles).

Danielle: Or maybe there is some confusion about the movement of the tectonic plates. (20140318:755–772)

During this conversation, the terms *continent* and *plate* get used interchangeably. Carrie even indicated that her *continents* were separate as she motioned with her hands that they could travel around the earth and crash into each other.

During the investigation of the earthquake machine, we noted another conversation about tectonic plates.

Danielle: But are the spaces between the plates that …
Carrie: Substantial.
Danielle: Yeah, that substantial.
Carrie: Yeah, I hope not. Like you are just standing there and it's going to collapse one day. (20140320:557–568)

Carrie projected each wood block to be a tectonic plate and the space between the blocks as actual spaces between plates. This is similar to the idea of plates crashing together discussed above. Carrie hoped this area between plates would not just collapse one day, but gave no indication of a possible cause or where that collapsing material might go.

During the activity with the seafloor data, the participants once again confused tectonic plates with continents.

Julie: How many tectonic plates are there? [There is a four second pause and everyone starts to laugh.]
Jane: I don't know.
Carrie: For some reason, I think- The first thing that comes to mind is seven, but I don't think that's right. (20140327:513–527)

Francek (2013) and Kirkby (2014) have noted this conflation as common. The participants revealed that the last time they formerly discussed plate tectonics was grade seven. Their common experience is with conventional maps, depicting continents separated by oceans; however, an accurate view requires students to visualize the earth without the oceans on top. Comparable to earthquake depth, Höhler (2003) articulated that what lay beneath the depth of the ocean was abstract. Thus, participants considered tectonic plates as separate and *separated* entities moving over the surface of the earth, crashing into each other, and causing earthquakes. The idea of space between plates is a common conception according to Francek (2013).

Rocks are brittle, not elastic. Participants demonstrated difficulty attributing elastic rebound in the earthquake machine to elastic rebound in rocks. The model demonstrated friction and the increase and release of elastic potential energy (stretching and contracting the rubber band). Students mapped the different variables from the source (earthquake machine) to the target concept (actual earthquake). The following excerpts demonstrate participants making general descriptive claims and mapping concrete aspects from source to target. No data demonstrate mapping the concept of elastic potential to earthquakes.

Lucie: Do you see some vibrations?
Danielle: In the elastics?
Lucie: No. In the … (She points to the rock on top of the two blocks)
Danielle: So, this would be like, us, basically, in a building …
Julie: Okay so what would the elastics … What would the elastics represent? (201240320:484–528)
Danielle: (She pulls a couple more times) I would think this happens immediately, but with the elastic – I had to pull out the elastic farther before any movement in the blocks happened … See, like, when I pull it, see how it bounces back? Like, that's when I would imagine – that's when the seismic waves would be going outward from the epicenter. (20140320:897–904)

Lucie recognized the 'vibrating' rock resulting from the sudden acceleration of the block, and Danielle identified that action as what she might experience in a building; these are examples of concrete, descriptive mapping of source onto target. She did not take the next step in identifying the source of the energy causing the shaking. She did not know 'what … the elastics represent'.

Jane: Like, it's easy to examine the friction, or something like that, or when the blocks are turned … or something more connected. I can see that in the real world. Whereas, the elastics, I don't know what, what that is, what force that is. (20140320:861–865)

Similar to Danielle, Jane was able to map the concrete, 'more connected' friction and blocks, but not the role of the elastics.

We note that analysis of the earthquake machine is difficult. Different macroscopic aspects of the model map on either a macro- or micro-scale target phenomenon. It is straightforward to consider the blocks of wood as rocks or even plates, as with Carrie's concern about 'substantial' spaces between plates. Likening the friction from the sand paper to plates 'rubbing together' or 'sliding past each other' is easily derived from common experience. In contrast, mapping the build-up and release of elastic potential seemed difficult for the participants. The deformation of bonds between atoms happens in the micro-scale and is therefore not directly observable. Macroscopic deformation of the crust is measureable, but requires 10s to 100s of kilometers to measure it. This, coupled with the idea of rocks bending, or stretching and 'snapping back', pushes the target concept outside the realm of personal experience.

Discussion and implications

To address the findings regarding our first question concerning student mental model building, we make the following recommendations. These students had very little prior instruction concerning earthquakes and plate tectonics. Their mental models were quite incomplete compared to the consensus view. Given the state of earth science education in most places in the world (noted in the introduction), this observation would be more the rule than the exception. Because their mental models were incomplete, student mental model building favored accretion with an emphasis on descriptive aspects of their experiences. With this in mind, we suggest that as students participate in modeling activities, they be given time and scaffolding to develop understanding *of* the model prior to understanding *with* the model (Kuorikoski & Ylikoski, 2014). For instance, have students answer 'what' questions about the model prior to answering 'why' questions or 'what if' questions. Small group discussion and full class discussion about salient descriptive facets of a model can help set the trajectory for developing a foundation for the desired explanatory aspects. In this way, students focus 'on the *scientific* in scientific explanation' (Woody, 2015). It also takes into consideration the increase in cognitive demand from description to explanation (Thagard, 2012).

To address the instances where model building did not proceed as anticipated, we propose an explanation, which also carries with it implications for future curricular development, teaching and learning. Our explanation derives from the growing body of literature dealing with embodied cognition and conceptual metaphors.

Recent advancements in the cognitive sciences point toward a new model for learning: knowledge creation (Bereiter & Paris, 2004; Paavola & Hakkarainen, 2005), as it differs from knowledge acquisition or knowledge situated within a community of practice (Anderson, Reder, & Simon, 1996, 1997; Sfard, 1998). Thagard (2012) referred to it as *combinatorial conjecture*. Students create knowledge via the novel combination (convolution in neural networks) of aspects of other, possibly unrelated concepts. Thagard (2012) confirmed this conjecture for over 100 important scientific discoveries and 100 important technological advancements. Detailed accounts of knowledge creation by Maxwell (Nersessian, 2008), Darwin (Gruber & Barrett, 1974), and Kepler (Gentner, 2002), utilizing cognitive historical analysis, demonstrate that these scientists combined knowledge through the use of analogy, by utilizing previous experiences. Clement (2008b) asserted that knowledge creation in novices is similar, in such respects, to that of experts.

There were instances during instruction when mental model building did not proceed as desired; participant models did not align with learning goals. This includes conflating or associating earthquake depth with magnitude, conflating continents with tectonic plates, and difficulty attributing elastic properties to rocks. To explain why mental model building did not follow the planned trajectory in these specific instances, we invoke a *deeper* explanation (Thagard, 2012, p. 12) for the MBL mechanism that guided instruction. This requires looking at the *parts* of MBL and deriving even more fundamental mechanisms to explain how MBL works.

The mechanisms of MBL are processes such as thought experiments (Clement, 2008b; Khan, 2008b), visualization (Gilbert, 2008), and analogical thinking (Jee et al., 2010; Nersessian, 2008; Niebert et al., 2012). For this investigation, we focus on the analogical thinking mechanism for a deeper understanding of the participants' mental model building.

Analogical reasoning utilizes similarities between two systems of relations; one fairly well understood compared to the other in which understanding is sought. Effective analogies are those having good structural alignment from the source (understood system) to the target (less understood system) (Nersessian, 2008). Through the process of relating the source to the target (analogical mapping), students can make inferences about the target concept based on behaviors or understandings of the source concept (Jee et al., 2010). In most cases, investigations of analogical transfer, or analogical reasoning, emphasized logical reasoning by study participants (Gick & Holyoak, 1983; Tobin & LaMaster, 1995; Taber, 2003), also known as *slow thinking* (Kahneman, 2011). This logical reasoning or slow thinking allows us to reflect, or reason, focus our attention and make choices. In contrast, more recent work has described application of analogical mapping in a more intuitive, unconscious and automatic manner (Johnson-Laird, 2010; Gallese & Lakoff, 2005), or *fast thinking* (Kahneman, 2011). Automatic, or fast thinking happens when we detect or show emotion, perform routines, identify a sound in space and interpret stereotypes and metaphors. Metaphor is situated within the family of analogy (Gilbert & Watt Ireton, 2003). For this project, we pay particular attention to student use of metaphor as a form of analogical reasoning and a mechanism of MBL. In particular, we are interested in students' automatic thinking during the use of metaphor. Jensen (2006) stated that 'metaphors are a valuable research tool for gaining new insights into education practice and theory' (p. 49), because 'the researcher is able to enter into the inner world of the perceptions, understandings, and experiences of the participants' (p. 41).

Advancements in understanding about how the brain works have revealed that:

- abstract, imaginative thought is largely based on metaphors and analogies,
- metaphors and analogies engendering a conceptual understanding are embodied, or grounded in concrete experience, and
- imaginative thought is unavoidable and ubiquitous in understanding science (Niebert et al., 2012, p. 871).

We learn about our environment via concrete, embodied experiences. For abstract concepts with which we have no concrete experiences (love, mind, energy, etc.), we project, as metaphors, meaning from our embodied experiences onto them (Lakoff & Johnson, 1999). Thagard (2012) stated, 'the creative mind can employ a full range of sensory modalities derived from sight, hearing, touch, smell, taste, and motor control' (pp. 107–108). Lakoff and Johnson (1980) identified this as *experientialism* or *conceptual metaphor*. Pertinent here is that the brain does not interpret metaphors as a literary device to enhance meaning, but as the literal meaning derived from the source or embodied experience (Kahneman, 2011; Reddy, 1979). For example, recent studies provide evidence that thinking about the metaphor, 'the bird is flying *in the air*' (*air* is a bounded container), activates the same parts of the brain as physically exploring the inside of a cup (Gallese & Lakoff, 2005).

In science, we use many metaphors to both identify and teach concepts (selfish gene, black hole, electron orbits). Mapping the metaphors from source to target will both highlight and hide aspects of the target concept (Lakoff & Johnson, 1980), and 'The more vivid the [metaphoric] image, the more dangerously seductive and resistant to change it is' (Ball, 2011). It is difficult to maintain awareness of the hidden aspects. Learners' prior and common experiences hold sway over what is highlighted or hidden (Cheek, 2010; Francek, 2013; Taber, 2003), even after direct instruction (Clark et al., 2011; Libarkin & Anderson, 2005). Taber reported that, depending on the student, the metaphor 'metallic bonding is a sea of electrons' acted as either an impediment or an intermediate step for learning, and that an instructor needs to explore metaphor meaning in the context of students' prior knowledge and raise awareness to the use of the metaphor so the learner can derive, without guessing, intended meaning. Amin (2015) also found that experts mapped scientific metaphors better and developed fewer misconceptions from the metaphors than novices.

We explain the conflation, or correlation, of *depth* of earthquake epicenter with *magnitude* of event through the students' use of metaphor. A very common metaphor, the *location event structure metaphor* (Lakoff & Johnson, 1999) maps states-of-being as locations. Statements like

- It was a long hard journey *to get to this point* in her career, and
- These financial issues have *driven him to insanity*

are examples of the location event structure metaphor. In the earthquake example, above, participants linked magnitude, as a state, with a location below Earth's surface ('the deeper it is in the earth, the more dangerous the earthquake'); where depth is associated with strength, or having more *gravitas*. Common phrases like,

- *deep insights*,
- *deeply entrenched beliefs*,
- *shallow understanding*, and
- *deeply rooted convictions*.

illustrate this. The participants over-mapped (Amin, 2009) the common metaphor relating a state of being (magnitude of earthquake) with its actual vertical place in space (depth); deep earthquakes are strong, shallow earthquakes are not.

Conceptual metaphor explains the ways in which students expressed their understanding of *tectonic plates* as separate entities that move, rub against each other and crash into each other. They accreted neither 'wholeness' nor elastic properties to their mental models. For novices, *tectonic* holds no special meaning. Due to the scale of size (Vollmer, 1984), a tectonic plate and its dynamics is well out of the realm of their observational experiences. However, the word *plate* is very meaningful. Most likely they each ate off a plate for dinner the night before. They utilized their experiences in the mesocosm (Niebert & Gropengiesser, 2015), and through a cascade of associations (Kahneman, 2011) or experiential gestalt (Lakoff & Johnson, 1999), they automatically and unconsciously mapped their experiences with the source concept, *ceramic plate*, onto the target concept of *tectonic plate*.

General experience is that ceramic plates are separate entities we can push together and stack up; if they are dropped, they break. This parallels participants' descriptions of plates moving apart and crashing into each other, and concerns about the spaces between the plates being too 'substantial'. This projection is further reinforced by the typical map of the earth displaying separate continents, with oceans obscuring an abstract portion of crust (Höhler, 2003). Francek (2013) has also noted that it is quite common for students to define plate boundaries at continental coastlines, that there are gaps between them and that they are 'stacked up' under the ground. Francek also reported that it was common for students to think that tectonic plates cannot bend and that the edges break when they run into each other. Similarly, our participants could not map elastic properties to the rocks. Their common experience with plates, or rocks, was as brittle entities. Students' automatic mapping of *plate* onto lithosphere hid the wholeness of the lithosphere and the elastic properties of the materials making it up.

Experts often describe Earth's lithosphere as 'divided into plates that move relative to each other', and the plate's 'internal area remains mostly, but not perfectly, rigid and intact' (Marshak, 2012, p. 80). Participants' descriptions were similar, here. Lancor (2015) reported that students utilizing metaphors for energy and conservation had to navigate from a 'common' meaning to a scientific one. Amin (2009) pointed out that experts and novices referred to energy in terms of some similar common experiences (energy is: a causal agent, an ingredient, an activity, etc.). However, experts were better able to discriminate and maintain a coherent definition of energy than novices. The novices had less discriminatory skills, therefore they developed broader, less useful conceptualizations. Due to their experiences, expert geologists are likely better able to discriminate a more nuanced conception for 'plate' than novices.

For the students, the unconscious and automatic mapping (Kahneman, 2011) of dinner plate attributes to tectonic plate attributes, reinforced by maps of continents separated by ocean and the brittle nature of rocks, impeded the planned learning. Similarly, Müller-Wille and Rheinberger (2012) asserted, in their work on the history of the discipline of genetics, 'the *lock and key* principle … acted as an 'epistemological obstacle' to the molecularization of genetics … as its vivid imagery made it hard to adopt a different and new perspective' (p. 163). Our participants' common, embodied experiences with plates, supplemented and reinforced by experiences with the brittle nature of rock as well as visual representations that emphasize the separateness of continents, acted as an epistemological obstacle to attributing wholeness and elastic properties to the lithosphere. This conclusion gives us direction for enhancing the instruction, highlighted in the next section.

Future direction for research

We gave a source experience (action of rubber bands, blocks, and sandpaper) for students to map onto a target concept (elastic rebound theory). However, the participants were not able do this. To facilitate the desired learning trajectory, we would use conceptual metaphor strategies highlighted by Niebert et al. (2012).

- Enable experiences in the target domain
- Refer to an embodied source domain
- Reflect an embodied source domain
- Reflect on what the metaphor highlights and hides

First, we seek to develop a different model for elastic rebound with more structural coherence to the target concept. It seems that a frame containing an elastically deformable material within (foam rubber, perhaps) undergoing lateral deformation could afford an embodied experience of strain build-up, as well as provide an opportunity to parallel Reid's (1910) work quantifying crustal deformation over multiple surveys. This could be seamlessly incorporated into the case study, maintaining the emphasis on historical contextualization and inquiry.

We also would like to test the efficacy of a different conceptual metaphor. Such a metaphor should have a very common embodied source domain. This leaves little room for student imagination to create a divergent meaning (Niebert et al., 2012). What we propose is to utilize the metaphor, *lithosphere is the skin of the earth*, prior to introducing the term, *plate*. The *skin* metaphor does have a history (Rodgers, 1949), but in a narrower context.[2] For our purposes, saying the lithosphere is the *skin* of the earth, we reflect on a very common and embodied source domain, an individual's skin, which highlights many of the aspects that seemed to be giving students difficulty within the current research. The skin is a *continuous* outer layer of our body, as the lithosphere is the continuous outer layer of Earth. Skin is deformable, demonstrating elasticity, like the lithosphere. Instead of discussing plate *boundaries*—emphasizing separateness between plates—we would emphasize zones of deformation caused by stress between areas moving relative to each other. This is easily demonstrable with fingers moving portions of skin in different directions on an arm.

This is in contrast with the way textbooks present the topic. Though geologists have constructed plate boundaries based on the evidence of deformation, like zones of earthquakes and volcanoes, textbooks and traditional instruction reinforce the idea of separateness by rationalizing observations of deformation in terms of the boundary construct; earthquakes happen here *because* it is a boundary (Marshak, 2012; Plummer, McGeary, Carlson, Eyles, & Eyles, 2007). The skin metaphor has students rely on the observations to construct their knowledge of crust dynamics.

We would give other experiences as scaffolding, or the *few logical steps* (Stent, 2002) between brittle and elastic rocks. A 'marble tong'[3] created by sawing a central notch along almost the entire length of long, narrow piece of marble affords experience in the target domain, elastic deformation. The rock on either side of the notch can be squeezed together, like tweezers and when released the sides spring back. We would also use a molecular model, having balls as atoms and springs as bonds. Pressure to one side of the model will cause deformation, demonstrating where the elastic strain takes place molecularly; an embodied source domain.

In summary, we would like to iterate that though we may use the 'language of the science' in our teaching, which is an important part of the socialization of students into the discipline, that language might not (and most often does not) hold the same meaning for novices as it does for experts (Clement, 2008b). A useful mental model of a concept is 'not only about learning and memorizing true propositions, but about the capability to put one's knowledge to use' (Kuorikoski & Ylikoski, 2014). As implicated above, it is not enough to ask students *if* they understand the concept, but to ask *how* they understand the concept. The latter can tell us about student thinking, and whether they have developed useful mental models from the metaphors (in this case) we have used while teaching, or whether we need to spend more time clarifying our meaning. Reflecting on the metaphors we teach by for their 'everyday' interpretation, and discussing the difference can also help to facilitate useful mental model building.

Notes

1. For example, visualizations: http://www.iris.edu/hq/programs/education_and_outreach/visualizations, a view of seismic wave form data from multiple locations on Earth: http://rev.seis.sc.edu/, patterns of earthquake epicenters on Earth's surface: http://www.iris.edu/ieb/index.html, and a kinesthetic model of P and S waves for understanding how they inform geoscientists of the earth's interior: http://serc.carleton.edu/introgeo/roleplaying/examples/seismic.html.

2. The term is actually derived from Chamberlin's (1919) use of *thin-shelled* and *thick-shelled* mountain ranges, again, only designating the supposed depth of deformation in the crust (Rodgers, 1949).
3. See http://www.iris.edu/hq/inclass/lesson/brittle_vs_ductile_rocks.

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