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Learners' Ontological Categories According to Their Mental Models of Plate Boundaries

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ABSTRACT

The present study investigates the learners' mental models of plate boundaries and the ontological categories according to their mental models. 116 Korean high school students were asked to draw the 3 types of plate boundaries described in the theory of plate tectonics and to respond the written test with ontological questions. In order to reveal the mental models of students, the result of drawings and interviews was analyzed quantitatively and qualitatively. The findings revealed that the mental models of plate boundaries were classified as one of the following: 'naïve model', 'unstable model', 'causal model', and 'conceptual model'. The learners who were categorized as the naïve mental type showed the highest proportion in the Matter ontological category. On the other hand, the learners who were categorized as the causal mental type did not appear in the Matter category, they use more Event and Constraint Based Interaction categories.

Key Words: Mental Model; Plate Tectonics; Plate Boundaries; Ontological Category; Constraint Based Interaction; Korean High School Students.

INTRODUCTION

Mental models have drawn much attention of science education researchers in recent years for they exist virtually in all sciences among students, teachers, experts, etc., and play an essential role not only in scientific development but also in science teaching and learning(Adbo & Taber, 2009; Chiou & Anderson, 2009; Clement, 2003; Gilbert, Boulter & Elmer, 2000; Lin & Chiu, 2007; Vosniadou & Brewer, 1992, 1994). There has been increased interest in mental models in the discussion of the factors affecting the formation of scientific concept among students. Students employ semantic and visual representations during mental activities to form an internal representation system regarding the present mental activity. The internal representation of recognizing the current phenomenon by integrating these two types

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of information within the working memory is referred to as a mental model (Johnson-Laird, 1983).

Mental Models and Ontological belief as Sources of Learners' Alternative Conceptions

It is also generally accepted that models and modelling are important tools in science teaching and learning as well as an integral part of scientific products– scientific progress is typically marked by the production of a series of models and their coupling theories. In the present study, mental models refer to individuals' internal, mental representations of external, physical phenomena or systems. The major feature of this mental representation is its analogous structure to what is represented. That is, a mental model can be thought of as an imaginary structure that corresponds to the externally represented or perceived system in terms of the spatial arrangement of elements involved in the system and the relationships between or among these elements. From this perspective, a mental model of a specific domain is not merely a collection of memorized facts or beliefs relevant to that domain (Clement, 2003; Clement & Rea-Ramirez, 2008), but a set of mentally perceivable elements which can be manipulated within specific conceptual constraints that determine the relationships between or among those elements under certain conditions. Moreover, if the relationships between elements are causal in nature, these relationships can help not only to reveal the mechanisms underlying the processes of the system but also to determine the sequence of the changes in the states of each element based on the system's initial condition. It is in this sense that mental models can be run "in the mind's eye" (de Kleer & Brown, 1983), or through mental simulation (Nersessian, 2002, 2008), to generate predictions and explanations, which are among the crucial functions of mental models.

In the past, research on student conception analyzed and listed the students' misconceptions of different phenomena and concepts. Such research has received criticisms in that the student conceptions discovered in these studies do not accurately represent the concepts of students in particular situations, but rather, represent the interpretation of the researchers on students' thoughts in a general situation (Gilbert, Watts & Osborne, 1983; Gilbert *et al.*, 2002).

There is now a broad consensus that mental models first originate from an individual's constant interactions with related physical phenomena and systems (Norman, 1983) and then develop on the basis of a series of assimilations and accommodations, or conceptual changes, stimulated by continuous exposure to diverse events in her/his cultural and social environments (Glynn, Duit & Thiele, 1995; Nunez-Oviedo, Clement & Rea-Ramirez, 2008; Vosniadou , 1994; Vosniadou & Brewer, 1994). However, beyond this consensus, there is no overall agreement about the detailed mechanisms underlying the development of mental models accompanied by the processes of conceptual changes. Much research effort is made to discover and characterize different types of models that exist in the classroom, curricula and scientific community. Gilbert and colleagues (1998), for example, identified a number of different types of models: mental model (what we visualize in our mind), expressed model (another form of mental model when we try to explain and present it), consensus model (a commonly accepted expressed model), historical model (a consensus model in the past) and teaching model (a specially produced model in order to teach a difficult consensus or historical model).

According to a previous study (Libarkin *et al.*, 2005) regarding the mental models of the crust and the inside of the Earth, 'unstable mental model' applies when the mental model is easily modified when a new situation is presented. Gobert (2000) hypothesized that students are able to make use of their spatial/static model as a base to build a causal/dynamic model.

There were studies that only employed the drawing activity (Gobert, 2005; Samarapungavan et al, 1996; Sibley, 2005; Skinner, 2001) to reveal the students' conceptual understanding of the theory of plate tectonics, while there were studies that conducted a combination of drawing activities and interview (Jung, 2007; Libarkin *et al.*, 2005; Beilfuss, 2004). In this study, students' mental models of plate boundaries were investigated using drawing activities in combination with individual interviews. Vosniadou and her colleagues conducted a series of studies cross-culturally to investigate the patterns of common results and provided us with specific information on young people's and adults' concepts of the earth (in terms of the size, shape, movement, location, etc.), sun, moon, and stars, and their explanations of familiar astronomical phenomena(Vosniadou *et al.*, 2005).

On the other hand, ontological belief refers to the basic belief about the nature of objects. Conceptual change occurs when the perception of a concept changes from one ontological category to another. Ontological aspects of mental representations, including a student's ontological belief, are defined in this research as students' presuppositions about the ontological nature of things, i.e., the representational entities or elements that comprise an interpretation of phenomena, particularly those that have a correspondence to scientific concepts. Pupils' ontological belief of a specific conception or mental model has attracted many researchers' attention since the 1990s (Chi, 2008; Chi, Slotta & deLeeuw, 1994; Lee & Law, 2001; Slotta, Chi & Slotta, 1993; Vosniadou & Brewer, 1994). Their underlying assumption is that to achieve a radical change in a conception or mental model, the correspondent ontological belief of that conception or mental model must be changed. For example, Vosniadou and Brewer (1994) claimed that children's mental models are built on the constraints of their ontological and epistemological beliefs (theses two are called presuppositions).

Chi and colleagues (1994) suggested that the most difficult changes are those that involve ontological re-categorization. Their theory has three important claims. First, is an epistemological claim that proposes that all entities in the world belong to three primary ontological categories: 'matter', 'processes' and 'mental states'. When a new concept is learned, it is associated with a particular ontology, which helps the learners to understand the nature of the concept involved and the attributes that it may possess. Second, many scientific concepts are 'constraint based interactions'(CBI), which is a subcategory of processes in which a defined system behaves according to the principled interaction of two or more constraints. Third, proposing that many alternative conceptions belong to the 'matter' category and that learn in these instances requires a shift in the concepts' ontological status from the matter category to the process category.

Three primary ontological categories (henceforth referred to as "trees" and signified by capital letters) are depicted in Figure 1: MATTER, PROCESS and MENTAL STATES. There is a hierarchy of subcategories embedded within each of three major trees (i.e., PROCESS can be divided into Events, Procedures or Constraint-Based Interactions; MATTER can be divided into Natural Kinds and Artifacts) These are shown in Figure 1 with members of an ontological category appearing in parentheses and ontological attributes appearing in quotes. Objects in the MATTER category(such as sand, paint, or human being) have such ontological attributes as "being containable", "storable", "having volume" and "mass", "being colored", and so forth. PROCESS reflects its own distinct set of attributes, such as "occurring over time", "resulting in" and so forth.

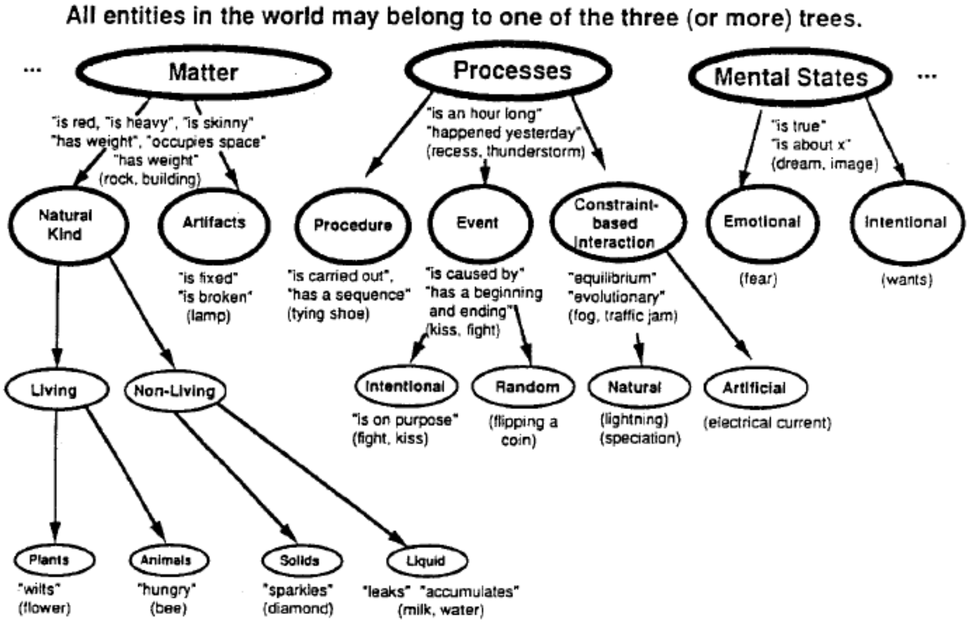

Figure 1. *Three primary ontological categories (Adapted from Chi et al., 1994)*

Current exists only when electrically charged particles are moving, usually because of an electric field. A field fills all space, but an electrical current exists only when a charged particle is introduced into the field. Hence, an electrical current is neither MATTER nor does it have properties of MATTER, but a PROCESS that is fundamentally constraint-based and has no causal agents. The same applies to the concept of heat, force, and light, which are all entities whose veridical conception belongs in the Constraint-Based Interaction category. Some of the attributes of this Constraint-Based Interaction category may be characterized more clearly by contrasting them with attributes of Events, another PROCESS category. A Constraint-Based Interaction has no obvious beginning and end, but an Event does. A working definition of constraint-based interactions follows: a special type of process in which a defined system(e.g., an electric circuit) behaves according to the principled interaction of two or more constraints(e. g., the voltage at different points in the circuit). These principled interactions typically correspond to physical laws of nature, such as Ohm's law, Newton's second law, the laws of thermodynamics, or Maxwell's equations.

Many obvious reasons have been entertained for explaining why science concepts are difficult to learn: they are often represented by mathematical expressions; they are often abstract; they often use technical jargon that overlap with everyday usage (such as the concept of weight or heat). We believe, however, that these are not the key reasons for why certain science concepts are hard to learn. This difficulty stems from the existence of a mismatch or incompatibility between the categorical representation that students bring to an instructional context, and the ontological category to which a science concept truly belongs. That is, students' naïve conceptions represent a concept such as “forces” as a kind of substance that an object possesses and consumes. Thus, in students' minds, “forces” are entities that belong to the MATTER category, when in fact forces are a kind of Constraint-Based Interaction between two objects (a PROCESS). Chi (1994) further suggested that the major barrier to conceptual change relates to the difficulty in making the shift between two distinct ontological categories. They argue that students should be taught explicitly about the constraint-based interactions and their characteristics in order to foster conceptual change. There is little research to investigate the relevance between the mental models and ontological categories.

Therefore the purpose of this study is to identify how students' ontological categories differ depending on their mental models. The findings of this study will provide significant insight into teaching and learning in the geosciences.

Within the context of the preceding discussion, the present study aims to investigate high school students' mental models of plate boundaries in terms of both characteristics of mental model and ontological categories.

In order to reveal the mental models of students, we conducted interviews in combination with drawing activities and we made an attempt to analyze the result of interviews and drawings quantitatively and qualitatively. Recently Oh (in press) have claimed that continental drift hypothesis (Plate tectonics) must be explained with abduction involving deduction-induction cycle in philosophy of science. However in science education, in particular, the theory of plate tectonics investigated in this study is a complex concept that not only requires students to understand the basic concepts of convection, volcanoes and earthquakes, pressure and tension, but also other various concepts such as the characteristics of the mantle, continental drift, flexure and fault as well as use higher-order thinking skills.

The findings of this study can make a major contribution to our understanding of students' learning of the plate tectonics theory. Based on a previous definition of mental models, adopting the construct of mental model highlights the importance of investigating both the fundamental elements and their underlying mechanisms involved in students' mental models. Hence studying students' mental models of plate boundaries may extend our understanding of students' learning of plate tectonics theory from a less-sophisticated conception level of geological domain toward a model level of the dynamic processes of plate interactions. Regarding the participants, since high-school students have learned the magma, earthquakes, plate movement they are supposed to be able to use a more diverse representation related to plate boundaries. Moreover, given that the scope of children's mental models are rather limited, studying more advanced students' manipulation of mental models has at least a twofold advantage. It may help to discover more diverse mental models of the concepts related to plate tectonics, given the greater depth of content knowledge of the respondents, and then to explore the ways in which different mental models are utilized to generate predictions and explanations (Clement, 1989, 2003). Hopefully, the findings of this study can provide some theoretical and instructional suggestions for improving the teaching and learning of physical phenomena when represented by mental models.

The study will answer the following research questions:

1. What are the types and characteristics of learners' mental models regarding plate boundaries?
2. What are the learners' ontological categories in the related concepts of plate tectonics according to their mental models ?

METHODOLOGY

a) Participants

The participants of this study were 10th grade South Korean high school students, all of whom were either 15 or 16 years old. 116 students were asked to draw the 3 types of plate boundaries described in the theory of plate tectonics, i.e. collisional, subduction and divergent boundaries and to respond the written test with ontological questions regarding magma, earthquakes, and tectonic plate. This high school located in Pusan, Korea, which is the second largest city in Korea.

The students took the Plate Tectonics course that was conducted in a lecture style, across a total of four weeks, two hours per week. During the course the teacher utilized power point teaching materials including several video clips, and the test conducted for this study 4weeks after the course. The teacher was an experienced teacher (having 12 years of experience in teaching earth science for high school students). All of 116 participants took the drawing and written test, the results of which were analyzed and 15 students were selected. The 15 students were those who were at ease regarding an interview with the teacher with an intention to spend the necessary time for the interviews.

b) Data Sources

All participants of this study were asked to draw the three types of plate boundaries described in the theory of plate tectonics, i.e. collisional, subduction and divergent boundaries. The drawing assignment consisted of factors reflecting the theory of plate tectonics that are taught in the national-level science curriculum of Korea. The items for the drawing task are listed in Table 1; students were asked to indicate the mantle convection and plate movement with arrows and explain the changes in the lithospheric plates. The 15 students were asked for additional explanations on their drawings after the assignment. We checked whether the students could distinguish the plate from the mantle, understand the motion of lithospheric plates and the convection currents of lower mantle. Also we tried to reveal they understand and relate the topographic features of the plate boundaries to those of mantle convection. Students' drawings, then, are representations of their mental models (Glynn, Duit & Thiele, 1995) and 'reveal qualities of understandings that are hidden from other procedures' (White *et al*, 1995). The procedures of the study is shown in Figure 2.

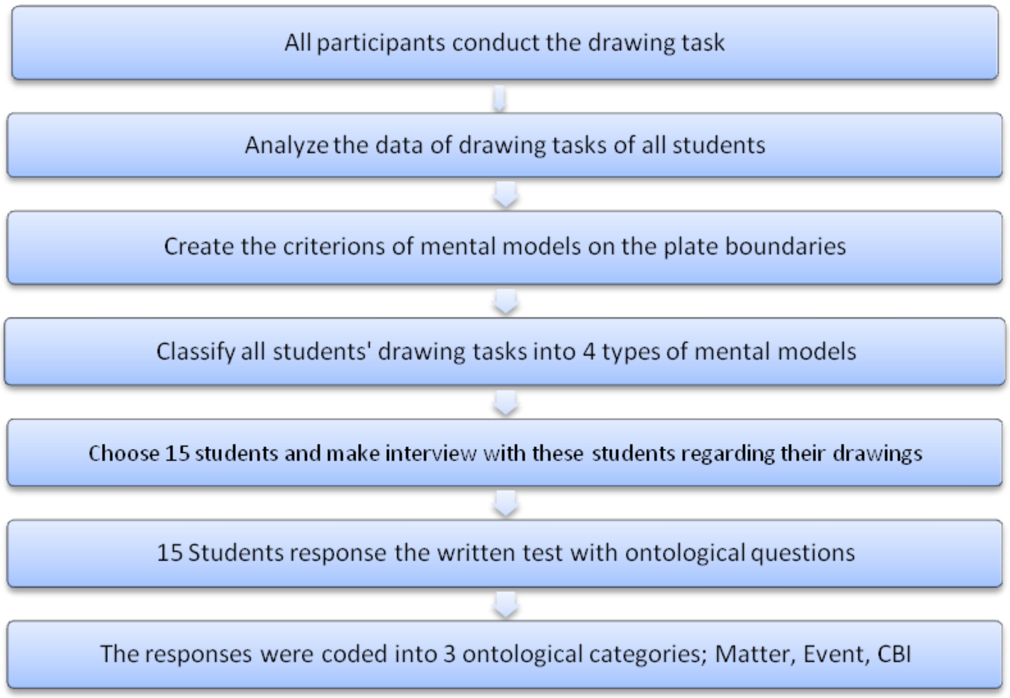

Figure 2. *Research procedures*

Table 1. *Drawing task questions in 3 plate boundaries*

Type	Drawing Task
Collisional boundary	Draw a figure of the continental-continental boundary producing the Himalayas and indicate the motion of the lithospheric plates and the convection currents of the mantle by using arrows.
Subduction boundary	Draw a cross-section of the volcanic island arcs and an ocean trench(Japan and Japan trench) and indicate the motion of the lithospheric plates and the convection currents of the mantle by using arrows.
Divergent boundary	Draw an illustration of the sea-floor spreading along the mid-ocean ridges and indicate the motion of the lithospheric plates and the convection currents of the mantle by using arrows.

A list of questions for the interview was created in advance followed by a semi-structured interview during which the students were asked similar questions, was conducted. The entire dialog for the interview was recorded and voice data were analyzed. The results of written test were segmented into ideas and each unit was then coded into three categories: 'M-matter' and 'Event' and 'CBI- constraint based interaction' according to the conceptual attributes of the unit as described by Chi *et al*.(1994).

c) Data Analysis

The researchers and three Earth Science teachers analyzed the data from the drawings and the interviews as raters. Of the raters, two were in the process of obtaining their Ph.D's in Science Education, and one was in the process of obtaining a Master's Degree. We referred to the mental model categories presented in the previous studies (Beilfuss, 2004; Gobert, 2000; Gobert & Clement, 1999; Libarkin *et al*, 2005) to set the criterions for the plate boundaries. Based on the analysis criterions, the 4 raters conducted a primary analysis of the students' drawings and engaged in a discussion. The raters then modified the analysis criterions for each of the mental models and categorized the mental models regarding plate boundaries into four types. The four types of mental model were the naïve model, unstable model, causal model and conceptual model.

Students were categorized as having a 'naïve model' when they could not use straightforward and specific terms in their description. Students who were categorized into this model did not understand the causal relationships among the topographic features such as mountain range, ocean trench, oceanic ridge and mantle convection. Students with an unstable model describe the topographical features of the plate boundaries incompletely. They cannot relate the mantle convection and the topographical features of the three boundaries. Students with a 'causal model' can differentiate the lithospheric plates from the mantle, and explain the motion of the lithospheric plates and lower mantle. They can also relate the mantle convection and the topographical features of the three boundaries. The conceptual model is the mental model that is closest to the scientific concept, according to the analysis criterions.

The analysis criterions for the four types of mental models regarding plate boundaries are shown in Table 2. The distribution of the mental models based on the drawing tasks performed by the entire participants was quantitatively analyzed. Also, qualitative analysis was conducted on the mental models of 15 students who participated in the interview. In order to increase inter-rater reliability, the researchers shared and discussed the analysis criterions derived from repetitive analysis to increase consistency.

Table 2. *Criterions for the four types of mental model*

Mental model	Criterions
Naïve model	• Does not differentiate the lithospheric plates from the mantle. • Does not explain the motion of the lithospheric plates. • Does not demonstrate the topographical features of the plate boundaries.
Unstable model	• Differentiates the lithospheric plates from the mantle inappropriately. • Explains the motion of the lithospheric plates and mantle incompletely. • Demonstrates the topographical features of the plate boundaries incompletely. • Does not relate the mantle convection and the topographical features of the three boundaries.
Causal model	• Differentiates the lithospheric plates from the mantle. • Explains the motion of the lithospheric plates and mantle incompletely. • Demonstrates the topographical features of the plate boundaries incompletely. • Relates the mantle convection and the topographical features of the three boundaries.
Conceptual model	• Differentiates the lithospheric plates from the mantle. • Explains the motion of the lithospheric plates and mantle. • Demonstrates the topographical features of the plate boundaries completely. • Relates the mantle convection and the topographical features of the three boundaries completely.

RESULTS and DISCUSSION

The students' mental models of plate boundaries were classified based on the criterions derived in this study and ontological categories according to their mental models were analyzed. The results of this study are as follows:

Different Types of Mental Models regarding Three Plate Boundaries

The students' drawings representing the three plate boundaries and the distribution ratio derived from the analysis criterions are shown in Table 3 and Figure 3.

Table 3. *Mental models and number of students in each boundary (percentage)*

	Naïve model	Unstable model	Causal model	Conceptual model
Collisional	12(10.3%)	36(30.8%)	43(37.1%)	25(21.8%)
Subduction	10(8.8%)	41(35.3%)	44(38.2%)	21(17.6%)
Divergent	19(16.2%)	55(47.1%)	32(27.9%)	10(8.8%)

Figure 3 displays example drawings of each mental model regarding three boundaries. The learner shows a naïve mental model (C-1) regarding collisional boundary do not differentiate the lithospheric plates from the mantle and do not explain the motion of the lithospheric plates. In comparison, the student has unstable mental model(C-2) incompletely differentiate the plates from the mantle and explain the motion of the plates and lower mantle. He did not associate mantle convection and cause of topographic features. The drawing of causal mental model shown in C-3 represents an unclear distinction between the mantle and the plate. However, it clearly depicts the direction of movement and subduction of the Indian Plate and the Eurasian Plate. Also, it shows that the subduction of the plates while the sedimentary layer in between is pushed upward to form the mountain range. Also the student showed C-4 model explained that the submarine sediment of the sea is pushed and lifted to increase the height of the mountain range during the Paleozoic.

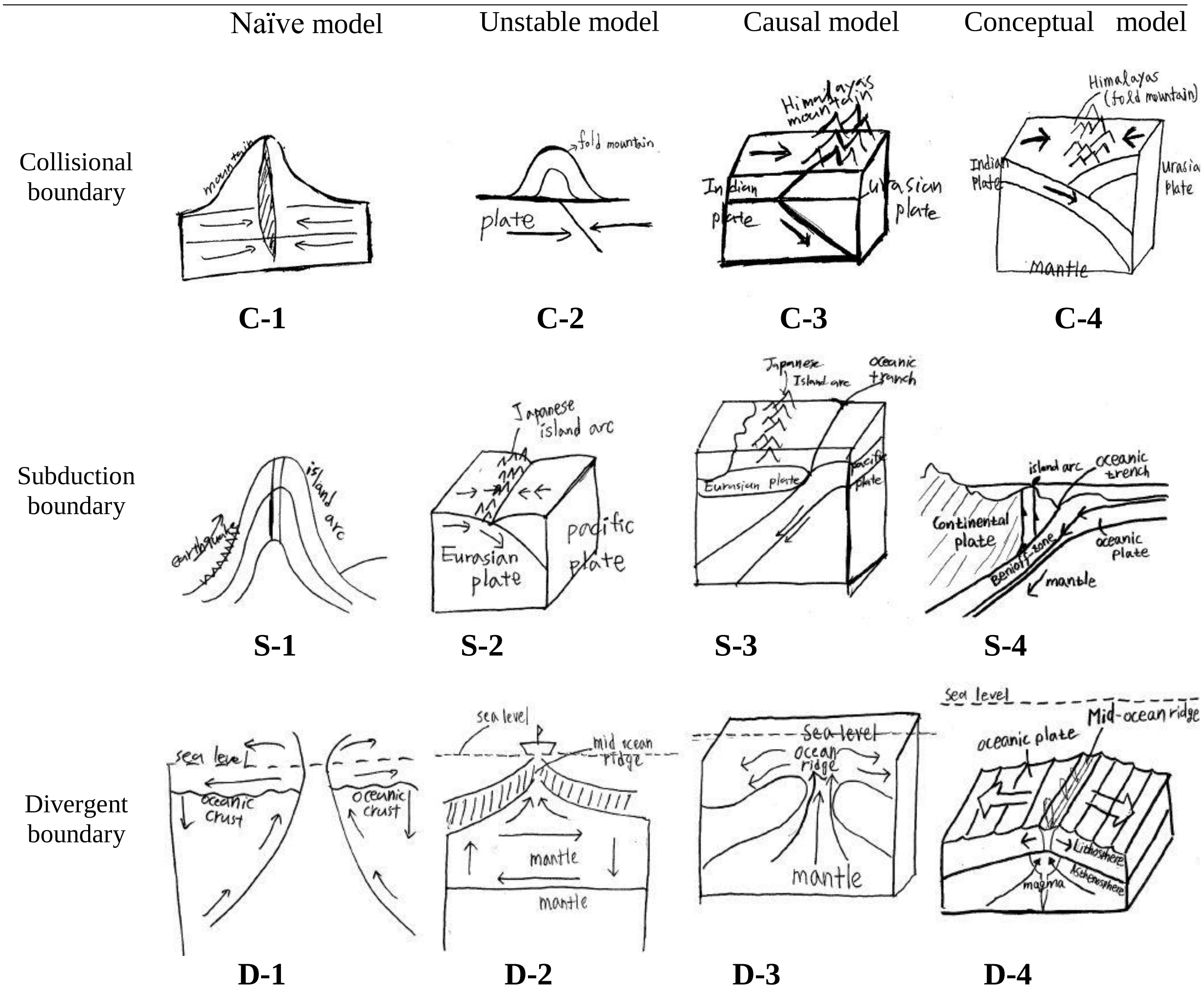

Figure 3. *Students' drawings representing the three plate boundaries*

The distribution of the mental models regarding the collisional boundary is shown in Table 3; the causal model had the highest distribution (37.1%), followed by unstable model (30.8%) and conceptual model (21.8%), with the naïve model being the lowest(10.3%).

The learner who has naïve mental model S-1 shows that this student could not distinguish the plates and the asthenosphere of mantle and had an alternative concept in the motion of the lithospheric plates. During the interview, she could not give a basic explanation of the forms of the volcanic island arcs and ocean trenches. Also she could not associate the mantle convection and formation of topographic features, and thus was classified as a naïve model. This is a simple presentation of a phenomenon or an event, and it is equivalent to the matter category in terms of the ontological belief. In this case, there is a need to change the ontological belief from 'matter' to the 'process' category (Libarkin *et al*, 2005). In this regard will cover the following research question.

The learner who has unstable mental model (S-2) drew ocean trenches and volcanic island arcs. However she misunderstood the slope of the Eurasian Plate moving underneath the Pacific Plate. She did not relate the mantle convection and the shapes of the volcanic island arcs or oceanic trench. A causal mental model (S-3) shows that the ocean trenches form as the oceanic plate (Pacific plate) sinks underneath the continental plate(Eurasian plate). It depicts the location of the ocean trenches with direction of the mantle, however it did not represent topographic features and the overall directionality of the plate movement in detail.

As a matter of fact, he was classified as having an untable model in the initial analysis. (S-4) model shows that magma was formed from the material that melted during the subduction of the oceanic plate below the continental plate, and was then discharged to form the volcanic island arcs. This student's drawing showed high fidelity to the actual process. He used accurate terminology in the additional explanation, and accurately explained the plate interaction and volcanic activity.

The distribution ratio for the mental models of the subduction boundary was similar to that of the collisional boundary. The causal model had the highest distribution (38.2%), followed by unstable model (35.3%) and conceptual model (17.6%), with naïve model being the lowest(8.8%).(Table 3**)**

With respect to the mental model regarding the divergent boundary depicted in D-1, she could not explain the structure of the oceanic ridge with the concept of rift valley or mantle convection. During the interview, she demonstrated that the oceanic crust is formed as the mantle itself moved and lifted, and thus was classified as naïve model. On the other hand, in order to examine her epistemological belief, we asked the following questions: 'How did you learn the concept you explained?' and 'Why do you think that way?' In response to these questions, she answered, 'My teacher explained this to me in class'.

Concerning D-2, the motion of the lithospheric plates and the lower mantle are incompletely represented. This learner misunderstood the direction of mantle convection in which mantle currents are similar to those of the collisional boundary. Causal mental model D-3 shows correct direction of convection in the asthenosphere of mantle and the movement of the lithosphere. However, there is poor depiction of the topography of the undersea mountains and the rift valley. D-4 model shows the topographical features of the plate boundaries completely. He relates the mantle convection and the topographical features of the boundary completely.

The distribution of the mental models of the divergent boundary is shown in Table 3; the unstable model had the highest distribution (47.1%), followed by causal model (27.9%) and naïve model (16.2%), with the conceptual model being the lowest(8.8%). The distribution ratio for the mental models of the subduction boundary was similar to that of the collisional boundary. In contrast, the distribution of the divergent boundary mental models showed a higher percentage of naïve and unstable models compared to the other two boundaries, with the conceptual model being only 8.8%.

Ontological Categories According to the Learners' Mental Models

The responses of the written test question were coded into three categories according to the conceptual attributes of the unit as described by Chi *et al* (1994): MATTER, Event, CBI(Constraints Based Interaction), Event and CBI are the subcategories of the PROCESS. The ontological categories regarding 3 concepts namely magma, earthquakes, tectonic plate of 15 students were investigated individually. The first written test question to investigate ontological categories regarding magma was "Explain all the facts that you know about magma". If the answer was a sentence such as the form (or pattern?) of "magma *is* something", it classified into the 'MATTER' category. The typical examples were coded in the M *ontological category are:*

Magma is made of the same matter as the mantle.
Magma comes from the mantle.
Magma is melted mantle.
Magma is melted rock.
Magma is the liquid inside volcanoes.
Magma is molten material inside the Earth's interior.

Magma is melted crust.
Magma is melted material plates.
Magma is the liquid jet that is erupted to the surface.
Magma is melted material in the boundaries of crust and mantle.

A clause such as ‘Magma is melted plate caused by heat. The heat is caused by friction, which in turn is created by plate subduction’ was coded as an 'Event' because it was caused by something and also has an obvious beginning and end (Chi *et al*, 1994). The following are the typical examples of idea units coded as the E *ontological category:*

Crust was melted by heat and a change in pressure and then expelled.
Magma is generated because the melting point of substances underneath the earth surface is lower than the surrounding temperature.
When the plate rises, it lowers the pressure and the crust is changed into magma.

The second written test question to investigate he ontological categories concerning earthquakes was "Explain all the facts that you know relating to earthquakes" The following is the typical examples of ideas on the earthquake coded as belonging to the E *ontological category:*

An earthquake is the earth shaking
An earthquake is caused by volcanic activity, lava flowing out.
An earthquake occurs when plates collide.
Earthquakes occur as plates collide.
Caves collaping underneath the earth’s surface form earthquakes.
Earthquakes occur at the edges of plates colliding with each other.

The underlined predicates were taken as evidence that the student conceptualizes an earthquake as an event and that this idea should be coded as E. As you can see from the examples above, the learners' epistemological feature on earthquakes is to associate it with 'plate collision'.

Meanwhile, many scientific concepts belong to an ontological category which we currently refer to as Constraint-Based Interaction, a subcategory of PROCESS. Take the concept of electrical current as an example of the Constraint-Based Interaction category: Current exists only when electrically charged particles are moving, usually because of an electric field. A field fills all space, but an electrical current exists only when a charged particle is introduced into the field. The same applies to the concept of heat, force, and light, which are all entities whose veridical conception belongs in the Constraint-Based Interaction category(Chi *et al.*, 1995; Lee & Law, 2001). Here follows a working definition of Constraint-Based Interactions: a special type of process in which a defined system(e.g., an electric circuit) behaves according to the principled interaction of two or more constraints(e.g., the voltage at different points in the circuit). These principled interactions typically correspond to the physical laws of nature, such as Ohm's law, Newton's second law, the laws of thermodynamics or Maxwell's equations.

In this study, concerning the ontological category for earthquakes, the learners who use terminology like energy, strength, impact and so forth were classified into the Constraint-Based Interaction category. The following are the typical examples of ideas on earthquakes coded as belonging to the CBI *ontological category:*

Earthquakes occur when <u>the energy</u> is delivered.
Earthquakes occur when <u>force</u> is released.
Earthquakes occur due to <u>the impact</u> of plate interaction inside the boundaries, that includes convergent, divergent and transform fault.
Earthquakes occur due to <u>the impact</u> of the crust being bent or torn by various powers.

Concerning the third concept i.e. the plate, the clauses such as 'The plate can be defined as the crust and the upper mantle material' and 'A rigid plate that covers the floor of the mantle' were coded as 'MATTER'.

Following are typical examples of ideas regarding the plate coded as belonging to the E *ontology:*

Mantle convection in the earth is powered by it's internal heat. Thus, the plate moves over the mantle.
Plates lie above the convective mantle and these move and collide with each other.

We classified students' mental models into three types based on the result of investigating 15 students' mental models regarding the three kinds of plate boundaries. The students who showed more than two kinds of the naïve mental model were classified as the naïve type. If the learners showed more than two kinds of the unstable mental model were classified as the unstable type. The learners who represented the causal and conceptual mental model, they were classified as the causal type. The ontological categories regarding 3 concepts of these students were investigated individually. The results are shown in Table 4 and the ratios of total frequency of the ontological categories are shown in Figure 4.

Table 4. *The ontological categories of the students in each mental model*

		Magma	Earthquakes	Tectonic plate
Naïve type	S1	MATTER	Event	MATTER
	S2	MATTER	Event	MATTER
	S3	MATTER	Constraint-Based Interaction	MATTER
	S4	MATTER	Event	MATTER
	S5	Event	Constraint-Based Interaction	Event
Unstable type	S6	Event	Event	MATTER
	S7	Event	Constraint-Based Interaction	Event
	S8	Event	Event	Event
	S9	Event	Event	Event
	S10	MATTER	Event	MATTER
	S11	Event	Constraint-Based Interaction	Event
	S12	Event	Event	MATTER
Causal type	S13	Event	Event	Event
	S14	Event	Constraint-Based Interaction	Event
	S15	Event	Constraint-Based Interaction	Event

In Figure 4, the learners who are the naïve mental type had the highest proportion in the MATTER ontological category. In the Event category, the proportion was relatively lower than the Matter category. Only 2 students were identified as part of the CBI category. On the contrary, the learners who are an unstable mental type showed the highest proportion in the Event ontological category. The number of students responding to the CBI category was slightly lower in terms of percentage.

The learners who are categorized as a causal mental type did not appear in the MATTER category, they showed only Event and CBI categories. They had the highest proportion in the Event ontological category.

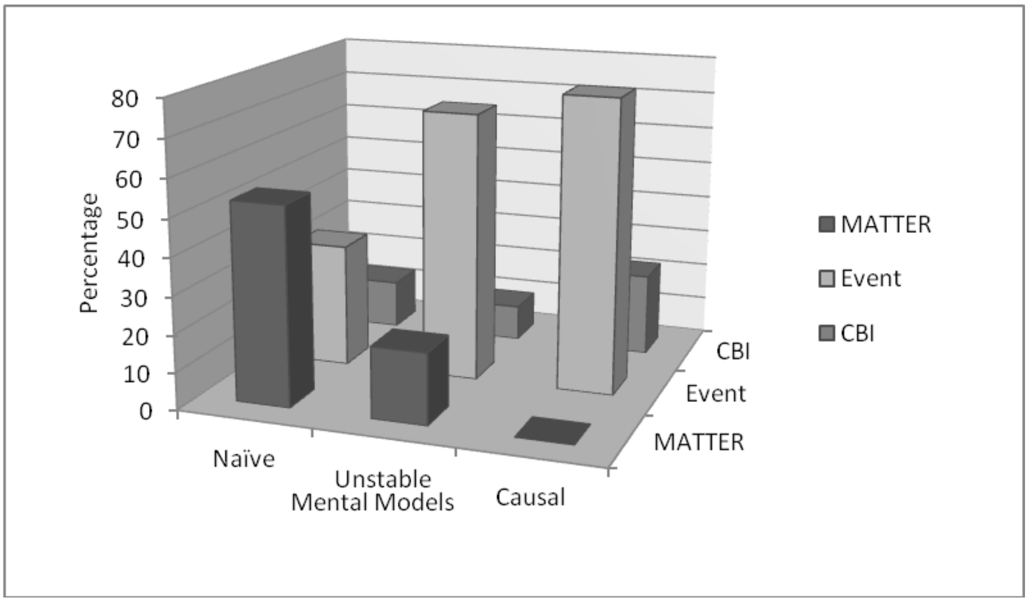

Figure 4. *The ratio of total frequency of the ontological categories*

Many obvious reasons have been considered trying to explain why science concepts are difficult to learn. The reason are often represented by mathematical expressions; they are often abstract; they often use technical jargon that overlap with everyday usage and so forth. We believe, however, that these are not the key reasons for why certain science concepts are hard to learn(Chi *et al.*, 1994). This difficulty stems from the existence of a mismatch or incompatibility between the categorical representation that students bring to an instructional context, and the ontological category to which the science concept truly belongs. That is, students' naïve conceptions represent a concept such as "forces" as a kind of substance that an object possesses and consumes. Thus, in students' minds, "forces" are entities that belong to the MATTER category, when in fact forces are a kind of Constraint-Based Interaction between two objects(a PROCESS). When a student's initial representation of the concept is incompatible with the concept's veridical ontological status, then learning the concept requires *conceptual change*, meaning that the concept's categorical membership has to be re-assigned *across trees*.

CONCLUSION and IMPLICATION

Within the context of the preceding discussion, the present study analyzed mental models of plate boundaries of Korean high school students. We classified mental models regarding plate boundaries into 4types, 'naïve model', 'unstable model', 'causal model', and 'conceptual model' based on established criteria. The learners have a naïve mental model do not differentiate the lithospheric plates from the mantle and do not explain the motion of the lithospheric plates. The students showed unstable mental model do explain the motion of the plates and lower mantle, however, they did not associate mantle convection and the cause of topographic features. The Causal model gave an explanation by associating the mantle movement with the topographic formation, however, it showed no association between the height of the mountain range and the sediment under the sea. Such a model results from the lack of in-depth understanding of the dynamic process of the thick sedimentary layer of submarine strata rising due to plate collision. The conceptual model demonstrates the topographical features of fold mountains, volcanic island arcs and oceanic ridge completely. Also the student showed the conceptual model explained that the submarine sediment of the sea is pushed and lifted to increase the height of the mountain range. The distribution ratio for the mental models of the subduction boundary was similar to that of the collisional boundary, i.e. the causal model had the highest distribution followed by the unstable model. On the other hand, the distribution of the mental models of the divergent boundary was revealed as the unstable model had the highest distribution, followed by causal and naïve model, with the conceptual model being the lowest. The distribution of the divergent boundary mental models showed a higher percentage of naïve and unstable models compared to the other two boundaries. One possible explanation for this result is that due to the difficulty in direct observation of the physical form of the oceanic ridge fundamentally. It was assumed that a consensus model (a commonly accepted expressed model) or teaching model (a specially produced model in order to teach a difficult consensus or historical model) regarding the oceanic ridge are less specific than the fold mountains and volcanic island arc in terms of teaching materials. Therefore the teaching strategies such focused on verbal interaction between teacher-student are required to facilitate the formation of mental model or expressed model. In the similar context, there were a number of students who described the form of the volcanic island arcs in a reasonable manner, but there were many students who could not clearly explain the actual topographic features of an oceanic trench. The results of this study, regarding alternative concepts by high school students appear as follows. A representative example of an alternative concept regarding fold mountains is that continental plate itself formed the high mountains without the sediment that was in between the two plates. This type of alternative concept is similar to that of the number of students who thought plates existed in the form of flat plates as in a previous study(Libarkin *et al.*, 2005) that investigated the level of understanding among college students. Students tended to represent their theories about volcanic and earthquake activity in volcanic island arcs in their drawings and explain it in their interviews. On the contrary, the volcano and earthquake are not represented in detail in oceanic ridge furthermore alternative concept was exposed in the form of towering peaks without rift valley. The reason for this trend was interpreted as a lack of focus in Korean Science textbooks on the differences between illustrations of volcanic island arcs and oceanic ridges. For instance, the illustrations of volcanic arcs included volcanic eruption, however, the figure of oceanic ridges did not include volcanic eruptions. The finding in this study should be considered as a starting point for the redesign of textbooks and considered when constructing a new curriculum.

In order to reveal the ontological categories regarding magma, earthquakes and tectonic plates according to learners' mental models, we investigated some students whose mental model of three plate boundaries have been analyzed. The responses of the written test question were coded into three categories based on the primary ontological categories quoted from Chi *et al.* (1994): MATTER, Event, CBI (Constraints Based Interaction).

We found that the learners who were categorized as the naïve mental type showed the highest proportion in the MATTER ontological category. They had relatively less Event category than the Matter category, and did not have CBI category regarding basic concepts relevant to the theory of plate tectonics. For example, they simply responded “Magma is certain substance” to the written test question i.e. "Explain everything you know related the magma". In these students’ minds, “magma” is entity that belongs to the MATTER category, in fact, magma is generated by a kind Event caused by mantle convection.

On the other hand, the learners who were classified as the unstable mental type showed the highest proportion in the Event ontological category. The learners who were categorized as the causal mental type did not appear in the MATTER category, they learned more towards Event and CBI categories. They had the highest proportion in the Event ontological category. These findings indicate that learners with a causal mental model tend to have the PROCESS ontological category compared to students with a naïve or an unstable mental model.

According to the previous research (Chi *et al.*, 1994), the CBI has an obvious beginning and end, but the Event does not, therefore ‘earthquake’ corresponds the CBI category and ‘the tectonic plate’ and ‘magma’ belong to both the Matter and Event categories. The reason that science concepts are difficult to understand stems from the existence of a mismatch or incompatibility between the categorical representation that students bring to an instructional context, and the ontological category to which the science concept truly belongs to.

This relationship between the ontological category and learners' mental model reported here provide further evidence in support of Chi *et al.*’s theory in understanding scientific phenomena, students need to become acquainted with the understanding of constraint based interactions. Thus Chi *et al.*’s framework probably needs to include the selection of particular constraints for designing effective teaching programs based on mental model. They need to be aware of the specific constraint in order to help students to focus their attention on the proper constraint. The concepts on plate tectonics can be more effectively taught by helping students to focus on the concept of plate interactions as the key constraint in an essentially constraint-based paradigm. Furthermore, these findings indicate that students should not only be given some knowledge of CBI ontology but also need to be guided to focus on the appropriate constraint in order to bring about a conceptual change effectively. Hopefully the findings in this study may shed some light on redesigning the instructional strategies for conceptual change and provides empirical data for further in-depth investigation of students’ thinking processes.

We then suggest ways in which practical reasoning may be developed in students so that they are enabled to better understand how scientific knowledge is produced and how they may be better able to contribute to improving scientific practices. Perhaps the greatest value of this research is that is has offered concrete suggestions for the ways that can change the mental models and ontological categories. In future studies the specific reasoning strategies should allow students to create their own reasoning and predictions, to actively move towards the conceptual mental model, and it should be studied in depth. Research is also needed to reveal the relationship between the learner's epistemological beliefs and their mental model, to find out how other cognitive factors such as metacognition and creativity could affect the mental model.

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