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A typology of causal models for plate tectonics: Inferential power and barriers to understanding

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Forty-seven fifth grade students (40 group-tested and 7 individually interviewed) read a text describing plate tectonics. At four points they drew diagrams of the spatial, causal, and dynamic processes inside the earth. These diagrams along with students' corresponding explanations, think-aloud protocols (for those individually interviewed), and answers to inference questions were analysed in order to characterize students' models of the interior of the earth, and models of its causal and dynamic processes. Types and characteristics of models, and reasoning associated with them are presented. Additionally, data from two exemplary students are presented as case studies. One student has considerable misunderstandings regarding both her understanding of the spatial layout of the interior of the earth and its causal mechanisms. The second student is more typical in terms of his initial models, but makes large gains in revising his understanding about the causal and dynamic processes inside the earth. In both cases, data are used to infer how each student used their diagrams as artefacts for externalizing knowledge, inference making, and model-revision.

Introduction

In a previous study (Gobert and Clement 1999) it was found that having students generate diagrams during their reading of a text about plate tectonics was better at promoting students' post-text conceptual understanding of the spatial, causal, and dynamic features of the domain compared to generating summaries while reading the text or simply reading the text only (control). Although the diagram group outperformed the summary group on post-text performance, the summaries (generated by the summary group) during the reading of the text contained more semantic information than did the diagrams (generated by the diagram group). These data were interpreted in accordance with current literature on constructing mental models from textual information sources (Johnson-Laird 1983, Kintsch 1998, Schmalhofer 1998) as follows. For the summary group, because the media was the same (i.e. they were reading and generating text), they were able to rely on a rote memory of the textual material in order to generate their summaries. For the diagram group, on the other hand, the task of generating diagrams was a higher-level task which required them to do additional processing on the textual material

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they had read in order to generate their diagrams. Thus, the cognitive processing of the textual materials and interaction of the text with the learning tasks, i.e. either diagram-drawing or summary-writing, are reflected in each groups' performance on the post-text assessment and the intermittent tasks during students' reading of the text. More specifically, the summary group's summaries generated during their reading of the text contained a great deal of content-related information which was processed on a rote level, as evidenced by their resulting mental models which were not as rich as those in the diagram group. The diagram groups' diagrams contained less content-related information due to the difficulty of generating diagrams from text, but their resulting mental models were richer and allowed greater inference-making as evidenced by their superior scores on the post-text (see Gobert and Clement 1999 for a more thorough explanation of these findings).

In extending the findings of Gobert and Clement (1999), the purposes of the present study were to: identify and characterize the different types of models held by middle schools students about the inside of the earth and of the causal and dynamic mechanisms involved in plate tectonics, and to characterize the nature of the reasoning associated with these models. Additionally, since it was found that drawing diagrams promoted a richer understanding of the domain compared to generating summaries (Gobert and Clement 1999), this research was conducted in order to identify the learning gains and inferences afforded when students construct diagrams for learning and use these diagrams to support model revision.

Domain studied

The present research addresses students' models and model construction processes central to learning a middle school science domain, namely plate tectonics. The research draws on current findings from research on causal models (White 1993, Schauble *et al*. 1991, Raghavan and Glaser 1995), model-based teaching and learning (Gilbert, S. 1991, Gilbert, J. 1993); model revising (Clement 1989, 1993, Stewart and Hafner 1991); diagram generation and comprehension (Gobert 1994; Gobert and Frederiksen 1988; Kindfield 1993; Larkin and Simon 1987, Lowe 1989, 1993), the integration of text and diagrams (Hegarty and Just 1993), and text comprehension (van Dijk and Kintsch 1983, Kintsch 1998). Findings about both students' causal models and model-based learning should be applicable to other science domains involving convection (e. g., other earth science topics and weather systems), other science topics at the middle school level (e. g., photosynthesis, properties of matter, heat and temperature, day/night cycle, seasonal change, planetary motion, and density), as well as scientific reasoning in general (Clement 1993).

Plate tectonics, representative of a difficult middle school science topic, was chosen for the domain of study because of the important role that model building and causal reasoning play in understanding the hidden, explanatory mechanisms, i.e. convection, underlying continental drift, earthquakes, volcanoes, mountain formation, and sea floor spreading. Briefly, the theory of plate tectonics, which offers a unified explanation of the past, present, and future geographic distribution of the earth's landmasses and oceans (Bencloski and Heyl 1985) proposes that the outer layer of the earth (the crust) is broken up into slabs (the plates) which move on the partially molten layer of the earth (the mantle) due to the slow convective movement of hot magma in the mantle (Feather *et al*. 1995, Plummer and McGeary 1996). This topic is typically covered in the fifth or sixth grade and then again in the eighth or ninth grade (MEGOSE 1991, Massachusetts Department of Education 1996).

Plate tectonics is difficult to learn for many reasons: (1) the earth's internal layers and unobserved processes, e. g., convection, are outside our direct experience (Ault 1984, Gobert and Clement 1994, 1999); (2) the size scale is difficult for children to understand (Ault 1984); (3) the time scale of geological processes is difficult for people to conceptualize since it surpasses our reference of a human lifetime (Jacobi *et al*. 1996); and (4) it involves the comprehension and integration of several different types of information, namely, spatial, causal, and dynamic information (Gobert and Clement 1994, 1999).

It is important to note that the goal in this program of research is to facilitate students' understanding of simplified, qualitative models of plate tectonics. As such, issues like whether radioactive decay in the mantle acts, in part, as a heat source in addition to the earth's core (Feather *et al*. 1995) are not addressed. Also, the physics involved in convection is not addressed. It is assumed that the models that students develop through instructional interventions such as those in the present study will scaffold further model revision and knowledge integration in later years when plate tectonics is addressed again in high school (MEGOSE 1991, Massachusetts Department of Education 1996), at which point more conceptually-difficult aspects of the domain can be addressed.

Previous research on earth science

Plate tectonics falls under the larger domain of Earth Science. More generally, the topic of learning in Earth Science has not been well studied, particularly when compared to students' learning and conceptions in the physical sciences (Stofflett 1994). The lack of research on learning in the Earth Sciences is likely due to the fact that in the past, it has received much less emphasis than the Physical and Life Sciences. Now however, the National Science Education Standards (National Committee Science on Science Education Standards and Assessment 1996) are recognizing Earth Science as a necessary and important component of science training across elementary, middle, and high school levels and considered equivalent in importance to training in the Life and Physical sciences (AAAS 1989, 1993).

Of the studies that have been carried out in the domain of earth science, some of the sub-topics and concepts that have been addressed are: the earth as a cosmic body (Vosniadou and Brewer 1992, Nussbaum 1979, Nussbaum and Novak 1976, Sneider and Pulos 1983); knowledge of rock-cycle processes (Stofflett 1994); conceptions of earth and space as it relates to seasons and phases of the moon, (Schoon 1992, Bisard *et al*. 1994); sea floor dynamics (Bencloski and Heyl 1985); knowledge of the earth's gravitational field (Arnold *et al*. 1995); mountain formation (Muthukrishna, *et al*. 1993); modelling to promote understanding of subtopics of earth science including the geosphere, hydrosphere, atmosphere, and biosphere (Tallon and Audet 1999); and environmental problem-solving (Pinet *et al*. 1995).

One study directly relevant to the present research is that by Ross and Shuell (1993) who investigated children from kindergarten through sixth grade regarding their beliefs about the characteristics and causes of earthquakes. Regarding their cause, the majority of children answered that they didn't know. Idiosyncratic responses included: that the core gets too hot and hits the surface of the earth; the earth is letting out air like a sneeze; and that earthquakes are caused by the wind, thunder and rain, or by mountains. Asked about what happens below the surface when there is an earthquake, again, a large proportion of the children answered that they did not know. Incorrect responses included: that roots underground pop; the plants might get 'screwed up' because the seeds would jiggle around; and that the earth has too much energy just like children who need to get rid of it. The responses to these questions not only indicate a lack of knowledge regarding the underlying processes of plate tectonics responsible for earthquakes, but also indicate difficulties in understanding the size scale of the earth, as was also found by Ault (1994). It is also important to note that misconceptions regarding earthquakes are not just found in children; for example, Bezzi (1989) found that 1/3 of secondary students interviewed from an area with considerable seismic activity thought that the occurrence of earthquakes was related to the occurrence of volcanoes. Furthermore, Turner *et al*. (1986) found that of 1450 adults interviewed from southern California, many held the misconception that earthquakes could be predicted by 'earthquake weather'. Thus, in the case of understanding plate tectonics, as with other science domains as well, it is not likely that children's views become more scientifically accurate as they mature. This further necessitates the need to identify the nature of students' pre-instruction models of plate tectonics, and design instructional strategies and tools to promote conceptual change towards more scientifically accurate models.

Method

Purpose

The purpose of this study was to identify and characterize the different types of models held by middle schools students about the inside of the earth and of the causal and dynamic processes involved in plate tectonics, and characterize the types of reasoning associated with these models. Additionally, this research was conducted in order to identify the learning gains and inferences afforded when students construct diagrams for learning and use these diagrams to support model revision.

Subjects

The data upon which this research is based was drawn from two classroom-based studies $(n = 40)$ and additional students $(n = 7)$ who were interviewed individually. All students were drawn from fifth grade classes in a rural town in Massachusetts; they ranged in age from 10-12 years. The students who were individually interviewed volunteered to participate in the study after an introduction to the research given by the interviewer; they were paid $5.00 per hour for their participation.

Procedure

For the students who were interviewed on an individual basis; the interviews were approximately 45 minutes to 1 hour in length. Two video cameras and an audio-video mixer were used: one videocamera was embedded in the ceiling which recorded the student's drawings as they were generated in real time; the second video camera recorded all interaction between the interviewer and the student. For those who were group-tested, one class period was used (approximately 45 minutes), all data was in the form of paper and pencil, thus, no videotaping was done.

Students were given a short text describing plate tectonics (the full text is given in the appendix); at four intermittent points in the text, the students were given a prompt in the text that they would be requested to draw a diagram of what they had read *after* each of the four respective sections of text. These prompts provided an orienting task for the students while they were reading. Providing orienting tasks is a commonly used strategy in text comprehension research in order to focus learners' goals when reading (Schmalhofer and Glavanov 1986, Schmalhofer 1998). In the present study, informing students before each section of text that they would be subsequently asked to draw diagrams may have lead them to focus on specific features of the text that fostered their diagram-drawing activities and their mental model construction (Gobert 1997, Gobert and Clement 1999). It is important to note that students were not permitted to look back at the text in order to draw their diagrams; thus students' drawings are reflections of the mental models they formed on the basis of reading the text and remembering relevant information in order to draw diagrams. (For more detail on the interaction between text processing and diagramming, see Gobert 1997 or Gobert and Clement 1999).

The four diagram tasks requested during students' reading of the text were ordered as follows:

Thinking back to what you just read,...

(1) ... draw a picture of the *different layers of the earth*.
(2) ... draw a picture of the *movement in the different layers of the earth*.
(3) ... draw a picture of the *movement in the different layers of the earth when mountains are being formed*.
(4) ... draw a picture of the *movement in the different layers of the earth when volcanoes are erupting*.

Post-text assessment

After the students had finished reading the text and drawing their diagrams, they were asked questions about the domain to which they provided verbal responses; again, all verbalizations (for the students who were individually interviewed) were recorded via the videocameras (as described earlier). For the students who were group tested $(n = 40)$ their responses to these items were done on paper. The questions were of several different formats including multiple choice, short answer, and explanation questions; additionally, diagrams were provided to the students for specific questions, and two diagrams to be drawn by the student again were requested. All items were designed to assess either knowledge of spatial/static aspects of the domain or causal/dynamic aspects of the domain. Examples of questions assessing spatial/static knowledge are: 'Where is the thinnest part of the crust?', 'If the continents were all together, would the rest of the earth be water?', as well as spatial features of diagrams depicting volcanic eruption and sea floor spreading. Examples of questions assessing causal/dynamic knowledge are', the movement in the crust of the earth is caused by. . . ?', 'Rock from the floor of the Atlantic Ocean tests to be younger than rock from the middle of the North American Continent because. . . . ', and causal and dynamic features of diagrams depicting volcanic eruption and sea floor spreading (drawn during the post-text assessment).

All told, the data in this study on which students' mental models and reasoning (Gyselinck and Tardieu 1994) were examined are: their diagrams, think aloud protocols generated while drawing, verbal and/or written explanations accompanying their diagrams, and answers to the post-text assessment items. In the two case studies presented, the items of the post-text assessment were used to further investigate the types of inferences and reasoning each student was able to make on the basis of his or her models, as well as to test for consistency between each student's models and their respective answers to questions about the domain.

Tutoring to promote model revision

For the students who were individually interviewed $(n = 7)$, each student was given tutoring in order to remediate their misconceptions and promote model revision. Since this was done on an individual basis, the type of tutoring depended on the nature of the student's models. In the two case studies presented, the tutoring given to each of these two students is outlined in the Results section.

Coding of students' diagrams

Propositional analysis (Frederiksen 1988) was conducted on the source text, allowing for the identification of all the semantic information given in the textual information source. From this analysis, four coding schemes were developed (one of each of the four diagramming tasks) to evaluate the spatial, causal and dynamic knowledge expressed in students' diagrams, text written on their diagrams, and corresponding think aloud protocols. Since the coding scheme is based upon semantic information as expressed via diagrams or textual/verbal descriptions, the coding schemes can be used to score verbal comments and or textual annotations made to the diagrams. An example of this coding for task 4 (volcanic eruption) is shown in table 1. The instructions for its corresponding diagram task were as follows: 'Thinking back to what you just read, draw a picture of the movement in the different layers of the earth when volcanoes are erupting. Include and label all the information about these layers that you can.'

Results

A. Types of models identified

Based on protocol analyses (Ericsson and Simon 1980) of students' interview data and detailed analyses of their diagrams as well as data from the classroom studies (Gobert 1997, Gobert and Clement 1999), two types of student models of the

Table 1. Coding protocol for diagrams of volcanic eruption

Spatial/Static Components	*Score*
crust:	
LOCATION: on surface	1 point
PART: plates	2 points
mantle:	
PART: magma	2 points
LOCATION: below crust	1 point
magma:	
ATTRIBUTE: hot	1 point
ATTRIBUTE: liquid	1 point
core:	
LOCATION: center of earth	1 point
ATTRIBUTE: hot mass	1 point
	10 points
Causal/Dynamic Components	
heated core (label 'hot' is acceptable)	2 points
currents are shown	2 points
heat 'rises' from core to mantle	2 points
heat currents push on plates	2 points
plates move apart	2 points
magma rises from mantle (not from core)	2 points
magma rises above surface	2 points
	14 points

spatial layout of the inside of the earth were identified at this age level; five types of student models of the causal and dynamic mechanisms inside the earth have been identified at this age level.

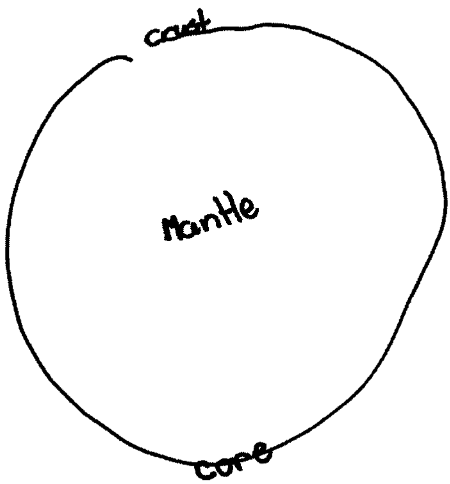
Models of the inside of the earth

There were two types of models identified regarding students' conceptions of the inside of the earth: spatially incorrect models and spatially correct models. These are referred to as Type 0 and 1, respectively. A diagrammatic example of each type of model is shown in table 2a. The percentage of each type of model observed in the data was 10.6% and 89.4%, respectively. A description of each of these types of models is shown in table 2b.

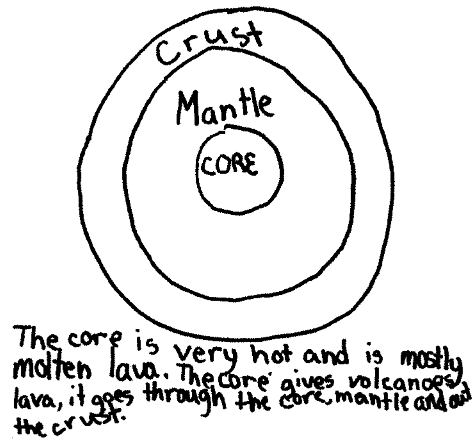
Models of the causal and dynamic processes inside the earth: the case of volcanic eruption

Models of the causal and dynamic processes inside the earth are those which were generated in response to the diagram task for volcanic eruption. The data from this task was chosen to examine students' models of the causal and dynamic processes inside the earth because students' models of volcanic eruption were, in most cases, the most detailed for the four diagramming tasks. This may be due to students having more prior knowledge about volcanic eruption than other plate tectonic-related phenomena.

Table 2a. Diagrammatic models of the interior of the earth



Type 0: Spatially Incorrect Model



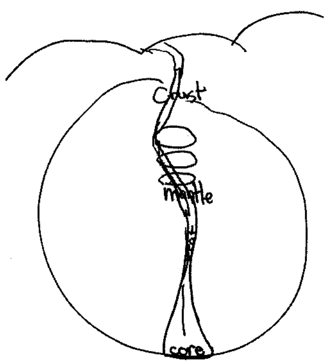
Type 1: Spatially Correct Model

Table 2b. Types of models of the inside of the earth and their characteristics ($n = 47$)

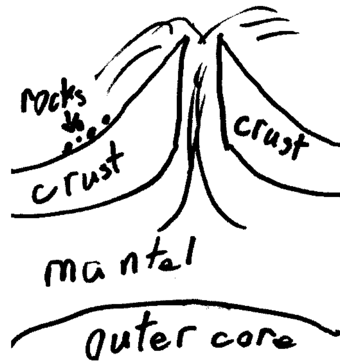
	Type of Model	*Characteristics*	*Frequency*	*Percentage*
TYPE 0	Spatially Incorrect Models	Spatial layout of interior is not correct; few inferences afforded on this type of model	5	10.6%
TYPE 1	Spatially Correct Models	Spatial layout of interior is correct	42	89.4%

Although the models are described as categories (1a, 1b, 2, or 3), they can be thought of as a continuum with Type 1a and 1b reflecting models with only heat-related or movement-elated causal mechanisms, respectively, to Type 3 models reflecting the most sophisticated model (observed at this age level) which include multiple heat- and movement-related mechanisms. An integrated model of volcanic eruption refers to one in which students have integrated their spatial model of the earth with a number of heat-related mechanisms (i.e. heated core, convection currents, and currents pushing on plates) and movement-related mechanisms (plates moving apart, magma rising from mantle, and magma rising above the surface) into a rich causal model. It is assumed that from these rich causal models, inferencing can be done about the causal and dynamic processes in other plate tectonic phenomena. A canonical model (and coding protocol) of the components involved in volcanic eruption are shown in table 1. A diagrammatic example of each type of model of the causal and dynamic processes inside the earth when volcanoes are erupting is shown in table 3a. A summary table of their characteristics and the frequency with which these were observed in the data are provided in table 3b; a more detailed description of their characteristics can be found in table 4.

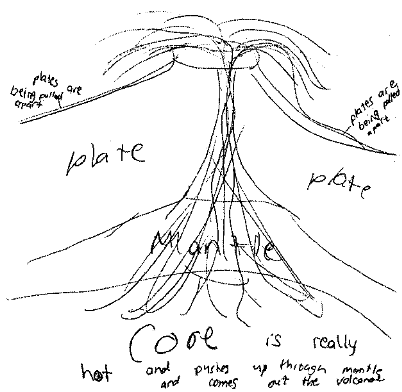
Table 3a. Diagrammatic models of volcanic eruption



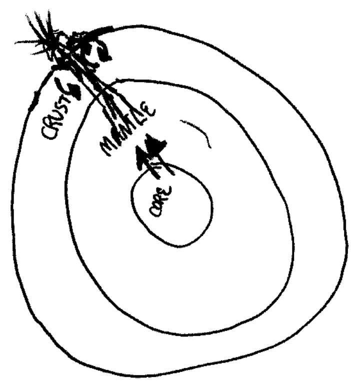
Type 1a: local 'Heat' model



Type 1b: Local 'Movement' model



Type 2: Mixed model



Type 3: Integrated model

Table 3b. Types of models of the causal and dynamic mechanisms in volcanic eruption (n = 47)

	Type of Model	*Characteristics*	*Frequency*	*Percentage*
TYPE 1a	Local 'Heat' Models	Heat-related mechanism(s) only; No movement-related mechanisms as causal	2	4.25%
TYPE 1b	Local 'Movement' Models	Movement-related mechanism(s) only; No heat as causal	29	61.7%
TYPE 2	Mixed Models	Few movement- and heat-related mechanisms; Notion(s) of heat and pressure	14	29.8%
TYPE 3	Integrated Models	Movement- and heat-related mechanisms;Includes heat as a causal agent	2	4.25%

Table 4. Characteristics of models of causal and dynamic mechanisms in volcanic eruption

TYPE 1a: These models are simplistic, 'Local Models' involving heat as the only causal mechanism involved in volcanic eruption. The critical feature of Level 1a models is that they do *not* include any movement-related mechanisms involved in volcanic eruption (mantle or magma movement, plate movement, crust movement/breakage, etc.). These local, heat-only models are infrequently observed at this age group because most children by this age have prior knowledge about volcanoes which includes, at least, magma ('lava') rising above the surface (a movement-related mechanism). Thus, students' models are more likely to fall into the Type 1b classification, namely, Local, movement-only models.

TYPE 1b: These models are simplistic, 'Local Models' involving movement-related mechanisms as the only type of causal mechanisms used to describe and depict the causal and dynamic processes in volcanic eruption. Thus, heat is not seen as causal in these models. The inclusion of 'magma rising' as a movement-related causal mechanism is one which is frequently included in students' models of this type.

TYPE 2: Type 2 models are classified as 'Mixed Models' and are more sophisticated than Type 1a or 1b because they include both classes of causal mechanisms, i.e., both heat- and movement-related mechanisms, but these models are not very elaborate in that they do not include all of either type of causal mechanism. Students who hold these models lack an understanding of how and why convection currents form which then push on the plates, and as such, their models are not well integrated in terms of the heat-related and movement-related mechanisms included.

TYPE 3: Type 3 models are 'Integrated Models' which are well-integrated and include many heat-related and movement-related mechanisms. In these models there is some understanding of heat as a causal agent in causing the currents to form, some understanding of convection in the mantle, and the heat currents as a causal agent in pushing on the mantle and plates. Understanding reflected in models such as these have been achieved by some students at this age level in which students were given tutoring, particularly on the topic of convection (Gobert and Clement,1994).

Table 3b summarizes the types of models of the causal and dynamic processes inside the earth during volcanic eruption, their characteristics, and the frequency with which each of these were observed in the data [this table is based on individual interviews with seven students as well as data from two classroom studies, $n = 40$, as described fully in Gobert 1997 and Gobert and Clement 1999)]. The percentage of each type of model observed was 4.25%, 61.7%, 29.8%, and 4.25%, respectively. It can be seen that the local models which include movement-related mechanisms only (Type 1b) are the most frequently observed type of model at this age level.

B. Students' models: Barriers to deeper understanding or artefacts for model-revision and reasoning

In the next section two cases studies are described; each was selected as an exemplary case of model-based reasoning using diagrams as artefacts for inference and model-revision. From these data it is suggested that models, once constructed, can either serve as a barrier for further understanding, or alternatively, support and facilitate integration and inference-making. Each will be addressed in turn.

Student 1: Models as a barrier to deeper understanding

The first case presented is one in which the student does not have a correct 'concentric circle model' of the inside layers of the earth and she perseveres with this model in all her diagrams.[1] Furthermore, it is argued that until her model of the spatial arrangement of the inside layers of the earth is remediated to reflect the earth's layers as concentric circles, she will not be able to use her model of the inside of the earth to engage in model-building and inferencing about the causal and dynamic processes involved in plate tectonics.

Student 1's first diagram reflects a Type 0, spatially incorrect model in which she has depicted the core at the bottom rather than in the centre of the earth. In this case, the student has not formed a rich mental model of the internal layers of the earth, which reflects the correct spatial arrangement of the layers. Rather, it appears as though she has interpreted parts of the text literally because she has not depicted the mantle as a concentric circle around the core, rather, she has depicted the mantle 'under' the crust and the core 'under' the mantle. The section of the text which immediately preceded her drawing of diagram 1 reads (the relevant sections of text which refer to the spatial layout of the earth's layers are italicized; the full text can be found in appendix A):

> The inside of the earth is made up of three different layers. If you could drill through the earth, *the first layer you would drill through is the crust*, which is 96 miles thick in some places. The continents we see and live on are only part of the crust. In other places, the crust dips down underwater to form the sea bed. The crust is divided into moving sections called plates. Some continents are made up of more than one plate. *Under the crust is the second layer called the mantle*. It is a layer made up of very thick liquid called magma. At the *centre of the earth's interior is the core* which is very hot.

It is hypothesized that spatially incorrect models such as this cannot support inferencing by means of perceptual cues such as spatial adjacency (Larkin and Simon 1987). Thus, her model of the inside of the earth as depicted in diagram 1 cannot support knowledge integration and inferencing which is needed in order to understand the causal and dynamic processes inside the earth (diagram 2).

As can be seen in her second diagram which requested that she depict '. . . the movement and processes of the layers of the earth', she perseveres with her non-concentric model of the layers of the earth: she depicts the core at the bottom, rather than at the centre of the earth; the mantle layer is on top of the core, rather than surrounding it; and the plates are not embedded in the crust as they should be. Additionally, this diagram does not include magma as liquid layer inside the mantle. Here again, it is likely that she has interpreted the text literally. In the section of text which immediately preceded her drawing (diagram 2) the text reads (relevant sections are italicized):

> Remember that the crust is divided into sections called plates. *Each plate can be thought of as a sheet of rock, riding on top of the mantle*. As mentioned before, *the core of the earth is very hot. This heat creates currents that rise up through the mantle. When these currents get near the top of the mantle, they push on the plates, and force the plates to move in many directions. As the mantle moves, the plates move with it*. Since the continents are part of the plates, the continents move too.

In diagram 2 (and in diagram 1) because her diagram does not depict the mantle layer surrounding the core and the crust surrounding the mantle as concentric circles, this figure cannot support reasoning by means of perceptual cues about how the heated core acts as a heat source for the magma which causes convection currents to form which then push on the plates. Thus, her diagrams at this point serve as a barrier for further understanding about the causal mechanisms responsible for plate tectonic-relate phenomena.

In her third diagram which requested that she draw a diagram to depict '... the different layers of the earth when mountains form', she has replicated a portion of her two previous diagrams. This model, as depicted in diagram 3, is a local, movement-only model (described in table 3b) which includes plate movement as the only causal mechanism. Here she has included the crust with the plates embedded in it, and a mountain 'floating' above the crust. Again, it appears that she has understood the text literally; for example, her diagram depicts the plates on top of each other. The text immediately preceding this diagram reads as follows:

> When two plates are forced together, mountains can form. As the plates are forced together, the edges may be arched like a deck of cards being squeezed from both sides. *Eventually one plate moves under the other plate.* As the plates continue to move together, the crust is slowly bent and crumpled, and mountains are formed. While the rock may rise only a quarter of an inch per year, over millions of years it can form very high mountains. The Himalayan Mountains are the best example; they were formed when the plate of India collided with the plate of Southern Asia.

In her final diagram which depicts volcanic eruption (diagram 4), she has again depicted the core at the bottom of the earth with the mantle on top of the core rather than surrounding it, and the crust on top of the mantle rather than surrounding it. As in her second diagram (depicting the movement and processes inside the earth), she has not included magma within the mantle, nor did she depict magma rising above the surface of the earth. She has drawn a vertical line, which divides the volcanic mountain in half. Perhaps this is intended to represent cracks in plates as taken literally from the text. The portion of the text, which immediately preceded her diagram, reads:

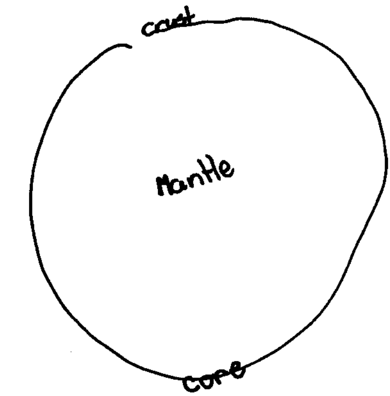
> *Volcanoes occur mostly along, or very near, the edges of plates. This is because it is at the edges where most of the stress and cracks occur.* One way that volcanoes can form is when the plates move apart. As they move apart, hot liquid magma from the mantle rises up above the surface to form volcanoes.

Again, her diagram (diagram 4), as depicted, cannot support reasoning about how convection currents form in the mantle, nor how magma currents push on the plates and rise above the surface to cause volcanic eruption. Thus, her understanding of the causal mechanisms underlying volcanic eruption is limited to her model, which includes no causal mechanisms.

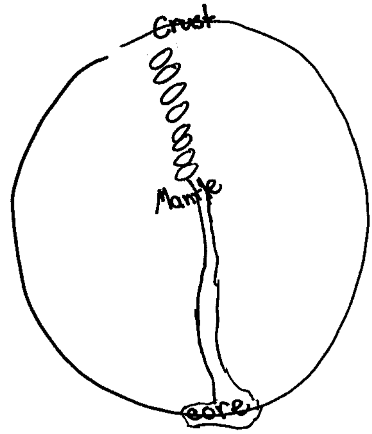
Post-text Assessment for student 1

As previously stated in the method section, a post-text assessment was done after students finished reading and generating their diagrams. Specific answers from Student 1's post-text assessment were selected to investigate the types of inferences the student was able to make on the basis of her models, as well as to test for consistency between her models and answers to questions about the domain. Here the data is discussed with respect to this student's understanding of the spatial/static features of the inside of the earth, and the causal/dynamic processes of plate tectonics. Each will be addressed in turn.

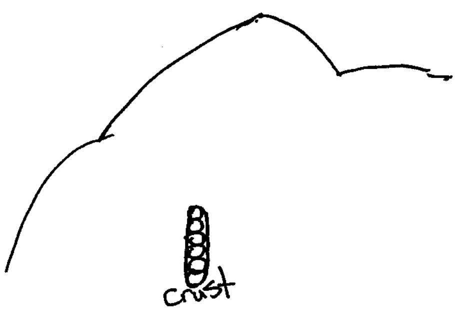
Table 5a. Student 1, Diagrams 1-4, time 1



Student 1: diagram 1



Student 1: diagram 2



Student 1: diagram 3

Student 1: diagram 4

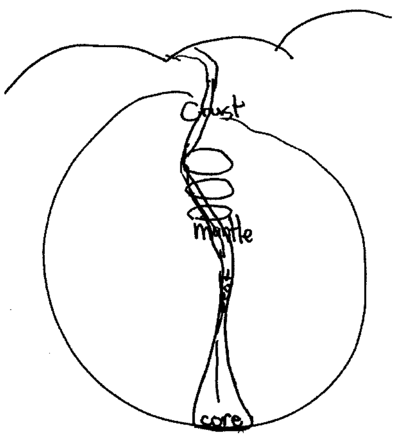
Understanding of the spatial arrangement of the inside of the earth

On the post-text assessment, when given a multiple-choice question asking 'Where is the thinnest part of the crust?', she circled (incorrectly) 'land at sea level'. From her answer to this question, it appears that she does not understand that the earth's crust dips under the ocean to form the seabed. From this response, as well as her poor, spatially incorrect diagram of the inside of earth (diagram 1), it appears that this student has a poor understanding of the earth, both the spatial arrangement of the interior, as well as the three-dimensional nature of the exterior of the earth's crust.

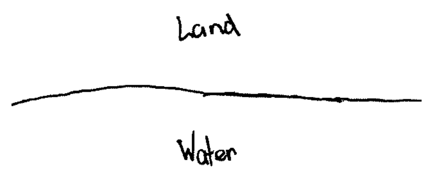
When asked to draw a diagram depicting what happens to the layers of the earth when volcanoes erupt (this item was asked again in the post-text assessment), she drew diagram 10. The spatial arrangement of the layers in this diagram are incorrect: the core, mantle and crust are on top of each other, rather than depicted as concentric circles. This is consistent with her diagram 4 drawn during her reading of the text; the only difference between diagram 4 and diagram 10 is that in the latter, she has included a 'channel' for the heat to move up through the earth. Again, diagram 10 reflects her literal understanding of the text, as the mantle 'under' the crust and the core 'under' the mantle.

When asked to draw a diagram depicting what happens to the layers of the earth when the sea floor spreads, she drew diagram 11. This diagram is not at all informative because it does not include the interior layers of the earth.

Table 5b. Student 1, diagrams 10 and 11



Student 1: diagram 10



Student 1: diagram 11

Understanding of the causal and dynamic of the processes in plate tectonics

When asked 'Name three occurrences which suggest that the plates in the earth are still moving', she replied that she did not know. Her response to this item again reifies her poor understanding of how the causal mechanisms inside the earth are responsible for geological phenomena on the earth's surface.

When asked 'movement in the crust of the earth is caused by . . .', she circled 'Heat in the core.' This is only partly correct since it does not include any movement-related mechanisms as causal in plate tectonics. Her response to this item is consistent with her diagram 2, table 5a (during reading of the text) which depicts a local heat-only model of the processes inside the earth. It is also consistent with her diagram depicting volcanic eruption drawn during post-text assessment (diagram 10) which includes heat 'rising' from the core, but no plate movement as a causal mechanism responsible for volcanic eruption.

When asked 'The sea floor gets bigger over time because . . .', she circled 'The tide washes up earth from the bottom of the ocean'. This misconception, which was also elicited in other students who participated in this study, indicates a lack of understanding of the causal mechanisms responsible for sea floor spreading. Her response to this question is also compatible with her diagram depicting sea floor spreading (diagram 11, table 5c) since it includes no causality about how or why the sea floor spreads (in fact her diagram 11 does not include the inside of the earth at all). Her lack of understanding about how the sea floor spreads is also reflected in her response to the question, 'Rock from the floor of the Atlantic Ocean tests to be younger than rock from the middle of the North American continent because. . . .'; to this she responded that she did not know. The finding that her model of sea floor spreading does not include any correct causal mechanisms (not even heat-related mechanisms as do her other models) may indicate that she does not understand that sea floor spreading is another example of plate tectonic phenomena even though this sub topic was presented along with mountain formation and volcanic eruption in the text.

When asked 'How did India get to fit into Asia?', she replied that she did not know. This is compatible with her poor understanding of mountain formation as depicted in diagram 3, table 5a. It is interesting that she did not use her 'understanding' of plate movement as depicted in diagram 3 to answer this question about mountain formation. It is likely that she did not know that the Himalayas were formed due to continental plate movement. It is also possible that she is very unsure of her conceptions. All told, these data reflect her poor understanding of the causal mechanisms involved in plate tectonics.

Tutoring used to promote model-revision

At this point the interviewer attempted to see if she could help the student revise her spatial model of the earth since it was believed that if the student had a correct spatial model of the layers of the earth depicted as concentric circles, she would be better able to use this model to make inferences about the causal and dynamic processes involved in plate tectonics. The first strategy tried here was to allow her to re-read the first section of the text, 'The layers of the earth'. After she re-read the first section of the text, she drew diagram 1, time 2, table 5c which again depicts the core at the bottom of the earth, the mantle on top of the core, and the crust on top of the mantle; the plates are not embedded in the crust, and there is no magma in the mantle layer. This diagram includes what appears to be a channel coming up from the core and ending on the earth's surface.

Since she did not revise her model substantially based on a second reading of the text, the interviewer then described the inside layers of the earth as an onion cut in half creating concentric circles and drew a cross-section of the earth with the core at the centre, the mantle layer surrounding the core, and the crustal layer surrounding the mantle. The interviewer asked if the student could see how her diagram and the interviewer's diagram differed; she replied, 'Yes'. The interviewer then asked her to draw another diagram to depict movement and processes inside the earth. She drew diagram 2, time 2, table 5c and added circular lines of magma in the mantle layer. When the interviewer asked her how her original diagram (diagram 2) and this one differed, she replied that she had '. . . forgotten the liquid' in her original diagram. This newer diagram (diagram 2, time 2) is a significant advance over her previous drawing of the movement and processes in the earth (diagram 2) because it depicts the core in the centre of the earth and includes magma in the mantle layer. The inclusion of both of these features provides a visual model from which she could reason and make inferences. As previously stated, it is argued that this type of model is a necessary condition for reasoning about the causal and dynamic processes in plate tectonics. In particular, it is argued that a correct concentric model is a necessary condition for reasoning about how convection currents form and how currents of magma cause movement of crustal plates.

Next the interviewer requested that she draw another diagram to depict mountain formation. Diagram 3, time 2, table 5c appears to be a synthetic model (Vosniadou and Brewer 1992) of her original model (diagram 3) and her newer model in that it depicts the core close to the bottom of the earth (as in her original model) but has the mantle layer surrounding the core. In her description of this, she said that 'the heat heats up the liquid'. Here she has revised her original mountain formation model to include the notion that the core acts as a heat source on the liquid magma. This is a significant advance over her original model depicting mountain formation (diagram 3, table 5a) because she is beginning to understand multiple causal mechanisms involved in plate tectonics.

Lastly, the interviewer requested that the student draw another diagram of volcanic eruption. This model (diagram 4, time 2, table 5a) is a significant advance over her original volcano model (diagram 4, table 5a) as well as that generated during the post-text assessment (diagram 10, table 5c) for many reasons. First, it depicts the core at the centre of the earth, the mantle is surrounding the core, and magma is contained in the mantle layer. As such, her new model (diagram 4, time 2, table 5c) includes a spatially correct model of the inside of the earth. Additionally, she drew arrows to indicate plate movement, also an advance over her two previous volcano models (diagram 4, table 5a and diagram 10, table 5b) in terms of including plate movement as a causal mechanism involved in volcanic eruption.

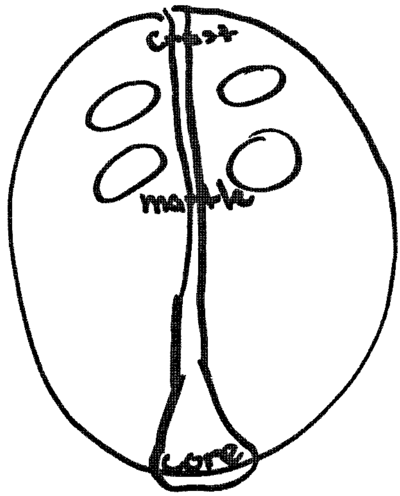
At this point, the student's understanding of the domain appears to be better than that which was reflected in her original diagrams (diagrams 1-4, table 5a). In terms of the classification scheme in table 3b, this student now has a 'mixed model' of the causal mechanisms responsible for volcanic eruption since she has included both heat-related and movement-related mechanisms in her model (diagram 4, time 2).

Student 2: Models as tools for model-revision and reasoning

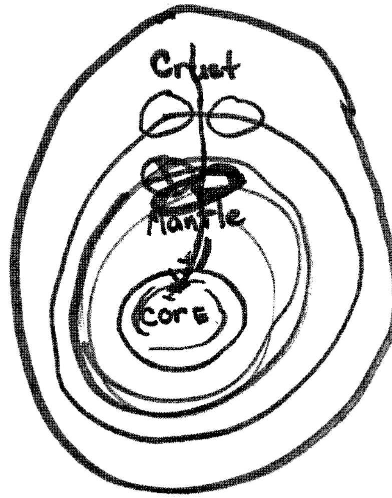
In the second case study, it is shown how spatially correct models can serve as useful tools for reasoning (Kindfield 1993) about the causal and dynamic mechanisms inside the earth and how partially correct models can serve as useful tools for progressive model building.

In Student 2's first diagram depicting the layers of the earth (diagram 1), a spatially correct model of the interior layers of the earth is depicted. (In actuality, the crustal layer is proportionately much thinner than the student has depicted here but for the purposes of this research and grade level, this is not a grave error in that it does not limit the nature of the inferences afforded). He has annotated his diagram with text (unsolicited by the interviewer) which reads 'The core is very hot and is mostly molten lava, it goes through the core, mantle and out the crust'. This statement does not reflect a complete understanding of volcanic eruption but as the following analysis will demonstrate, he is able to use his spatially correct model to make inferences as he proceeds through the text and diagramming tasks.

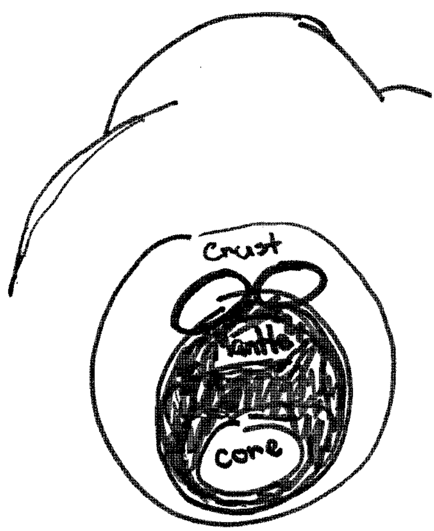
Table 5c. Student 1, Diagrams 1-4, time 2



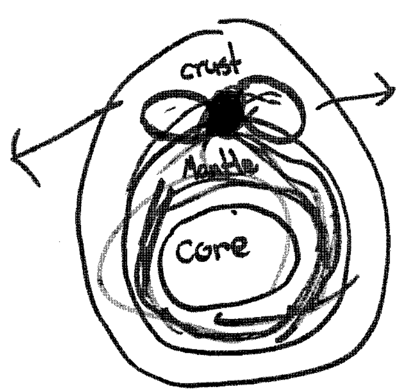
Student 1: diagram 1, time 2



Student 1: diagram 2, time 2



Student 1: diagram 3, time 2



Student 1: diagram 4, time 2

Since the textual information that he added to his diagram was not contained in the section of the text that he read before he generated his diagram, one can assume that this student has some prior knowledge of volcanoes.

During his reading of the next section of text 'Movement in the layers of the earth', he made a meta-level comment about how he might depict the plates as moving. He said, 'I was just wondering how you might draw the movement of the plates'. This is anecdotal evidence that the diagramming prompts in the text may have influenced some students to attend to specific features of the text that would be useful in producing their diagrams (see Gobert and Clement 1999 for more discussion on this aspect of the research). After he finished reading this section of text, he drew a diagram to depict the causal and dynamic processes inside the earth (diagram 2). While he drew he said, 'The currents form here, push on the mantle so that the mantle moves and makes the crust move, and the plates will move if the mantle and crust moves, and if they overlap, they make an earthquake'.

Diagram 2 and his corresponding protocol (above) indicate that he has a fairly good understanding of the movement-related mechanisms underlying plate tectonics, but he does not appear to understand the heat-related mechanisms involved in plate tectonics. More specifically, he does not appear to understand why or how the currents form (i.e. that the core acts as a heat source in causing convection currents to form). As such, his model as depicted in diagram 2 is a mixed model (Type 2) as described in table 3b because although it includes multiple movement-related mechanisms, it only includes the presence of currents as a heat-related causal mechanism. At this point the interviewer asked if he knew what was causing the currents to form. He responded, 'I think its when the core gets too much pressure and if it didn't have earthquakes and volcanoes, it might explode'. This validates the assumption that the student did not understand how heat from the core was causal in heating the magma.

The student's third diagram depicts mountain formation (diagram 3) and he has included 'force' in his diagram. His protocol (below) demonstrates that he has notions of pressure and force. It is important to note that although some of his assumptions are not correct (e.g., lava building up in the core and getting 'pressurized'), he appears to be trying to integrate what he is understanding from the text with his prior knowledge of heat and pressure. This is an example of how intuitive conceptions are rich, effective starting points for instruction (Clement *et al*. 1989). Below is an excerpt of our conversation:

Student: The plates on top of the crust, when they are forced together, they form a mountain. . . . the mantle that is making the force so that mountains are formed when the two plates, I guess that those lines are force, and the force is coming from the mantle.

Interviewer: Why is there force coming from the mantle?

Student: Because maybe before it came from the core and then it went to the mantle and stayed there and then that got too pressurized. It has to let it go, it probably came form the core. . . . I think that most of the movement of the earth comes from the core because the lava builds up that in there and there's too much pressure in it so it has to let out all the pressure and it will go through the core and go through the crust and let it out on the plates.

In his fourth diagram, which depicts volcanic eruption (diagram 4), the student has drawn a local, movement only model of volcanic eruption. The only causal mechanisms that are included are magma rising from the mantle and magma rising above the surface. At this point, the interviewer attempted to see if the student could integrate some of his intuitions about pressure into his model in order to achieve a more causally sophisticated model of volcanic eruption. He generates the notion of heat 'rising' and develops a more causally sophisticated understanding of volcanic eruption. Important to note is the interesting inference he makes about the magma being hot based on a visual cue of spatial adjacency between the core and the mantle and his prior knowledge of heat 'rising'. Excerpts from our conversation are as follows:

Student: I'm drawing, this is coming from the mantle and then the magma is going up and then its coming through the volcano and its coming out of the volcano.

Interviewer: So why is the magma rising?

Student: I'm not sure.

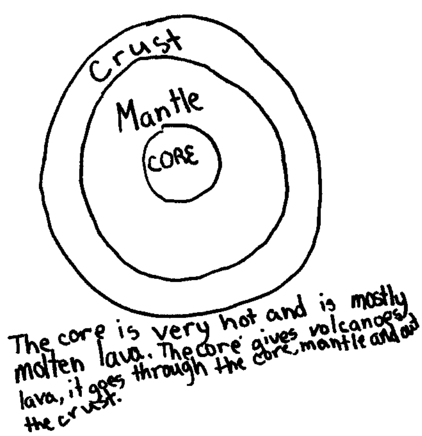
Interviewer: Any ideas?

Student: Because *heat rises, the magma is really hot and so it would go up*, and basically any way that you face from the mantle is up and that's why it goes up (*good spatial reasoning*).

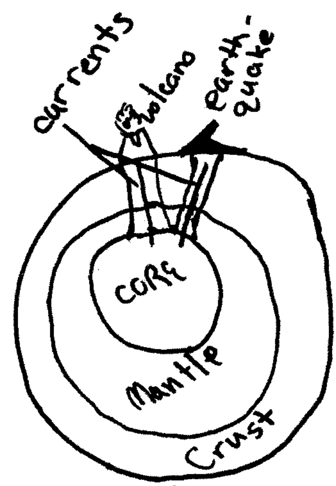
Interviewer: Let's pursue that idea a little bit - why is the magma hot?

Student: *Because the magma is a hot liquid and the core is really hot and the mantle is right near the core... (excellent inference using his diagram and prior knowledge)*

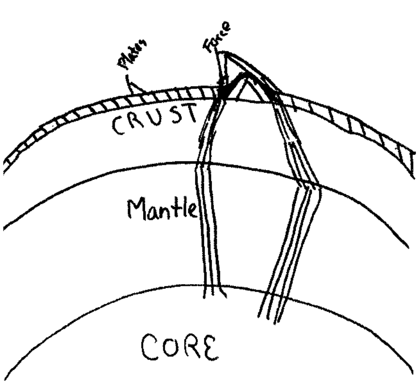
Table 6a. Student 2, Diagrams 1-4, time 1



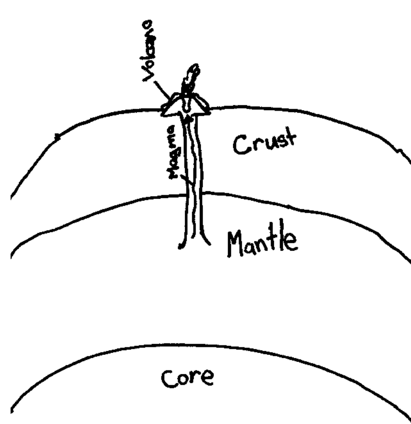
Student 2: diagram 1, time 1



Students 2: diagram 2, time 1



Student 2: diagram 3, time 1



Student 2: diagram 4, time 1

Post-text assessment

For the next part of the analysis, specific items of Student 2's post-text assessment were selected to investigate the types of inferences the student was able to make on the basis of his models, as well as to test for consistency between his models and answers to questions about the domain. Here, the data is discussed with respect to the student's understanding of the spatial/static features of the inside of the earth, and the causal and dynamic processes involved in plate tectonics. Each will be addressed in turn.

Understanding of the spatial arrangement of the inside of the earth

When given a multiple-choice question asking 'Where is the thinnest part of the crust?' he circled (correctly) 'at the ocean floor'. This response indicates that he has a good three-dimensional representation of the earth's crust. Additionally, his spatially correct models of the earth (diagrams 1-4 and 10, tables 6a and 6b, respectively), indicate that this student has a good understanding of the inside layers of the earth. His correct spatial understanding is also reflected in his answer to the following question, 'Plates moving apart causes . . .'; here he circled both b and c: 'causes volcanoes', and :causes other plates to move together'. His answer to this question also reflects excellent spatial reasoning, i. e. that plates moving will cause others to move. Few students in this study were able to answer this question correctly.

Understanding of the causal and dynamic of the processes in plate tectonics

When asked 'Name three occurrences which suggest that the plates in the earth are still moving', he responded, '. . . the continents are still moving apart about 4 inches per year; there are earthquakes, and there are volcanoes.' All of these are correct, and as such, reflect a good understanding of the effects of plate tectonics on the earth's surface.

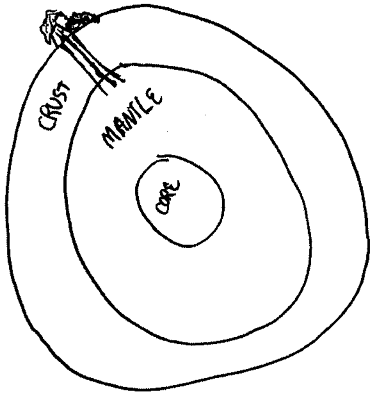
Other indicators of this student's understanding of the causal and dynamic mechanisms involved in plate tectonics are his diagrams 10 and 11, table 6b and their corresponding protocols. In both cases, the diagrams reflect local, movement-only models, compatible with his diagram of volcanic eruption (diagram 4, table 6a). More specifically, when asked to draw a diagram of volcanic eruption during the post-text assessment (diagram 10, table 6b), he said:

> Well, right now I'm drawing the layers. . . . . and this is the volcano and this is the currents coming up from the mantle up through the crust and out . . .

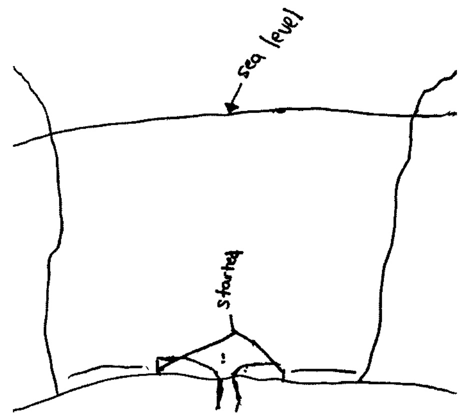
When asked to draw a diagram to depict sea floor spreading, he drew diagram 11, table 6b. While he drew he said:

> Right now I'm drawing the sea level, and here's the bottom of the sea, say that this is one plate and this is another, and when the ocean floor gets bigger because the plates are moving. . . I'm going to say that this is where they started and then they move to here because the plates have moved because that's the section of the plates and then the currents fill up the gaps in the plates and then it makes the other plates move.

Table 6b. Student 2, Diagrams 10 and 11



Student 2: diagram 10, time 1



Student 2: diagram 11, time 1

From this protocol, it is unclear whether this student has a full understanding of what causes the plates in the sea floor to move, i.e. there is no heat as causal in this model, but he appears to understand the relevant movement-related mechanisms, i.e. that magma rises into a gap and fills in the sea floor. There is some consistency between his model of the causal and dynamic processes inside the earth (diagram 2, table 6a) and his model of sea floor spreading (diagram 11, table 6b) in that both include multiple movement-related mechanisms, which are well integrated into a causal chain.

Model Revision

At this point in the interview, we revisited the diagrams, which this student drew during his reading of the text. In each case, the interviewer asked him if there was anything that he wished to add to his diagrams. For diagram 1, he added nothing but said, ‘It isn’t supposed to be the core. . . the mantle gives the volcanoes magma not lava, and it’s not from the core.’ The student here corrected the text which he had annotated to his first diagram, namely that the magma (not lava) comes from the mantle layer, not the core.

For his second diagram the interviewer asked if there was anything that he wanted to add to his diagram to show the movement in the different layers of the earth. He replied, ‘I’m not really sure how they move besides the currents and how the crust and plates move apart or together.’ At this point the interviewer gave him the relevant section of text to read again. Excerpts from our conversation after he had re-read the text are as follows:

Student: The heat rises up through the mantle from the core so that should be there, ‘cuz it comes from the core and it goes to the mantle and creates currents from the mantle up to the crust so that would cause an earthquake or a volcano. When the current gets to the top of the plates it pushes on the plates, it forces the plates to move in many directions.

> Interviewer: Do you understand that? Does that seem reasonable to you that the currents push on the plates?
>
> Student: Yeah, it's sort of like currents on the water because they push on things in the water. They would push on the plates and they would either go together or apart or in any direction
>
> Interviewer: So . . . can you explain to me clearly knowing what you do about how the plates move?
>
> Student: When the currents get to the top of the plates, it will make the plates move in a lot of directions and that movement from the core, it gives heat to the mantle and the mantle would start off the currents in the mantle and then it would go to the crust, and would come out in the crust as an earthquake or a volcano . . . *It's sort of like a relay, the core to the mantle and the mantle to the crust!*

From this excerpt, it appears that the student has revised his model of movement and processes in the earth to include more heat-related mechanisms, (which was what was lacking in his original, diagram 2, table 6a). More specifically, he has now integrated into his model the notion that it is the heat from the core, which causes currents to form in the mantle, etc. As such, his model reflects a greater number of causal mechanisms. Furthermore, his description of the causal processes into a concise causal chain and his analogy of this process as a relay suggests that he understands the causal mechanisms as a causal system.

The interviewer then asked if there was anything that he wanted to add to his diagram depicting mountain formation (diagram 3). He did not significantly revise his diagram. He was confused during this part of the interview about how the currents could be 'strong enough to push on the plates and cause them to move' (this is a common difficulty with this age level). Excerpts from our conversation are as follows:

> Student: They're being squeezed from both sides, from the left and the right.
>
> Interviewer: But why are they being pushed?
>
> Student: the force is, but it doesn't say. . . .
>
> Interviewer: Remember when we read about plate movement and what causes it, when the mantle heats up, the magma heats up, and it causes the mantle to move, it's like this layer that's wiggling and jiggling and the plates are on top of it and it causes the plates to move too, right? Do you think that that can cause the plates to move in the way that mountains are formed?
>
> Student: If the mantle is wiggly like Jell-O think that it's not strong enough to push the plates together to make a mountain, it's the mantle that forms the mountain.
>
> Interviewer: How?
>
> Student: By pushing the plates together, but I don't know . . . if it's currents or if it's just the mantle moving around.

Tutoring to promote model revision

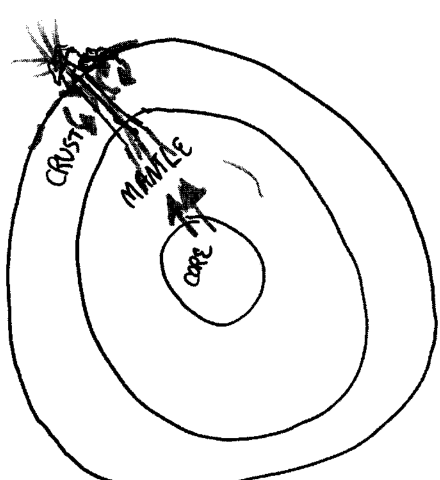
At this point the interviewer drew the student a visual analogical model of a boiling pot of water and macaroni on a stove. Together we compared the core to the element on the stove, the mantle to the pot, the magma to the water, and the plates to the macaroni. The interviewer described, in brief, how the water was hotter where it was closer to the element and less hot near the top of the surface of the water, and that the difference in the two temperatures and densities caused the hotter water to 'rise' and the less hot water to 'sink'. Further, the interviewer explained that the rising and sinking pattern was called convection and that this also happens within the mantle layer (Gobert and Clement 1994 presents additional data to demonstrate the efficacy of this visual analogy).

After this tutorial, we returned to his post-text diagram of volcanic eruption (diagram 10, table 6b), the interviewer asked if there was anything that he would like to add to it. He revised his diagram to include currents rising up through the mantle and pushing on the plates of the crust. In his revised diagram (diagram 10, time 2, table 6c), the currents, as depicted, are not contained within the mantle layer, rather they are directly below the crustal plates. This could be due to the fact that he did not fully understand the relative thickness of the layers (excerpts from his transcript confirmed this) and if the interviewer had helped him to revise him model regarding the relative thickness of the layers, that he would not have depicted the currents in the crustal layer. Excerpts from our conversation are as follows:

> Student: Yeah the heat would cause, from the core, since it was so hot, would push against the mantle, and then the mantle would have the magma go up and it would come up in a volcano.
>
> Interviewer: So what's happening with the plates?
>
> Student: The plates are moving apart.
>
> Interviewer: Why are they moving apart?
>
> Interviewer: Because the magma is hitting right here (he points to section on the top of the mantle), it comes back down and keeps on hitting it, so that forms a gap and then if there is a gap, then the magma comes up and goes through the volcano.

From the student's transcript, it appears that he has a better understanding of what causes volcanic eruption and that he has some understanding that there is convection in the mantle, and that it is caused by heat from the core. As such, his revised model (diagram 10, time 2, table 6c) is categorized as an Integrated Model (as described in table 3b) because it includes both heat- and movement-related

Table 6c. Student 2, Diagram 10, time 2



Student 2: diagram 10, time 2

mechanisms, and includes heat as a causal agent in forming the convection currents. As previously said, the goal of this program of research is to promote the development of simplified, qualitative models of plate tectonics. This student's model, especially when taking into account that he is in fifth grade, is a good, qualitative model of the causal and dynamic mechanisms involved in plate tectonics.

Types of models observed

Two types of models of the inside of the earth were identified: spatially incorrect models, such as in Student 1's case, in which the spatial arrangement of the layers is not correct; and spatially correct models, such as Student 2's case, in which the inside of the earth is depicted as concentric circles. The proportions of each type of model observed in the data were 10.6% and 89.4%, respectively. At this age level, it is not surprising that the large proportion of students who participated in this research held spatially correct models of the inside of the earth. This is likely due to prior knowledge that students obtained from diagrams in books, the media, etc. It is possible that a greater proportion of younger students hold spatially incorrect models; however, this was not the focus of the present study. In terms of the spatially incorrect models observed, it is important to note that Student 1's model differed from the other models which were also classified as spatially incorrect; that is, of the 5 spatially incorrect models observed, each differed in terms of the spatial arrangement of the layers. Further research is needed in order to more fully understand the origin of these various types of spatially incorrect models.

Four types of models of the causal and dynamic processes involved in volcanic eruption were identified, ranging from local models including heat-related mechanisms only, local models including movement-related mechanisms only, mixed models including some heat- and movement-related mechanisms, and integrated models (the most sophisticated type of model observed at this age level) which include some understanding that heat acts as a causal agent in causing the formation of convection currents which then push on the plates and cause crustal movement/breakage. The proportions of each type of model in this category were 4.25%, 61.7%, 29.8%, and 4.25%, respectively. In terms of the relative proportions of these types of models, again, local heat-only models were observed very infrequently and these models tended to include the notion that heat only was responsible for plate tectonic phenomena but with no knowledge of *how* heat was causal. As such, these models are very simplistic but are effective points for instruction, as evidenced by the substantial gains made by Student 1. The highest proportion of models observed were Type 1b, local movement-only models, which included, in most cases, the idea that in volcanic eruption, magma rises above the surface. It is likely that the high proportion of models observed in this category is due to prior knowledge that students have from the media. This type of model is also very simplistic but partially correct and as data from Student 2's model building indicates, students' rich prior knowledge about magma rising presents an effective starting point for instruction. Probing questions such as 'Why does the magma rise?' may facilitate progressive model building by engaging the student to seek to integrate his or her prior knowledge. The third category, Mixed models, which include notions of heat and pressure as well as magma movement as causal mechanisms in volcanic eruption, were the second largest category observed in these data. These models are interesting in that they have many correct causal mechanisms included in them. Given the proportion of these in the data (29.8%), it is reasonable to assume that many students at this grade level could achieve at least this level of understanding if engaged in instructional tasks which promoted model-building such as the tasks in the present study. Research in which students generate their models and then pose questions to each other about their models in the planning stages (Gobert 1999), and it is hypothesized that if students engage in problem-posing in which they address questions such as 'Why is the magma rising? and What causes the magma to be hot?, etc., that they will be able to progressively refine their models to include both heat-related and movement-related causal mechanisms. Previous research has shown that diagrams can serve as cognitive artefacts and that these can mediate conversations between individuals (Pea *et al*. 1993). In terms of the students who were classified as having integrated models, it is important to note that they were classified so on the basis of individual interviews in which they were given a tutorial of a visual analogical model of a pot of boiling water on a stove. No integrated models were observed on the basis of the reading and diagramming tasks alone; however, the visual analogy which was used in these tutorials helped students to understand how convection currents were formed in the mantle and how these currents pushed on the plates. These data suggest that visual analogical models, such as the one used in the tutorials in the present study, might be used successfully in classroom instruction in order to promote deep learning.

Reasoning with spatially incorrect models: the case of Student 1

On the basis of Student 1's diagrams generated during her reading of the text (diagrams 1-4) as well as her responses to questions during the post-text assessment, student 1 had a flawed understanding of the spatial layout of the layers inside the earth, that is, a spatially incorrect model of the inside of the earth (a Type 0 model as described in table 2b). She also held a very rudimentary model, i.e. a local, heat-only model of the causal and dynamic mechanisms involved in plate tectonics (a Type 1b model as described in table 3b). These models appeared to reflect a very literal interpretation of the text she had read.

It is hypothesized that her flawed model of the arrangement of the layers of the earth (diagram 1—core depicted at the bottom of the earth) could not support further model building about the causal and dynamic processes inside the earth because all of visual cues that are needed to understand the earth as a causal system were missing in her models. More specifically, her original, non-concentric earth model (diagram 1) could not support inference-making by means of perceptual cues about the causal mechanisms and processes inside the earth (diagram 2), and how these mechanisms cause mountain formation (diagram 3) and volcanic eruption (diagram 4). The lack of viability of her original models was further evidenced by her responses to post-text assessment items.

Regarding Student 1's model revision, it is important to note that once she was able to correctly depict the earth with the core at the centre and revised her diagrams to include magma in the mantle layer (diagram 2, time 2), she was better able to use this model to reason about the causal mechanisms underlying mountain formation (diagram 3, time 2) and volcanic eruption (diagram 4, time 2). From this, it appears that having a correct model of the spatial layout of the earth is a necessary (but not sufficient) condition for understanding the causal and dynamic processes involved in plate tectonics because with a model which depicts the layers of the earth as concentric circles with the magma-filled layer surrounding the hot core it is easier to visualize and understand how the core acts as a heat source for the magma. Once students have understood the causal chain or attributive cluster (Brown 1993, 1995) that the core is a heat source for the mantle, it is then easier to address instructionally how convection currents form in the mantle, and how currents push on the plates, both of which are necessary to understand how plate tectonics accounts for crustal activity such as mountain formation, volcanic eruption, and sea floor spreading.

After her model revision, student 1's model of the causal and dynamic processes inside the earth can be described as a 'Mixed' model because it includes both heat- and movement-related mechanisms (diagram 4, time 2). Thus, in terms of conceptual gains made, this student has made considerable progress in understanding the spatial arrangement of the layers of the earth in that she now understands that the layers are not depicted as piled on top of one another (as in her first diagram). Conceptual gains were also made in her understanding of the causal mechanisms involved in plate tectonics from her original model (diagram 2) which included heat as the only causal mechanism to her final model of volcanic eruption (diagram 4, time 2) which included both heat-related and movement-related causal mechanisms. It is likely that her understanding of heat as causal provided an important source of knowledge that was used in further developing her understanding of the causal mechanisms inside the earth. As such, the notion that there is heat in the core of the earth, which is relevant prior knowledge which many students have, is a usable anchor for conceptual change (Clement *et al.* 1989). It is also important to note that without feedback from the student's drawings, a teacher might not have detected what was blocking the student's understanding of the domain. Thus, this is an example of how students' diagrams can be used to diagnose misconceptions, and an example of how misconceptions, if they are not remediated, can adversely effect understanding.

Reasoning with spatially correct models: the case of Student 2

Student 2 was chosen as a case study to be described for two reasons. First, his pre-instruction model of the inside of the earth, i.e. a spatially correct model, is representative of the majority of students who participated in this research. Similarly, many of his pre-instruction models of the causal and dynamic processes inside the earth are local, movement-only models (diagrams 2, 4, 10, and 11), also representative of the majority of students who participated in this research.[2] Secondly, this student was chosen to describe in depth because of the ways in which he used his relevant prior knowledge of heat, pressure, and force as well as visual cues from his diagrams to revise his models.

After a brief tutorial in which the interviewer drew a visual analogy of a boiling pot of water on the stove, the student was able to better integrate his prior knowledge with his models in order to substantially revise his models, and thus, his understanding of the domain. The student constructed his understanding based on his prior knowledge of heat, pressure, and force, what he had learned from the text, inferences made on the basis of his own diagrams, and the visual analogy. In sum, he progressively revised his local, movement-only models to his final, Integrated model, which includes multiple heat- and movement-related mechanisms as well as the notion of the core acting as a causal agent in forming the convection currents. It is hypothesized that having a spatially correct model of the interior layers of the earth, as in the case of this student, facilitates inference-making by means of perceptual cues such as spatial adjacency (Larkin and Simon 1987) which then promotes model revision.

Models as coherent frameworks versus knowledge in pieces

Using a combination of qualitative and quantitative measures, these data demonstrate that there are a small number of well-defined models, which are held by students at this age level regarding the causal mechanisms involved in plate tectonics. Furthermore, there was a large degree of correspondence between students' diagrams, their corresponding explanations, and their answers to inference questions. Similar findings were reported by Vosniadou (Vosniadou and Brewer 1992). In Vosniadou's research, she has interpreted the commonality of the models observed and the correspondence between students' models and answers to inference questions as evidence that conceptual knowledge in the domain of astronomy is theory-like rather than fragmented and unconnected, as others have suggested (di Sessa 1985, 1993). Although data from the present study can be used to argue for a theory-like view of students' knowledge, a cautionary note is included. The present data suggest that students are using their models consistently in order to reason about plate tectonic-related phenomena, however, it is possible that they did so because they understood that the various phenomena addressed were all examples of plate tectonic-related phenomena. In fact, the text, which was used in the study, was written explicitly to promote this. It is possible, that if the text had not made these explicit connections, that the students may have reasoned in a manner more similar to a 'knowledge in pieces' fashion, that is, not attributing the same causal mechanisms to the various plate tectonic-related phenomena addressed. This study was not designed to address the knowledge in pieces versus knowledge in theories debate; however, empirical studies could be conducted in order to do so.

Discussion

Focus on diagram-drawing rather than diagram presentation

The focus of the present research, diagram drawing, is in direct contrast to many studies which simply present diagrams to students. In the latter type of studies, diagrams are given to students as adjunct sources of information to text, which is considered to carry the principal informational burden. The assumption is that the presence of the diagram should facilitate learning. More recently however, studies have demonstrated that there are problems associated with this. First, students often don't know how to search through diagrams in a systematic fashion in order to understand complex information (Gobert 1994, Lowe 1989), nor do they know what information is important (Anzai 1991). Additionally, scientific diagrams usually have domain-specific symbol systems which students are not skilled at interpreting (Gobert 1994, Hill 1988). Lastly, simply presenting diagrams to students puts them in a passive role as learners (Gobert and Clement 1999). From an applied perspective, this is deeply problematic because it does not promote the development of rich mental models from which inferences can be made (Lowe 1993), thereby defeating one of the main goals of science education. From a theoretical perspective, simply presenting diagrams to students is antithetical with both constructivist theories of learning (cf., von Glasersfeld 1987, 1995) and with current emphasis in science education on students' *active* model building (White 1993, Frederiksen *et al.* in press, Raghavan and Glaser 1995, Penner *et al.* 1997, Linn and Muilenberg 1996, Keys 1997). For these reasons, the present research employed active diagram construction as a means to promote model building and model revision.

Student-generated diagrams: Contributions to basic research and science education

These data on diagram generation are important in terms of what they can tell us about the cognitive processes used in constructing and making inferences from diagrams, and as such are important to basic research on cognition. Findings from these data are compatible with previous research in this area, namely, that drawing diagrams provides a means to externalize knowledge, thereby freeing up cognitive resources for inference-making (Kindfield 1993). In terms of contributions that these data make to science education, it is argued that detailed, systematic analyses of students' diagram drawing and their corresponding think aloud protocols provide fine-grained methodological tools which can be used to evaluate students' pre-instructional models (Glynn 1997), trace conceptual change over time, particularly if multiple drawings are generated (as in the present study), and test for the robustness of students' models.

A comment on prior knowledge and epistemology

The prior knowledge and inference strategies which particular students bring to bear on the tasks in the present study can be thought of as part of a student's conceptual ecology (Toulmin 1976). Another aspect of a student's conceptual ecology which is likely important to their model construction and model revision is their epistemology of scientific models, i.e. their understanding of the nature and purpose of scientific models. Although students' epistemologies were not addressed in the present work, it has been argued elsewhere that this is an important component to be addressed in students' model construction and model revision (Grosslight *et al.* 1991, Gobert and Discenna 1997, Schwarz and White 1999). Moreover, it has been shown that students with a more sophisticated understanding of the nature and purpose of models are better able to make inferences from their models, once constructed (Gobert and Discenna 1997). These findings are consistent with studies of the effects of epistemology on the integration of textual material (Rukavina 1991, Rukavina and Daneman 1996) and studies on the effects of epistemology on the integration of scientific principles (Songer and Linn 1993). Further research is necessary and is planned in order to address the relationship between the nature of students' understanding of scientific models and how this influences their model building (Gobert 1999). It is hoped that this will provide further insight into both the nature of students' science learning as well as how this might be addressed pedagogically in science teaching.

Conclusions

In the existing literature, questions have been raised as to whether students can be taught to produce diagrams from which rich inferences can be drawn (Anzai 1991), and whether students can make inferences form their own diagrams, once constructed (Schwartz 1993). Results from these studies suggest that young students can construct rich mental models of complex causal and dynamic systems, which they can then use to make inferences. These data also suggest that developing rich integrated causal models may be facilitated when models are constructed by the learner beginning with the static components first followed by increasingly complex models involving causal and dynamic information.

This research utilizes student-constructed modelling tasks and progressive model revision in order to promote deep learning of subject-matter material, as well as promote the development of modelling skills required in science learning and in scientific reasoning in general. In doing so, it examines both the process and product of science learning, and focuses on model construction as a very important process skill and an integral part of science learning and science literacy (Linn and Muilenberg 1996, Penner *et al*. 1997). This approach to science education emphasizes diagrams as important tools for model-construction and reasoning as opposed to the more conventional use of diagrams as merely illustrations of science concepts.

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Notes

1. Due to a technical problem with the recording equipment, this student's think aloud protocol was only partially audible; thus, no think aloud data for this student is included.
2. See tables 2b and 3b for percentages of students in each category.

References

American Association for the Advancement of Science (1989) *Science for All Americans: Project 2061* (Washington, DC: American Association for the Advancement of Science).

American Association for the Advancement of Science (1993) *Benchmarks for Science Literacy* (New York: Oxford: Oxford University Press).

Anzai, Y. (1991) Learning and use of representations for physics expertise. In K. Anders Ericsson and J. Smith (eds) *Toward a General Theory of Expertise: Prospects and Limits* (New York: Cambridge University Press).

Arnold, P., Sarge, A. and Worrall, L. (1995) Children's knowledge of the earth's shape and its gravitational field. *International Journal of Science Education*, 17(5), 635-641.

Ault, Jr., C. R. (1984) The everyday perspective and exceedingly unobvious meaning. *Journal of Geological Education*, 32, 89-91.

Bencloski, J. W. and Heyl, R. J. (1985) Teaching plate tectonics with the aid of a model of sea- floor dynamics. *Journal of Geological Education*, 33, 274-276.

Bezzi, A, (1989) Geology and Society: A survey on pupils' ideas as an instance of a broader prospect for educational research in earth science. Paper presented at the 28th International Geological Congress, Washington, DC.

Bisard, W. J., Aron, R. H., Francek, M. and Nelson, B. D. (1994) Assessing selected physical science and earth science misconceptions of middle school through university pre-service teachers. *Journal of College Science Teaching*, September/October, 38-42.

Brown, D. E. (1993) Refocusing core intuitions: a concretizing role for analogy in conceptual change. *Journal of Research in Science Teaching*, 30(10), 1273-1290.

Brown, D. E. (1995) Theories in pieces? The nature of students' conceptions and current issues in science education. Presented at the Annual Meeting of the National Association for Research in Science Teaching, April 22-25 (San Francisco, CA).

Clement, J. (1989) Learning via model construction and criticism: Protocol evidence on sources of creativity in science. In J. A. Glover, R. R. Ronning, and C. R. Reynolds (eds), *Handbook of Creativity: Assessment, Theory and Research* (New York: Plenum Press), 341-381

Clement, J. (1993) Model construction and criticism cycles in expert reasoning. In the Proceedings of the Fifteenth Annual Conference of the Cognitive Science Society (Hillsdale, NJ: Erlbaum).

Clement, J., Brown, B. and Zietsman, A. (1989) Not all preconceptions are misconceptions: finding 'anchoring conceptions' for grounding instruction on students' intuitions. *International Journal of Science Education*, 11, 554-565.

di Sessa, A. (1985) Knowledge in pieces. In G. Forman and P. Pufall (eds), *Constructivism in the Computer Age* (Hillsdale, NJ: Lawrence Erlbaum).

di Sessa, A. (1993) *Toward an epistemology of physics. Cognition and Instruction, 10 (2 and 3),* 105-226.

Ericsson, K. A. and Simon, H. (1980) Verbal reports as data. *Psychological Review*, 87, 215-251.

Feather, R., Snyder, S. and Hesser, D. (1995) *Earth Science*. (Westerville, Ohio: Glencoe/McGraw-Hill).

Frederiksen, C. (1988) Text comprehension in functional task domains. In D. Bloom (ed.), *Learning to Use Literacy in Educational Settings* (Norwood, NJ: Ablex).

Frederiksen, J., White, B. Y. and Gutwill, J. (in press) Dynamic mental models in learning science: the importance of constructing derivational linkages among models. *Journal of Research in Science Teaching*.

Gilbert, J. (1993) The role of models and modelling in science education. Presented at the Annual Conference of the National Association for Research in Science Teaching, April, 1993 (Atlanta, GA).

Gilbert, S. (1991) Model building and a definition of science. *Journal of Research in Science Teaching*, 28(1), 73-79.

Gobert, J. (1994) Expertise in the comprehension of architectural plans: Contribution of representation and domain knowledge. Unpublished doctoral dissertation (Toronto, Ontario: University of Toronto).

Gobert, J. (1997) Summarizing, Explaining, and Diagramming: The differential effects on text-base representations and mental models. Presented at the Annual Meeting of the Cognitive Science Society, August, 7-10 (Stanford University, Palo Alto, CA).

Gobert, J. (1999) Making thinking visible: Promoting students' model-building and collaborative discourse in WISE. Grant funded by the National Science Foundation.

GOBERT, J. and CLEMENT, J. (1994) Promoting causal model construction in science through student-generated diagrams. Presented at the Annual Meeting of the American Educational Research Association, April 4-8 (New Orleans, LA).
GOBERT, J. and CLEMENT, J. (1999) The effects of student-generated diagrams on conceptual understanding of causal and dynamic knowledge in science, *Journal of Research in Science Teaching*, 36(1), 39-53.
GOBERT, J. and DISCENNA, J. (1997) The relationship between students' epistemologies and model-based reasoning. Kalamazoo, MI: Western Michigan University, Department of Science Studies. (ERIC Document Reproduction Service No. ED409164).
GOBERT, J. and FREDERIKSEN, C. (1988) The comprehension of architectural plans by expert and sub-expert architects. Proceedings of the Tenth Annual Meeting of the Cognitive Science Society (Montreal, Canada. Hillsdale, NJ: Lawrence Erlbaum).
GROSSLIGHT, L., UNGER, C., JAY, E. and SMITH, C. (1991) Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching*, 28(9), 799-822.
GLYNN, S. (1997) Drawing mental models. *The Science Teacher*, 30-32.
GYSELINCK, V. and TARDIEU, H. (1994) Illustrations, mental models, and comprehension of instructional text. In W. Schnotz and R. Kulhavy (eds.), *Comprehension of Graphics. Amsterdam* (The Netherlands: North-Holland Publishers).
HEGARTY, M. and JUST, M. (1993) Constructing mental models of machines from text and diagrams. In H. Mandl and J. R. Levin (eds), *Knowledge Acquisition from Text and Pictures* (North Holland: Elsvier Science Publishers B. V.).
HILL, D. (1988) Difficulties with diagrams, *Journal of Science and Mathematics Education in S. Asia*, XI(2), 32-40.
JACOBI, D., BERGERON, A. and MALVESY, T. (1996) The popularization of plate tectonics: presenting the concepts of dynamics and time. *Public Understanding in Science*, 5, 75-100.
JOHNSON-LAIRD, P. N. (1983) *Mental Models: Toward a Cognitive Science of Language, Inference, and Consciousness* (Cambridge, MA: Harvard University Press).
KEYS, C. W. (1997) An investigation of the relationship between scientific reasoning, conceptual knowledge and model formulation in a naturalistic setting. *International Journal of Science Education*, 19(8), 957-970.
KINDFIELD, A. C. H. (1993) Biology diagrams: tools to think with. *Journal of the Learning Sciences*, 3(1), 1-36.
KINTSCH, W. (1998) *Comprehension: A Paradigm for Comprehension* (Cambridge, UK: Cambridge University Press).
LARKIN, J. and SIMON, H. (1987) Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, 11, 65-100.
LINN, M. C. and MUILENBERG, L. (1996) Creating Lifelong Science Learners: What Models Form a Firm Foundation? *Educational Researcher*, 25(5), 18-24.
LOWE, R. (1989) October, Scientific diagrams: How well can students read them? What research says to the science and mathematics teacher, 3. Available from Key Centre for School Science and Mathematics, Curtin University of Technology, GPO Box U1987, Perth, Western Australia 6001).
LOWE, R. (1993) Constructing a mental representation from a abstract technical diagram. *Learning and Instruction*, 3, 157-179.
MASSACHUSETTS DEPARTMENT OF EDUCATION (1996) Science and Technology Curriculum Framework: Owning the questions through science and technology.
MEGOSE (1991) *Michigan Essential Goals and Objectives for Science Education, K-12* (Michigan State Board of Education, Michigan Department of Education).
MUTHUKRISHNA, N., CARNINE, D., GROSSEN, B. and MILLER, S. (1993) Children's alternative frameworks: Should they be directly addressed in science instruction?. *Journal of Research in Science Teaching*, 30(3), 233-248.
NATIONAL COMMITTEE ON SCIENCE EDUCATION STANDARDS AND ASSESSMENT (1996) *National Science Education Standards: 1996* (Washington, DC: National Academy Press).
NUSSBAUM, J. (1979) Children's conceptions of the earth as a cosmic body: a cross age study. *Science Education*, 63, 83-93.

NUSSBAUM, J. and NOVAK, J. D. (1976) An assessment of children's concepts of the earth utilising structured interviews. *Science Education*, 60, 535-550.

PEA, R. D., SIPUSIC, M. and ALLEN, S. (1993) Seeing the light on optics: classroom-based research and development of a learning environment for conceptual change. Draft manuscript.

PENNER, D. E., GILES, N. D., LEHRER, R. and SCHAUBLE, L. (1997) Building functional models: designing an elbow. *Journal of Research in Science Teaching*, 34(2), 125-143.

PINET, P. R. (1005) Rediscovering geological principles by collaborative learning, *Journal of Geological Education*, 43, 371-376.

PLUMMER, C. and MCGEARY, D. (1996) *Physical Geology* (Wm. C. Brown Publishers).

RAGHAVAN, K. and GLASER, R. (1995), Model-based analysis and reasoning in science: The MARS curriculum. *Science Education*, 79(1), 37-61.

ROSS, K. and SHUELL, T. (1993) Children's beliefs about earthquakes. *Science Education*, 77, 191-205.

RUKAVINA, I. (1991) The effect of knowledge-building approach on advancing learning in science. Unpublished Doctoral Dissertation (Toronto, Ontario: University of Toronto).

RUKAVINA, I. and DANEMAN, M. (1996) Integration and its effects on acquiring knowledge from competing scientific theories from text. *Journal of Educational Psychology*, 85, 406-411.

SCHAUBLE, L., GLASER, M., RAGHAVAN, K. and REINER, M. (1991) Causal models and experimentation strategies in scientific reasoning. *Journal of the Learning Sciences*, 1(2), 201-238.

SCHMALHOFER, F. (1998) *Constructive Knowledge Acquisition: A Computational Model and Experimental Evaluation* (Hillsdale, NJ: Erlbaum).

SCHMALHOFER, F. and GLAVANOV, D. (1986) Three components of understanding a programmer's manual: verbatim, propositional and situational representations. *Journal of Memory and Language*, 25, 279-294.

SCHOON, K. J. (1992) Students' alternative conceptions of earth and space. *Journal of Geological Education*, 40, 209-214.

SCHWARTZ, D. (1993) The construction and analogical transfer of symbolic visualizations. *Journal of Research in Science Teaching*, 30(10), 1309-1325.

SCHWARZ, C. and WHITE, B. (1999) What do seventh grade students understand about scientific modeling from a model-oriented physics curriculum? Presented at the National Association for Research in Science Teaching, March 28-31, Boston, MA.

SNEIDER, C. and PULOS, S. (1983) Children's cosmologies: understanding the earth's shape and gravity. *Science Education*, 67, 205-221.

SONGER, N. and LINN, M. C. (1991) How do students' views of science influence knowledge integration? *Journal of Research in Science Teaching*, 28(9), 761-784.

STEWART, J. and HAFNER, R. (1991) Extending the conception of problem in problem-solving research. *Science Education*, 75(1), 105-120.

STOFFLETT, R. (1994) Conceptual change in elementary school teacher candidate knowledge of rock-cycle processes. *Journal of Geological Education*, 42, 494-500.

TALLON, R. and AUDET, R. (1999) Three-dimensional representation of student mental models: Exploring conceptual development in the Earthview classroom. Presented at the National Association for Research in Science Teaching, Boston, MA. March 28-31.

TOULMIN, S. (1976) *Knowing and Acting: An Invitation to Philosophy* (New York: Macmillan).

TURNER, R. H., NIGG, J. M. and DAZ, D. H. (1986) *Waiting for Disaster: Earthquake Watch in California* (Berkeley, CA: University of California).

VAN DIJK, T. and KINTSCH, W. (1983) *Strategies of Discourse Comprehension* (New York: Academic Press).

VON GLASERSFELD, E. (1987) *The Construction of Knowledge: Contributions of Conceptual Semantics* (Seaside, CA: Intersystems Publications, Inc.).

VON GLASERSFELD, E. (1995) *Radical Constructivism: A Way of Knowing and Learning* (Washington, DC: The Falmer Press).

VOSNIADOU, S. and BREWER, W. (1992) Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology*, 24, 535-585.
WHITE, B. (1993) ThinkerTools: causal models, conceptual change, and science education. *Cognition and Instruction*, 10(1), 1-100.

Appendix a: the text and diagramming tasks: what causes the continents to move?

Scientists have shown that the pattern of the continents has changed over time. They believe that at one time all of the continents were close together and formed one very large continent, called Pangaea. Scientists estimate that about 200 million years ago, Pangaea started to break into several pieces. Since that time the pieces have slowly drifted apart. These pieces have become the continents that we see today. The continents continue to move about three-quarters of an inch to 4 inches per year. These paragraphs explain how the change from one big piece of land to several continents happened.

The layers of the earth

Note: After this paragraph you will be asked to draw a picture (on the next page) of the different layers of the earth.

The inside of the earth is made up of three different layers. If you could drill through the earth, the first layer you would drill through is the **crust**, which is 96 miles thick in some places. The continents we see and live on are only part of the crust. In other places, the crust dips down underwater to form the seabed. The crust is divided into moving sections called plates. Some continents are made up of more than one plate.

Under the crust is the second layer called the **mantle**. It is a layer made up of very thick liquid called magma.

At the centre of the earth's interior is the **core**, which is very hot.

Please go on to the next page.

(D1) Draw a picture of the different layers of the earth. Include and label all the information about these layers that you can.

Movement in the layers of the earth

Note: After this paragraph you will be asked to draw a picture (on the next page) of the movement and processes in the layers of the earth.

Remember that the crust is divided into sections called plates. Each plate can be thought of as a sheet of rock, riding on top of the mantle.

As mentioned before, the core of the earth is very hot. This heat creates currents that rise up through the mantle. When these currents get near the top of the mantle, they push on the plates, and force the plates to move in many directions. As the mantle moves, the plates move with it. Since the continents are part of the plates, the continents move too.

Please go on to the next page.

(D2) Draw a picture of the movement and processes in the different layers of the earth. Include and label all the information about these layers that you can.

How movement causes: mountains, volcanoes, and sea floor spreading.

How mountains form

Note: after this paragraph you will be asked to draw a picture of mountain formation.

When two plates are forced together, mountains can form. As the plates are forced together, the edges may be arched like a deck of cards being squeezed from both sides. Eventually one plate moves under the other plate. As the plates continue to move together, the crust is slowly bent and crumpled, and mountains are formed. While the rock may rise only a quarter of an inch per year, over millions of years it can form very high mountains. The Himalayan Mountains are the best example; they were formed when the plate of India collided with the plate of Southern Asia.

Please go on to the next page.

(D3) Draw a picture of the movement and processes in the different layers of the earth when mountains are being formed. Include and label all the information about these layers that you can.

How volcanoes form

Note: after this paragraph you will be asked to draw a picture of volcanic eruption.

Volcanoes occur mostly along, or very near, the edges of plates. This is because the edges are where most of the stress and cracks occur.

One way that volcanoes can form is when the plates move apart. As the currents of hot magma push on the plates, they move apart. Hot liquid magma from the mantle then rises up above the surface to form volcanoes.

Please go on to the next page.

(D4) Draw a picture of the movement and processes in the different layers of the earth when volcanoes are erupting. Include and label all the information about these layers that you can.

Why the Atlantic Ocean is getting wider

Since North America is still moving away from Europe, the Atlantic Ocean is getting wider! This is how it happens.

There are two plates, which reach under the Atlantic Ocean. The place where these two plates meet runs right down the middle of the ocean floor, from north to south. Over time, the hot currents in the mantle causes these plates to move further apart; the magma then rises up through the crack and fills in the resulting gap in the ocean floor. As the magma cools down it forms rock, which becomes a new part of the ocean floor. This is how the ocean floor gets bigger over time.