What Students' Diagrams Reveal about Their Sense-Making of Plate Tectonics in Lower Secondary Science

Felicity McLure, Mihye Won & David F. Treagust

Understanding plate tectonics is pivotal to development of an integrated understanding of Geoscience topics. However, geology is frequently introduced to students in lower secondary school by describing separate processes, such as sedimentary rock formation, rather than investigating the overall driving forces for change. This study investigates what Grade 8 students (N=37) drew to explain plate tectonics in relation to convection currents and how they integrated their prior learning into a holistic understanding through the drawing process. Students' explanatory diagrams revealed challenges to students' sense-making of this dynamic process which have not previously been documented, such as integrating understanding of temperature, density and pressure into an explanation for bulk movement of material in convection currents; and interactions between convection currents in the mantle and the tectonic plates. Understanding students' alternative conceptions at these fundamental levels provides opportunities for teachers to address these conceptions earlier in the teaching cycle. The results suggest that introduction to geology through student-generated visual representations may support students to construct better scientific explanations of the dynamic, complex processes of plate tectonics.

Introduction

Understanding how plate tectonics shapes and influences geological events and features of the Earth is central to students' developing conceptual understanding in Geoscience. Providing a scientific causal explanation of movement of tectonic plates involves the integration of concepts learned in physics and chemistry topics such as those of energy transfer, density, pressure, temperature, motion and interactions of particles (Orion & Libarkin, 2014). However, studies of introductory Geoscience units at university have shown that students have difficulty comprehending why mantle convection occurs (Libarkin & Kurdziel, 2006; Raia, 2008). University level students struggle to see the Earth as a complex, dynamic system, linking convergent and divergent boundaries with plate tectonics over huge time periods and resulting in formation of rocks with differing characteristics depending on the environment in which they are formed (Orion & Ault, 2007; Orion & Libarkin, 2014).

Despite the complexity of these Geoscience topics, they are generally taught in lower secondary school in Australia and the USA (ACARA, 2015; NGSS, 2013). It is little wonder then that students in these grades have great difficulty in understanding plate tectonics and that teachers find this topic challenging for instruction (McDonald et al., 2019). Additionally, studies of teaching Geoscience have identified hundreds of alternative conceptions held by students, teachers and even found in texts (Francek, 2013; King, 2010). As a consequence, this important Geology topic is frequently taught by focusing on the results of plate tectonics, such as volcanoes and earthquakes, rather than focusing on the underlying causal processes.

A large learning progressions study by McDonald et al. (2019) of Grade 6-9 students (11-15 years of age) who had participated in a plate tectonics summer program described a complex map of conceptions that students move through when learning about plate tectonics. Their observations showed that understanding of geological processes progresses from a static view of plates to one where plates are part of a system in constant motion. In terms of understanding the movement of tectonic plates as a system, students have been shown to progress from a non-integrated view of the layers of the Earth and the tectonic plates, to a realisation that there is a global system of plates and that plate material is constantly being either broken down or reformed at plate boundaries (McDonald et al., 2019). McDonald and colleagues observed the highest learning progression amongst these students as being able to use understanding of heat transfer to explain density differences resulting in changes in buoyancy in order to explain convection currents and hence plate movement. However, only approximately 5% of the students (or less) in their study appeared to be categorised as operating at these higher learning progressions.

The current school curriculum for secondary school Geology in Australia and the USA involves teaching separate geological events, such as earthquakes and volcanic activity and categories of rocks and their formation, without establishing a good understanding of plate tectonics (ACARA, 2015; McDonald et al., 2019; NGSS, 2013). McDonald and his colleagues (2019) suggest that teaching Earth Sciences in this way, unrelated to the big picture of plate tectonics and convection currents, has severe limitations as students focus on local interactions rather than progressing towards a dynamic and holistic understanding of Earth processes. In order to overcome this limitation, they suggest that teaching of Earth Sciences should begin by introducing students to understanding of plate tectonics as the fundamental driver of Earth Science processes.

One way forward may be to develop approaches that involve students producing multiple representations of their understanding (Mills, Tomas, & Lewthwaite, 2016). Multiple representational studies suggest that student-generated diagrams are a powerful tool in helping students to reason about and understand scientific phenomena (Fan, 2015; Leopold & Leutner, 2012; Tippett, 2016; Tytler, Prain, Aranda, Ferguson, & Gorur, 2019). The systematic literature review of Chang et al. (2020) identified ways in which producing drawings of conceptual understanding benefits students and teachers. Further, this literature review demonstrated evidence that there is now a research tradition to use drawings to understand students' conceptual understanding. In particular, where students may struggle to communicate ideas in other modes, such as writing, due to a student's poor command of the correct terminology or low levels of literacy, drawing provides an opportunity to express ideas about dynamic processes and reveals conceptual understanding that otherwise may be uncommunicated. Education researchers who have investigated the affordances of student-generated diagrams in Geoscience topics, such as plate tectonics (Gobert, 2000, 2005; Smith & Bermea, 2012) have found that production of diagrams at various points while learning promoted a deeper processing of understanding compared to writing summaries (Gobert, 2005). However, these studies did not involve students representing an explanation of the mechanism of formation of convection currents through their diagrams. In prior studies in other Science topics, we have documented the benefits to students of producing multiple representations of their conceptual understanding in order to construct *complex* scientific explanations (Author, 2018, 2020). In particular, construction of diagrams to represent the scientific links between macroscopic, microscopic and sub-microscopic processes provide affordances which challenge students to develop more complex understanding of the interconnectedness of entities and processes (Author, 2021; Leopold & Leutner, 2012; Tytler, Prain, & Hubber, 2018).

Based on prior studies that indicated the efficacy of drawing to promote deeper processing (Gobert, 2005; Tytler et al., 2018) and as a tool for communication of conceptual understanding (Chang et al. 2020), in this study, we adopted a drawing-based teaching approach to support students' learning of plate tectonics and integration of different concepts and factors. Specifically, once the drawing tasks were given to the students, the teacher and researchers facilitated students' learning by evaluating students' diagrams and engaging students in discussion. In our opinion, drawing by itself does not facilitate learning. Rather drawings need to be accompanied by students' mental engagement and thoughtful discussion with peers and knowledgeable others to facilitate their learning. The first step of using drawing tasks to facilitate their learning is to analyse students' diagrams to understand students' initial ideas and how to guide them in developing more advanced conceptions. It was thought that students' diagrams may help to identify not only sources of confusion and misunderstanding, but also how students linked new pieces of information into their knowledge base. Understanding the challenges that students encounter in integrating their understanding to explain these dynamic processes which drive geological change may allow identification of alternative conceptions, missing conceptions and schema that may be addressed in Geology lessons. As an effort to use drawing tasks to scaffold understanding, this manuscript documents how students represent their understanding of mantle convection.

Research question: For the topic of plate tectonics, we focused on one subcomponent: the cause and mechanism of mantle convection. Using their own explanatory diagrams, how do students build an explanation of the mechanism of mantle convection currents underlying plate tectonics and communicate that explanation to others?

Methods

Context and Participants

Two mixed-ability Grade 8 Science classes (13-14 years of age) and their teachers from a government school in Australia participated in this research. Both classes contained a similar mix of abilities, as reported by their teachers. Both teachers had received training from the researchers about how to implement the drawing-based teaching strategy and were given continued support on questioning strategies as well as detailed lesson plans throughout the duration of the study. As part of the Australian Earth Science curriculum (ACARA, 2015), students completed five lessons on mantle convection, sedimentary, igneous and metamorphic rock formation and the rock cycle. The lessons encourage students to discuss amongst group members, integrate different ideas and represent their understanding in explanatory diagrams. Students had already learned about changes in landscapes, particularly through describing weathering and erosion, volcanoes and earthquakes, in Geography earlier in the year (ACARA, 2015). However, the focus was on the changes in landforms due to geomorphic processes rather than the underlying causes of these processes. In previous Science lessons the students had learned about the kinetic theory of matter and density. An introductory lesson investigating the role of convection currents in large scale plate movements, particularly at the mid-ocean ridge is the focus of this paper. The goal of this lessons was to lay the groundwork for understanding of the underlying large-scale processes that result in formation of different types of rocks. Without understanding what students drew in the first lesson, it is difficult to understand how students used the drawing task to improve their understanding of the science concept and how they progressed over the series of lessons. That is why we are documenting how students represented their ideas of mantle convection in the first lesson of the series. Our next manuscript looks at the dialogs around the diagrams that afforded more scientific understanding on the concept. A total of 37 out of 51 students participated, from whom informed consent had been obtained and whose parents had also given consent. 15 students were from one class and 22 students from the second class participated.

Lesson

The lesson focused around the guiding question: How does convection in the mantle explain the movement of ocean crusts? Why does a new ocean crust layer form at the mid-ocean ridge? The format of the lessons were based on the Thinking Frames Approach (Author, 2020; Newberry, Gilbert, & Cams Hill Science Consortium, 2011) during which students worked in small groups to produce verbal explanations of their observations of a video of convection current formation in a tank of water. They then individually constructed a series of diagrams on worksheets that were provided in response to the guiding question. Diagrams were scaffolded with four questions: Why do convection currents form in the mantle? Why do the plates get pushed apart? What happens at the mid-ocean ridge? What happens to the whole ocean crust over long periods of time? While students were drawing their diagrams, teachers (and researchers) moved between groups asking questions and encouraging greater elaboration through diagrams. The lesson was of 60 minutes duration, during which 15-20 minutes was spent by students in drawing the series of diagrams. The authors observed and interacted with students in class and it was obvious that students made genuine effort to communicate their ideas and integrate different concepts in the diagrams.

This study focuses on student responses to the first two drawing prompts: why do convection currents form in the mantle? And why do the plates get pushed apart? Students needed to consider various aspects of the mechanism of heat convection and then link them to movement within the mantle.

Data Collection

Thirty-seven student worksheets from the first lesson were collected from two classes and two drawings from each student were analysed. Each worksheet contained a set of four diagrams (if complete) addressing each of the four prompts described above. We focused on diagrams in response to the first two prompts (37*2=74 drawings) as these were used by students to most clearly explain their thinking about the causes and effects of convection currents.

Analysis

This study was part of a larger study which investigated the effects of drawing science diagrams on students' creative thinking in science. An inductive approach (Merriam & Tisdell, 2018) was adopted to analyse students' explanatory diagrams in which students represented their understanding of convection currents and tectonic plate movement. A constant comparative process was used to draw out major themes (Bryman, 2012). Firstly, the first two diagrams of each student were carefully examined and features of the explanation that each student presented about formation of convection currents were described to identify scientific and alternative conceptions. The first drawing, which was in response to the prompt: why do convection currents form in the mantle? was examined to identify the students' understandings of the mechanism of convection currents. The second drawing was examined to understand students thinking about the factors causing the plates to be pushed apart (Prompt 2: Why do the plates get pushed apart?). The two drawings were also considered as a whole to check whether additional information about convection currents that was missing in the first drawing, for instance, was found in the second drawing. Initial analysis of the drawings was carried out by the first author to identify alternative conceptions found in each student's drawing. From this analysis the second author identified major themes that arose. These were discussed by the authors and determined to be: energy transfer as a driver for mantle convection; buoyancy due to density differences as a driver of mantle convection; the area within which convection occurs; and the direction of the mantle convection currents.

Further examination of each representation in terms of these themes then led to the identification of sub-themes within each theme. In the theme of energy transfer as a driver for mantle convection, for instance, we noted that Katelyn (Figure 2) had represented heat and parallel currents that were evenly spaced rising up within the mantle, suggesting even heating from the core. This led to us examining other students' drawings to find that a number of other students also represented the even heating of mantle material by the core.

Once the thematic framework describing students' representations had been developed and consensus was reached by the authors with no further themes or subthemes arising, students' diagrams were coded to determine whether each student successfully or unsuccessfully integrated these elements into their representations. All drawings were evaluated to find evidence of themes/sub-themes. For instance, it was possible to show evidence of both sub-themes, 1A and 1B (upward movement of mantle material and downward movement) and so drawings were independently examined for evidence of each sub-theme. However, Theme 2 describes the buoyancy via two different mechanisms, so in this case students' drawings were identified as belonging to either sub-theme 2A or 2B. Similarly, sub-themes 3A, 3B and 3C; and 4A, 4B and 4C were also mutually exclusive and drawings could only be categorised in one each of these sub-themes.

The scientific explanation that teachers were encouraging students to adopt was one in which uneven heating of the lower mantle material by heat generated in the core resulted in areas near the hot spot being hotter than adjacent areas close to the core. This results in differences in density due to the greater vibration of particles in the hotter material. The lower density material rises as the higher density material sinks down. The heated material rises directly upwards in the mantle. Heat is transferred from the hotter mantle material to the cooler crust. As currents of material rise they interact with the crust and diverging currents are formed which push the crust apart as the upper mantle moves and drags the solid crust with it. As the mantle material cools it increases in density and begins to move downwards.

Results

As a result of the thematic analysis of students' explanatory drawings we realised that this task involved integrating many concepts. The ways in which students used their representations to integrate these processes to build understanding about the mechanism of formation of convection currents were categorised in themes which are presented in Tables 1-4. Students mainly focused on two underlying causes for the formation of convection currents: temperature differences between the upper and lower mantle due to energy transfer from the Earth's core through the mantle to the crust and; buoyancy due to density differences in the mantle material. Students had varying levels of success in integrating these two ideas to explain the bulk movement of material within the mantle. Depending on the students' successful adoption of scientific explanations of energy transfer (Theme 1), differential densities and buoyancies (Theme 2), students described where the convection currents formed (Theme 3) and the paths and directions of those currents (Theme 4). Each theme is divided into subthemes - two subthemes each for Themes I and 2 and three each for Themes 3 and 4.

In order for students to represent their understanding of the mechanism of formation of convection currents, integration of the following processes was required: (a) an understanding of heat transfer from the core through the mantle and crust resulting in a temperature gradient throughout the mantle material; (b) recognition of the effect of temperature on density and buoyancy resulting in bulk movement of mantle material from deep in the mantle directly upwards towards the crust; (c) interaction of the moving mantle material with the crust resulting in formation of diverging currents and plate movement; and (d) movement downwards as the material loses energy to the crust and increases in density.

Theme 1: Energy Transfer as a Driving Factor of Mantle Convection (Table 1)

Insert Table 1 here

Subtheme 1A: Gain in Heat Energy Associated with Mantle Material Rising up

Drawings from all students were analysed to determine their understanding of upward movement of mantle material due to heat energy gain. About one third of students explicitly showed that the lower mantle receives heat energy from the outer core of the Earth unevenly (n = 4) or evenly (n = 9) (Table 1, 13 students). A further 50% of students indicated that temperature differences or heat energy transfer was a driving factor in the development of convection currents without showing the source of the energy. However, six students did not include any explanation of energy transfer as an underlying cause of the bulk movement of material in the mantle.

Of the 13 students who recognised that the core of the Earth is hotter than the mantle and that the mantle is heated from underneath, Nate (Figure 1) was one of four students who recognised that for convection current cells to form, *uneven heating* of the mantle from the core must be occurring. He chose to represent the flow of energy with a wiggly arrow showing that for mantle convection, the heat energy is gained from one area of the outer core, travels through the mantle to the top, and then is lost to the crust. He recognised that the currents form large convection cells which take up the whole of the mantle. While Nate showed the convection currents travel straight up, he missed the opportunity to investigate the effects of heat on density within the mantle material and hence produce a more complex causal explanation of convection currents in terms of differential buoyancy.

Insert Figure 1 here

However, 27 students who showed heating of the mantle from the core (n=9) or that there were temperature differences in the mantle (n=18), did not realise that heating may not be uniform across the lower mantle. Even after they watched a video of convection currents in water produced through heating at the centre of an aquarium, they did not make the link that uneven heating is required for convection currents in the mantle to form. This lack of correspondence between observations and claims suggests that most students drew diagrams to present their current understanding without critical reflection on their observations or modifying their understanding. Figure 2 illustrates Katelyn's conception of *even heating*. She shows multiple rising currents next to one another, suggesting widespread, even heating from below. There is no clear indication of how big the convection cells are (i.e., where the convection currents go downwards), and why the currents move in two opposite directions (i.e., four currents move to the left while four move to the right). Heating from the core is implied but not explicitly represented. Katelyn does not describe any causal link between heating, change in density and the formation of convection currents. A further six students did not represent either that energy transfer from the core nor temperature differences within the mantle material were explanatory factors in formation of convection currents.

Insert Figure 2 here

Subtheme 1B: Heat Loss Results in the Mantle Material Sinking Down

In conjunction with understanding that heating in the mantle comes from the core, an understanding that heat loss is occurring through contact with the cooler crust is necessary to explain formation of convection currents. All students' drawings were examined for evidence that they recognised that heat loss in the upper mantle resulted in material sinking down. Almost all students (Table 1: 31 (2+9+20) students) indicated that there was a temperature gradient within the mantle material in their diagrams which they implied was a causal factor for formation of convection currents. However, only Nate (Figure 1) and one other student specifically indicated that energy loss from the upper mantle to the crust contributed to mantle convection. Nine students indicated that heat loss was occurring at the upper mantle but did not specifically link this with transfer of energy to the crust.

Rather than recognising that heating was occurring in the lower mantle and that the mantle would lose energy at the upper mantle as it came into contact with the cooler crustal material, Harry and two other students indicated that the mantle material was slowly gaining heat as it rose towards the crust (Figure 3) and slowly losing heat as the material moved downwards. Harry appears to believe that there are heating (and cooling) mechanisms within the mantle rather than recognising, as many of his classmates did, that the Earth's core is much hotter than the mantle.

Insert Figure 3 here

Theme 2: Buoyancy as a Driver of Convection Currents within the Mantle (Table 2)

Since the two sub-themes within this theme are mutually exclusive, drawings were analysed to determine with which sub-theme the representation most closely aligned.

Insert Table 2 here

Subtheme 2A: Buoyancy in Relation to Density Differences

To explain why convection currents occur in the mantle, students first need to consider buoyancy in relation to heat and density of materials at the bottom of the mantle. Students understood that 'heat rises' but understanding the change in density due to heating requires application of sub-microscopic models of the kinetic theory of matter (Chi, 2005). Furthermore, understanding buoyancy requires understanding of relative density differences of adjacent materials. Although students had completed a unit on the kinetic theory, states of matter and density, many found it challenging to integrate these concepts in order to explain differences in density and buoyancy in this lesson. This challenge was compounded when students also considered that the pressure within the mantle increases significantly with depth. Students adopted different strategies to resolve these issues.

Students directly translated their understanding of water convection currents to mantle convection currents—drawing less dense materials rising to the top and denser materials coming down to the bottom. These students did not consider how the enormous pressure would impact the density of materials at the bottom of the mantle. As they also lacked the understanding of buoyancy, they did not explain why and how denser materials push less dense materials to the top. Twenty-five (Table 2, n = 13+9+3) students linked temperature difference with a resulting change in density and bulk movement of material within the mantle. In order to show differences in density most students represented a unit volume of material and drew particles that were closer together (more dense) or further apart (less dense). Rather than showing step-wise changes in density and temperature, as in heating, rising, cooling, and sinking, Sarah (Figure 4), along with 12 other students (Subtheme 2A, n = 13), simply used her diagrams to compare the movement upwards of low density material with the downward movement of higher density material.

Insert Figure 4 here

Likewise, Andrei (Figure 5) hints at density differences as a causal factor for formation of a current. He shows heating all across the boundary even though there is no clear reason why a convection current occurs at a particular point when particles are heated the same amount at the bottom of the mantle. He makes a comparison of the particle distance at the bottom of the mantle and at the top. However, he does not recognise that there is a considerable difference in pressure between the top and the bottom of the mantle.

Insert Figure 5 here

Only three students attempted to integrate multiple factors into their diagrams to explain mantle convection (Table 2). Mike (Figure 6) used four levels of density in his diagrams to integrate the ideas of temperature, density and pressure. Mike's diagram compares adjacent sections of the mantle at the bottom and the top, indicating that heating of the dense material at the bottom reduces the comparative density and results in the material rising towards the top of the mantle. This is where heat loss occurs and the density of the material increases, resulting in the material sinking downwards. The key that he used suggests that the mantle material becomes denser as it sinks, due to greater pressure. This denser material replaces the less dense material formed due to heating, completing the convection cycle. Despite these impressive attempts to integrate the impact of pressure and heat with their understanding of density, it is not clear how they understood buoyancy. Nevertheless, the diagrams indicate that students are successfully integrating different concepts to explain mantle convection currents.

Insert Figure 6 here

Katelyn (Figure 7) used a confusing analogy of solid, liquid and gas in her diagram to explain the differences in density of materials in the mantle due to heating/cooling and increasing/decreasing pressure. Heat appears to decrease the density of material at the bottom of the mantle ('solid' becomes 'liquid'). The denser material comes down to the bottom, it heats up to become less dense, which moves upwards. As the pressure decreases, the density also decreases ('liquid' becomes a 'gas'). At the top of the mantle, it becomes denser, sinking again and becoming denser still under pressure ('gas' becomes a 'liquid' then a 'solid). Katelyn, however, did not explicitly mention heat or pressure.

Insert Figure 7 here

Although Harry (Figure 3) seemed to be confused about where heat gain and loss is occurring, his representation of the separation of particles at different points in the current, indicate that he may have recognised that the density of mantle material increases as the material moves towards the core, due to the pressures involved. However, because of his alternative understanding about where heating and cooling was occurring, the most 'spread apart particles' are all across the upper mantle. As the mantle comes down from the top, it slowly loses heat resulting in the most 'dense and compact particles' at the bottom. Harry's diagrams indicate that he is using the drawing activity as part of his reasoning process to describe differential densities and their connection with the convection currents. This effort at integrating concepts of density and pressure has led to confusion about the location of heating and cooling and the reason why mantle material rises near the core. Harry's case indicates the challenges that students encounter when trying to incorporate several concepts at the same time into their representations.

Subtheme 2B: Convection Occurs without any Indication of Density Differences

Nate (Figure 1) focused entirely on the transfer of heat energy from a point in the core through the mantle material to the crust to describe the formation of convection currents. However, he did not relate this flow of energy with changes in density and buoyancy. Nine other students (Subtheme 2B, n=10) also focused on temperature differences as the main driver of convection currents without addressing density or buoyancy changes.

On the other hand, although Julia (Figure 8) incorrectly implicated the material in the core with the formation of convection currents she did use her diagram to reason about possible causes of the currents. She and another student (Subtheme 2B: n=2) linked the heating up of material in the core with a build-up of pressure rather than a change in density, resulting in the particles from the core being pushed upwards, spreading apart and rising through the mantle to the surface. There is some conflation between a belief that heat intrinsically rises, a recognition that there are enormous pressures at the core and the gain in energy of particles which results in them spreading apart to explain buoyancy. Despite the difficulty explaining the rise of materials, the downward movement was explained easily in both diagrams by saying that materials cool down and they become denser to come down to the bottom of the mantle.

Insert Figure 8 here

Theme 3: Location of Mantle Convection (Table 3)

Each of the sub-themes in Theme 3 are mutually exclusive and all student drawings were analysed to determine which sub-theme they fitted into.

Insert Table 3 here

Subtheme 3A: Convection Currents are found in the Mantle Only

All students depicted convection currents, and the majority of students showed that convection currents were found within the mantle (Subtheme 3A, n = 26). For instance, Figures 1-7 all show that the convection currents are found in the mantle.

Subtheme 3B: Convection Currents Move through the Core and the Mantle

Only a few students (Subtheme 3B, n=4) showed convection currents going through the core of the Earth. Although students watched a video showing a model of mantle convection currents inside the Earth, these students seem to have confused heat transfer from the core with transfer of material from the core. Charlotte (Figure 9), for instance, focused on currents in the mantle which travel through the centre of the Earth in a circular motion until they meet at the opposite side of the Earth and then sink down again into the core. In this case, she is communicating her knowledge that convection currents travel in divergent circuits. However, while she showed the crust being pushed apart where the currents diverge, she did not use her diagram to consider what would happen to the material in the crust as the currents converge. She also has not aligned her diagram with the model of the Earth's structure.

Insert Figure 9 here

Subtheme 3C: Convection Currents are Represented but Unclear in Which Part of the Earth

Seven students (Table 3) drew convection currents occurring in an unspecified area of the Earth. This lack of representation of the Earth's inner structure indicates that these students are not integrating understanding of the differences in make-up and temperature of each of the sections of the Earth and the role that this plays in heating, changes in density and bulk movement of materials.

Theme 4: Direction of Mantle Convection (Table 4)

Insert Table 4 here

After observing the convection currents in the demonstration and possibly as a result of seeing scientific diagrams of convection currents in their textbook, most students recognised that bulk movement of material within the mantle is occurring which is in some way connected to the movement of tectonic plates. However, students' diagrams highlighted a number of areas in which students were not able to use their diagrams to integrate their observation of convection currents in water with an underlying causal explanation related to buoyancy forces. Since they did not pay close attention to the direction and path of movement in the demonstration and relate these to visuo-spatial arrangements within their diagrams, this resulted in alternative conceptions about the shape and the direction of these currents. The sub-themes 4A, 4B and 4C are mutually exclusive and so all student drawings were analysed to determine which of these three subthemes best described the student's understanding.

Subtheme 4A: Two Diverging Convection Currents

Eleven students (Subtheme 4A, n=11) carefully observed the demonstration and checked that their diagrams corresponded with those observations and successfully producing diagrams of convection currents which showed that material from near the core rose straight up, travelled sideways as it interacted with the cooler crust and then sank down again towards the core to produce two complete circuits in opposite directions (see Figures 1 & 3). However, as noted above, these students did not always use their diagrams to present a causal explanation for movement of material or changes in direction.

Rather than showing material that moves directly upwards due to increased buoyancy and then is pushed in two opposite directions as it reaches the crust, 15 students (Subtheme 4A, n=15) showed two *circular* divergent currents (see Figure 6). These diagrams suggest that these students did not carefully observe or recognise the most important features of the fluid movement in the demonstration. Rather than considering the cause of current formation, they focused on communicating the divergent nature of two currents. These students appear to view the two currents to be independent of each other, as indicated by their distance apart, and having some intrinsic property that causes them to rotate in opposite directions. They may have recognised that, for these currents to be linked with a divergent boundary, they too must be divergent and hence concluded that the currents must also travel in opposite directions. It appears that these students have adopted the idea of material completing a circuit and possibly combined it with the idea of mechanical circular movement, for example of cogs or wheels, rather than integrating understanding of a buoyancy force acting directly upwards on less dense material. This alternative representation may also be linked with a lack of recognition of the importance of uneven heating to produce an area of higher temperature.

Subtheme 4B: Single Convection Current, Circular Movement Upwards and Downwards

Further to the confusion surrounding the production of two circular divergent currents, three students drew a single circular current which is formed as a result of heating from the core. Andrei (Figure 5) indicated that hot material at the bottom of the circle is made up of less densely packed particles that rise and at the top, near the crust, it contains cooler, denser material which "falls down". However, he did not recognise that, as the material that has risen within the mantle interacts with the crust, the material diverges in opposite directions resulting in the formation of counter-currents. In these cases, students did not use their diagrams to reason about the connection between their understanding of the movement of convection currents and its relationship with movements of the crust.

Subtheme 4C: Non-diverging Currents

Other students, such as Tanya (Figure 10) initially drew convection currents that all move clockwise (or anticlockwise). Some students then recognised that this would result in the plates moving in the same direction rather than diverging and amended their diagrams accordingly to show currents that also diverged at the crust. However, Tanya and two other students (Subtheme 4C, n=3) developed an alternative explanation of how currents moving in one direction could cause plates to be pushed apart by suggesting a mechanical, cog-like movement of the convection currents in the same direction. The cogs appear to act independently to push magma from the mantle out of the crust. Rather than the movement of the convection currents and their interaction with the crust resulting in plates separating and new crust being formed, in this view of the Earth system, the magma welled-up, physically pushing the plates apart.

Insert Figure 10 here

Five students such as Katelyn (Figure 2) represented incomplete convection currents showing mantle material moving upwards together with translational movements at the crust. These students appeared to be focusing on the buoyancy of less dense material and the resultant movement upwards, as well as the interaction with the crust resulting in divergence of the plates. The driving factor of energy transfer and cooling at the crust which leads to material becoming denser and sinking downwards to force up more buoyant material has been ignored.

Discussion

Many studies have documented the challenges that students experience in integrating different concepts to understand plate tectonics. The inconceivable scale of the Earth system, consideration of multiple competing factors, and understanding of difficult physics concepts such as buoyancy, all add to the difficulty in understanding the dynamic and complex phenomenon of mantle convection.

In this study, the Year 8 students used detailed diagrammatic explanations to build their understanding of the mechanism of convection current formation in the mantle and plate tectonics (c.f. Gobert, 2005; Tytler et al., 2018). Drawing explanations let students integrate several dynamic processes in order to communicate their understanding (c.f. Chang et al., 2020). However, examination of students' diagrams indicated that some students did not fully engage with the affordances available to them to reason through drawing or reason from their drawings; rather, they tended to use their diagrams to communicate ideas that they considered important without engaging in more complex sense-making strategies (Tytler et al., 2019). Nevertheless, there were a number of students who successfully integrated concepts such as effects of heat gain and loss on density and buoyancy, pressure effects at depth, bulk movement of material within the crust and interaction between the crust and the moving material in the convection currents (for instance Mike).

Students encountered a number of challenges as evidenced by some of the alternative conceptions (e.g. subtheme 3B) or representational difficulties (e.g. Figure 4) that arose in their diagrams during the process of sense-making as they integrated these concepts. The need to concurrently consider the factors of heat transfer, temperature differences, and density differences as well as the effects of increasing pressure at depth when constructing an understanding of the mechanism of formation of convection currents, presented a considerable challenge to the majority of students. This is consistent with other studies that showed that students from primary to undergraduate levels tend to focus on one dimension only when considering buoyancy (Ginns & Watters, 1995; Hardy, Jonen, Möller, & Stern, 2006; Minogue & Borland, 2015).

The source of temperature differences as a result of *uneven* heat transfer from the core to the crust and the atmosphere (Table 1: Subtheme 1A) was neglected by a majority of students. Other studies of students' conceptualisations of plate tectonics showed limited understanding of the formation of convection currents (Cheek, 2010; Gobert, 2000; Hemmerich & J., 2002; Smith & Bermea, 2012) and either ignored their importance or focused on heat transfer from the core without recognising the importance of uneven heat transfer or relating this to density changes.

Although two thirds of students indicated that convection currents were due to density differences and related these differences to temperature differences resulting in material rising up or moving down through the mantle, only one third of students successfully used their drawings to elaborate these explanations by showing that lower density material rises and higher density material falls (Table 2: Subtheme 2A). The additional consideration of pressure differences within the mantle as students were attempting to explain convection currents may have been a source of confusion for some students. Only three students attempted to integrate the effects of pressure with changes in density, temperature and buoyancy in their diagrams. Most students chose to ignore pressure effects and focused on the effects of temperature differences on density within the mantle. However, two students, Harry (Figure 3) and Julia (Figure 8) focussed on the effects of pressure on density rather than the effects of heat gain and loss. This resulted in the production of some alternative conceptions about where heating and cooling was taking place and the source of buoyancy forces deep in the mantle.

For some students who did link heat and density changes with formation of convection currents, a lack of recognition that heating from the core must be uneven for convection currents to form and *a limited understanding of upward thrust* due to buoyancy forces led to further challenges in recognising that less dense material in the lower mantle is slowly forced *directly* upwards (Table 4: Theme 4). This issue was evident from the number of students who drew circular paths for convection currents, rather than showing that lower density material is thrust straight upwards through the mantle.

Some students also found it challenging to explain the importance of the formation of complete convection currents. These students recognised that material from deep in the mantle rises up through the mantle as it is heated but did not follow the movement of this material as it moved sideways, cooled and sank back down. This suggests a lack of understanding that the difference in buoyancy between two adjacent areas of mantle causes the thrust upwards of material as denser material is being forced downwards due to gravitational forces. This explanation requires application of Newtonian dynamics to understanding of buoyancy effects which is challenging for undergraduates, let alone grade eight students (Loverude, Kautz, & Heron, 2003). Additionally, although all students represented the formation of convection currents in some form and linked these with plate movements, some students found it challenging to explain why diverging currents are formed, since they did not recognise that the rising material interacts with the crust. As a result, three students drew single convection currents (see Figure 5), indicating that they did not recognise that the material that reaches the mantle/crust interface will be forced to diverge into two currents.

Despite these challenges, the task of drawing diagrams to explain mantle convection seemed effective in prompting and encouraging students to explore and develop their ideas linking the formation of convection currents with understanding of plate tectonics. The analysis of students' diagrams also raises an interesting and recurring question of how much information we provide to students to help them understand a complex science concept, such as plate tectonics. Particularly in grades 6-8, we do not teach students to consider multiple variables concurrently. However, by not explicitly discussing the interaction of multiple forces (e.g. increased pressure at depth and density), students who recognise the existence of these variables may experience additional difficulties and fail to make better sense of the phenomenon in question, as displayed in this study.

Implications for practice

Understanding challenges posed for students as they produce explanatory diagrams of the cause of convection currents and movement of tectonic plates opens up new avenues for teaching. Teaching should specifically address difficulties that students have in building conceptual understanding in these areas. For instance, a focus on the necessity of uneven heating to form convection currents by providing comparative demonstrations or experiments showing the effects of even and uneven heating may help to focus on this important aspect of convection current formation. Similarly, drawing students' attention to the path that material takes within the convection currents, including interaction between the upwardly moving material and the crust may lead students to further consider scientific mechanisms of plate movement. Although a detailed understanding of buoyancy may be beyond the grasp of students at this level, it may be addressed in simple terms to highlight the importance of comparing the density of adjacent material within the mantle and the effects of cooling and heating on density. Rather than ignoring the added effects of increasing pressure with depth, this factor can be tackled by helping students to focus on adjacent areas of the mantle at the same depth undergoing different degrees of heating due to uneven heating from the core.

When we compared students' understanding of plate tectonics with the learning progressions observed by McDonald et al. (2019), we noted that a majority of students recognised that the mechanism for plate motion was due to convection currents. These students also were able to connect at least some of the sub-microscopic entities and processes occurring in the mantle with the bulk movement of material throughout the mantle and relate this movement to plate movements. We would suggest that this represents a higher learning progression in this category than that documented by McDonald et al. (2019).

This study shows that many Grade 8 students who are being introduced to Earth Science for the first time are capable of integrating their prior understanding of concepts from chemistry, physics and geography to begin to form a holistic and dynamic understanding of the driving processes behind plate tectonics. Drawing their understanding in detailed explanatory diagrams supports these students in investigating concepts and producing elaborated explanations. However, further support may be required to encourage students to consider the interplay of more than one causal feature (e.g. in combining effects of temperature, density, buoyancy and pressure). This finding supports the suggestion by McDonald et al. (2019) that introducing students to the plate tectonics system prior to learning about different rock formation within the rock cycle may be a powerful method for developing holistic student conceptual understanding in this topic.

Conclusion

Geophysical phenomena involve applying various physics concepts and also considering multiple variables concurrently. Student-generated diagrams may provide a powerful visualisation tool which can be used by students to consider different processes occurring within the Earth and their interactions and to construct a more complex understanding of plate tectonics. However, many students in this study focused on temperature differences and/or density differences to explain the formation of mantle convection currents, and did not consider other aspects (e.g., uneven heating, energy transfer, the principles of buoyancy, increasing pressure with depth in the mantle, etc.). This confusion seems to be caused by the difficulty in considering pressure, temperature, and density all at the same time. As a result of identifying the major challenges students have in integrating their understanding of convection current formation and plate tectonics, we suggest areas on which teachers may focus that may enable students to overcome some of these challenges to building a holistic scientific understanding of these processes. Despite the challenges that students encountered, by supporting students to produce a series of diagrams communicating the dynamic causal processes underlying plate tectonics, they were able to show considerable progression in construction of their scientific understanding.

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Table 4 Students' understanding of the direction of mantle convection currents

Theme 4: Direction of mantle convection		No. of students (%)
Subthemes		
4A	Two diverging convection currents	
	Material rises straight upwards, travels sideways and then downwards	11 (30)
	Circular movement upwards and downwards	15 (41)
4B	Single convection current, circular movement upwards and downwards	3(8)
4C	Non-diverging currents	
	Circular currents in the same direction	3 (8)
	Incomplete currents (for example, not falling)	5 (14)

Table 1 Students' understanding of energy transfer as a driving factor for mantle convection currents (N=37)

		No. of students (%)
	Uneven heating of the mantle from the core creates convection currents	4 (11)
	Even heating of the mantle from the core creates convection currents	[illegible]
	Temperature differences evident but heat source or reason for heating unclear	18 (49)
1B	Heat loss results in the mantle material sinking down	
	Heat loss at the upper mantle	
	Heat loss at the upper mantle to the crust	2 (5)
	Heat loss at upper mantle evident but is not connected with loss to the crust	9 (24)
	Temperature differences or heat loss noted but reason unclear	20 (54)
	No mention of temperature differences or heat loss	6 (16)

Table 2 Students' understanding of buoyancy as a driver of convection currents

Theme 2: Buoyancy as a driver of convection currents within the mantle		No. of students (%)
Subthemes		
2A	Buoyancy in relation to density differences	
	Density differences are related to temperature differences	
	Both density differences in adjacent parts of the mantle and the effect of pressure at depth included	3 (8)
	Pressure differences in mantle not acknowledged	
	Low density material moves upwards, high density moves down	13 (35)
	High density material moves upwards and low density moves down	9 (24)
2B	Convection occurs without any indication of density differences	
	Build-up of pressure in the core/mantle is the driver or upward movement	2 (5)
	Convection is related to temperature differences but not density differences	10 (27)

Table 3 Students' understanding of the location of mantle convection

Theme 3: Location of mantle convection		No. of students (%)
Subthemes		
3A	Convection currents are found in the mantle only	26 (70)
3B	Convection currents move through the core of the earth and the mantle	4 (11)
3C	Convection currents are represented but unclear in which part of the earth	7 (19)

Table 4 Students' understanding of the direction of mantle convection currents

Theme 4: Direction of mantle convection		No. of students (%)
	Subthemes	
4A	Two diverging convection currents	
	Material rises straight upwards, travels sideways and then downwards	11 (30)
	Circular movement upwards and downwards	15 (41)
4B	Single convection current, circular movement upwards and downwards	3(8)
4C	Non-diverging currents	
	Circular currents in the same direction	3 (8)
	Incomplete currents formed (rising but not falling)	5 (13)