Examining the Conceptual Understandings of Geoscience Concepts of Students with Visual Impairments: Implications of 3-D Printing

DISSERTATION

Presented in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy in the Graduate School of The Ohio State University

By
Karen E. Koehler
Graduate Program in Education: Teaching & Learning

The Ohio State University
2017

Dissertation Committee:
Professor Tiffany Wild, Adviser
Professor Lin Ding
Professor Mollie Blackburn
Abstract

The purpose of this qualitative study was to explore the use of 3-D printed models as an instructional tool in a middle school science classroom for students with visual impairments and compare their use to traditional tactile graphics for aiding conceptual understanding of geoscience concepts. Specifically, this study examined if the students’ conceptual understanding of plate tectonics was different when 3-D printed objects were used versus traditional tactile graphics. Additionally, this study explored the misconceptions held by students with visual impairments related to plate tectonics and associated geoscience concepts. Interview data was collected one week prior to instruction and one week after instruction and throughout the 3-week instructional period. Data sources included pre and post student interviews, student journals and other student documents and audio taped instructional sessions. All students in the middle school classroom received instruction on plate tectonics using the same inquiry based curriculum but during different time periods of the day. One group of students, the 3D group, had access to 3-D printed models illustrating specific geoscience concepts during instruction and another group of students, the TG group, had access to tactile graphics illustrating the same geoscience concepts.
The videotaped pre and post interviews were transcribed, analyzed and coded for conceptual understanding using constant comparative analysis, as well as to uncover student misconceptions. Additionally, all student responses to the interview questions were categorized in terms of conceptual understanding. Analysis of student journals and classroom talk served to uncover student mental models and misconceptions about plate tectonics and associated geoscience concepts to measure conceptual understanding.

A slight majority of the conceptual understanding before the instruction fell into the category of no understanding or alternative understanding and after instruction the larger majority of conceptual understanding was categorized as scientific or scientific with fragments. Most of the participants in the study increased their scientific understandings of plate tectonics and other geoscience related concepts and held more scientific understandings after instruction than before instruction. All students had misconceptions before the instructional period began, but the number of misconceptions were fewer after the instructional period. Students in the TG group not only had fewer misconceptions than the 3D group before instruction, but also after instruction. Many of the student misconceptions were similar to those held by students with typical vision; however, some were unique to students with visual impairments.

One unique aspect of this study was the examination of student mental models, which had not previously been done with students with visual impairments, but is more commonplace in research on students with typical vision. Student mental models were often descriptive rather than explanatory, often incorporating scientific language, but not clearly showing that the student had a complete grasp of the concept.
Consistent with prior research, the use of 3-D printed models instead of tactile graphics did not seem to make a difference either positively or negatively on student conceptual understanding; however, the participants did interact with the 3-D printed models differently, sometimes gleaning additional information from them. It also provides additional support for inquiry-based instruction as an effective means of providing science instruction to students with visual impairments.
Dedicated to my husband, my son and my parents whose support and confidence in me have been instrumental to my success.
Acknowledgments

First, I would like to thank my advisor, Dr. Tiffany Wild, for her support and encouragement throughout this doctoral journey. You have been a fantastic mentor and advisor, carefully helping me chart a course and providing me with opportunities for research and scholarship. Thank you for helping me realize that this degree was indeed possible.

Thank you to my committee members, Dr. Blackburn and Dr. Ding. Dr. Blackburn, you have truly helped me become a better qualitative researcher and I am thankful for the constructive feedback you are always willing to give. Dr. Ding, thank you for helping me explore my understanding of the foundational concepts of science and encouraging me to challenge my preconceived notions about the nature of science.

I wish to thank my OSSB family, including my administrators, fellow teachers, students and parents. Kim, Al and Chris, Ceil, Sarah and Ron have been especially important to me and I thank you for your support.

Thank you to my co-researcher, Trudy, for taking her precious time to help make data collection and analysis go very smoothly. I would also like to thank my colleague,
Sean Tikkun, for his hard work designing and producing the fantastic 3-D printed models for use in my research.

I also want to thank my whole family for their support and encouragement, especially my sister Kristin. To my dad – thank you for leading me down the path of special education and instilling in me the confidence to pursue this advanced degree. To my mom – thank you for being there for me every step of the way and for understanding when I was too busy to call or attend a family get together. To my son, Matthew – I am thankful that we were able to take this educational journey together and I am so thankful for your support and confidence in me.

Finally, I would like to thank my husband, Jay, of almost 30 years for all of his love, support, encouragement and advice throughout this process toward my doctoral degree. You have been with me every step of the way, understanding when I needed to write many weekends, picking up extra work around the house – so I could study - and acting as a sounding board when my stress levels rose or when I needed advice on my writing, research or thought process. Your support throughout this journey has been unfailing and without it, this degree would not have been possible.
Vita

1982.........................................................Grove City High School

1986..........................................................B.S. Science Education, The Ohio State University

1995..........................................................M.A. Special Education, The Ohio State University

1990 to present ...........................................Science Teacher and Teacher of the Visually Impaired, The Ohio State School for the Blind

2010 to present.............................................Lecturer, The Ohio State University

Publications


Fields of Study

Major Field: Education Teaching & Learning
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CHAPTER 1: Introduction

The dynamic processes of the earth, including earthquakes and volcanoes captivate the imaginations of students of all ages and the popularity of blockbuster movies such as *Dante’s Peak, San Andreas* and *Volcano* highlight societies’ fascination with these natural disasters. Students often visualize earthquakes as opening large cracks in the earth’s surface, swallowing cars and buildings, and volcanoes erupting with massive rivers of lava burying all in their path. While these visions, often prompted by encounters with popular media, may help excite students to learn more about these important geologic processes, they also pose barriers to true conceptual understanding (Capps, McAllister & Boone, 2013). The unifying theory of plate tectonics explains the underlying processes of earthquakes, volcanoes and mountain building, yet K-12 and college age students alike, as well as preservice teachers and in-service teachers have considerable difficulty understanding the theory, which leads to many misconceptions (Ford & Taylor, 2008; Gobert, 2005; Libarkin, 2005; Libarkin, Anderson, Dahl, Beilfuss & Boone, 2005; Marques & Thompson, 1997; Sibley, 2005; Smith & Bermea, 2012). One only needs to turn on the nightly news to see the damaging effects of a recent earthquake or volcanic eruption and its devastating effect on a local or distant community. An understanding of plate tectonics is necessary for true science literacy in
the geosciences and is also important as our society grapples with issues related to energy sources, fossil fuel extraction and the preparation for and mitigation of the effects of geologic natural disasters.

Educational and geoscience researchers call for the need for better instruction in the geosciences to correct student misconceptions of the processes underlying these natural geologic events (Libarkin et al., 2005). The Next Generation Science Standards (NGSS), based upon the National Research Council’s *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*, stress the need for improved instruction in all areas of science using standards that are arranged in a coherent manner and internationally benchmarked (NRC, 2012). The Next Generation Science Standards were designed to incorporate the research of conceptual change and cognitive theorists, as they promote student understanding of important science concepts through a K-12 framework. This new framework encourages students to develop a knowledge about science and includes crosscutting concepts which “help provide students with an organizational framework for connecting knowledge from the various disciplines into a coherent and scientifically based view of the world” (Achieve, 2013). These standards are also designed to foster a depth of knowledge rather than a breadth of knowledge and core concepts are revisited throughout various grade bands with deepening complexity at each level.

The impetus for the development of these standards was to address the need for an educated workforce that could compete on the global scale and achieve high levels of scientific and technological literacy. These standards call for instruction on geologic
concepts across grade levels focused on core ideas such as Earth systems - how and why the earth is constantly changing, how tectonic forces continually produce and destroy earth seafloor, how geoscience processes have changed the earth’s surface at varying time and spatial scales and the history of the planet Earth (radioactive and relative dating) (Achieve, 2013). The NGSS middle school standards below showcase the need for students to understand the earth as a system and highlight the importance of plate tectonics as a unifying theory in geosciences instruction.

ESS2.A: Earth’s Materials and Systems:
- All Earth processes are the result of energy flowing and matter cycling within and among the planet’s systems. This energy is derived from the sun and Earth’s hot interior. The energy that flows and matter that cycles produce chemical and physical changes in Earth’s materials and living organisms.
- The planet’s systems interact over scales that range from microscopic to global in size, and they operate over fractions of a second to billions of years. These interactions have shaped Earth’s history and will determine its future.

ESS1.C: The History of Planet Earth:
- Tectonic processes continually generate new ocean sea floor at ridges and destroy old sea floor at trenches.

ESS2.B: Plate Tectonics and Large-Scale System Interactions
- Maps of ancient land and water patterns, based on investigations of rocks and fossils, make clear how Earth’s plates have moved great distances, collided, and spread apart. (Achieve, 2013)

Helping students understand the revolutionary and continually evolving theories in the geosciences, such as plate tectonics, not only produces students who have a high level of scientific literacy, it also helps students better understand the underlying causes of natural disasters, such as earthquakes and volcanic eruptions that continually shape the earth’s
surface. Additionally, the theory of plate tectonics is an excellent example of how science continually changes as scientists make observations, collect data, generate and test hypotheses, build theories and models to explain how something works – in other words – how scientists DO science. Instruction about the theory of plate tectonics also helps students understand the nature of science including understanding patterns and processes that underlie our major theoretical understanding of geology.

The theory of plate tectonics is particularly problematic for students to understand because plate movement is not observable (Dolphin, 2008, Ford & Taylor, 2008; Smith & Bermea, 2012) and students often lack a mental model for the earth’s interior, which limits their ability to understand the dynamic process of plate movement (Dolphin, 2008). Moreover, students often use geoscience terminology inaccurately or with minimal understanding in relation to plate tectonics (Cheek, 2010). Students with visual impairments struggle to understand geoscience concepts similarly to their sighted peers (Jones, Minogue, Oppewal, Cook, & Broadwell, 2006) and hold many of the same misconceptions (Koehler, Tikkun & Wild, 2015). While plate movement is not observable, many visuals and diagrams exist that seek to help students develop a mental model of the earth’s layers, plate boundaries and earth’s features related to those plate boundaries. Depending upon their level of vision, students with visual impairments may not have access to those visuals or diagrams commonly used to teach geoscience concepts, leaving them at a disadvantage.

Students with visual impairments require alternative methods of accessing the information commonly presented in a visual manner in a typical science classroom using
videos, visuals, demonstrations, computer based multimedia materials and white board activities (Koehler & Wild, 2016; Ross & Robinson, 2000; Sahin & Yorek, 2009). One common method of making visual material accessible to students with visual impairments is the use of tactile graphics. Tactile graphics are sometimes found in science textbooks and on most standardized assessments; however, the consistency of the graphics varies and studies show mixed results in students’ ability to identify these tactile pictures (Picard & Lebaz, 2012; Zebehazy & Wilton, 2014a; Zebehazy & Wilton, 2014c).

Approximately 60,000 children, ages three through twenty-one, in the United States, have a documented visual impairment, which may affect their educational functioning (American Printing House, 2014). Students who are blind and visually impaired have a significant sensory loss and perceive the world around them very differently than their sighted peers (Ferrell, 2000). They often lag behind those peers in the area of concept development and must have direct instruction on concepts that their peers learn incidentally by visually observing the world around them. Moreover, Scoy, McLaughlin, and Fullmer (2005) question whether one can truly measure a visually impaired student’s true mathematical or science ability, given that many of the challenges they face with these subjects is directly due to their visual impairment.

Conceptual change in science is the iterative process of “constructing, evaluating and revising models that exemplify features of the phenomenon” (Nersessian, 2008 p. 410) and the ability to analyze these models is paramount to understanding the process of conceptual change (Vosniadou, 2002). A major tenant of conceptual change theory is to recognize that students enter the classroom space with fragmented, incoherent and flawed
mental models (Chi & Roscoe, 2002) leading to a variety of misconceptions. Mental models are highly personalized (Norman, 1983) and incorporate knowledge from a variety of sources including: formal and informal educational experiences, media sources, simulations, or direct experiences with objects (Buckley & Boulter, 2000). Conceptual change in science is often difficult to measure because scientific concepts involve complex systems (Chi & Roscoe, 2002; diSessa, 2002) and conceptual change is not a simple, linear process from naïve conceptions to scientific conceptions (diSessa, 2002). Because of its complex nature, the theory of plate tectonics poses significant challenges for students as they move from naïve conceptions to more scientific understandings.

Purpose of study

The purpose of this qualitative study was to explore the use of 3-D printed models as an instructional tool in a middle school science classroom for students with visual impairments and compare their use to traditional tactile graphics for aiding conceptual understanding of geoscience concepts. Specifically, this study examined if the students’ conceptual understanding of plate tectonics is different when 3-D printed objects are used versus traditional tactile graphics. Additionally, this study sought to explore and understand misconceptions held by students with visual impairments related to plate tectonics and associated geoscience concepts. Data was obtained one week prior to instruction, throughout the 3-week instructional period, and one week after instruction. The setting of the study was a specialized school for the blind in the Midwestern United States. All students received instruction on plate tectonics from an inquiry-based
curriculum; however, one group, the 3-D group, had access to 3-D printed models illustrating specific geoscience concepts and the tactile graphics group, TG group, had access to tactile graphics illustrating the same geoscience concepts.

Rationale for the Study

Federal education legislation such as the No Child Left Behind Act of 2001, its replacement Every Student Succeeds Act (ESSA, 2015) and the Individuals with Disabilities Education Improvement Act (IDEIA, 2004) call for the use of evidence-based or research based practices in educational programming and that these research based strategies be used when making educational decisions for students with disabilities; thereby, strengthening the connection between research and practice. According to Mills (2008), NCLB requires the “application of rigorous scientifically based research (SBR) standards to educational programs and practices to ensure that students are exposed to teaching strategies and methods for which a strong evidence base exists” (p. 10). In 2005, following the federal mandates of No Child Left Behind (NCLB) and the Education Sciences Reform Act of 2002, the National Research Council released a policy document that called for educational policy and practice to be based upon rigorous research. The field of visual impairments suffers from a lack of practices which would meet the Every Student Succeeds Act requirements of “scientifically based research” and as Ferrell states, there is not a significant research basis for most instructional practices used in the education of students with visual impairments and that the majority of best-practices are based upon anecdotal evidence, tradition, common sense and even superstition. Ferrell (2006) suggests that the research foundation in the field of visual impairments is quite
weak and is mostly filled with well-designed correlational and single subject studies or expert committee reports and experience of experts in the field. There is almost no research base in the field of visual impairments that would meet the mandates set by No Child Left Behind or the Every Student Succeeds Act and rigorous, scientifically based research is almost nonexistent (Ferrell, 2006; Kelley & Smith, 2011; Wild & Allen, 2009). Few studies have been replicated and most of the existing studies are based upon accommodations and modifications to curricula or product studies (Ferrell, 2006; Kelley & Smith, 2011; Wild & Allen, 2009). A large research to practice gap exists in the field of visual impairment research, and this gap exists across the fields of general and special education, as well (Abbott, Walton, Tapia & Greenwood, 1999; Carnine, 1997; Spencer, Dietrich & Slocum, 2012). This research study not only adds to the lack of empirical research in the field of students with visual impairments but addresses the research to practice gap by focusing on the use of 3-D printed models as instructional tools in the science classroom for students with visual impairments.

Additionally, there is a need for research on the efficacy of 3-D printing as an instructional tool for access to visual content for students with visual impairments. Three-dimensional models have been suggested as superior to tactile graphics because they give the students with visual impairments a clearer picture of a concept and should be used when the real object is not available (Robinson & Ross, 2000). For example, a 3-D model of DNA is superior to a tactile graphic for helping a student understand the structure of this important macromolecule. Given the increased availability of 3-D
printers in school classrooms, 3-D printing may hold promise for making visual information accessible and concrete for students with visual impairments.

Given the limitations of tactile graphics for representing important science concepts to students with visual impairments and the difficulty these students have interpreting the information conveyed in a tactile graphic, 3-D printed models may help aid conceptual understanding of important science concepts. Geoscience concepts, including plate tectonics, are difficult for students to understand and this study sought to illuminate how students with visual impairments interact with these models and how their understanding is different when using 3-D printed models compared to traditional tactile graphics.

Research Questions

The following research questions guided the design and analysis of this qualitative study.

1. How do the conceptual understandings about plate tectonics of middle school students with visual impairments differ before and after instruction, using an inquiry based science curriculum?
2. How do the conceptual understandings of middle school students with visual impairments regarding plate tectonics compare between those who have access to 3-D printed models and those who have access to tactile diagrams?
3. What misconceptions do middle school students with visual impairments have about plate tectonics and associated geoscience concepts and how do these
misconceptions compare between those that have access to 3-D printed models and those who have access to tactile diagrams?

Significance of the Study

Given the limitations of tactile graphics for accurately conveying information to students with visual impairments, especially those involving 3-dimensional or unusual views, 3-D printing may hold the key to improving science instructional practices for students with visual impairments. The New Media Consortium Horizon Report states that within the next four to five years, 3-D printing will become more prevalent in schools, as the cost and obstacles to widespread adoption continue to decline (NMC, 2013). Practical uses for 3-D printing technology in educational settings have been outlined, including STEM related activities, a 3-D pen for creating tactile maps and even suggestions for the use of 3-D models for giving access to the visual arts for students with visual impairments, by creating 3-dimensional models of famous works of art. The use of 3-D printing for helping students with visual impairments learn science concepts has also been suggested by Hasper et al. (2015) and Horowitz and Schultz (2014). Calls for the use of 3-D printed models for use with students with visual impairments are growing but only one previous study has been done to test their effectiveness for conceptual change (Koehler et al, 2015). This qualitative study helps determine how 3-D printed models may help students understand important science concepts and adds to the growing body of research in instructional strategies for science education of students with visual impairments.
Currently, the field of research in visual impairments is far from meeting the federal mandates for the use of evidence-based practices and current classroom practices have little to no research backing. In addition, almost no studies have been replicated and are often based upon accommodations and modifications to curricula or product studies (Ferrell, 2006; Kelley & Smith, 2011; Wild & Allen, 2009). This qualitative study builds upon and replicates a previous pilot study examining the use of 3-D printed models and their relation to conceptual understanding of students with visual impairments; thereby, adding to a growing base of evidence based practices.

Inquiry based instruction has been showed to be effective for students with visual impairments in a variety of science content areas and to benefit students’ conceptual understanding of science concepts. This study adds to growing research base on the effectiveness of inquiry based instruction for students with visual impairments.

Finally, student misconceptions related to plate tectonics is well documented in the literature; however, only one previous small scale study documented the misconceptions held by students with visual impairments. This study will continue the examination of misconceptions held by students with visual impairments and determine whether they are different than misconceptions held by students with typical vision. Moreover, it examined whether those misconceptions are reduced when students are exposed to 3-D models rather than traditional tactile graphics.

Definition of Terms

3-D group – middle school students with visual impairments who are taught plate tectonics using 3-D printed models
3-D printing - is a manufacturing process in which material is laid down, layer by layer, to form a three-dimensional object from a set of digital instructions (Hoffman, 2016)

Conceptual change - a slow, gradual (Vosniadou, 2003) iterative, constructivist process that involves restructuring of prior knowledge (Entwistle, 2007; Vosniadou, 2001) which is heavily influenced by not only the learner’s cognitive processes but also by the cultural and social surroundings (Hatano & Inagaki, 1997).

Legal blindness – central visual acuity of 20/200 or less in the better eye with corrective glasses or central visual acuity of more than 20/200 if there is a visual field defect in which the peripheral field is contracted to such an extent that the widest diameter of the visual field subtends an angular distance no greater than 20 degrees in the better eye (Koestler, 1976, p. 45)

Low vision – a person who has measurable vision but has difficulty accomplishing or cannot accomplish visual tasks, even with prescribed corrective lenses, but who can enhance his or her ability to accomplish these tasks with the use of compensatory visual strategies (Corn & Lusk, 2010).

LP – light perception

Misconceptions – naïve understandings that students bring into the learning situation (Driver and Easley, 1978) and are often deeply held and difficult to change, even when confronted with targeted instruction (Chi & Roscoe, 2002)

NLP – no light perception
Tactile graphics - represent a variety of print illustrations that contain information conveyed in graphic formats and may be produced by a variety of methods using different materials. They accompany textual information to give a tactile representation of diagrams and information presented in print (BANA, 2012).

TG group – middle school students with visual impairments who are taught plate tectonics using tactile graphics.

Theory of Plate Tectonics – the Earth’s outermost layer is fragmented into a dozen or more large and small plates that are moving relative to one another (Kious & Tilling, 1996).

Visual Impairments – any degree of vision loss that affects an individual’s ability to perform the tasks of daily life, caused by a visual system that is not working properly or not formed correctly (Koenig & Holbrook, 2000)
CHAPTER 2: Literature Review

Introduction

The purpose of this qualitative study was to examine students with visual impairments’ conceptual understandings of geoscience concepts and associated misconceptions. The study explored the use of 3-D printed models as an instructional tool in a middle school science classroom for students with visual impairments and compared their use to traditional tactile graphics as a way of representing visual images of geoscience concepts. Specifically, this study examined if the students’ conceptual understanding of plate tectonics is different when 3-D printed objects were used versus traditional tactile graphics. Chapter 2, a review of selected and relevant research is divided into eight sections: conceptual change theory, which is further divided into three sections: changing mental models, constructing mental models, and misconceptions; mental models in geosciences which is further divided into three sections: flawed mental models, mental model building process and student drawings; misconceptions in the geosciences; mitigating against misconceptions which is further divided into five sections: using student drawings, refutation and cognitive conflict, use of analogies and metaphors, use of computer based instruction, other promising instructional practices; implications for classroom practice; science education for students with visual impairments which is
further divided into five sections: historical perspective, visualizing without vision, inquiry-based instruction, tactile graphics, 3-D printing; limitations; and suggestions for future research.

Theoretical Framework

The idea of conceptual change theory has its roots in the work of cognitive and developmental psychology and is heavily influenced by the constructivist learning theories of both Vygotsky and Piaget. Piaget believed that children are not passive learners but active participants in learning - constructing their own knowledge of how the natural world operates by incorporating ideas into previously learned knowledge structures. Vygotsky developed the theory of social constructivism, expanding the meaning of constructivism by adding a social, collaborative element to learning.

Conceptual change theorists have a variety of definitions for conceptual change; however, the theory of conceptual change centers on understanding that students bring naïve views into the classroom and science instruction involves creating learning environments and interventions that will help students move toward a more scientific understanding of phenomena. In the 1970’s, science education researchers began to use conceptual change as a theoretical framework to undergird research in science instructional methods and student learning in the classroom. Much of the early conceptual change research began in the scientific domain of physics but over the decades was applied to all areas of science, as well as mathematics. Hewson and Hewson (1983) describe learning as a change in a student’s conceptions and suggest that there are three important conditions that are necessary for a new idea to be integrated into a
student’s existing framework of knowledge. Those three conditions are that the new idea be intelligible, plausible and fruitful. Therefore, for conceptual change to occur, one must understand the alternative conceptions that the students are bringing into the classroom space.

One of the major thinkers and researchers in conceptual change theory, Vosniadou (2001), describes conceptual change as “a constructivist approach that rests on certain fundamental assumptions that knowledge is acquired in domain-specific, theory-like knowledge structures and that knowledge acquisition is characterized by theory changes” (p. 48). According to Vosniadou (2001), conceptual change involves a restructuring of prior, experiential, and lay cultural knowledge and is a key component in science instructional design. Vosniadou (1999) argues that naïve, alternative frameworks that children develop early in life can hinder later learning in science because scientific explanations are often very different from the ones that children construct from their experiences with real world phenomena. According to Vosniadou et al. (2008), the process of conceptual change is evident, gradual and shows a formation of more sophisticated mental models and a gradual shift away from naïve presuppositions.

Thagard (1992) describes conceptual change as a continuum of degrees from small details to radical leaps in understanding of core concepts. Halldén, (1999) illuminates three processes within conceptual change: 1) replacing naïve conceptions with approved conceptions through direct instruction or reading, 2) providing a new concept or conceptual framework in which the students can interpret their existing
knowledge, and 3) the independent development of a new conceptualization from one’s own experiences and knowledge structures (p. 56).

diSessa (2002) problematizes the thinking of conceptual change by arguing that much of the conceptual change research suffers from too little theoretical accountability and an oversimplified view of the process of conceptual change. diSessa (2002) states that scientific concepts are complex systems, there is not a simple path from naïve conceptual understanding to expert conceptual understanding, and that there are many “complex intermediate states with which teachers have to deal in the classroom” as they guide students toward conceptual understanding (p.30) and argues that “if indeed a concept is in fact a complex system, there is likely no point in the learning trajectory where we can unequivocally decide a person ‘has’ the concept”. This poses difficulty for truly measuring conceptual change because a student’s understanding of a concept may be fragmented but fluid while they are in the process of conceptual change.

Producing conceptual shifts in students poses additional challenges because many of the most difficult concepts for students to understand in science are “complex, dynamic processes” (Chi & Roscoe, 2002). Research by Ferrari and Chi (1998) demonstrate that these complex, dynamic processes are often reclassified as causal processes rather than emergent processes and that students often lack this emergent process category which is one of the factors that precludes them from undergoing true conceptual change and leads to misconceptions that are difficult to change even through the most targeted instruction.
Changing Mental Models

Another view of conceptual change involves changing mental models. Schnozt and Preuβ (1999) describe mental models as “hypothetical internal quasi-objects that hold a structural or functional analogy to another object or scenario” (p. 197) and Nersessian (2008) describes mental modeling as central to conceptual change in science education and cognitive science and recognizes that it is based upon the interaction between an individual’s biology and their learning and interaction within “natural, social and cultural realities” (p. 399). Conceptual change in science is the iterative process of “constructing, evaluating and revising models that exemplify features of the phenomenon” (Nersessian, 2008 p. 410) and the ability to analyze these models is paramount to understanding the process of conceptual change (Vosniadou, 2002). Conceptual change involves a gradual shift toward more complex mental models from naïve preconceptions (Vosniadou, Vamvakoussi, & Skopeliti, 2008) and a naïve mental model is often fragmented, flawed and incoherent (Chi & Roscoe, 2002). Students may possess a flawed, but coherent mental model, making them unaware of their lack of understanding because they can answer questions correctly on a consistent basis but have not achieved deep understanding of a scientific concept, in the manner achieved by a student with a coherent and accurate mental model. In addition, this flawed mental model allows students to make sense of real world events; therefore, they see no need to repair their misconceptions and shift their mental model. When students encounter scientific concepts with a flawed or naïve mental model of that concept, they are unable to reason, problem solve, give explanations or make predictions and do not truly have a deep
understanding of that concept (Chi & Roscoe, 2002; Nersessian, 2008). Additionally, Greca and Moreira (2000) explain that when students encounter conceptual or scientific models in the classroom and attempt to reconcile their mental model with the conceptual model by incorporating the new information into the existing model, they often create a hybrid model or simply memorize the new information to pass an assessment. This does not lead to deep understanding and conceptual change which is problematic for science educators. The concept of naïve and scientific mental models is supported by research with children (Chi, Slotta & de Leeuw, 1994; Vosniadou & Brewer, 1992). According to Chi and Roscoe (2002), flawed mental models can be repaired in two ways: assimilation - new information is embedded into the existing mental model because it is compatible with existing understanding; and revision - new information conflicts with existing beliefs and the incorrect belief is revised. According to Chi (2008), transformation of mental models is necessary for conceptual change and a useful mental model allows the learner to put their knowledge to use (Kuorikoski & Ylikoski, 2014).

Constructing Mental Models

Mental models are highly personalized (Norman, 1983) and incorporate knowledge from a variety of sources including: formal and informal educational experiences, media sources, simulations, or direct experiences with objects (Buckley & Boulter, 2000). Franco and Colinvaux (2000) state that mental models must be generative, synthetic, involve implicit knowledge, and are limited by world-view and experiences of the individual holding the mental model. According to Clement (2008), if a mental model is considered to be a scientific model it must be internally consistent,
precise and plausible. Furthermore, Vosniadou and Brewer (1992) differentiate between three different types of mental models that learners construct: 1) initial models – models based upon everyday observations and experiences, 2) synthetic models – attempts to reconcile initial models with scientific explanations and finally, 3) scientific models – models that agree with the scientific view. Johnson-Laird (1983) describes building mental models as a dynamic process which is never complete because the learner is constantly adding new information to these models, improving them and enlarging them as they are being constructed. These naïve mental models often lead to misconceptions in their understanding of scientific phenomenon, especially if that phenomenon is complex and difficult to observe directly and conceptual change is often thought of as the process of removing misconceptions or repairing them in order to move students toward a truer understanding of scientific phenomena (Hewson, 1981; Posner, Strike, Hewson, & Gertzog, 1982).

Misconceptions

Misconceptions, according to Driver and Easley (1978), refer to the naïve understandings that students bring into the learning situation. These misconceptions, or alternative conceptions are often deeply held and difficult to change, even when confronted with targeted instruction (Chi & Roscoe, 2002) posing major barriers to conceptual change. Additionally, Chi (1992) asserts that difficulties in learning science concepts comes from the understanding that misconceptions are in a different ontological category than scientific conceptions and this requires a fundamental shift in category before learning can take place. For example, coldness could be categorized as a
substance that certain objects possess rather than a process involving the movement of heat energy out of an object. Substances and processes are in two different ontological categories and moving a student from having misconceptions of heat transfer and temperature to a scientific understanding of those concepts is inherent in their difficulty of making the ontological switch. Chi and Roscoe (2002) also believe that many misconceptions occur because students have a flawed or incoherent mental model of a concept. This mental model is quite distinct from the accepted scientific model shared by a community of practitioners, often referred to as the scientific conceptual model (Greca & Moreira, 2000). Finally, these mental models are highly personalized (Norman, 1983) and incorporate knowledge from a variety of sources including: formal and informal educational experiences, media sources, simulations, or direct experiences with objects (Buckley & Boulter, 2000). The misconceptions are often attempts of students to incorporate their everyday experiences as they attempt to construct a more scientific model.

Vosniadou (1999) describes misconceptions as the attempt of children to “synthesize inconsistent and conflicting pieces of information: the information they receive through instruction and their existing beliefs and presuppositions (based on interpretations of everyday experience)” (p.7). Much of Vosniadou’s early research on conceptual change was in children’s concepts of the Earth as it changed throughout their scientific educational experience. She found that children’s initial understanding of the earth was as a physical object, flat, stationary, and stable; however, as they were exposed to the scientific concept of earth in elementary school, they learned that the earth is a
spherical object in space, rotating and orbiting the sun. This new understanding causes both a conflict with their prior understanding and a major categorical shift in their understanding of the earth from physical object to astronomical object, which created several alternative misconceptions. Many major science concepts fall under the category of complex, dynamic processes and research shows that misconceptions abound in such diverse concepts as evolution (Gregory, 2009; Sinatra, Brem & Evans, 2008), climate change (Porter, Weaver, & Raptis, 2012; Rebich & Gautier, 2005; Shepardson, Roychoudhury, Hirsch, Niyogi & Top, 2014), seasonal change (Wild & Trundle, 2010b) and plate tectonics (Ford & Taylor, 2008; Gobert, 2005; Libarkin, 2005; Libarkin et al, 2005; Marques & Thompson, 1997; Sibley, 2005; Smith & Bermea, 2012).

Mental Models in the Geosciences

Research in geoscience education has followed a path through domains such as physics, chemistry and biology by attempting to uncover student’s naïve and unscientific cognitive models as a way of understanding how to move students through the process of conceptual change. Seminal work by Vosniadou and Brewer (1992) found that elementary students experienced changing mental models of the earth as they were confronted with scientific conceptual models during instruction on the earth-sun system. While this work is primarily in the domain of astronomy, the earth-sun system is also traditionally taught in the K-12 earth sciences curriculum. However, more recent research by Nobes and Panagiotaki (2007) challenged the findings of Vosniadou and Brewer (1992), questioning the method used to elicit responses of the students, as well as, the conclusions drawn by the researchers regarding the presence of naïve mental models.
Nobes and Panagiotaki (2007) repeated Vosniadou and Brewer’s study with adults and found that the adults also gave nonscientific answers and drew many of the same types of pictures as the students had drawn (i.e. flat earth or earth as a flattened sphere in which people live on the flat top). The researchers did not believe that these alternative models were reflected in the adults’ drawings due to their lack of knowledge about the shape of the earth; but because the adults were confused by the researchers’ requests and instructions. Based upon these findings with adults, Nobes and Panagiotaki (2007) repeated the study with children and tested Vosniadou and Brewer's original questions against less ambiguous and reworded questions and found significant increases in children's scientific mental models.

Flawed Mental Models

While there are inconsistent results from the previous studies on earth-sun mental models, research does demonstrate that students have flawed and inconsistent mental models in other areas of the geosciences, especially in the areas of plate tectonics and layers of the earth. Smith & Bermea (2012) found that undergraduate students lacked an explanatory mental model that linked plate boundary processes with earthquakes, volcanoes and magma generation which causes misconceptions regarding the effect of plate tectonics on earth processes. By analyzing student drawings, the researchers found that students often displayed a descriptive mental model by correctly drawing arrows to indicate the location of plate boundaries; however, they did not possess a strong explanatory mental model for plate tectonics theory. Explanatory models are much more difficult for students to possess than descriptive models, making abstract concepts such as
plate tectonics rife with student misconceptions (Dolphin & Benoit, 2016; Gobert, 2005; Smith & Bermea, 2012).

Mental Model Building Process

Researchers are also very interested in how students build mental models of geoscience concepts and processes as they progress through the learning cycle and how this relates to misconceptions that they possess. Dolphin and Benoit (2016) studied how students use personal and classroom experiences to build mental models of plate tectonics and earthquakes that are different than scientific conceptual models. They completed a qualitative case study focusing on five undergraduate students by coding the mental model building process of both descriptive and explanatory models. Data from student discourse and written documents were coded as 1) generation mode (student initiated a mental model) 2) accretion mode (student added to previous mental model 3) reduction (student removed aspects of a mental model) 4) competition mode (student actively compared two models of the same phenomenon). The researchers found that most of the student model building happened at the accretion mode and was primarily descriptive rather than explanatory in nature, likely because the students had very little prior knowledge of the concepts being taught and, therefore, were simply adding information to their prior understandings.

In a study examining 5th grade students’ pre-instruction mental models using data collected via one on one interviews, Gobert (2005) found that students had difficulty setting up correct models of the layers of the earth, did not possess an accurate mental model of causal and dynamic processes (i.e. convection currents) and were unable to link
causal and dynamic knowledge to create an integrated system model of plate tectonics. Based upon the findings, Gobert (2005) suggests that to assist students in constructing scientific conceptual models of plate tectonics, they need to be presented with simpler conceptual knowledge first which provides a platform for more complex conceptual knowledge. As an example, she suggests that instructors initially present spatial information (i.e. structure of earth) prior to engaging students in causal processes (dynamic processes in the earth) followed by the plate tectonic processes of mountain building and volcanic eruption. Additionally, she found the use of concentric circles as the spatial layout for the layers of the earth led to students’ ability to revise their model to incorporate an understanding of the causal and dynamic factors associated with plate tectonics.

Student Drawings

In a study by Gobert and Clement (1999), researchers explored the use of student drawings on mental model construction and conceptual understanding by having students create drawings while reading textual information on plate tectonics. One group generated diagrams while reading a two-page expository text passage, while another group wrote a summary of the text and the a third, control group, simply read the text. The researchers found that generating diagrams while reading expository text on plate tectonics promoted richer mental model construction in students.

There is agreement that flawed mental models can produce student misconceptions and it is possible to explore student mental models using student generated diagrams and descriptions (Dankenbring & Capobianco, 2015; Dolphin &
Benoit, 2016; Gobert, 2005; Gobert & Clement, 1999; Sibley, 2005; Smith & Bermea, 2012; Vosniadou & Brewer, 1992). Also, researchers found that student mental models often possess more descriptive features than explanatory features, most likely because explanatory or causal processes are more difficult for students to comprehend due to the abstract nature of many of these processes (Dolphin & Benoit, 2016; Gobert, 2005; Smith & Bermea, 2012). Finally, students’ lack of explanatory models often impedes their understanding of complex geologic systems.

Misconceptions in the Geosciences

Misconceptions abound in many areas of the geosciences and students have considerable difficulty understanding one of its major underlying theories – the theory of plate tectonics. Researchers postulate that the theory is so difficult for students to grasp for several reasons: 1) the process is not observable, 2) the plates move so slowly, 3) convection in the mantle cannot be seen, and 4) radioactive decay as an energy source for plate movement is a difficult concept for students to understand (Dolphin, 2008, Ford & Taylor, 2006; Smith & Bermea, 2012). Many of the common student misconceptions related to the earth’s structure and the theory of plate tectonics are highlighted in the table below.
<table>
<thead>
<tr>
<th>Concept</th>
<th>Misconception</th>
<th>Research Study Cited</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth’s Structure</td>
<td>Crust is on top of the lithosphere rather than part of it</td>
<td>Libarkin, Dahl, Belifuss, &amp; Boone, 2005; Sibley, 2005; Smith &amp; Bermea, 2012</td>
</tr>
<tr>
<td></td>
<td>Asthenosphere and lower mantle are liquid</td>
<td>Kirkby, 2014</td>
</tr>
<tr>
<td></td>
<td>Core of earth is liquid or molten</td>
<td>Dahl, Anderson, &amp; Libarkin, 2005</td>
</tr>
<tr>
<td></td>
<td>Crust floats on a liquid layer called the mantle</td>
<td>King, 2008</td>
</tr>
<tr>
<td></td>
<td>The asthenosphere produces magma rather than the mantle</td>
<td>Smith &amp; Bermea, 2012</td>
</tr>
<tr>
<td>Tectonic Plates</td>
<td>The tectonic plates stack on one another like the layers of the earth</td>
<td>Libarkin et al., 2005; Marques and Thompson, 1997; Ford &amp; Taylor, 2006; AAAS Project 2061, n.d.</td>
</tr>
<tr>
<td></td>
<td>Plates are made of melted rock</td>
<td>AAAS Project 2061, n.d.</td>
</tr>
<tr>
<td></td>
<td>Plates are only composed of crust</td>
<td>Smith &amp; Bermea, 2012</td>
</tr>
<tr>
<td></td>
<td>Tectonic plates are somewhere below the surface</td>
<td>Libarkin &amp; Anderson, 2005</td>
</tr>
<tr>
<td></td>
<td>Tectonic plates and continents are the same thing</td>
<td>Dolphin &amp; Benoit, 2016; Francek, 2013; Kirkby, 2014</td>
</tr>
<tr>
<td></td>
<td>Melting tectonic plates produce magma</td>
<td>Smith &amp; Bermea, 2012</td>
</tr>
<tr>
<td></td>
<td>The tectonic plates never touch one another and are separated by empty gaps</td>
<td>AAAS Project 2061, n.d.; Dolphin &amp; Benoit, 2016</td>
</tr>
<tr>
<td></td>
<td>Oceans are responsible for oceanic crust</td>
<td>Kirkby, 2014</td>
</tr>
<tr>
<td></td>
<td>Plate boundary types are the same thing as a plate</td>
<td>Kirkby, 2014</td>
</tr>
<tr>
<td></td>
<td>Only continents move, not oceans</td>
<td>Kirkby, 2014</td>
</tr>
</tbody>
</table>

Table 2.1 *Common Student Misconceptions*  
Continued
<table>
<thead>
<tr>
<th>Category</th>
<th>Misconception</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tectonics Plates</td>
<td>Continents are on top of the plates or next to the plates but are not part of the plates</td>
<td>AAAS Project 2061, n.d.</td>
</tr>
<tr>
<td>Earthquakes</td>
<td>Earthquakes cause volcanoes</td>
<td>Barrow &amp; Haskins, 1996</td>
</tr>
<tr>
<td></td>
<td>Earthquakes are caused by weather, people, animals, gas pressure, gravity, the Earth’s rotation, volcanoes</td>
<td>Libarkin, Dahl, Belifuss, &amp; Boone, 2005</td>
</tr>
<tr>
<td></td>
<td>Earthquakes happen from the collapse of subterranean hollow spaces</td>
<td>Kirkby, 2014</td>
</tr>
<tr>
<td></td>
<td>Earthquakes only happen at the surface rather than being generated below the surface</td>
<td>Smith &amp; Bermea, 2012</td>
</tr>
<tr>
<td></td>
<td>Earthquakes are not related to plate boundaries</td>
<td>Smith &amp; Bermea, 2012</td>
</tr>
<tr>
<td>Volcanoes</td>
<td>All volcanoes erupt violently</td>
<td>Fries-Gaither, 2008</td>
</tr>
<tr>
<td></td>
<td>Volcanoes only form near bodies of water</td>
<td>Boudreaux et al., 2009</td>
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<tr>
<td></td>
<td>Volcanoes are randomly located across the earth’s surface</td>
<td>Fries-Gaither, 2008</td>
</tr>
<tr>
<td></td>
<td>Volcanoes are not formed at plate boundaries</td>
<td>Smith &amp; Bermea, 2012</td>
</tr>
<tr>
<td></td>
<td>Volcanoes are only found in hot climates and only on land</td>
<td>Fries-Gaither, 2008</td>
</tr>
<tr>
<td>Mountains</td>
<td>Mountains sit on top of rigid plates</td>
<td>Sibley, 2005</td>
</tr>
<tr>
<td></td>
<td>Mountain form when plates push together</td>
<td>Gobert, 2000; Sibley, 2005</td>
</tr>
<tr>
<td></td>
<td>Mountains form by piling up pieces of rock</td>
<td>AAAS Project 2061, n.d.</td>
</tr>
</tbody>
</table>

Table 2.1. Common Student Misconceptions
Similar to their sighted peers, students with visual impairments have described geologic concepts, such as volcanoes, contour and undersea maps, topographic maps and geologic time, as difficult to understand (Jones et al., 2006). Students with visual impairments hold many of the same misconceptions about plate tectonics as students who are normally sighted (Koehler, Tikkun & Wild, 2015) and these misconceptions include plates being stacked and not related to the Earth’s surface, as well as, plates never being joined and gaps existing between the plates (Ford & Taylor, 2006). Some unique misconceptions found in students with visual impairments include, plates floating on the ocean, earthquakes moving with the plates, and volcanoes working together with the plates to cause earthquakes (Koehler et al., 2015).

Militating Against Misconceptions

An avenue of misconceptions research focuses on recognizing and uncovering misconceptions and designing instruction to rectify or refute them (Clement, 2008; Duit, Treagust & Widodo, 2005; Hatano & Inagaki, 1997). Smith and Bermea (2012) state that a primary role of an instructor is to recognize that misconceptions are brought into the learning space and address these rather than assuming that students have previously corrected them. They recommend the need for research into instructional strategies for uncovering and correcting student misconceptions. As stated above, misconceptions are rampant in geosciences education at all levels and are well documented in research, especially in plate tectonics and associated geological processes;
however, research on instructional practices to correct misconceptions is sparse (Kusnick, 2002).

Using Student Drawings

Not only is the analysis of student drawings helpful for uncovering student mental models in science it has also been shown effective at uncovering student misconceptions and addressing them. By having students draw their understanding of a scientific concept, one can quickly point to inconsistencies or flaws in their thinking. The strategy has been used effectively to uncover and confront student misconceptions in geology (Dankenbring & Capobianco, 2015; Dolphin & Benoit, 2016; Gobert, 2005; Gobert & Clement, 1999; Sibley, 2005; Smith & Bermea, 2012; Vosniadou & Brewer, 1992). Sibley (2005) recommends the use of student drawings for uncovering misconceptions and describes three types of misconceptions related to plate tectonics 1) lexical or definition based 2) knowledge based or an explanation of what the theory explains - i.e. how mountains are built and 3) prototype - student drawings do not include characteristic features of expert drawings. Not only did Sibley find these misconceptions in the student drawings, but he also found them in interviews at the end of the research study, indicating they were quite persistent. Smith and Bermea (2012) also recommend the use of student drawings to quickly uncover and refute students’ misconceptions. They suggest that instruction should highlight the evidence for plate tectonics and demonstrate the connection between the plate motions and processes that can be observed, such as earthquakes and volcanoes, to help students build an explanatory model of plate tectonics.
Refutation and Cognitive Conflict

Direct refutation of persistent student misconceptions by contrasting student alternative conceptions with scientific or expert views is a strategy advocated by Clement (2008). He recommends the use of discrepant events by presenting information in the form of experiments, data or demonstrations, to create cognitive conflict, forcing the student to question her/his own model. Cognitive conflict typically involves “evaluating a learner's current knowledge, presenting contradictory information, and then re-evaluating to identify changes in the learner's conceptions” (Rebich & Gautier, 2005 p. 357). Data supporting direct refutation comes from research by Tsai and Chang (2005) involving ninth grade students learning about the reason for the seasons. Students were encouraged to explain their mental model of why seasons occur on Earth and were then confronted with conflicting evidence. Many students initially believed that seasons were related to the distance of the Earth to the Sun (i.e. sun is closer to earth in the summer) but were confronted with discrepant evidence showing that the sun is further from the earth in the summer. Students in the experimental group showed greater long term understanding of the reason for the seasons and the strategy of refutation showed positive results. However, Dega, Kriek and Mogese (2013) caution that cognitive conflict may not be as effective if a student has little or inconsistent knowledge of a concept or if the concept is abstract or complex. Students need to recognize that the new information conflicts with their preconceptions before cognitive conflict can take place.

In another study by McCuin, Hayhoe and Hayhoe (2014), students who read expository passages about the greenhouse effect and climate change that included both
accurate scientific information and common misconceptions showed significantly higher gains in conceptual understanding than students who read passages that only included scientific information. Additionally, the students exposed to common misconceptions also showed delayed post-test gains which may imply a long-term strategy of this instructional practice. The use of cognitive conflict alone is not enough to ensure that students will overcome their misconceptions and should be paired with other knowledge building strategies (Chan, Burtis & Bereiter, 1997).

Use of Analogies and Metaphors

Jee et al. (2010) suggest that the use of analogies as a powerful instructional strategy for teaching both basic and complex concepts to novice learners in the geosciences which helps militate against misconceptions. The analogy of the structure of a peach helps students correct misconceptions regarding the layers of the earth and the 24-hour day as an analogy for helping students understand the basic concept of geologic time are well documented in geology instruction (Jee et al., 2010). It is critical that the analogy be well designed so it does not hinder student understanding. As an example, Dophin and Benoit (2016) suggest that the use of the term “plate” may hinder a student’s construction of a mental model for plate tectonics and lead to misconceptions in novices due to confusion linked to their everyday use of the word “plate”.

Use of Computer Based Instruction

Boudreaux et al. (2009) designed a virtual reality volcano learning environment, called V-Volcano to help repair students’ misconceptions about volcanoes in an undergraduate geology program. The authors recognized that students develop many
misconceptions about volcanoes from popular media sources which depict eruptions in an inaccurate way and the students bring these misconceptions into the classroom. The researchers believe that virtual reality simulations are a promising instructional practice for correcting these misconceptions because virtual reality simulations are engaging and students can manipulate variables, thereby, controlling the simulation as they construct important concept knowledge. Lowe (1999) highlighted the practice of using computer animation to help students build mental models and improve their understanding of large scale systems because they give the student the ability to “construct, test and revise their mental models” (p. 245). Given the connection between flawed mental models and misconceptions which are so prevalent in students at all levels, the use of animation has the potential to be a powerful instructional tool and Cheek (2010) suggests the need for more research into computer animations and 3D images as instructional tools for helping uncover and correct common geoscience misconceptions.

Other Promising Instructional Practices

Dankenbring and Copobianco (2015) explored the effect of the use of an engineering design process as a part of Science Learning through Engineering Design (SLED) with elementary students to reduce misconceptions and facilitate conceptual understanding on the reason for the seasons. While there were no significant differences in the post-test performance of the engineering design group compared to the control group, the researchers found that the treatment group demonstrated a higher frequency of mental models, many of them being accurate and determined that the use of the engineering design process does not necessarily hinder accurate mental model formation;
suggesting the need for future research as an instructional strategy. Kusnick (2002) used narrative stories to uncover student misconceptions about rock formation in preservice elementary teachers in an undergraduate geology course and recommended building constructivist instruction practices to help students uncover their misconceptions through writing activities. Finally, helping students uncover their own misconceptions through metacognitive strategies using group discussion and collaborative learning has been suggested, however, there is no literature to support specific instructional strategies in geoscience education. Collaborative learning practices encourage students to engage in activities that allow them to express their ideas and beliefs, as well as, encounter the ideas of others and as such, is a fertile area for constructivist geoscience pedagogy.

Implications for Classroom Practice

Problems underlying conceptual change are experienced by all levels of students from primary to college level and difficulties making conceptual shifts presents barriers to students’ understanding of science and mathematics. This difficulty is a primary reason why students often struggle with the acquisition of scientific knowledge. One of the major concerns in conceptual change research is the gap between theory and practice in the classroom. Teachers are unaware of research in conceptual change and do not use research based strategies designed to induce conceptual change (Duit, Gropengießer & Kattmann, 2008). Additionally, Duit, Treagust, and Widodo (2005) found that the practice of science teaching in physics classrooms in German and Swiss schools was
primarily transmissive rather than constructivist with students as passive receivers of concepts and facts, which is not facilitative for conceptual change.

Designing a classroom setting that promotes conceptual change is a major goal of science education researchers and there are a variety of research based practices that have emerged over the last decade with this goal in mind. Conceptual change should be designed into the instructional curricula from the beginning, not added on as an afterthought. A classroom that fosters conceptual change would show increased student input, high levels of student reflection and negotiation of scientific meaning. When teaching for conceptual change the teacher’s role becomes more of a facilitator, helping students to collaboratively construct their own knowledge regarding important science concepts. Research by Hatano and Inagaki (2003) discuss the importance of social and dialogic interactions within the classroom, which teachers as facilitators can encourage within the classroom space. This provides opportunities for students to examine their metaconceptual awareness which has been shown to improve conceptual change (Hennessey, 2003; Inagaki & Hatano, 2008). Fostering a classroom climate that motivates students to engage in authentic learning of science through inquiry-based learning or problem based learning may lead to a deeper processing of complex scientific knowledge and lead to conceptual change. Problem based learning or project type approaches often involve more authentic learning environments, giving students agency in the classroom to direct their own learning within the confines of the required science content and could also be a method of utilizing motivational strategies to increase conceptual change. Project based learning offers the student opportunities to complete
“real experiments” and tackle real life issues that can hold more relevance for them; thereby increasing motivation. However, as Pintrich (1999) points out, the use of these authentic tasks, changes the classroom structure and may create challenging classroom management situations for the teacher. Likewise, some students may not have the requisite self-regulatory skills to maintain continued interest and active involvement when they have been accustomed to more task oriented activities. However, with some amount of preparation on the part of the teacher, scaffolding and modeling of positive student behavior and science process skills, problem based learning has the potential to be an important strategy for inducing conceptual change in science.

According to Smith, diSessa and Rochelle (1993), much of the classical approach to conceptual changes focuses only on changing students’ misconceptions and their prior knowledge and ignores productive ideas that may lead to scientific understanding. Also, they encourage researchers to move beyond the sole identification of misconceptions toward a better understanding of the long-term evolution of knowledge systems. Educators need to design curricula to promote conceptual change by planning the sequence of the introduction of concepts to facilitate understanding that is based upon research on narrowing the gap between conceptual leaps (Vosniadou, Ioannides, Dimitrakopoulou & Papademetriou, 2001).

Classroom Talk

The analysis of classroom talk has emerged as a method of uncovering student ideas in science and examining conceptual change. Classroom talk is important because it
allows teachers to support students as they reconcile their views with the scientific viewpoints and allows students to engage consciously in meaning making (Mortimer & Scott, 2000), providing students with the tools to think through scientific views by on their own (Mortimer & Scott, 2003; Scott, 1998). Mortimer and Scott (2003) state that "meaning making can be seen to be a fundamentally dialogic process, where different ideas are brought together and worked upon" (p. 3). According to Mortimer and Scott (2003), there is a direct connection between learning and talking and analyzing classroom talk provides an avenue for determining if science learning is happening and the analysis of student-student dialog helps one determine if internalization of concepts has taken place. Mortimer and Scott (2003) found that scientific language and everyday social language are often quite different and it is not surprising; therefore, that these language differences lead to many misconceptions which are robust and difficult to change. Through their research of classroom talk in science, Mortimer and Scott (2000) found three important features of science social language and describe student utterances as falling into 3 categories:

- **Description** - statements that involve aspects that are directly observable.

- **Explanation** - using a model or a mechanism to account for what is happening.

- **Generalization** - giving an overall description or explanation that is not tied to the particular context of the phenomenon
The examination of these student utterances allows one to categorize student responses as primarily descriptive, explanatory or generalizations and this categorization will provide insight into how students are progressing through conceptual change, examining student mental models and uncovering misconceptions. Morton (2012) recommend the need for a greater understanding of the importance of the role of classroom talk for producing conceptual change in science teaching.

Science Education for Students with Visual Impairments

The field of science education for students with visual impairments lacks a solid research base especially in rigorous, empirical and longitudinal studies. Most research is descriptive in nature, utilizes small sample sizes or a single-subject design. Comprehensive literature reviews demonstrate that empirical studies on students with visual impairments in science are sparse and generally fall into two categories; instructional strategies and curriculum comparisons (Mastropieri & Scruggs, 1992; Rooks-Ellis, D.L, 2014). Simpson, LaCava and Graner (2004) expressed concern over the mandates of No Child Left Behind Act of 2001 on special education teachers and educators, especially those who teach students with severe and low incidence disabilities. Students with visual impairments are considered a low incidence population and many of these students have secondary disabilities including intellectual disabilities. The requirement for randomized group-design methodologies is almost impossible given the low sample sizes and heterogeneous educational settings in which most students with visual impairments are educated (Wild & Allen, 2009).
Historical Perspective

While rigorous, empirical research is lacking, there is an historical base of studies dating back to the early half of the 20th century. Most of these studies report on the laboratory and visual modifications for allowing students with visual impairments to successfully complete introductory college level biology courses (Branch, 1942; Bryan, 1950; Hance, 1936). Each of these studies suggest that multisensory approaches work best for students with visual impairments in science instruction. The large majority of studies and associated journal articles in the latter half of the 20th century expand on the science content areas and their suggested accommodations for laboratory and classroom instruction to include chemistry (Bryan, 1952), physics (Baughman, 1977), and general science (Eichenberger, 1974; Gough, 1979). One empirical study by Franks (1970) reported on the use of adapted measuring devices to teach measurement operations and basic properties of matter to students with visual impairments in elementary and middle school and found that 86% of students successfully performed physical science experiments using the adapted measuring equipment. Another study by Franks (1977) examined the ability of 61 visually impaired, elementary age students to discriminate textures in a pull-apart cell and locate and identify the distinct cell parts and found that 97% of the subjects could discriminate the parts correctly.

Research by Piaget (1970) on students who were blind surmised that they lagged behind their peers with sight in the area of logical reasoning due to the lack of experience with objects in their environment. This research, in addition to prior findings regarding the need for tactile manipulatives and concrete experiences to aid students in learning
important science concepts, ushered in the development of an adapted science curriculum for students with visual impairments - Adapting Science Materials for the Blind (ASMB). These materials were adapted from the Science Curriculum Improvement Study (SCIS), developed by the University of California at Berkeley, and included 12 units in physical and life sciences for use with elementary students. The units, replete with concrete objects and live organisms, were designed to teach both science content knowledge and science process skills, as students conducted their own investigations. The experiential and sequential SCIS curricular materials and the ASMB adaptations were based on current research on the importance of concrete experiences to the learning of science, the learning cycle, and were intended to improve scientific literacy among early learners (Linn & Their, 1975). Numerous studies conducted on these materials throughout the early 1970’s found positive results for experiential learning and a statistically significant increase in concept development in students with visual impairments who had used the AMSB curriculum compared to the control group (Linn, 1972). An additional experimental study by Linn and Peterson (1973) conducted on 15 students with visual impairments showed that the AMSB curriculum had a positive impact on the students’ ability to classify and sort material objects based upon various properties, including the objects’ ability to sink or float. Finally, Linn and Their (1975) found that students with visual impairments including those with multiple disabilities made significant gains in concrete and manipulative areas after completing various AMSB activities, but only students with average to above average ability, as measured by an IQ score, made gains in the science process skills of interpreting the results of experiments. Follow-up studies
continued to demonstrate the efficacy of hands-on, concrete, experiential learning and its positive outcomes for students with visual impairments (Struve, Thier, Hadary & Linn, 1974).

Research on the importance of concrete, experiential learning and the positive research results of the AMSB curriculum led to the development of Science Activities for the Visually Impaired (SAVI) in the early 1980s followed by Science Enrichment for Learners with Physical Handicaps (SELPH) (Keller, Keefer & Keller, 1994). The SAVI/SELPH curriculum, designed for students in grades 4-7, included specially adapted equipment and interdisciplinary, multisensory learning activities that could be used with students with a variety of learning and physical disabilities. Developed by the Lawrence Hall of Science, these nine science modules were designed to give students with visual impairments full access to science learning. Finally, the SAVI/SELPH program led to the development of the Full Option Science System (FOSS) for grades K-8, a hands-on science curriculum that promotes learning through inquiry and is still in use today throughout the country. While FOSS is not specifically designed for students with visual impairments, many of the activities and equipment are identical to those developed for the SAVI/SELPH programs in the 1970’s and are compliant with the principles for universal design for learning (UDL).

Even though students with visual impairments lack the full range of visual stimuli experienced by students with unimpaired vision, they have been found to have the full range of cognitive abilities as their sighted peers (Kumar, Ramasamy, & Stefanich, 2001). Recent, though limited, research into the conceptualizations of students who are
congenitally blind determined that these students were able to formulate mental representations and models of abstract science phenomena even though they have never experienced the concept visually (BÜLBÜL, Garip & Özdemir 2015; Smothers & Goldston, 2009). Smothers and Goldston (2009) reported on a case study of 4 male students who were congenitally blind and found that 2 of the students could form mental representations of microparticulate and macroparticulate views of matter and demonstrated their reasoning through the formation of clay models of matter in the processes of condensation, dissolution, expansion and chemical change. Additionally, they were found to hold similar alternative conceptions as their sighted peers regarding the abstract microparticulate view of matter. BÜLBÜL, Garip and Özdemir (2015) described a case study of 6 congenitally blind students in Turkey and found that these students were able to conceptualize force in a similar manner as their peers with sight and had no difficulty understanding basic physics principles regarding force.

An innovative study that examined the use of haptic technology to help students with visual impairments understand cellular biology was undertaken by Jones, Minogue, Oppewal, Cook and Broadwell (2006). This study explored the efficacy of using a haptic tool to convey cellular concepts to students with visual impairments and to understand if this tool could help students cognize the 3D nature of the animal cell. This tool, the PHANToM, allowed the 21 students in the study to explore the organelles of the cell both visually and by touch. Participants made significant gains in their ability to recall cell parts, could give more information about the cell and used more haptic terms to describe
the cell parts. The use of this haptic technology demonstrates the importance of tactile experiences for students with visual impairments as a pathway for input.

Visualizing without Vision

Typical instruction in the science classroom tends to be very visual with a reliance on diagrams, graphics, demonstrations, videos, and other forms of multimedia; however, little is known about how students with visual impairments interpret and internalize the science concepts that are presented in this way (Jones et al, 2006). In a recent survey study by Koehler and Wild (2016), teachers of the visually impaired (TVIs) reported that lectures, videos, demonstrations, pictures and whiteboard activities were most commonly experienced by their students with visual impairments in the science classroom and that their students were not often included in dissections, microscope work or experiments involving chemical reactions. Additionally, students with visual impairments often have a difficult time with scientific concepts because of this reliance on highly visual instructional strategies (Sahin & Yorek, 2009). Similar to the historical research, much of the current research in the field of the education of students with visual impairments stresses the importance of tactile representations, manipulatives, verbal descriptions, models and laboratory modifications as a way to accommodate students in the highly visual world of the science classroom (Kumar, Ramasamy, & Stefanich, 2001; Rule, 2011; Sahin & Yorek, 2009; Watson & Johnston, 2004). Poon and Ovadia (2008) describe the need for tactile learning aids in organic chemistry for students with visual impairments and make recommendations for use of tactile ball and stick models as well as low tech solutions such as Wikki Sticks © for making tactile representations of organic
molecular formulas. Butler, Bello, York, Orvis, and Pittendrigh (2008) describe the use of “fuzzy DNA”, adapting Legos© by adding various textural elements, to teach concepts in genomics, including gene sequencing and electrophoresis. Using Legos© to teach these important concepts has been researched with sighted students and found to be an effective instructional tool; however, its effectiveness has not yet been examined regarding students with visual impairments.

Adapting science materials for use by students with visual impairments is beneficial for helping students learn important science concepts and improving their success in the science classroom. Rule (2011) found that when students with visual impairments are appropriately accommodated during science instruction they made measurable gains in science content knowledge and expressed very positive attitudes about their ability to do science. In a recent survey study by Koehler and Wild (2016), TVIs reported that the most common adaptations used in science classrooms attended by their students were tactile and hands-on materials, models, verbal descriptions, peer/adult helpers, electronic equipment, pre-teaching concepts and vocabulary, magnification/low vision devices and braille materials. However, there is limited data on whether any of these accommodations are commonplace in the general education science classrooms, in which over 90% of students with visual impairments are served or whether science content is truly made accessible for these students. Wild and Paul (2012) sought to examine the types of practices that were in use in general education science classrooms to make science accessible to students with visual impairments and their study found that most students with visual impairments are being educated according to state science
standards, in the general education science classroom, and are participating in experiments with their sighted peers.

While it is known that general education science classrooms serve as the most common educational setting for students with visual impairments, research indicates that general education science teachers feel inadequate when it comes to meeting the needs of students with visual impairments in their classrooms, have had little to no formal training on important instructional methods, and often hold stereotypical views of students with disabilities (Kahn & Lewis, 2014; Norman, Caseau & Stefanich, 1998). General education teachers in the U.S. are often unaware of the modifications and accommodations needed for students with visual impairments in the science classroom and more professional development in this area is needed (Kumar, Ramasamy, & Stefanich, 2001). Rule et al (2011) shared the results of a year-long program that provided science teachers with adaptive materials for students with visual impairments and professional development, as well. They discovered that the teachers in the program felt more comfortable working with students with visual impairments after the completion of the year-long program and the researchers saw measured improvement in teacher attitudes toward working with students with disabilities and greater teacher willingness to make accommodations in the science classroom to meet student needs. Likewise, when regular educators become more knowledgeable about strategies that are beneficial to students with visual impairments there appears to be increased empathy towards working with these students (Penrod, Haley & Matheson, 2006).
Inquiry-based Instruction

One type of instructional strategy found to be very effective with a wide range of students with disabilities including those with visual impairments is inquiry-based instruction (Hilson, Hobson & Wild, 2016; Koehler, Tikkun & Wild, 2015; Linn & Their, 1975; Mastropieri & Scruggs, 1992; McCarthy, 2005; Palinscar, Collins, Marano & Magnusson, 2000; Rooks, 2009; Scruggs, Mastropieri, Bakken & Brigham; 1993; Trundle, 2008; Wild, Hilson, & Farrand, 2013; Wild, Hobson, & Hilson 2012; Wild & Trundle, 2010a; Wild & Trundle, 2010b).

Inquiry-based instruction helps students understand how science works and to “act and think like a scientist” using the processes of science including: observing, classifying, inferring, measuring, communicating, predicting, hypothesizing, and experimenting. Inquiry-based instruction allows students to take on the role as scientific investigator and develop their own investigations, which may be descriptive, classificatory or experimental (Bass, Contant & Carin, 2009). Through their investigations, students construct their own knowledge about scientific phenomena, building on prior knowledge and experiences.


Students often have limited opportunity to develop understanding because the curriculum, textbooks, and tests emphasize memory and recall. Too much emphasis on memory results in knowledge that is fragmented, incomplete, and tied to specific situations. In contrast, understanding in science must be based in knowledge that is integrated rather than
fragments, that is growing in completeness, and that can be transferred to a wide range of contexts and situations. (p. 63)

Researchers found positive effects on students with disabilities when they were engaged in hands-on and inquiry-based science learning versus textbook based learning (Scruggs, Mastropieri, Bakken, & Brigham, 1993; McCarthy, 2005). Trundle (2008) illuminated various accommodations for inquiry-based activities to enable students with disabilities to participate in these learning experiences. She also explained the importance of creating multisensory formats and collaborative learning environments which encourage student flexibility and build problem solving skills in students with disabilities. Erwin, Perkins, Ayala, Fine, and Rubin (2001) studied an inquiry-based curriculum called Playtime is Science for Children with Disabilities (PSCD) which was adapted for nine students with visual impairments in a residential classroom at a state school for the blind. This qualitative study found positive results for the learning of science concepts, acquisition of science vocabulary, positive peer interaction and meaningful real world connections. Furthermore, they found that the curriculum facilitated student exploration and experimentation, as well as science process skills. Finally, additional support for inquiry-based instruction for students with visual impairments comes from research on middle school students’ conceptual understanding of important science concepts such as seasonal change, geology and sound (Koehler et al., Rooks, 2009; Wild, Hilson, & Farrand, 2013; Wild, Hobson, & Hilson 2012; Wild & Trundle, 2010b). A growing body of research continues to develop showing inquiry-based learning as an evidence based practice for students with visual impairments.
Tactile Graphics

Best practice instruction for students with visual impairments has traditionally called for the use of tactile graphics to replace visual materials; thereby, giving students access to the same content as their typically sighted peers (Zebehazy & Wilton, 2014b). Tactile graphics are raised line drawings of pictures, diagrams, charts, graphs, or “graphics intended to be read principally by touch rather than vision” (Aldrich, Sheppard & Hindle, 2003, p. 284). While guidelines were written by The Braille Authority of North America to standardize the design and production of tactile graphics, variability in production methods of tactile graphics exists from one vendor to another and often the method chosen is not based upon what students prefer, but is based upon cost or ease of production (Smith and Smothers, 2012). Research shows that tactile graphics are often difficult for students to comprehend, (Bolt & Thurlow, 2004) and require much concentration, time and practice (Andréou & Kotsis, 2005; Kamei-Hannan, 2009). Bolt and Thurlow (2004) also indicated that student conceptual understanding might not be indicative of their ability to read a tactile graphic.

Standardized assessments in braille contain a multitude of tactile graphics which pose problems for students with low vision or no vision because they are only seeing a piece of the diagram or graph at one time and they do not get “the big picture”, whereas students with typical vision can see the “big picture” at once. In a series of investigations of tactile recognition of embossed pictures by students who were blind, researchers found that two dimensional outlines of common objects held some value to the students but three dimensional designs representing perspective in a two-dimensional drawing had no
real meaning for blind students (Merry, 1932; Merry & Merry, 1933). Tactile graphics are often absent in science textbooks and when they are present, can pose difficulties for students with visual impairments, as they can be lacking in detail and quality (Zebehazy & Wilton, 2014a; Zebehazy & Wilton, 2014c). When tactile graphics are absent, students often rely on verbal descriptions of the diagram or graph given to them by an adult or peer in the classroom and often request a description even when tactile graphics are present (Zebehazy & Wilton, 2014c). The lack of access to tactile graphics in daily instruction robs the student with visual impairments of the ability to practice a skill they have been expected to master in order to access important content on a standardized test, which puts them at a definite disadvantage. Additionally, teachers of the visually impaired report that they often have difficulty finding the time to teach students how to read a tactile graphic (Zebehazy & Wilton, 2014a). It is unclear whether a raised line drawing, read principally by touch is truly giving the student with visual impairments access to important information that is typically conveyed through a diagram or picture. According to a study by Zebehazy and Wilton (2014b), students with visual impairments also reported that tactile graphics did not greatly aid their understanding of many concepts, especially if the tactile graphics were too complex or contained too many details. The students believed that tactile graphics were most helpful in math and science but that it would be beneficial to have a short description and other textual support along with the tactile graphic (Zebehazy & Wilton, 2014b). Concerns regarding the difficulty of students to read and interpret tactile diagrams, especially those attempting to convey concepts of scale or 3-dimensional views of an object, has been discussed by researchers

3-D Printing

An exciting area of research is developing in the field of 3-D printing and its impact on learning for students with visual impairments. Researchers have suggested that 3-D printing may hold promise for students with visual impairments in addressing concept development and providing access to visual information (Horowitz & Schultz, 2014; Horvath & Cameron, 2016; Jo et al, 2016; Koehler, Tikkun, & Wild, 2015; Rosenblum & Herzberg, 2015). Two small scale studies, recently conducted, examine the impact of using 3-D printed objects with students with visual impairments in core content areas. The first was a pilot study by Koehler et al (2015) to examine the effectiveness of using 3-D printed models to teach geosciences concepts to middle school students with visual impairments. The four students in the study had access to either 3-D models or tactile graphics displaying important geoscience concepts and the students’ conceptual understanding was measured before and after a 3-week instructional unit on plate tectonics. All but one student showed an increase in scientific understandings of the geologic concepts as evidenced by the post assessment and there was a greater gain in scientific understanding in the group who had access to the 3-D models compared to the group who had access to the tactile graphics. While this study has limitations due to the small sample size, it provides preliminary information about the potential promise that 3-D printing may hold on improving conceptual understanding for students with visual impairments.
The second study, conducted by Jo et al (2016), examined the use of 3-D printed historical maps and relics in a Korean school for the blind. Four elementary students explored these 3-D printed objects while receiving instruction during a semester long history class. Upon completion of the semester, survey results indicated that students highly valued the use of the 3-D objects and believed that they aided their memorization and understanding, as well as adding an interesting element to their classroom learning. According to the survey results, the teachers in the study also felt that the 3-D printed models had a positive learning effect on the students and the models enabled students to grasp concepts in a way that was superior to simply providing a verbal description. While this study had no control group and was limited by its sample size, it adds to the developing body of research that examines 3-D printing as an emerging best practice for content area instruction for students with visual impairments.

Conclusion

While there is a long history of research in the field science education for students with visual impairments much of it involves small sample sizes and describes instructional strategies or making accommodations to existing practice for students without visual impairments. Very little research exists that describes how students with visual impairments may understand science concepts differently because of their lack of vision or unique misconceptions that may exist related to geoscience concepts. Likewise, the research that has been done on the use of tactile graphics as an instructional tool for increasing access to visual materials indicates that students do not always have access to them and when they do, tactile graphics may not give them adequate information to
visual content. 3-D printed models may be a superior alternative to tactile graphics to aid in student conceptual understanding; however, almost no empirical research has been done now.

A review of the literature documents that conceptual change theory forms the basis of research in the field of science education but it suffers from little theoretical accountability (diSessa, 2002) and much of the research has not been replicated. Additionally, the majority of the research involves pre/post design which does not measure where, in the complicated process of conceptual change, a student’s understanding may lie. Conceptual change theory involves the study of student misconceptions, and many of these misconceptions have been discovered in the domain of geosciences, however, little research involves militating against these misconceptions in order to produce conceptual change. Likewise, research into the possible unique science misconceptions of students with visual impairments is sparse which limits the ability to inform instructional practice.

Instructional practices that have shown promise in science education for students with visual impairments include inquiry-based instruction (Hilson, Hobson & Wild, 2016; Koehler, Tikkun & Wild, 2015; Linn & Their, 1975; Mastropieri & Scruggs, 1992; McCarthy, 2005; Palinscar, Collins, Marano & Magnusson, 2000; Rooks, 2009; Scruggs, Mastropieri, Bakken & Brigham, 1993; Trundle, 2008; Wild, Hilson, & Farrand, 2013; Wild, Hobson, & Hilson 2012; Wild & Trundle, 2010a; Wild & Trundle, 2010b), hands-on, concrete experiential learning (Struve, Thier, Hadary & Linn, 1974), use of tactile models and experiences (Kumar, Ramasamy, & Stefanich, 2001; Rule, 2011; Sahin &
Yorek, 2009; Watson & Johnston, 2004) and making appropriate accommodations to visual materials (Robinson & Ross, 2000; Rule et al, 2011).

There is a dearth of empirical research in the field of education for students with visual impairments and federal mandates, including IDEA and ESSA call for more rigorous, empirical studies that can be replicated to demonstrate that a practice is indeed research based. While there are a number of online resources, handbooks and even a foundational textbook discussing instructional methods and strategies for students with visual impairments in science, the almost 100-year research base is quite thin. It is clear there is a great need for more empirical research in this field in order to determine if what appears anecdotally about how students with visual impairments learn science is supported by research.
CHAPTER 3: Methodology

Introduction

The purpose of this qualitative study was to examine students with visual impairments’ conceptual understandings of geoscience concepts and associated misconceptions. The study explored the use of 3-D printed models as an instructional tool in a middle school science classroom for students with visual impairments and compared their use to traditional tactile graphics as a way of representing visual images of geoscience concepts. Specifically, this study examined if the students’ conceptual understanding of plate tectonics was different when 3-D printed models were used versus traditional tactile graphics. This study helped to inform evidence based instructional practices in science for students with visual impairments and added to the call for research based practices mandated by federal legislation.

Data was collected one week prior to and one week after instruction, as well as during the 3-week instructional period. This chapter outlines the qualitative research methodology used in this study and is divided into six sections: description of study participants, setting, methods, data collection, data analysis, reliability and validity.
Participants

Students

All students in the middle school classroom (grades 7 and 8) at the specialized school for the blind were asked to participate, but only those who agreed to participate and obtained parental consent were videotaped and interviewed; however, all students received instruction. The five students participating in the study were placed into either the tactile graphics group or the 3-D group with an attempt to have roughly equal numbers of students in each group. An attempt was made to equalize the groups by gender, additional disabilities, academic ability and level of visual impairments; however, there is an understanding that there were differences among the students in the two groups. Attempting to equalize the groups based upon those factors lends validity and reliability to the findings of the research (Fraenkel, Wallen & Hyun, 2015). I provided instruction to each group of students for 42 minutes per day in the same science classroom, but during two different class periods to ensure that the 3-D group only had access to 3-D printed models and the tactile graphics group only explored tactile graphics.

The five students participating in the study were placed into each group as shown in Table 3.1 below. The 3-D group contained three eighth grade students, two females and one male. Both females were large print readers and the male was a braille reader. Their academic abilities in math and English language arts varied, as evidenced by their most recent standardized assessment scores, however, all students in this group received proficient or accelerated scores on their 5th grade standardized achievement
assessment. The tactile graphic group contained one eighth grade student and one seventh grade student, one male and one female. One of the students was a braille reader and the other student was a large print reader. The academic abilities in math and English language arts were varied in this group as well, as evidenced by their most recent standardized assessment scores, however, the students received proficient or advanced scores on their 5th grade standardized achievement assessment.

<table>
<thead>
<tr>
<th>Student Number</th>
<th>Grade</th>
<th>Gender</th>
<th>Reading Media</th>
<th>Standardized Achievement Levels</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Math</td>
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<tr>
<td>3-D Group</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td>M</td>
<td>Braille</td>
<td>Proficient</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>F</td>
<td>Large Print</td>
<td>Limited</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>F</td>
<td>Large Print</td>
<td>Basic</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>M</td>
<td>Large Print</td>
<td>Limited</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>F</td>
<td>Braille</td>
<td>Basic</td>
</tr>
</tbody>
</table>

Table 3.1. Student Demographics
All students were taught lessons from the “Plate Tectonics: The Way the Earth Works” (Cuff, Carmichael, & Willard, 2002) from the Great Explorations in Math and Science series from Lawrence Hall of Science. This series uses inquiry-based methods to teach students science concepts. Inquiry-based methodologies have been found to be effective in helping students with visual impairments learn science concepts (Hilson, Hobson & Wild, 2016; Koehler, Tikkun & Wild, 2015; Linn & Their, 1975; Mastropieri & Scruggs, 1992; McCarthy, 2005; Palinscar, Collins, Marano & Magnusson, 2000; Rooks, 2009; Scruggs, Mastropieri, Bakken & Brigham; 1993; Trundle, 2008; Wild, Hilson, & Farrand, 2013; Wild, Hobson, & Hilson 2012; Wild & Trundle, 2010a; Wild & Trundle, 2010b). All students were taught the same curriculum; however, one group of students received tactile graphics demonstrating specific science concepts from the American Printing House’s Basic Science Tactile Graphics Curriculum or teacher-made tactile graphics and the other group of students received 3-D printed models of the same science concepts. Each group of students was taught during separate time periods in the day. The teacher made tactile graphics were produced using specialized paper and a device called Pictures in a Flash (PIAF©). The 3-D printed models were designed by a fellow doctoral candidate and certified teacher of the visually impaired from the University of Northern Illinois. I provided science content input to him, indicating the major concept that the 3-D model should depict and he provided the computer aided design and 3-D printing expertise. The models were successfully utilized in a previous research study examining the conceptual change of students with visual impairments related to geoscience concepts (Koehler et al., 2015). Upon completion of the research
study, students in both groups had the opportunity to explore the 3-D printed models and the tactile graphics to ensure that no student was left out of a potentially important learning experience.

The Researchers

In this research, I acted as the primary researcher and instructor in the classroom. I am a certified teacher of the visually impaired and a certificated middle school and high school science teacher with 27 years of experience teaching science to students with visual impairments. The research study took place in my own middle school science classroom and was conducted with students whom I have been teaching for either one or two years. In addition to serving as the instructor, I coded and analyzed the data as described in the data analysis section in Chapter 3. The pre and post interviews were conducted by a co-researcher and fellow doctoral student from The Ohio State University, who is also a certificated science teacher. As a doctoral student in the STEM education program and she brought expertise in content, middle school science pedagogy and prior research experience to this study. By having another researcher conduct the interviews, I had no prior knowledge of how students responded to the pre or post interview questions; therefore, there was no influence on either my instructional decisions or my analysis of the data.

Setting

School Setting

The inquiry-based instruction and data collection was conducted at a Midwestern specialized school for the blind. The specialized school for the blind has been in
continuous operation for over 175 years and the school is operated through appropriations from state government and supplemental federal funds.

Per the most recent annual report, this school serves more than 100 students, with approximately 43% of them residing within the county limits and the other 57% residing in one of 34 other counties. Many of the students who attend the school are visually impaired and have additional disabilities including learning disabilities or mild intellectual disabilities. Approximately 28% of the students have multiple disabilities including severe to profound intellectual disabilities. The racial makeup of the school is as follows: 72% white, 20% Black, 5% Asian, 2% Hispanic, and 1% Multi-racial. 56% of the school population is male and 44% are female (Annual Report, 2012). The most recent graduating class included 13 students with 62% planning to attend college or post-secondary education, 15% planning to enter the workforce and 23% planning to transition to supported employment.

Classroom setting

The science classroom is located on the second floor of the school and is a new, state of the art, science lab equipped with six classroom tables arranged in a u-shape which can accommodate two students per table and two large laboratory benches at the rear of the classroom each containing a sink, two methane gas and two compressed air outlets. Along the north facing wall is a long, wall mounted table with five computer stations and an electronic video magnifier, as well as braille writers, braille and large print paper and a large bookshelf with braille, large print, science tactile graphics and other accessible materials. On the south wall is an emergency shower, eyewash station,
an additional lab sink and storage cabinets for the multitude of science supplies. On the east wall is the teacher’s desk, another bookshelf with science materials, a whiteboard and screen for a projection unit and a full size periodic table. On the west wall are additional storage cabinets, a full-size fume hood for chemical experiments and a door leading to a large chemical storage and teacher prep room.

Methods

Denzin and Lincoln (2000) generically define qualitative research as “a situated activity that locates the observer in the world and involves an interpretive, naturalistic approach to the world” (p. 3). Qualitative research aims to describe in detail what is going on in a situation or activity and occurs in a natural setting, not in a laboratory setting. Qualitative methodologies provide the researcher with thick descriptions, rich with detail (Denzin & Lincoln, 2000) and are well suited to research in the classroom.

Examining student learning through the theoretical lens of conceptual change can give researchers insight into how to design and modify instruction to help students move from naïve understandings to more scientific understandings. Qualitative research offers the researcher a wide variety of data collection tools including observation, surveys, interviews, content analysis, audiovisual methods, spatial mapping, etc. (LeCompte & Schensul, 1999), which are well suited to the classroom or school setting. These data collection methods could help the researcher identify points at which students are making progress towards conceptual change.

Teacher Research
This research study sought to improve instructional practice for students with visual impairments and to determine whether 3-D printed models are effective as an instructional tool for improving conceptual understanding in the science classroom. As such, teacher research provides a unique qualitative research method available to classroom teachers or practitioners to examine and improve their own practice or solve a problem within a particular setting. If the researcher is a teacher and the goal of the research is to improve pedagogy or address a problem in their own practice, then this action research is typically referred to as teacher research (Fraenkel, Wallen & Hyun, 2015). According to Goswami and Rutherford (2009), teachers have a unique position as researchers because of their emic perspective. As a qualitative research method, teacher research allows teachers to “transform their teaching in important ways because they become theorists who articulate intentions, test assumptions and find connections with practice” (p. 3). As both the researcher and instructor in this middle school classroom, teacher research provided a method of analyzing what was going on in my own classroom to help improve my own instructional practice.

Participant Observation

Participant observation requires the researcher to be in the setting with the participants, actively recording the day to day activities, to learn about the interactions, actions, behaviors and cultural knowledge of the research participants (Schensul & LeCompte, 2013). As the researcher engaged in participant observation, I immersed myself in the classroom setting, acting as the instructor, to get a sense of the participants’ realities as they engaged in activities that promote conceptual change. Inherent in the
qualitative research paradigm is the concept of reflexivity, the sharing of biases, beliefs, experiences and background of the researcher and the realization that these beliefs and biases shape the interpretation of the research (Creswell, 2016). Acting as both instructor and researcher, the uncovering and reporting of biases is extremely important. The unique role of instructor and researcher gave me an emic perspective which helped me recognize important significances in the data and better recognize outliers that existed in the data; however, it was critical for me to be cognizant of the issues concerning objectivity and naïve realism as expressed by Agar (2013). As the previous instructor of the students in this study, I had prior knowledge of the students and a relationship with them that an outside researcher would not have. As such, it is important to recognize and state those biases that my unique role presented and attempt to mitigate those biases by designing data collection and analysis techniques that promoted objectivity and transparency.

Data Collection

Methods of data collection are varied in conceptual change research and often involve some form of pre/post assessment. The use of structured interviews is a commonly used qualitative data collection tool (Creswell, 2007) and has been used in conceptual change research in science with students as a pre/post assessment bracketing a period of instruction (Hilson et al., 2016; Koehler, et al., 2015; Wild, Hilson & Farrand, 2013; Wild, Hilson & Hobson, 2013; Wild & Trundle, 2010b). The co-researcher, mentioned previously, who is trained in qualitative research methods and is a certificated science teacher, conducted two structured interviews composed of a fixed set of questions
designed to elicit certain responses from the participants (Fraenkel et al., 2015). The pre-
interview took place at least 1 week before instruction and the post interview took place
at least 1 week after instruction. The researcher asked the questions exactly as stated in
the interview protocol and asked for clarification if the student response was unclear.
The researcher could also repeat student responses back to them for clarification or ask
additional probing questions to elicit more detail, such as “what do you mean by that” or
“can you tell me more” or “is there anything else you would like to add” or “can you
explain that in more detail”; however, the researcher said nothing that could influence the
student’s response. The same set of questions was asked during the pre and post
interviews and video recorded for later transcription and coding to aid in determining if
student conceptual change had occurred over the instructional period. The interview
questions, vetted by an expert in visual impairments, and shaped by a previous research
study (Koehler et al, 2015) were based upon core concepts in geoscience from the Next
Generation Science Standards (Achieve, 2013) and the learning objectives from “Plate
Tectonics: The Way the Earth Works” (Cuff et al., 2002) from the Great Explorations in
Math and Science series from Lawrence Hall of Science (see appendix A for interview
questions).

This interview protocol, composed of open-ended questions, developed by
Trundle (2002) has been used to measure science conceptual change in both students and
preservice teachers (Koehler et al., 2015; Hilson et al, 2016; Ucar, 2007; Wild, Hilson &
was interviewed individually by the co-researcher in a secure location. The remaining
students were monitored by me to ensure that they did not communicate about the content of the interview questions.

Field notes are critical tools of any qualitative research and are typically recorded observations of any kind that are made in the field (Schensul & LeCompte, 2013). According to Schensul and LeCompte (2013), the main task of field notes is to record as accurately as possible the behaviors, conversations, processes, and institutional structures that unfold in the presence of or manifest themselves to the researcher. As such, field notes were taken after each student interview and after each instructional day, providing a source of data for analysis to help the researcher examine the process of student conceptual change. The field notes helped highlight behaviors or conversations in which students were expressing misconceptions or that indicated difficulty or success reconciling naïve understandings with scientific understandings.

Due to my role as the instructor during the three-week period, it was impossible to complete field notes as instruction was taking place; therefore; a secondary data collection method was employed to capture interactions and conversations as they happened. All classroom instruction was audiotaped and analyzed for student discourse indicating progress toward conceptual change (Batista, 2007) and scientific ways of thinking (Mortimer & Scott, 2003; Scott, 1998). Classroom talk is important because it allows students to reconcile their views with scientific viewpoints and engage in meaning making, through dialogic interaction with the teacher and each other (Mortimer & Scott, 2003; Scott, 1998). Examining student discourse during instruction, allows the one to examine increased student use of scientific language, student mental model construction,
as well as, language indicating the continued presence of student misconceptions. As students begin to use new scientific language in classroom talk, they often appear uncertain and faltering in their use of the language because the idea has not become fully internalized; however, as the scientific concepts become more internalized, students are able to articulate these new scientific ideas more fluently (Mortimer & Scott, 2003).

Additionally, the audiotapes served as a check on the consistency of instruction between both groups of students.

Photographs of students were taken during the instructional period to show students interacting with the 3-D printed models and tactile graphics. Only students participating in the study were in the frame of the photograph and students without written permission to participate in the study were placed outside the frame. If a student without parental permission inadvertently appeared in the photo, this was erased from the device taking the photo.

Lastly, the use of student journaling has been documented as a data collection method to help researchers understand conceptual change in preservice teachers and document misconceptions (Trundle, 2002; Ucar, 2007). The students documented all work in a geologic notebook as a part of the inquiry-based lessons and journaled their understanding of targeted science concepts at designated points during instruction.

The 3-week instructional unit contained four lessons in which students engaged in an inquiry-based curriculum called “Plate Tectonics: The Way the Earth Works” including teacher led discussions and hands-on activities designed to provide students with an understanding of the theory and study of plate tectonics (Cuff et al., 2002).
These lessons, adhere to national science standards and place the students in the role of scientists conducting geologic studies around the world. The lessons help students generalize what they learn at multiple field sites and apply those findings to the unifying theory that underlies various geosciences phenomena. The instructional unit is broken up into four sessions covering the topics of geologic time and processes that form the earth’s crust; faults and their relationship to earthquakes; shield and stratovolcanoes and their relationship to viscosity and temperature of magma; and the distribution of earthquakes and volcanoes around the world and their relationship to tectonic plate boundaries. Appendix B includes more detailed information about the curriculum, standards and methods of adaptation used in this research study and Appendix D includes the actual adapted curriculum. As a certified teacher of the visually impaired, I adapted these lessons using best practices from the field (Hoffman & Kitchel, 2006; Koenig & Holbrook, 2000) and the lessons were successfully used in a previous research study with middle school students with visual impairments (Koehler et al., 2015).

Data Analysis

The coding of the qualitative data followed a typical qualitative analysis protocol, including transcription of audio and video data. Transcription allowed for in-depth understanding of what was happening during the interviews and supplements field notes and participant observations, substantiating themes and patterns that develop during data analysis. As the primary researcher, I transcribed all audio and video data and made notes in the margins indicating potential responses that might be coded.
Coding and analysis of data can take many forms in qualitative research; however, the constant comparative analysis method has proven to be an effective method of analysis for conceptual change research. The constant comparative analysis method described by Bell and Trundle, (2008) and Trundle, Atwood, and Christopher (2002, 2007a, 2007b) was used in this research study. This analysis method has been used in various science content areas (Adadan, Trundle & Irving, 2008; Bell & Trundle, 2008; Ucar, Trundle & Krissek, 2007), as well as in previous conceptual change research with students with visual impairments (Koehler et al. 2015; Hilson et al, 2016; Wild, Hilson & Farrand, 2013; Wild, Hilson & Hobson, 2013; Wild & Trundle, 2010). Constant comparative analysis (CCA) is a process of analyzing data via recoding that is most closely associated with grounded theory (Glasser & Strauss, 1967). CCA begins with open coding to develop categories followed by a recoding which prompts core categories to emerge (Charmaz, 2001; Glasser & Strauss, 1967; Strauss, 1987). Constant comparison involves the repeated analysis of data and examining new data in light of emerging categories and patterns until the categories become saturated – meaning that new data easily fits into one of the previously designated categories and helps bolster the validity of a qualitative study.

Boeiji (2002) used CCA as a method of analyzing interviews for comparing data collected within a single interview, between interviews in the same group and between interviews of different groups. Boeiji (2002) began by using open coding on a line by line basis in each interview to determine what had been said and to code each answer. The aim for this first level of comparison was to develop coding categories that were
appropriately labeled. The second level of comparison was between members of the same group in which axial coding was performed. The aim of this step was to make sure that similar ideas were coded the same way and to further conceptualize the subject. The third level of comparison was between interviews of members of different groups. The aim of this level of comparison was not to develop new codes but to get a deeper understanding of the data. As Boeiji’s research centered on married couples, the fourth and fifth levels of comparison involved comparisons between couples in one group and couples in different groups and is inappropriate for classroom research. However, the five levels of comparison have been modified for use in conceptual change research by Ucar (2007) and were useful for analyzing data gathered from pre/post interviews, transcripts of student dialog during instruction, and student journals. Ucar (2007) modified Boeiji’s five levels of comparison shown in Table 3.2 below:

<table>
<thead>
<tr>
<th>Comparison</th>
<th>Aim of Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data from a single interview are compared to the coding scheme</td>
<td>To verify the consistency of answers, to code the transcripts, and to add new codes</td>
</tr>
<tr>
<td>Codes are compared within each interview</td>
<td>To categorize participants based on their conceptual understanding</td>
</tr>
<tr>
<td>Comparisons are made between the participants’ interviews to determine the types of conceptual understanding</td>
<td>To summarize overall conceptual understanding categories with percentages per interview group</td>
</tr>
</tbody>
</table>

Table 3.2. *Five levels of comparison for the analysis of qualitative data (Ucar, 2007)*

68
Table 3.2 continued

Comparisons are made between the conceptual understandings before and after instruction within each group to distinguish conceptual change.

Comparisons are made between each group to distinguish any similarities or differences in conceptual change.

Table 3.2. *Five levels of comparison for the analysis of qualitative data (Ucar, 2007)*

Prior to analyzing the coded data, a general coding framework was developed. This initial coding framework was developed through a thorough literature review to determine scientific understandings of the targeted science concepts, common student misconceptions or alternative conceptions, as well as categories of misconceptions. Additional resources used to develop the coding framework included content experts, federal and state curriculum standards and well established science textbook sources.

The coding framework; however, was flexible enough to allow for the addition of codes that emerged from the data. Once the coding framework was established, the transcript data was coded using the five levels of comparison developed by Ucar (2007). The initial coding framework was used to analyze student journals and classroom talk during instruction to gain a deeper understanding of progress toward conceptual understanding or persistent misconceptions that exist throughout the instructional phase.

Another phase of analysis was to develop categories of understanding based upon the work of Trundle et al (2007a, 2007b) which divides conceptual understanding into
seven major categories: scientific, scientific fragments, scientific with alternative fragments, alternative with scientific fragments, alternative, or no understanding.

The categorization of understanding has been used previously in a variety of conceptual change studies in multiple science content areas (Adadan et al., 2008; Bell & Trundle, 2008; Trundle, Atwood & Christopher, 2002, 2007a, 2007b; Ucar et al., 2007) and has been used in science conceptual change research with students with visual impairments (Koehler et al.; Hilson et al, 2016; Wild, Hilson & Farrand, 2013; Wild, Hilson & Hobson, 2013; Wild & Trundle, 2010). This allows the researcher to categorize individual student understanding to determine the level of conceptual change that has occurred during the instructional period and compare this from individual to individual and group to group.

This coding method was used on the four interview questions that most directly related to the unifying concept of plate tectonics and its relationship major earth processes including earthquakes and volcanoes. Not only was this concept the focus of the three-week instructional unit, but it is also one of the crosscutting concepts for middle school science as evidenced by the Next Generation Science Standards. Table 3.3 below demonstrates how the coding criteria was developed for each of the categories of conceptual understanding.
### Types of Conceptual Understandings and Criteria for Identification of Student Understanding

<table>
<thead>
<tr>
<th>Types of Conceptual Understandings</th>
<th>Criteria for Identification of Student Understanding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scientific Understanding</td>
<td>Student answer agrees with accepted scientific understanding and contains all components (see table for criteria)</td>
</tr>
<tr>
<td>Scientific Fragments</td>
<td>Student answer is based on accepted scientific understanding but is not complete and contains no alternative understandings</td>
</tr>
<tr>
<td>Scientific with Alternative Fragments</td>
<td>Student answer contains all the elements of the scientific understanding but also contains at least one alternative conception</td>
</tr>
<tr>
<td>Alternative with Scientific Fragments</td>
<td>Student answer contains mostly alternative conceptions but also has at least one scientific fragment</td>
</tr>
<tr>
<td>Alternative</td>
<td>Students answer does not agree with accepted scientific understanding</td>
</tr>
<tr>
<td>No Understanding</td>
<td>Student shows no evidence of understanding the concept</td>
</tr>
</tbody>
</table>

Table 3.3. *Types of conceptual understandings and criteria for identification (Trundle et al., 2007a, 2007b)*

In order to determine the accepted scientific understanding for each question, I utilized scientific sources such as the disciplinary core ideas from The Next Generation Science Standards (Achieve, 2013), as well as content from Ohio’s Learning Standards (2011) and Plate Tectonics: The Way the Earth Works” (Cuff et al., 2002). Table 3.4 below shows the criteria for an answer to be coded as a scientific understanding for each of the four questions related to plate tectonics.
<table>
<thead>
<tr>
<th>Question</th>
<th>Scientific Understanding</th>
</tr>
</thead>
<tbody>
<tr>
<td>What processes cause major changes in the earth’s surface?</td>
<td>Student description must include more than one of the following:</td>
</tr>
<tr>
<td></td>
<td>• Plate movement</td>
</tr>
<tr>
<td></td>
<td>• Earthquakes</td>
</tr>
<tr>
<td></td>
<td>• Volcanoes</td>
</tr>
<tr>
<td></td>
<td>• Erosion</td>
</tr>
<tr>
<td></td>
<td>• Glacial movement</td>
</tr>
<tr>
<td></td>
<td>• All processes must be natural not manmade (Achieve, 2013)</td>
</tr>
<tr>
<td>What is the relationship between tectonic plates and these earth processes that cause major changes in the earth’s surface?</td>
<td>Student must mention that the plates move and generate these earth processes but do not need to describe how they move.</td>
</tr>
<tr>
<td>What can you tell me about the relationship between tectonic plates and earthquakes?</td>
<td>Student must mention that the plates move, and also demonstrate how they move, either through an explanation or by showing with hand movement.</td>
</tr>
<tr>
<td>Can you describe the relationship between tectonic plates and volcanoes?</td>
<td>Student must mention that the plates move and demonstrate how they move, either through an explanation or by showing with hand movement.</td>
</tr>
</tbody>
</table>

Table 3.4. *Criteria for Scientific Understandings*

In addition to CCA as a method of analysis, analyzing field notes and writing conceptual memos to highlight themes or patterns that emerge from the data sources was used in this research study because this enhances the researcher’s ability to describe what is going on in the classroom as students engage in knowledge construction (Heath & Street, 2008). Heath and Street (2008) recommend the use of conceptual memos or analytic memos to reflect on data collected at regular intervals which may contain generic
ideas or queries that have been placed in the reflection column of field notes. The process of analyzing data in this way is iterative and often leads the researcher to review additional literature to theoretically ground the themes and patterns that emerge.

Reading, re-reading and reflecting on the data often leads one to uncover “rich points” which can lead to further analysis and new lines of investigation (Agar, 2013). As themes began to emerge, I went back to the data sources to identify examples that supported those themes; which could involve student discourse, journal entries, photos, student drawings or any other source of data collected. These analytic memos then formed the basis of the assertions or results that emerge from the qualitative data.

Qualitative research is an inductive research paradigm which does not seek to test theory but allows theory to emerge as the researcher interacts with and interprets the data; and analytic memos and assertions are important parts of the interpretive process.

Validity and Reliability

In qualitative research, validity is determined by whether the findings are plausible or believable, based upon the data that is collected. Qualitative research has historically been attacked by more positivistic researchers because it does not adhere to the canons of reliability and validity inherent in the quantitative research paradigm (Schensul & LeCompte, 2013). Reliability refers to the dependability of the research (Lincoln & Guba, 1985) and validity equates to the trustworthiness and defensibility of the research (Golafshani, 2003). In order to measure and analyze conceptual change and generate findings that were both valid and reliable, the researcher used the following methods: triangulation, disconfirming evidence, and prolonged engagement to ensure
validity; and intercoder agreement to ensure reliability. Triangulation of multiple data sources took place during the analysis of interview transcripts, field notes and audio transcripts, etc. to look for congruency among data sources. Validity and reliability are intertwined, lending credence and strength to the research findings; and apply both to the materials used in the research as well as the analysis of the data.

**Materials.** Ensuring the validity and reliability of the materials used in the research study was of upmost importance. Materials, including the 3-D printed models and tactile graphics were validated in a previous pilot study by Koehler et al (2015) and found to be effective instructional aids for supplementing the geoscience curriculum. I worked with a doctoral candidate from Northern Illinois University who is an expert in 3-D printing and a certified teacher of the visually impaired to develop the 3-D printed models. Likewise, I designed and produced the teacher made tactile graphics using best practices in tactile graphics production (BANA, 2011) and commercially available tactile graphics which were validated by prior research (Otto, Poppe & Hayden, 2002). Content experts and the prior research study by Koehler et al (2015) helped to shape the pre and post interview questions, thereby improving the validity of these questions. Additionally, input from experts in the field of visual impairments led to improvements in both the tactile graphics and 3-D printed models for use in this dissertation research (Koehler & Wild, 2016). Finally, the GEMS science curricular materials used in the research were previously adapted for students with visual impairments and were shown to be effective and beneficial for these students (Koehler et al, 2015). In addition, other GEMS science
curricula were also successfully adapted for students with visual impairments, showing positive results in promoting student conceptual understanding (Wild & Trundle, 2010b)

**Data.** Creswell (2016) describes triangulation as “building evidence from different sources to develop themes” (p.191) and the evidence can come from different sources such as field notes or interview transcripts (Denzin, 1978). Triangulation occurs naturally during the coding process as the researcher looks across data sources, codes the data, and organizes the data into themes, as well as during the process of writing analytical memos and assertions. The use of CCA and qualitative methods of data analysis provided many opportunities for triangulation, in addition to using multiple data sources including audio and video transcripts, interview transcripts, field notes, student journals and photographs.

The search for disconfirming evidence, or evidence that runs counter to the theme, as a method of ensuring validity in their research because it “helps establish a realistic picture of the theme and lends credence to the theme” (Creswell, 2016, p.192) helped ensure the validity of the data in this research study. As the teacher researcher I was not only a participant observer in the classroom throughout the 3-week instructional period giving me the unique perspective to observe potential conceptual change in action and document student understanding in a natural setting, but I also had an emic perspective of long term knowledge of the students in the classroom.

A measure of internal reliability in qualitative research often involves the use of an intercoder reliability calculation. Intercoder reliability is a measure of agreement between multiple coders, who have coded the data independently of each other. The
researchers then discuss any code discrepancies until agreement is reached (Miles & Huberman, 1994). As the primary researcher, I coded the pre and post interview data independently of the other researcher, and we met to discuss and compare the coded student interview data. A tally of agreements and disagreements was kept and intercoder reliability was calculated as a simple percent agreement. Measuring conceptual change involves coding student responses as scientific, alternative or no understanding and checking for the reliability between multiple coders is integral for determining the consistency and accuracy between coders.

Conclusion

Conceptual change theory undergirds much of the research in science pedagogy; however, measuring conceptual change in students with a pretest/posttest, quantitative research design may not be an accurate measure of a complex and messy process. Conceptual change theory is a constructivist learning theory, and as such, qualitative methodologies offer the researcher the opportunity for immersion into the setting in which that knowledge is being constructed, i.e. the classroom. diSessa (2002) advocates that changes in research design would address the weak theoretical accountability that plagues conceptual change research and suggests moving away from the use of before/after studies and the use of coding categories as the only measure of conceptual change to uncover the diversity and complexity that is conceptual change.

The addition of a variety of methods for data collection and analysis, helped to provide thick descriptions of what was going on in the classroom; potentially leading to a better understanding of conceptual change. This research study employed student
journaling, an analysis of classroom talk, and analysis of additional student documents to help determine conceptual change, student misconceptions and the use of 3-D printed models and tactile graphics as instructional aids in the science classroom for students with visual impairments.
CHAPTER 4: Findings

Introduction

The purpose of this qualitative study was to explore the use of 3-D printed models as an instructional tool in a middle school science classroom for students with visual impairments and compare their use to traditional tactile graphics for aiding conceptual understanding of geoscience concepts. Specifically, this study examined if the students’ conceptual understanding of plate tectonics was different when 3-D printed objects were used versus traditional tactile graphics. Additionally, this study sought to explore and understand misconceptions held by students with visual impairments related to plate tectonics and associated geoscience concepts. Qualitative data was collected in the form of pre and post interviews and throughout the 3-week instructional period. The setting for the research was a specialized school for the blind in the Midwest. All students in the middle school classroom received instruction on plate tectonics using an inquiry-based curriculum; however, one group of students had access to 3-D printed models illustrating specific geoscience concepts and the other group of students had access to tactile graphics illustrating the same geoscience concepts. The inquiry-based curriculum, as well as the tactile graphics and 3-D printed models was described in detail in chapter three.
Three research questions guided this qualitative research:

4. How do the conceptual understandings about plate tectonics of middle school students with visual impairments differ before and after instruction, using an inquiry-based science curriculum?

5. How do the conceptual understandings of middle school students with visual impairments regarding plate tectonics compare between those who have access to 3-D printed models and those who have access to tactile diagrams?

6. What misconceptions do middle school students with visual impairments have about plate tectonics and associated geoscience concepts how do these misconceptions compare between those that have access to 3-D printed models and those who have access to tactile diagrams?

All students were taught lessons from the “Plate Tectonics: The Way the Earth Works” (Cuff et al., 2002) from the Great Explorations in Math and Science series from Lawrence Hall of Science. The lessons were adapted for students with visual impairments using best practices and recommendations from experts in the field (Koehler et al., 2011; Koenig & Holbrook, 2000; Kumar et al., 2001; Rule, 2011; Rule et al, 2011). Students were placed into either the tactile graphics group (TG) or the 3-D printed model group (3D) as described in chapter three. The TG group of students received tactile graphics demonstrating specific science concepts from the American Printing House’s Basic Science Tactile Graphics book or teacher-made tactile graphics and the 3D group of students received 3-D printed models of the same science concepts. The 3-D printed models were designed by a fellow doctoral candidate at the University of Northern
Illinois who is a certified teacher of the visually impaired. The models were successfully utilized in a previous research study examining the conceptual change of students with visual impairments related to geoscience concepts (Koehler et al., 2015).

The videotaped pre and post interviews were transcribed, analyzed and coded for conceptual understanding using the constant comparative analysis explained in detail in chapter three. Each participant response was compared to an initial coding framework, developed through a thorough literature review and examination of federal and state curriculum standards and well established science textbook sources to determine scientific understandings of the targeted concepts, common student misconceptions, as well as categories of misconceptions. Each misconception was categorized using the code Alt_, as dictated by the coding framework developed by Trundle (2007a; 2007b) which categorized misconceptions as alternative conceptions. The term misconception, in this study, is used synonymously with the term alternative conception. Likewise, all scientific understandings were coded as Sci_. The comparison and coding of the pre and post interview transcripts was completed independently by the two researchers and scientific and alternative responses were coded, often requiring the addition of new codes based upon unique student responses. The codes emerged as each researcher independently compared the student responses to the interview questions to commonly accepted scientific conceptual understanding found in Table 3.4. The two researchers rejoined to compare their individual codes and discussion ensued until agreement on all codes was reached, enhancing the reliability of the data. During the comparison of the coded data a tally of agreements and disagreements was kept and the interrater reliability
was calculated at 100%. Triangulation of multiple data sources took place during the analysis of interview transcripts, field notes and audio transcripts, etc. to look for congruency among data sources.

This chapter will describe the findings of the study as they emerged through analysis of interviews, student documents and classroom talk, and will be presented in seven sections: a discussion of each category of conceptual understandings with a representative sample of each, a comparison of the categories of conceptual understanding among all students before and after instruction, a comparison of the conceptual understanding of the students in the TG group and the 3D group both before and after instruction, student misconceptions about plate tectonics and other related geoscience concepts, a comparison of the student misconceptions held by each group (TG & 3D), a discussion of student mental modeling and a discussion of student use of tactile graphics and 3-D printed models.

Categories of Conceptual Change with Representative Samples

Part of the interview data coding process involves determining scientific responses and misconceptions and categorizing them as such. Once the initial interview data is coded, then the student response can be placed into one of seven categories of conceptual understanding. The list of the scientific and alternative codes that emerged from the transcribed data of the pre and post interviews can be found in Table 4.1 below.
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt_animals</td>
<td>Animals are earth processes that cause major changes in the earth’s surface</td>
</tr>
<tr>
<td>Alt_continental drift</td>
<td>Continental drift is a process that causes major changes in the earth’s surface</td>
</tr>
<tr>
<td>Alt_continents</td>
<td>A plate and a continent are the same thing</td>
</tr>
<tr>
<td>Alt_falls in</td>
<td>Material from an eruption falls into the volcano and contributes to the earth’s recycling of materials because it goes back into the mantle</td>
</tr>
<tr>
<td>Alt_gap</td>
<td>When tectonic plates move apart it leaves a gap in the crust</td>
</tr>
<tr>
<td>Alt_people</td>
<td>People are earth processes that cause major changes in the earth’s surface</td>
</tr>
<tr>
<td>Alt_society</td>
<td>Scientists use other civilizations to understand that the earth has changed over time</td>
</tr>
<tr>
<td>Alt_volcano causes</td>
<td>Volcanic eruption causes the plates to move</td>
</tr>
<tr>
<td>Alt_weather</td>
<td>Scientists study weather to know that the earth changes over time</td>
</tr>
<tr>
<td>Sci_glaciers</td>
<td>Glaciers are a process that can cause major changes in the earth’s surface</td>
</tr>
<tr>
<td>Sci_horizontal movement</td>
<td>The horizontal movement of the plates is responsible for earthquakes</td>
</tr>
<tr>
<td>Sci_hot spot</td>
<td>A volcano can form over a hot spot in the mantle</td>
</tr>
</tbody>
</table>

Table 4.1. *Scientific and Alternative Codes and Their Descriptions*  
Continued
Table 4.1 continued

<table>
<thead>
<tr>
<th>Scientific Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sci_plate movement</td>
<td>Tectonic plates moving are responsible for major changes in the earth’s surface and/or are directly related to earthquakes and volcanoes</td>
</tr>
<tr>
<td>Sci_stuck</td>
<td>Tectonic plate getting stuck as they move can lead to an earthquake</td>
</tr>
<tr>
<td>Sci_under</td>
<td>At a plate boundary, one plate can sink under another one producing a volcano</td>
</tr>
<tr>
<td>Sci_volcano</td>
<td>A volcano is a process that causes major changes in the earth’s surface</td>
</tr>
</tbody>
</table>

Table 4.1. Scientific and Alternative Codes and Their Descriptions

In addition to analyzing and coding the interview data, additional data sources including student journals, classroom talk, and other student documents were analyzed to determine additional student misconceptions and to compare these from group to group, before and after instruction.

Categories of conceptual change have been documented in the literature and used to assess student conceptual change on a variety of scientific concepts (Adadan et al., 2008; Bell & Trundle, 2008; Trundle et al., 2002, 2007a, 2007b; Ucar et al., 2007) and to assess the conceptual change of students with visual impairments (Koehler et al.; Hilson et al, 2016; Wild, Hilson & Farrand, 2013; Wild, Hilson & Hobson, 2013; Wild & Trundle, 2010). These categories, based upon the work of Trundle et al., (2007a, 2007b) are as follows: scientific, scientific fragments, scientific with alternative fragments, alternative with scientific fragments, alternative and no understanding. Table 3.5 shows a complete list of these categories and their descriptions. Student responses to the four interview questions directly related to plate tectonics were coded into one of the seven
categories to assess student conceptual understanding before and after instruction, as well as, between 3D and TG groups. This categorization was used to answer the first research question:

1. How do the conceptual understandings about plate tectonics of middle school students with visual impairments differ before and after instruction, using an inquiry-based science curriculum?

Scientific

For a student’s answer to be coded as scientific it must agree with the accepted scientific understanding, include all components, and must not contain any misconceptions. Table 3.4 in chapter three shows the scientific understandings for each of the four questions regarding plate tectonics in order for the response to be coded as scientific.

An example of a scientific response to question is demonstrated by the following portion of the interview transcript from Student C, 3D group, Pre-Instruction.

Researcher:  What processes cause major changes in the earth’s surface?  
Student C:  Well, water, and wind erosion (Sci_erosion).  Tectonic plate changing, whatever that is, like when plates change and move around (Sci_plate movement), go on top of each other, make mountains, break things, move things, glacial movements (Sci_glaciers).

Scientific Fragments

A student’s answer was coded as scientific fragments if it was based on accepted scientific understanding but is not complete and contains no alternative understandings.

An example of an answer that was coded as a scientific fragment is demonstrated by the following portion of the interview transcript from Student I, TG group, Pre-Instruction.
Researcher: What can you tell me about the relationship between tectonic plates and earthquakes?
Student I: Uh, I know when earthquakes occur it’s because a tectonic plate shifted.
Researcher: What do you mean by shifted?
Student I: It moved (Sci_plate movement) in some way or another
Researcher: ok
This answer contains one scientific idea and did not contain any alternative understandings, but the student only mentions that the plates move and did not mention how they moved.

Scientific with Alternative Fragments

Coding a student response as scientific with alternative fragments means that the response contains all the elements of the scientific understanding but also contains at least one misconception. An example of this coding category comes from the following portion of the interview transcript from Student C, 3D group, Post Instruction.

Researcher: What processes cause major changes in the earth’s surface?
Student C: Tectonic plate movement (Sci_plate movement), continental drifting (Alt_continental drift), at least in some cases, volcanic eruptions (Sci_volcano) or at least minor changes, but tectonic plate movement for sure, over long periods of time so they only move like a centimeter or so a year – maybe not even a centimeter a year.
This student’s answer contains more than one scientific process but also an alternative understanding that continental drift is causing major changes in the earth’s surface.

Alternative with Scientific Fragments

An answer that is coded as alternative with scientific fragments contains more than one misconception but also has at least one scientific fragment. The following excerpt from the interview transcript of Student S, 3D group, Post Interview, demonstrates this category.

Researcher: What processes cause major changes in the earth’s surface?
Student S: Can you read that again?
Researcher: Sure, what processes cause major changes in the earth’s surface?
Student S: uh
Researcher: or events, what types of things might cause a change in the earth’s surface?
Student S: animals (Alt_animals) and people (Alt_people)
Researcher: How so?
Student S: When they walk on it, they’re footprint can go into it
Researcher: What about major earth surface changes?
Student S: earthquakes (Sci_earthquake)

The student’s response contains one scientific fragment that earthquakes are an earth process that cause major changes but the misconceptions that people and animals contribute to major changes. In this exemplar, the number of misconceptions was greater than the number of scientific understandings; thereby, categorizing the response as alternative with scientific fragments.

Alternative

Coding an answer as alternative means that the student’s answer contained only misconceptions and no scientific understandings and does not agree with accepted scientific thinking. One incident of this type of coding occurred in the interview transcript of Student I, TG group, Pre Interview.

Researcher: Can you describe the relationship between tectonic plates and volcanoes?

Student I: Um, I think when like a volcano erupts (Alt_volcano causes), it moves the tectonic plate or something, maybe.

The idea that a volcanic eruption can have the direct effect of moving a tectonic plate is not an accepted scientific understanding.
No Understanding

Finally, an answer was coded as no understanding if the student’s answer showed no evidence of understanding the concept. One exemplar of this category of coding is found in the student interview with student M, 3D group, Pre Interview.

Researcher: Can you describe the relationship between tectonic plates and volcanoes?

Student M: They possibly will make them erupt. I don’t know what a tectonic plate is.

Student M thought that it might have something to do with an eruption but stated an unfamiliarity with the term tectonic plate; therefore, the answer was coded as no understanding. Student responses before, after and during instruction contained both scientific understandings and misconceptions and represented each of the seven categories of conceptual change.

Conceptual Understanding Before and After Instruction

The first research question sought to examine the conceptual change before and after instruction by categorizing student responses to the pre and post interview questions, in terms of their conceptual category. Five students participated in the research study and were asked a total of ten questions in the student interviews. Four questions, relating to plate tectonics, served as the basis for the answering the first research question. This resulted in a total of twenty (20) total understandings, as shown below in Table 4.2. The researchers independently coded these twenty (20) understandings as scientific, scientific fragments, scientific with alternative fragments,
alternative with scientific fragments, alternative and no understanding per the criteria described in Table 3.3. The students improved their conceptual understanding of plate tectonics throughout the instructional unit as evidenced by the increase in scientific understandings from 4 (20%) before instruction to 11 (55%) after instruction (see Table 4.2 below), as well as the decrease in no understanding from 8 (40%) pre-instruction to 4 (20%) post instruction. Additionally, the number of responses containing scientific fragments decreased from 5 (25%) before instruction to 2 (10%) after instruction and the number of alternative responses decreased from 2 (10%), before instruction to 0 (0%) after instruction. The only category of conceptual understanding running counter to students progressing towards conceptual change was the category of scientific with alternative fragments. The number of answers containing a scientific understanding but holding alternative ideas increased from 0 (0%) before instruction to 2 (10%) after instruction. In this case, both answers involved the same student and this interesting data point will be described in more detail later in the chapter.

<table>
<thead>
<tr>
<th>Category of Conceptual Understanding</th>
<th>Before Instruction</th>
<th>After Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scientific</td>
<td>4 (20%)</td>
<td>11 (55%)</td>
</tr>
<tr>
<td>Scientific Fragments</td>
<td>5 (25%)</td>
<td>2 (10%)</td>
</tr>
<tr>
<td>Scientific with Alternative Fragments</td>
<td>0 (0%)</td>
<td>2 (10%)</td>
</tr>
</tbody>
</table>

Table 4.2. *Frequencies of Categories of Conceptual Understandings* continued
Table 4.2 continued

<table>
<thead>
<tr>
<th>Alternative with Scientific Fragments</th>
<th>1 (5%)</th>
<th>1 (5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative</td>
<td>2 (10%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>No Understanding</td>
<td>8 (40%)</td>
<td>4 (20%)</td>
</tr>
<tr>
<td>Total Understandings</td>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 4.2. *Frequencies of Categories of Conceptual Understandings*

Two additional interview questions expanded upon plate tectonics to include related geoscience concepts. When the responses to these questions were factored into the coding, most of the students (80%), increased their scientific understandings of plate tectonics and other geoscience related concepts as evidenced by the number of scientific or scientific fragments held before and after instruction. Table 4.3 below shows that every student except student C held more scientific understandings after instruction than they did before instruction. As stated earlier, this student incorporated more alternative fragments into the post interview responses that seemed to alter his understanding. For example, when Student C responded to the pre-interview question: “How do scientists know that the earth has changed over time and what can you tell me about the time scale on which these changes take place?”, his answer was coded as scientific because he stated that it was because of fossil evidence and rock dating and these changes took place over millions of years. His post interview answer included plate movement and an extensive discussion of how fossil evidence can be used, but it was coded as scientific.
with alternative fragments because he stated that “if you dig down in certain places you’ll find layers of other civilizations”, which is directly related to the misconceptions of society and archeology. In another situation, Student C was asked: “What processes cause major changes in the earth’s surface?” and during the pre interview he mentioned the processes of erosion, plate movement and glacial movement and his answer was coded as scientific. However, during the post interview, he incorporated the alternative fragment of continental drift which is not a process that changes the earth’s surface.

Some of the classroom talk during week one centered on the connection between plate movement at the San Andreas fault and earthquakes. As we discussed the plate movement, I would refer to the plate to the left of the fault as the Pacific oceanic plate and the plate to the right of the fault as the North American continental plate. During the San Andreas fault lesson, the following exchange took place:

Student C: How big are these plates?

Researcher: Some of them are as big as a continent. Many of the continents of the world have their own plate.

Student C: Wait, American, we are all on one plate?

Researcher: We’re all on the North American plate and all of the Pacific Ocean sits on its own plate, the Pacific Plate.

Also, during this lesson, one of the other students in the same group as student C mentioned that plate tectonics are “either a piece of earth that is on a continent or they can even be under the ocean. Student C also wrote in his journal that “there are several major plates and some minor plates and many faults throughout the earth’s crust and
sometimes plates in a fault catch on each other”. It is possible that Student C picked up the misconception, conflating tectonic plate movement and continental drift from the classroom talk associating continents with large tectonic plates, but either way, his answer could not be coded as scientific.

While there was an overall increase in scientific understanding throughout the instructional unit, not all students showed similar gains in their conceptual understanding. The following section provides the results of additional analyses beyond pre and post interview data.

<table>
<thead>
<tr>
<th>Student</th>
<th>Group</th>
<th>Pre Instruction Number of Scientific Understandings</th>
<th>Post Instruction Number of Scientific Understandings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student M</td>
<td>3D Group</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Student S</td>
<td>3D Group</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Student C</td>
<td>3D Group</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>3D Group</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Student E</td>
<td>TG Group</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Student I</td>
<td>TG Group</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Total</td>
<td>TG Group</td>
<td>8</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 4.3. *Individual Student Overall Scientific Understandings*
Analysis of Classroom Documents and Discourse

One of the concerns of relying only on pre and post interviews or pre/post assessments is that conceptual change is not a linear progression and is not always measurable in a single session (diSessa, 2002); therefore, additional data were collected and analyzed in this study to understand how student conceptual understanding of plate tectonics and related geoscience concepts changed throughout this 3-week instructional unit. All classroom sessions were recorded and transcribed for further analysis and students completed a pre and post assessment of field study questions and a weekly student journal response. The field study questions related to geoscience concepts covered in the instructional unit and the journal response (see Appendix C) asked students to “Summarize what you have learned so far about volcanoes, earthquakes and plate tectonics. Be sure to describe your understanding of how volcanoes and earthquakes are related to plate tectonics. You may include a drawing to illustrate your understanding, if possible”. The case analyses of each student give further insight into their various levels of conceptual understandings of the concepts in this study.

**Case analysis of student C.** Student C was by far the most verbally prolific student in the study, often dominating the classroom talk and sharing his ideas and “theories” on various geologic processes. In addition to his verbose language in the classroom, his student documents were also sources of vast amounts of information representing his thinking on the concepts covered in the instructional unit. In the discussion above regarding student C, his scientific understanding appeared to decrease from before instruction to after instruction per the categorization of his coded responses
to the interview questions; however, his journal responses give a somewhat different picture of his understanding. In the interview exchange below, his answer to the question is clearly muddled and it is difficult to determine his understanding of tectonic plates and volcanoes; therefore, his answer was coded as no understanding.

Researcher: Can you describe the relationship between tectonic plates and volcanoes?

Student C: Well, sometimes volcanoes form near the volcanic line, or no not volcanic line, the tectonic plates like with Mt. St. Helen for example or Mt. Fuji, with like Japan.

Researcher: Do you know why that is?

Student C: Not sure but I guess with like, um, but I guess with like I guess for like the magma chambers under the Pacific and the Eurasian Plate they wouldn’t have to travel very far to find a volcano to go through. Or I guess it could be a mountain and lava forms under it and blows it up.

In his answer above, he mentions a volcanic line, but realizes that is not the correct terminology and changes it to tectonic plates, but states that they are near the plates, not near their edges. An examination of student C’s journal response, however, indicates that he has a more developed understanding of the relationship between tectonic plates and volcanoes when he writes:

Strato volcanoes may be the more common variety of volcanoes, appearing and occurring, like some earthquakes and shield volcanoes, on the edges of tectonic plates. Sometimes plates, like the Pacific Plate, sink underneath other plates and melts, turning into magma, sometimes with water, that develops into magma chambers which move around and erupt lava through volcanoes.
Another example from student C shows that during his post interview, he discussed the fact that tectonic plates “move so obviously, the landscape is gonna change over a long period of time” but he is much more descriptive in his journal when he describes the plate movement at the San Andreas fault stating:

“faults are where tectonic plates meet. The San Andreas Fault is one fault that is above ground. They move slowly in opposite directions, and eventually, San Francisco and Los Angeles will be at the same latitude, because of the pace and direction of the movements of the Pacific Plate, which covers the entirety of the Pacific Ocean floor and the North American plate, which covers the entirety of North America.

Examining the classroom talk about the relationship between tectonic plates, earthquakes and volcanoes also demonstrates that student C does understand the relationship and is evidenced by the transcribed dialog below. In this example the students were examining the plotted volcanoes and earthquakes on their tactile world maps and I asked them to look for any patterns they noticed.

Student C: these earthquakes, these volcanoes, they all make a sort of almost oval or circle [he traces a circle with his finger on the tactile map]

Researcher: yeah they do, and where are those located, which ones?

Student C: points to each volcano, naming some of them.

Researcher: so they’re making a ring where?

Student C: I’m assuming this is a continental plate, except for Hawaii and the one in the…. 

Student M: almost wherever there is a volcano, there is a really bad earthquake that happened closer to it.
Researcher: interesting

Researcher: Are they specific kinds of volcanoes that you are linking with earthquakes or are they all volcanoes and you’re seeing volcanic activity and earthquakes…or is it, do you see that more with shield or do you see that more with strato?

Student M: I see it a bit more with strato

Researcher: strato, ok

Student C: Look, this volcano and this earthquake are buddy, buddy

Student C: all volcanoes happen around plates, so is that the pattern we’re looking for?
Researcher: so, what are you seeing a connection between volcanoes and plates.

Student C: they’re all on the edges near faults - all on the edges near faults?

Student C: I’m guessing that’s what I’m supposed to be thinking

Researcher: alright

Student C: they make patterns, some of them do, geological patterns.

Researcher: what do you mean?

Student C: like in the pacific, there’s that ring.

Student C: [pointing to some of the volcanoes and earthquakes] These are occurring on coastlines.

Researcher: ah, ok

Student C: or at least some of them

Student C: look at this in Argentina, this stratovolcano and this earthquake are right next to each other.

Researcher: do you see much activity in the middle of a continent.

Student M: no
Researcher: so you are seeing them on the edges of coastlines and also on the edges of what?

Student M & Student C: [respond in unison] plates

This example shows that student C did recognize that there is a relationship between tectonic plates and volcanoes, and he also recognized that volcanoes occur around plates or on the edges of coastlines and often near areas of earthquake activity. Using only the pre and post interview data of student C, his overall conceptual understanding of plate tectonics would show an increase in misconceptions and no understanding, but looking at additional data sources demonstrates that his overall conceptual understanding would be better categorized as scientific.

Case analysis of student M. Another example of how analyzing data beyond pre/post assessments can help measure conceptual change is evidenced by the following exchanges with student M. In the pre-interview student M mentions “plates moving” as an example of a process that can cause major changes in the earth’s surface. However, later in the interview student M is asked “What is the relationship between tectonic plates and these earth processes that cause major changes in the earth’s surface”. Her response is “Tectonic plates. I don’t know what that is”. She reiterates her lack of knowledge of a “tectonic plate” two other times during the interview. Student M has not made the connection between plates and tectonic plates in her use of scientific language but does know the ‘plates’ move. What becomes apparent through the examination of classroom talk is the moment when student M makes the connection between plates and tectonic plates. This classroom interaction occurred during the third week of instruction during a
discussion of the Pacific plate as one of the plates interacting in a subduction zone and this “aha” moment is detailed in the following exchange:

Student M: So would the Pacific Ocean, would that be a tectonic plate?

Researcher: Yes, the Pacific plate, under the Pacific Ocean, is a very large tectonic plate.

Student M: Plates are technically called tectonic plates?

Researcher: uh, huh

Student M’s realization that plates and tectonic plates were the same thing had a direct effect on her performance on the post interview and the number of scientific understandings that she exhibited. She referenced tectonic plate movement as both the cause of earthquakes, volcanic eruptions and major processes that cause changes in the earth’s surface. It was also evident in her comments during the classroom talk with student C, as shown above, that she noticed that earthquakes and volcanoes often occur on the edges of plates. This was also documented in her student journal when she wrote “a lot of volcanoes and earthquakes are along the coast” and that many are “by the ocean and when the tectonic plates move, it can make the volcanoes erupt and also start an earthquake. Student M’s overall conceptual understanding improved over the course of the unit and she finished the unit possessing only scientific ideas whereas prior to instruction she possessed almost no understanding of plate tectonics. Not only can additional data sources point to conceptual change as it is happening, it can also point to student misconceptions, as will be discussed later in the chapter.
Case analysis of student I. Student I improved his overall scientific understanding, and the analysis of student documents and classroom talk added to the evidence for conceptual change. Student I was very quiet during the classroom instruction, often making few comments and rarely adding his voice to the discussion. Also, his journal entries and answers to the field study questions were very brief. However, one noticeable area of conceptual growth for student I related to his understanding of the connection between earthquakes and plate tectonics. In his pre-interview, he mentioned that earthquakes occur because a tectonic plate “shifted or moved in some way or another”. In his post interview, he mentioned that the tectonic plate moves and sometimes the “plate’ll get stuck and the pressure gets released and it becomes an earthquake”. In his field study document, he stated that “Earthquakes along the San Andreas fault are caused by two plates that meet at the fault line, rubbing up against each other and get stuck”. In the course of a classroom discussion, student I found it surprising that earthquakes can occur in the middle of the ocean as he was plotting the earthquake locations on his tactile map. Examination of additional data sources demonstrate that student I made some conceptual shifts in his understanding of plate tectonics and earthquakes, but this was not the case for plate tectonics and volcanoes. Moreover, at the end of the unit he had no understanding about the relationship between plate tectonics and volcanoes as evidenced by the following statement in his post interview “I don’t know how those are related, they (referring to the plate) move around a lot”.

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**Case analysis of student E.** Student E had a good initial understanding of plate tectonics and improved her overall scientific understandings throughout the instructional period, evidenced by her interviews and through analysis of classroom documents and classroom talk. Student E had no initial understanding of the connection between plate tectonics and volcanoes. In her post interview she not only understood that plate movement was responsible for these eruptions, but was also able to distinguish between strato and shield volcanoes and discuss the plate movement causing each type of volcano. Analysis of her classroom talk demonstrated her ability to find patterns of volcanic eruptions and their location on the earth when she stated, “they all seem to be in the ocean, close to the ocean or in it” as she explored her tactile world map. In another classroom discussion, Student E made the connection between tectonic plates, earthquakes and volcanoes, maintaining this scientific understanding through the end of the instructional unit, as evidenced by the exchange below:

   **Researcher:** What is it about the earth that’s causing these earthquakes and volcanoes to be located in somewhat the same places?

   **Student E:** maybe because both earthquakes and volcanoes can occur between two plates.

   **Researcher:** ah, interesting, so it has something to do with plates.

   **Student E:** uh, huh

She also wrote in her field study document that “shield volcanoes don’t have to be between plates to form. The mantle just has to be really really, hot”. Analysis of additional data sources was helpful for pinpointing student E’s progression towards conceptual change.
Case analysis of student S. Student S showed very little change in her conceptual understanding during the instructional unit, as evidenced by her pre and post interviews, as well as, student documents and classroom discourse. It was evident during the classroom talk that Student S was extremely quiet, often speaking very little and just nodding her head or agreeing with the other students’ comments. I documented her lack of verbal participation on many occasions in my field notes. During the instructional sessions requiring students to plot volcanoes and earthquake locations on a tactile map, Student S did a superior job finding the latitude and longitude of each earthquake or volcano; however, by the end of the instructional unit was unable to see the pattern of volcano and earthquake distribution as it relates to plate boundaries. Her journal entries tended to focus on the shape of volcanoes or their characteristics and the destructive power of earthquakes as evidenced by the following journal entry:

“Volcanoes can be miles long and miles wide, they can make cracks in the earth and have magma spit out of those cracks, in some volcanoes the lava can come out of the top of the volcano at different speeds: the lava can come out slow or fast or at a medium speed. Some volcanoes can be very long and very tall, and others can be very short and very skinny. All volcanoes have a name. Earthquakes make the earth shake and make cracks in the earth. Some cracks are big, and some are small. Some earthquakes can be deadly, when you are in your house sleeping or something an earthquake can just randomly start and you won’t even know it until it happens. You can’t predict an earthquake is going to happen”.

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The journal entry question asked Student S to show her understanding of the relationship between tectonic plates and earthquakes and volcanoes; however, she never mentioned plates. Her answers in the field study document also show evidence that she did not conceptually understand this relationship. She wrote the same answer about both stratovolcanoes and shield volcanoes’ relationship to plate tectonics as:

“the way the location of volcanoes relate to tectonic plates is by them both being both in the ocean and on land and islands”

Her classroom talk shows the same understanding as evidenced below:

Researcher: where are you mostly seeing stratovolcanoes located?

Student S: in the ocean

Student S: by islands

In these examples, Student S’s responses were descriptive not explanatory and showed no evidence of understanding relationships or patterns. The analysis of student documents and classroom talk also bolstered the evidence that Student S did not make significant conceptual change related to her understanding of plate tectonics during the instructional unit. 

The conceptual understandings of the participants in this research study were different before instruction than after instruction. The students held more scientific understandings and fewer misconceptions or no understandings after instruction than before instruction, which shows positive results for this inquiry-based curriculum. All but one of the five participants showed individual gains in the number of scientific understandings but additional data analysis indicate that this student’s true understanding
may not be reflected solely by the results of the pre/post assessment. The analysis of additional data sources, including student documents and classroom talk gives one a fuller picture of student conceptual change during the instructional unit. The following section will address conceptual understandings as they differ between those students who explored tactile graphics and those who explored 3-D printed models.

Conceptual Understanding Between Groups

During this study, students were taught the same curriculum but placed into one of two groups, per the protocol described in chapter three. There was an attempt to have equal numbers of students in each group; however, one student in the tactile graphics (TG) group was forced to withdraw participation because of medical reasons. Therefore, there were three students in the 3D group and only two students in the TG group. The second research question focused on the differences between these two groups:

How do the conceptual understandings of middle school students with visual impairments regarding plate tectonics compare between those who have access to 3-D printed models and those who have access to tactile diagrams?

This question sought to compare 3-D printed models and tactile graphics as instructional aids for helping students with visual impairments learn geoscience concepts. The results shown below in Table 4.4 below help to illuminate the answer to that question.
<table>
<thead>
<tr>
<th>Category of Conceptual Understanding</th>
<th>Tactile Graphics Group (TG)</th>
<th>3-D Printed Model Group (3D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Instruction</td>
<td>After Instruction</td>
<td>Before Instruction</td>
</tr>
<tr>
<td>Scientific</td>
<td>2 (25%)</td>
<td>6 (75%)</td>
</tr>
<tr>
<td>Scientific Fragments</td>
<td>3 (38%)</td>
<td>1 (12.5%)</td>
</tr>
<tr>
<td>Scientific with Alternative Fragments</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Alternative with Scientific Fragments</td>
<td>0 (0%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Alternative</td>
<td>1 (12%)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>No Understanding</td>
<td>2 (25%)</td>
<td>1 (12.5%)</td>
</tr>
<tr>
<td>Total Understandings</td>
<td>8</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 4.4. Frequency of Categories of Conceptual Understandings Between Groups

As stated earlier in chapter 4, the TG group had fewer total understandings than the 3D group because there were only two students in the TG group; however, the calculated percentages account for the unequal numbers of participants in each group. The results for the TG group indicate that there was a large increase in their scientific understandings from 2 (25%) prior to instruction to 6 (75%) after instruction. In addition, the number of scientific fragments decreased from 3 (38%) before instruction to 1 (12.5%) after instruction. Finally, incidences of no understanding decreased from 2
(25%) before instruction to 1 (12.5%) post instruction. Students in the 3D group saw similar gains in their scientific understandings from 2 (17%) before instruction to 5 (42%) after instruction. Similarly, they saw a decrease in the number of times there was no understanding, by half, from 6 (50%) before instruction to 3 (25%) after instruction. Unlike the TG group, the number of scientific with alternative understandings increased from 0 (0%) before instruction to 2 (17%) after instruction. The results indicate that both groups of students made gains in their scientific understanding from the beginning of the study to the end; however, the TG group showed greater gains in their overall scientific understandings of concepts related to plate tectonics and their associated geoscience processes. As shown in Table 4.3, prior to instruction, the TG group held a total of 8 scientific understandings and post instruction they held a total of 13. The 3D group held a total of 10 scientific understandings prior to instruction and a total of 12 after instruction. While both groups made gains in their scientific understanding, the TG group made slightly more gains than the 3D group. In addition to assessing conceptual change, this study sought to uncover student misconception, including those unique to students with visual impairments.

Uncovering Student Misconceptions

The final research question sought to uncover and explore student misconceptions by asking:

What misconceptions do middle school students with visual impairments have about plate tectonics and associated geoscience concepts and how do these
misconceptions compare between those that have access to 3-D printed models and those who have access to tactile diagrams?

Through an analysis of pre and post student interviews, student documents and classroom talk, student misconceptions were uncovered and coded as alternative conceptions, using the coding framework established by Trundle et al (2007a, 2007b). All misconceptions are shown in Table 4.5 below. In this study, misconceptions and alternative conceptions are used synonymously and are defined as naïve understandings that students bring into the classroom setting which do not conform to scientific models (Driver & Easley, 1978). These misconceptions often stem from incomplete or incoherent mental models as students incorporate their everyday experiences, attempting to construct a more scientific model of a phenomenon. Many of the misconceptions found in this study related not only to plate tectonics, but also to how the earth has changed over time, how do scientists know the earth has changed, and how volcanoes contribute to the recycling of earth materials. The majority of the student misconceptions were uncovered during the pre and post interviews, however some additional unique misconceptions arose in student writing and classroom talk.
<table>
<thead>
<tr>
<th>Misconception</th>
<th>Description</th>
<th>Misconception Data Source</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt_animals</td>
<td>Animals are earth processes that cause major changes in the earth’s surface.</td>
<td>Pre-Interview</td>
<td>3D</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post Interview</td>
<td>3D</td>
</tr>
<tr>
<td>Alt_continental drift</td>
<td>Continental drift is a process that causes major changes in the earth’s surface</td>
<td>Post Interview</td>
<td>3D</td>
</tr>
<tr>
<td>Alt_continents</td>
<td>A plate and a continent are the same thing</td>
<td>Post Interview</td>
<td>3D</td>
</tr>
<tr>
<td>Alt_falls in</td>
<td>Material from an eruption falls into the volcano and contributes to the earth’s recycling of materials because it goes back into the mantle</td>
<td>Pre-Interview</td>
<td>3D</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post Interview</td>
<td>3D</td>
</tr>
<tr>
<td>Alt_gap</td>
<td>When tectonic plates move apart it leaves a gap in the crust</td>
<td>Pre-Interview</td>
<td>3D</td>
</tr>
<tr>
<td>Alt_people</td>
<td>People are earth processes that cause major changes in the earth’s surface.</td>
<td>Pre-Interview</td>
<td>3D</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Post Interview</td>
<td>3D</td>
</tr>
</tbody>
</table>

Table 4.5. All Misconceptions Found During the Study
Continued
<table>
<thead>
<tr>
<th>Misconception</th>
<th>Description</th>
<th>Context</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alt_society</td>
<td>Scientists use other civilizations to understand that the earth has changed over time</td>
<td>Post Interview</td>
<td>3D</td>
</tr>
<tr>
<td>Alt_volcano causes</td>
<td>Volcanic eruption causes the plates to move</td>
<td>Pre-Interview</td>
<td>TG</td>
</tr>
<tr>
<td>Alt_weather</td>
<td>Scientists study weather to know that the earth changes over time</td>
<td>Pre-Interview</td>
<td>3D</td>
</tr>
<tr>
<td>Alt_water</td>
<td>Water causes plates to move</td>
<td>Classroom Discourse</td>
<td>3D</td>
</tr>
<tr>
<td>Alt_shoot</td>
<td>Plate movement causes plates to shoot across the earth very rapidly</td>
<td>Student Journal</td>
<td>3D</td>
</tr>
<tr>
<td>Alt_earthquakes</td>
<td>Earthquakes cause volcanic eruptions</td>
<td>Student Journal</td>
<td>3D</td>
</tr>
<tr>
<td>Alt_magma</td>
<td>Volcanoes happen because there is too much magma.</td>
<td>Classroom Discourse</td>
<td>TG</td>
</tr>
<tr>
<td>Alt_volcano location</td>
<td>Volcanoes are randomly located on earth and are not connected to plate boundaries</td>
<td>Student Journal</td>
<td>3D</td>
</tr>
</tbody>
</table>

Table 4.5. All Misconceptions Found During the Study
Evidence of Student Misconceptions

The misconception that plates and continents are the same thing is well documented in the literature (Dolphin & Benoit, 2016; Francek, 2013; Kirkby, 2014). Not only do many students confuse the concepts of tectonic plates and continents, but they also confuse plate boundaries and plates, believing that they are the same thing. Plates moving apart and leaving a gap (Alt_gap) in the earth is a common misconception documented in the literature (Ford & Taylor, 2005; AAAS Project 2061, n.d.). Continental drift (Alt_continental_drift) as a process that causes major changes in the earth’s surface is a unique misconception, not previously found.

Some misconceptions uncovered in this study, relate to the processes causing major changes to the earth’s surface. Two of the students mentioned that the people (Alt_people) and animals (Alt_animals) were the processes responsible for major changes in the earth’s surface. This is considered a misconception because these processes should include geologic or natural processes such as volcanic eruptions, erosion, tectonic plate movement and should not refer to human influence or the influence of other living things. These misconceptions may have related to the students’ real life understanding of the ways that humans and animals interact with the earth’s surface in minor ways through agriculture or altering landscapes when building structures or societies.

Several of the misconceptions related to how scientists know that the earth has changed over time. One misconception expressed that scientists study civilizations (Alt_society) to understand about how the earth has changed over time. Scientific
understanding of large scale, geologic changes to the earth is evidenced by scientists studying rock layers and rock formations, using radioactive dating procedures and examining fossils. Student misconceptions of how scientists know that the earth has changed may involve the mention of society, tree rings or planetariums (Koehler et al., 2015). What was interesting is that this misconception occurred during the student’s discussion of using plate movement and fossil evidence to determine that the earth has changed over time. His thinking related to fossils was very scientific and even mentioned that finding oceanic fossils in Ohio can tell one that Ohio was once under water; however, he also mentions digging down to find “layers of other civilizations”. Another misconception regarding ways that scientists know that the earth has changed is the idea that one can study weather (Alt_weather) - specifically this student mentioned that scientists have found “…different weather changes. I guess there like used to be – I don’t know, they can just tell with using different technologies”.

One of the interview questions asked the students to explain how volcanoes contribute to the recycling of earth materials and energy, and the misconception (Alt_fall in) as seen above in Table 4.5 was stated by one of the students. This student held this misconception both in the pre interview and the post interview and expressed this misconception as evidenced in the pre interview transcript below:

“I’m assuming that energy is coming from the heat inside of the mantle which is what causes the fiery explosions and the lava and I guess material that falls into the volcanos, I guess would fall, would start falling towards the core of the planet,
the mantle where it gets melted down and probably shot up through the crust again.“.

The student demonstrated this misconception again in the post interview as evidenced in
the post interview transcript below.

“Well, some of it at least, magma, lava, and water, carbon dioxide come from
inside the volcano. And I guess material that would fall in would get melted or
recycled into the mantle”.

Even though this student demonstrated knowledge of the layers of the earth, was able to
name the crust, mantle, inner core and outer core, and identify them on the earth layer
model, he did not demonstrate a clear understanding of the internal structure of the earth
and envisioned material from a volcanic eruption falling into the caldera and making its
way towards the mantle or even the core of the planet.

Two of the student misconceptions related to why volcanoes erupt (Alt_magma)
and how they are distributed on the earth (Alt_volcano location). The misconception
that volcanoes erupt because there is too much magma appears to be a unique
misconception, not seen in previous literature. The student expressing the misconception
did so when attempting to explain her thinking about why volcanoes might occur in the
earth’s crust. This was an attempt to generate an explanation to account for a
phenomenon (Mortimer & Scott, 2000). The other student misconception, related to
volcano locations on the earth, has been documented in previous literature (Fries-Gaither,
2008). The student expressing this misconception did not recognize a pattern connecting
volcanoes with plate boundaries and believed them to be located “in the ocean, on land and on islands”.

One misconception related to the concepts of earthquakes (Alt_earthquakes) and volcanoes and their relationship to each other. The misconception that earthquakes cause volcanic eruptions is documented by (Barrow & Haskins, 1996). It is true that earthquakes and volcanoes often occur in similar locations around the world due to their connection to tectonic plate boundaries; however, the thought that earthquakes cause volcanic eruptions is a misconception.

The final three misconceptions found in this study related directly to the concept of tectonic plate movement. Plate movement is well documented in the literature as a very difficult concept for students to understand because of its complex and unobservable nature. Each of these misconceptions appear to be unique to this study and two of the misconceptions (Alt_volcano causes) and (Alt_water) were stated as explanations for the reason why plates move. One student stated that volcanoes cause plate movement and another believed that possibly water was the reason for plate movement at the San Andreas Fault. The third misconception related to plate movement (Alt_shoot) was expressed by one of the students in her week one journal entry. She documented her explanation for the connection between tectonic plates and earthquakes by writing “earthquakes happen because two tectonic plates rub against each other making each other shoot across the earth in the two polar opposite directions always very rapidly”. She could accurately describe that two plates move against each other, but her idea that they shoot in opposite directions at a high rate of speed is clearly a misconception.
Additionally, it appears that she may believe that the plates are somehow on top of the earth – distinct from it, which has been documented as a misconception in a previous study (Koehler et al., 2015).

All but two misconceptions listed in Table 4.5 shown above were held by the students in the 3D group and sometimes more than one student in the 3D group held the same misconception. Table 4.6 below shows the number of misconceptions held by each group before and after instruction as evidenced by pre and post student interviews, not including the misconceptions in Table 4.5 uncovered in student documents or discourse during instruction.

<table>
<thead>
<tr>
<th>Tactile Graphics Group (TG)</th>
<th>3-D Printed Model Group (3D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before Instruction</td>
<td>After Instruction</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
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</tbody>
</table>

Table 4.6. *Number of Misconceptions about All Geoscience Concepts per Group*

The students in the TG group held one misconception before instruction and no misconceptions after instruction. The students in the 3D group held 5 misconceptions before instruction and 6 misconceptions after instruction. Not only did the 3D group hold more misconceptions related to the plate tectonics and geoscience concepts included in the pre and post interviews but they also demonstrated more misconceptions in their journal writing, other student documents and during class discussions.
Uncovering Mental Models

Student misconceptions in the geosciences often occur because a student has a flawed or incomplete mental model of major geologic processes (Dolphin & Benoit, 2016; Gobert, 2005; Smith & Bermea, 2012). In this study, I attempted to uncover student mental models related to plate tectonics by using student journaling and analyzing classroom talk. Using student drawings and descriptions is well documented in the literature (Dankenbring & Capobianco, 2015; Dolphin & Benoit, 2016; Gobert, 2005; Gobert & Clement, 1999; Sibley, 2005; Smith & Bermea, 2012; Vosniadou & Brewer, 1992) and analyzing classroom talk is documented, as well (Mortimer & Scott, 2003; Scott, 1998). Each week, I asked the participants to describe their understanding of earthquakes and volcanoes and the relationship to plate tectonics. An examination of student mental models may give one an insight into how students are or are not progressing towards conceptual change and to uncover student misconceptions. Mental models are often more descriptive rather than explanatory and most student model building occurs at the generation stage, which means that students are in the early stages of model building (Dolphin & Benoit, 2016; Gobert, 2005; Smith & Bermea, 2012). Not only are mental models often more descriptive but the classroom talk is often descriptive, as well (Mortimer & Scott, 2003). Two mental models that often contribute to misconceptions in the geoscience are those related to the layers of the earth and those related to plate tectonics.
Mental Model of the Layers of the Earth

Mental models of the layers of the earth are often very difficult for students to build which leads to challenges developing an understanding of plate tectonics. For example, Student C could easily name the layers of the earth, point them out on the earth layer model, describe their characteristics and relation to each other, however, he struggled to develop a clear and accurate mental model of the earth layers. The exchange below demonstrates Student C’s thinking about the earth layers and his connection to volcanoes. This exchange was part of a discussion about how magma from shield volcanoes comes from deep in the mantle.

Student C: wait, hold the phone, if lava’s erupting from the mantle through the crust, how is it not shaking off to outer space?

Researcher: what do you mean by that?

Student C: if lava and magma are shooting up through volcanoes from the mantle, how does that not damage the crust enough, just breeching the crust from the mantle, how is that possible that the earth is still intact?

Researcher: typically it’s just oozing up through cracks

Student C: ah, and the volcanoes are the openings?

Researcher: Correct

Student C: but if it were on a larger scale, miles wide, then we’d have a problem

Student C: some are miles wide

Student C: oh

Researcher: lots of the shield volcanoes are miles wide – so there might be multiple cracks, right? So you might not have one opening, you might have many openings.
Student C seems to think that the lava coming from the mantle has enough force to break the crust off, sending it into space and potentially breaking apart the earth. His model may be influenced by informal sources that often show super volcanoes wrecking large scale destruction on the planet. Additionally, student C’s mental model contains descriptive features of lava and magma erupting but he does not have a clear explanatory model of an eruption (Dolphin & Benoit, 2016; Gobert, 2005; Mortimer & Scott, 2002; Smith & Bermea, 2012)

In another example from a classroom discussion, Student C attempts to explain the connection between lava, magma, the tectonic plates and how they move. He states that there is magma underneath those plates and appears to think the plates and crust are different things; however, he does understand that magma comes out of a volcano.

Researcher: Does the crust go under the ocean?

Student C: Yes

Student C: Otherwise the sand beneath the ocean…..if the sand was the very bottom of the crust then the earth would collapse into the mantle of the earth.

Researcher: Why do earthquakes happen in the crust….does anybody know?

Student C: It’s because plates move apart slightly

Researcher: What about volcanoes – how do they work.

Student C: I’m guessing the same way mountains form

Student C: It’s just that lava or plates under the sea – like lava – or here’s an explanation – this might just apply to ocean volcanoes…..but here goes. The plates, tectonic plates underneath the ocean move together, make a mountain, but there’s magma underneath those plates, possibly underneath the crust that have eventually comes out the top of the volcano
Student C has an understanding that the mantle is below the crust, but describes the sand as a barrier preventing the earth collapsing into the mantle and later in the description seems to view the tectonic plates and crust as distinct from each other. Additionally, the exchange above gives one insight into student C’s attempt to formulate an explanatory model of a volcano (Mortimer & Scott, 2003).

Mental Model of Tectonic Plates

An accurate mental model of tectonic plates is imperative for a scientific understanding of many geoscience concepts. The transcript below from the post interview with Student E shows her understanding of plates and their connection to volcanoes and gives a bit of insight into her mental model.

Student E: Tectonic plates move around a lot. They can move in different directions causing the processes. Like when earth plates get stuck and they shift a little, when they rub against each other horizontally, it causes a big earthquake. And trust me, I know what earthquakes feel like - I used to live in Alaska which was prone to earthquakes. You know that. Right after I moved they had a 7.5 earthquake, yeah.

Researcher: is there any other movement type?

Student E: uh, volcanoes can. Like one plate can actually sink under another that can cause volcanoes to form, especially stratos, to be more specific. Those really big explosive steep ones can be caused by when one plate can sink into another. Sometimes different parts of a plate will move in different directions which is kind of crazy if you think about it. The pacific plate – one part of it is actually rubbing against another plate and one part of it is actually sinking under that plate, which yeah.

Researcher: anything else you wanna tell me about that?

Student E: it’s always happening, it’s always happening. It does not stop – they are pretty much always moving, you know – next.
Her response indicates that her mental model of tectonic plates includes the concepts that they can move in different ways which causes different types of earth processes and their continuous movement is directly related to these processes. Her mental model includes both descriptive and explanatory features. She also relates the concept to her prior experience with earthquakes. Student E’s mental model was more complete and did not contain any misconceptions, unlike, Student C’s mental model, which was less coherent and showed a number of misconceptions. Using student descriptions can potentially give one an understanding into the mental models that students with visual impairments possess about geoscience concepts.

Use of 3-D Printed Models and Tactile Graphics

Examining student use of 3-D printed models and tactile graphics was a primary interest in this research study. Not only was it important to examine how students used the models but also whether the models provided an aid in student conceptual understanding or to reduce misconceptions. Four of the pre and post interview questions asked the participants to describe or explain the 3-D printed models or tactile graphics. For example, interview question number 5 (Appendix A) asked the students to explain the model of California shown in Figure 4.1 below and describe what happens at the fault.
The term fault was not used by the interviewer but the student’s hand was directed to the representation of the fault, either a groove on the 3-D printed model or a raised glitter glue line on the tactile graphic. In the pre-interview, Student C, who has no light perception and is a braille reader, recognized the 3-D printed model as the state of California but did not recognize the San Andreas fault or what happens there; however in the post interview he immediately recognized that the groove in the model represented the San Andreas fault as evidenced by the post interview transcript below:

Researcher: Can you explain what this model is about (either tactile graphic or 3-D model of California)? Can you show me or describe what happens here (point to fault on tactile graphic or 3-D model of California)?

Student C: California. The state of California.

Student C: Yeah, that’s the San Andreas fault, where the North American Plate and the Pacific Plate, they meet and this is actually one of the, like they only place if not one of the only places where you can see the fault above ground.

Researcher: What is the fault you’re talking of?
Student C: This is where the plates meet. This is the very edge of the North American Plate, right about here, and this is the edge of the Pacific Plate. They slide northwest in this case and in the Pacific Plates case, it slides southeast. This is LA, Los Angeles and this is San Francisco. This one is on the North American Plate where it’s meant to be and this one’s on the Pacific Plate – San Francisco. They’re both coastal.

Researcher: Anything else you wanna say about the movement?

Student C: It’s – I’m not sure – I’m not entirely sure what the name of the type of plate it is. Trans something – they move sideways, instead of on top of each other – they move along side each other [motions with hands sliding horizontally] like this.

Researcher: ok

Student C not only immediately recognized the model as the state of California, but was able to point to the fault and describe in great detail the plate movement that happens there.

Another model that showed positive results for aiding student understanding was the model of the earth layers as shown in Figure 4.2 below.

Fig 4.2: Layers of the Earth
This 3-D printed model was easily recognized by the students as a model of the earth and they were able to distinguish between each layer as evidenced by Student S’s description of the model below:

“This is the crust (pointing to the crust). This is the outer core, the inner core and the mantle”.

The tactile graphic proved more difficult for the students to distinguish the layers of the earth and led to some confusion and missing information in the student responses. Student I only recognized the core and the crust and Student E recognized the crust, mantle and the core, however, this commercially made tactile graphic did not distinguish between the inner core and outer core and the student only mentioned the core.

Both the 3-D printed model and commercially made tactile graphic of sedimentary rock layers were problematic for students to understand. While the students easily recognized the 3-D printed model as layers, they believed that it might be layers of soil and bedrock or earth layers. Only one participant, student M, thought that the layers might be sedimentary rock layers. The students who explored the tactile graphic also did not recognize the layers as sedimentary rock layers. Student I thought that the tactile diagram might be depicting an earthquake because he noticed that the layers did not seem to be even and remarked “the bottom one, this parts going down and this part’s going up”. He pointed to each layer and said “on the top one, it just looks like normal, maybe layers of rock and layers of….like this one would be the rocky layer…. this down here is the silty pancake part and then this is all something else down here”. In fact, student E explored the diagram tactilely in detail, identifying all the shapes (dots, circles, zigzags)
distinguishing each layer but was unable to explain what the diagram might represent. The students in the 3D group were able to make better inferences about what the layers might depict.

The participants that used the 3-D printed model of a convergent boundary all recognized that the model represented tectonic plates and two of them recognized that one plate was going under the other one. In the post interview, Student C recognized this model as a convergent boundary and stated “the Pacific plate is meeting the Eurasian plate….this part represents the ocean plate and the way its sliding under the Eurasian plate and melting as it goes”. Only one of the students in the TG group recognized the tactile graphic as plates moving together and thought that one plate was going under the other one. The 3-D printed model was designed to show movement at the convergent boundary by moving a thin Scotch Brite© pad which may have been a conceptual aid for the students in the 3D group. The concept of convergent boundaries and plate movement at those boundaries is difficult for students to understand because these earth processes are complex and unobservable.

Some of the 3-D printed models did not appear to improve conceptual understanding of plate tectonics of the participants in this research study, but some of models did provide additional information to the participants, giving them a better representation of earth layers, faults and convergent boundaries.

Chapter Summary

The conceptual understandings of the participants in this research study were different before instruction than after instruction. Most of the participants in the study
increased their scientific understandings of plate tectonics and other geoscience related concepts and held more scientific understandings after instruction than before instruction. All students had misconceptions before the instructional period began, but the number of misconceptions were fewer after the instructional period. Students in the TG group not only had fewer misconceptions than the 3D group before instruction, but also after instruction.

The 3D models did not necessarily improve student conceptual understanding of the targeted geoscience concepts; however, in some cases student interaction with the models was quite different, providing additional information that the tactile graphics did not. For example, the pull apart layers of sedimentary rock provided students with information through distinct texturing and the stackable nature of the 3-D printed model conveyed the idea of layers better than the tactile graphic. Also, the 3-D printed model of the convergent boundary provided information about movement at the plate boundary, through actual moving parts, that was not possible on the stationary tactile graphic.

Unlike previous studies, additional data sources were analyzed to help determine student conceptual understanding and detect additional misconceptions. These data sources included student journals, other student documents and classroom talk. Analysis of these data sources also helped uncover student mental models as they related to plate tectonics and their relationship to major earth processes.
CHAPTER 5: Conclusions

Introduction

The purpose of this qualitative study was to explore the use of 3-D printed models as an instructional tool in a middle school science classroom for students with visual impairments and compare their use to traditional tactile graphics for aiding conceptual understanding of geoscience concepts. Specifically, this study examined if the students’ conceptual understanding of plate tectonics was different when 3-D printed models were used versus traditional tactile graphics. Additionally, this study sought to explore and understand misconceptions held by students with visual impairments related to plate tectonics and associated geoscience concepts. The participants in the study were middle school student at a specialized residential school for the blind in the Midwest who received instruction on plate tectonics using an inquiry based curriculum; however, one group of students had access to 3-D printed models illustrating specific geoscience concepts and another group of students had access to tactile graphics illustrating the same geoscience concepts.

This chapter discusses the findings of the research and situates those findings among previous research on conceptual change and misconceptions, student conceptual understanding of plate tectonics and other geoscience concepts, and the use of 3D printed...
models as an instructional aid for student with visual impairments in science. This chapter has five sections: student conceptual change, student misconceptions, examining mental models, 3D printed models and tactile diagrams as instructional tools, limitations and recommendations for future research.

Plate Tectonics

The Next Generation Science Standards, based upon the National Research Council’s *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2012), call for instruction on geologic concepts across grade levels focused on core ideas. One core idea explored is Earth systems; how and why the Earth is constantly changing and the history of the planet Earth (radioactive and relative dating). The unifying theory of plate tectonics explains the underlying processes of earthquakes, volcanoes and mountain building. However, K-12 and college-age students alike, as well as preservice teachers and in-service teachers have considerable difficulty understanding the theory, which leads to many misconceptions (Ford & Taylor, 2008; Gobert, 2005; Libarkin, 2005; Libarkin et al, 2005; Marques & Thompson, 1997; Sibley, 2005; Smith & Bermea, 2012). The theory of plate tectonics is particularly problematic for students to understand because plate movement is not observable (Dolphin, 2008, Ford and Taylor, 2008; Smith & Bermea, 2012) and students often lack a mental model for the earth’s interior, which limits their ability to understand the dynamic process of plate movement (Dolphin, 2008). Moreover, students often use geoscience terminology inaccurately or with minimal understanding in relation to plate tectonics (Cheek, 2010).
Students with Visual Impairments

Students with visual impairments have described geologic concepts, such as volcanoes, contour and undersea maps, topographic maps and geologic time, as difficult to understand (Jones et al, 2006). This is only the second study undertaken to explore how students with visual impairments understand the concept of plate tectonics and their related geoscience processes and research on students with visual impairments understanding of science, in general, is somewhat limited. The findings of this research study are similar to a previous pilot study conducted on students with visual impairments to assess their conceptual understanding of plate tectonics (Koehler, et al., 2015); however, there are differences that will be discussed later in the chapter.

Conceptual Change

Examining conceptual change in the science classroom is a theoretical framework underlying much of research in the field of science education. Students in this study demonstrated all categories of conceptual change including: scientific, scientific fragments, scientific with alternative fragments, alternative with scientific fragments, alternative, or no understanding before instruction and all but one category of conceptual change after instruction. A slight majority of the conceptual understanding before the instruction fell into the category of no understanding or alternative understanding and after instruction the larger majority of conceptual understanding was categorized as scientific or scientific with fragments. Overall, students in this research study did improve their conceptual understanding of plate tectonics, which is also documented in previous research with students with visual impairments (Koehler et al, 2015) and aligns
with previous research showing positive results for students with disabilities using hands-on, inquiry based approaches to teaching science (Mastropieri & Scruggs, 1992; McCarthy, 2005; Palinscar et al., 2000; Rooks, 2009; Scruggs, et al., 1993; Trundle, 2008; Wild & Trundle, 2010b). The improvement in student conceptual understanding also supports prior research findings in other science content areas when using inquiry based approaches with students with visual impairments (Hilson et al., 2016; Wild, Hilson, & Farrand, 2013; Wild, Hobson, & Hilson 2012; Wild & Trundle, 2010a; 2010b).

Conceptual Change Between Groups

The findings also showed that while each group made progress towards conceptual change over the instructional period, the TG group made greater gains in their scientific understandings than the 3D group, and the decrease in no understanding or alternative understanding was roughly equal among the two groups. The TG group showed an overall 38% increase in their scientific understanding and the 3D group showed a 17% overall increase in their scientific understanding. The major difference between the two groups was the increase in the category of scientific with alternative fragments in the 3D group which was attributable to one student, student C. Without those alternative fragments the 3D group would have had an overall increase in their scientific understanding of 28% showing less of a difference between the groups in terms of overall increase in scientific understanding.

Previous research on conceptual change with students with typical vision, demonstrates that conceptual change is a complex process and students often incorporate new information into their existing understanding of a concept, creating a hybrid mental
model that contains alternative ideas (Greca and Moreira, 2000). It is not clear that levels of vision or cognitive abilities led to differences in understanding between the 3D and TG group because there was an attempt to keep groups as equal as possible. Each group contained both students with low vision and students who were blind and all students were proficient in science. This study’s findings mirror a previous study examining the conceptual understanding of middle school students with visual impairments in relation to plate tectonics and other geoscience concepts which showed no significant difference between those that used 3-D printed models and those using tactile graphics (Koehler et al., 2015).

Misconceptions

Participants in this study held many misconceptions throughout the study but held fewer misconceptions about plate tectonics after instruction than before instruction. Some additional misconceptions related to other geoscience concepts persisted throughout instruction and were found to be present both before and after instruction, consistent with documented misconceptions research showing that misconceptions are often resistant to change even with targeted instruction (Chi & Roscoe, 2002). The instructional unit primarily targeted plate tectonics, providing explicit instruction on those concepts; however, instruction on some geoscience concepts covered in the pre and post interview questions was more implicit, often arising through classroom talk and student questions and comments. The misconception that erupted material could fall back into a volcano and get recycled back into the mantle was not extinguished even with targeted instruction on how earth materials are recycled through volcanic eruptions.
Additionally, this misconception could also be tied to the student’s incomplete and possibly flawed mental model of the earth layers, consistent with the literature (Chi and Roscoe, 2002). It was not apparent that the misconception had anything to do with the 3-D printed models or instruction in the classroom because this student held the misconception both prior to and after instruction.

Many of the misconceptions demonstrated by the students with visual impairments in this research study were not unique to visually impaired students and have been documented in the literature with all ages of students, as well as, preservice and inservice teachers (Ford & Taylor, 2008; Gobert, 2005; Libarkin, 2005; Libarkin et al, 2005; Marques & Thompson, 1997; Sibley, 2005; Smith & Bermea, 2012). Some of the misconceptions related to students’ believing that people, animals and continental drift are processes responsible for the major changes on the earth’s surface and the human and animal influence was previously documented in an earlier study with students with visual impairments (Koehler et al., 2015). Part of the reason for these misconceptions may be due to the students misinterpreting the language of “major changes” or relating the question to events that happen in shorter periods of time – those on a human time scale. Research shows that students have difficulty with concepts of geologic time and the large expanses of time needed for major changes on the earth (Dahl et al., 2005; Libarkin et al., 2005; Libarkin & Anderson, 2005). The misconception about weather appears to be related to a previous misconception that seasons, and their variable weather conditions, can cause large scale changes in the earth’s surface, found in a previous research with students with visual impairments (Koehler et al., 2015). Other
misconceptions centered on the concepts of tectonic plates and their movement, including misunderstandings of how plates move, what causes them to move and the confusion between continents and plates. Most of these misconceptions have been documented in previous literature and are surprisingly common among all grade levels of students and even teachers (AAAS Project 2061, n.d.; Barrow & Haskins, 1996; Dolphin & Benoit, 2016; Francek, 2013; Ford & Taylor, 2005; Kirkby, 2014; Smith & Bermea, 2012). The concepts of plate movement and the causes of this movement are fraught with misconceptions because 1) the process is not observable, 2) the plates move so slowly, 3) convection in the mantle cannot be seen, and 4) radioactive decay as an energy source for plate movement is a difficult concept for students to understand (Dolphin, 2008, Ford and Taylor, 2006; Smith & Bermea, 2012). Additionally, flawed or incomplete mental models of the earth layers and a lack of an explanatory mental model of plate tectonics can lead to many misconceptions of plate movement and the associated earth processes of earthquakes and volcanoes (Dolphin & Benoit, 2016; Gobert, 2005; Smith & Bermea, 2012). Upon analyzing various data sources, an attempt was made to uncover student thinking about earth layers and plate tectonics to perhaps understand their mental models. Some of the students appeared to have a more complete mental model of earth processes than other students in this study, leading them to a more scientific understanding. Finally, some students lacked an explanatory mental model that linked plate boundary processes with earthquakes and volcanoes, consistent with research on students with typical vision (Smith & Bermea, 2012).
It was also found that the students in the 3D group held many more misconceptions both before, after and throughout the instructional period than the students in the TG group. Geoscience misconceptions are common among all types of students and it is unclear why the 3D group had so many more misconceptions. There was one more student in the 3D group than the TG group, which could account for part of the difference in the number of misconceptions. Additionally, student C had many scientific ideas, but also had persistent misconceptions with which he was unable to reconcile and overcome. Misconceptions exist among students as well as scientific experts, but experts are often able to overcome these misconceptions. Even though an attempt was made to equalize the instruction among the two groups, the dynamic nature of the classroom and its discourse can often lead to differences in instruction, perhaps leading to differences in the number of misconceptions. Also, the unique nature of each student and their prior understanding may have also accounted for a difference in the number of misconceptions, especially due to the small sample size in the study. The misconceptions unique to this study with students with visual impairments were, plates shooting across the earth, volcanoes causing the plates to move, volcanoes erupting because of too much magma, and volcanic material falling back into a volcano and getting recycled back into the mantle. These misconceptions are not documented in previous literature, either in students with visual impairments or students with typical vision.
Mental Models

One unique aspect of this study was the examination of student mental models, which had not previously been done with students with visual impairments, but is more commonplace in research on students with typical vision. Using student drawings and descriptions to uncover student mental models about plate tectonics and other geoscience concepts is a method of recognizing and addressing student misconceptions (Dankenbring & Capobianco, 2015; Dolphin & Benoit, 2016; Gobert, 2005; Gobert & Clement, 1999; Sibley, 2005; Smith & Bermea, 2012; Vosniadou & Brewer, 1992). The weekly student journal and an analysis of classroom discourse was used to help uncover student mental models related to plate tectonics and associated geoscience processes as described in chapter four. Students had the opportunity to draw their understanding, but the students were either unable to draw because of their visual impairment or chose not to document their understanding in that manner.

Student Mental Models

The findings, related to mental models, described in detail in chapter four show students in the dynamic process of building mental models by incorporating new information to their models (Johnson-Laird, 1993), but sometimes also including alternative understandings in these models as they progress towards conceptual change phenomena (Hewson, 1981; Posner, Strike, Hewson, & Gertzog, 1982). For example, Student C’s mental model of the layers of the earth and their connection to materials moving through these layers seems to incorporate ideas from informal educational experiences or media sources that often depict volcanic eruptions as so violent that they
have the potential to break apart huge expanses of the earth’s crust (Boudreax et al., 2009; Buckley & Boulter, 2000). For example, student E’s mental model of the connection between plate tectonics and earth processes, such as earthquakes and volcanoes incorporates a reference to her prior understanding of earthquakes based upon an initial model she has developed through her experience living in Alaska and the scientific model she has incorporated because of her involvement in this instructional unit (Vosniadou and Brewer, 1992). Additionally, the mental models were often descriptive rather than explanatory, often incorporating scientific language, but not clearly showing that the student had a complete grasp of the concept. Student mental models are highly personal (Norman, 1983), often incomplete, fragmented (Chi & Roscoe, 2002) and limited by world-view and experiences of the individual holding the mental model (Franco & Colinvaux, 2000). It is possible that the students’ limited visual experiences and access to visual materials and experiences may have contributed to their limited mental models which contained numerous misconceptions or alternative understandings. However, even with access to visual experiences through videos, simulations, drawings, etc., many students have difficulty developing an accurate mental model of plate tectonics, leading to true conceptual understanding.

Use of 3-D Printed Models and Tactile Graphics

Participants in each group held both scientific understandings and misconceptions before, during and after the instructional period. The use of 3-D printed models instead of tactile graphics did not seem to make a difference either positively or negatively; however, the participants did interact with the 3-D printed models differently, sometimes
gleaning additional information from them. Students that used the 3-D printed models recognized certain features, such as the San Andreas fault, rock layers, additional earth layers and plate movement at a convergent boundary more easily than those using the tactile diagrams; however, this did not appear to aid in their overall understanding of plate tectonics. The 3-D printed model of the earth layers does show promise as an instructional tool for helping students with visual impairments understand this often difficult concept because the model not only adheres to research by Gobert (2005) showing that a spatial layout of concentric circles depicting the layers helps students build a mental model for the dynamic factors of plate tectonics, but it also allows students to separate each layer, to explore their relative thicknesses and relation to each other. The 3-D printed model of the convergent boundary may also be beneficial as an instructional aid for student with visual impairments to better understand this very complex geologic process. Prior research indicates that tactile graphics can be difficult for students with visual impairments to comprehend (Bolt & Thurlow, 2004) and two-dimensional drawings of 3-dimensional objects often had no real meaning for blind students (Merry, 1932; Merry and Merry, 1933) leading some to suggest that 3-D printing may be beneficial for aiding concept development and providing access to visual information (Horowitz & Schultz, 2014; Jo et al, 2016; Koehler, Tikkun, & Wild, 2015; Rosenblum & Herzberg, 2015. While 3-D printed models may be an alternative instructional tool, this study does not show that 3-D printed models are superior to tactile graphics for improving student conceptual understanding of complex scientific concepts, such as plate tectonics in students with visual impairments.
Limitations

Several limitations exist in this research study. One of the biggest limitations of this study is its small sample size and the non-random assignment of students to each group. There were only five student participants in this study and they were diverse in their levels of vision, eye disorders, academic and achievement levels. In addition, the 3D group was larger than the TG group. There was an attempt to ensure that gender, additional disabilities, academic ability and level of visual impairments was roughly equal between groups. Past instruction in science may have also varied because these students were previously educated in different parts of the state prior to enrolling in this specialized school for the blind. Student understanding of past science content taught was not examined as part of this research study. An attempt was made to equalize instruction between groups by utilizing the same instructor and by using the same instructional materials; however, the dynamic nature of classroom discourse often leads to differences in the instructional content. However, all main ideas and content topics were taught to both sets of students. The demographic information found in chapter three can help the reader determine the applicability of these findings to other similar contexts.

The primary researcher previously conducted a study on the conceptual understandings of plate tectonics with a similar population of students and was aware of previous scientific understandings and misconceptions. This had the potential to influence the coding of data and bias the researcher towards prior codes. There was an attempt to limit this bias by utilizing a second researcher to assist in analyzing and coding the data. This same researcher conducted the pre and post interviews and was also a
science content expert. She had no previous experience with students with visual impairments or with teaching this content to students with disabilities. The coding was subject to an interrater reliability check to ensure that there was agreement on coding. The pre-interview and post interview questions were identical and had the potential to influence the students by guiding them to hone in on particular content during the instructional period; thereby influencing their answers on the post interview questions. However, Trundle et al (2002) found that pre-instruction interview questions are not likely to influence the answers given to the post-instruction interview questions.

Additionally, this same interview method has been used successfully in multiple prior research studies, including those with students with visual impairments (Koehler et al. 2015; Hilson et al, 2016; Wild, Hilson & Farrand, 2013; Wild, Hilson & Hobson, 2013;Wild & Trundle, 2010).

Implications and Recommendations for Future Research

Results from this study adds to the body of research on middle school students’ conceptual understandings and misconceptions of geologic processes related to plate tectonics. This study uncovered many student misconceptions about plate tectonics and associated geoscience processes; some that are the same as those seen in students with typical vision and some that are unique to students with visual impairments. Knowing these unique misconceptions is important for general education science teachers and teachers of the visually impaired who may be assisting students in the general education science classroom. Militating against misconceptions is a necessary step in helping
students achieve conceptual change in science and more research needs to be done in other science content areas to uncover additional misconceptions.

This study also helps to shed light on the use of 3-D printed models in the science classroom and their effectiveness at helping students with visual impairments learn important geoscience concepts. Traditionally, tactile graphics are used to give students with visual impairments access to visual content; however, with 3-D printing technology becoming more affordable and more widely available, many have suggested 3-D printed models as a beneficial instructional tool (Horowitz & Schultz, 2014; Horvath & Cameron, 2016; Jo et al, 2016; Koehler et al., 2015; Rosenblum & Herzberg, 2015). The use of 3-D printing technology did not appear to impact student conceptual understanding of plate tectonics or help to reduce misconceptions. This study was only the second study of its kind, and given the small sample sizes of each study, future research is warranted to determine if 3-D printed objects are a beneficial supplement to science instruction.

The results of this study provide further evidence that inquiry based instruction is an effective means of providing science instruction to students with visual impairments. All participants in this study improved their conceptual understanding of plate tectonics using this hands-on, inquiry-based curriculum. Not only does inquiry-based instruction stimulate creativity in the science classroom, it can also help students prepare for standardized assessments (Longo, 2010). Research shows that students with visual impairments lag behind their sighted peers on standardized assessments and an examination of limited data from statewide achievement data show similar gaps when compared to students with typical vision (Blackorby, Chorost, Garba & Guzman, 2003,
Furthermore, this study is unique because it provides insight into inquiry-based instruction in geosciences for students with visual impairments, adding to the limited research base on this topic. Given the results of the current and previous studies, continued research on inquiry-based instruction in all science content areas is warranted.

This was the first study using an analysis of additional student data, including examination of student mental models and classroom talk to measure conceptual change and uncover additional misconceptions in students with visual impairments. This study moved beyond the analysis of pre/post assessments or interviews to include additional student data sources including an analysis of classroom talk and student journaling. Additional research is warranted to help determine if these additions to the analysis are beneficial for measuring conceptual change.

In addition to replicating the study with additional students with visual impairments in specialized schools for the blind, repeating the study with students with visual impairments in a general education setting might help determine if they hold similar misconceptions and conceptual understandings. Much of the conceptual change research conducted on students with visual impairments is conducted in specialized schools for the blind even though most student with visual impairments are educated in the general education setting, according to Wild & Paul (2012).

Finally, the field of visual impairments suffers from a lack of practices, which would meet the NCLB and ESSA requirements of “scientifically based research” and many of the instructional practices are based upon anecdotal evidence. Few studies have
been replicated and most of the existing studies are based upon accommodations and modifications to curricula or product studies (Ferrell, 2006; Kelley & Smith, 2011; Wild & Allen, 2009). Additional empirical studies examining the effectiveness of products, curricula and instructional strategies will help build a collection of research based practices in the science content areas for students with visual impairments.

While the implications of this research make it difficult to determine if 3-D printed models aid in student conceptual understanding or reduce misconceptions for students with visual impairments, this research works to contribute to the body of research on geology education and provide further documentation of misconceptions about plate tectonics and fundamental geologic processes. Calls for improved instruction in the geosciences recognize the need for increased scientific literacy and a reduction of misconceptions as we prepare students to tackle societal issues such as climate change, alternative energy, fossil fuel extraction and the preparation for and mitigation of the effects of geologic natural disasters. The recommendations for future research should be considered to continue development of beneficial, research-based, science instructional practices as mandated by federal law.
References


Branch, H.E. (1942). That the blind may see. *American Biology Teacher*, 5(1) 34-36


National Research Council and National Academies Press (2012). *A framework for k-


Appendix A: Interview Questions and Student Journal

1. How do scientists know that the earth has changed over time? What can you tell me about the time scale on which these changes take place? (Achieve, 2013)
2. What processes cause major changes in the earth’s surface? (Achieve, 2013)
3. What is the relationship between tectonic plates and these earth processes that cause major changes in the earth’s surface? (Achieve, 2013)
4. Can you explain what this model is about (either tactile graphic or 3-D model of sedimentary rock layers)?
5. Can you explain what this model is about (either tactile graphic or 3-D model of California)? Can you show me or describe what happens here (point to fault on tactile graphic or 3-D model of California)?
6. What can you tell me about the relationship between tectonic plates and earthquakes?
7. Can you explain what this model is about (either tactile graphic or 3-D model of the Earth layers)?
8. How do volcanoes contribute to the recycling of earth materials and energy and where are these materials coming from? (Achieve, 2013)
9. Can you describe the relationship between tectonic plates and volcanoes?
10. What does this model show us (either tactile graphic or 3-D model of convergent boundary/subduction zone)?

Can you describe or show me how the plates are moving here (point to position where plates are interacting)?
### Appendix B: Research Study Curriculum and Adaptations

<table>
<thead>
<tr>
<th>Lesson Number and Topics</th>
<th>NGSS Standards Addressed</th>
<th>Tactile graphics</th>
<th>3-D printed models</th>
<th># of days of instruction</th>
<th>Additional Adaptations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – Geologic Time and Earth Processes</td>
<td>MS-ESS2.1 – developing models</td>
<td>Tactile graphic of Earth’s layers #28 in APH Basic Science Tactile Graphics book</td>
<td>3-D Earth layer Model based on page 54 of GEMS Plate Tectonics book.</td>
<td>2 days</td>
<td>Braille and Large Print Geologic Field Notebooks</td>
</tr>
<tr>
<td></td>
<td>MS-ESS2.A – geologic time and processes</td>
<td>Tactile graphics of sedimentary rock layers #30 in APH Basic Science Tactile Graphics book</td>
<td>3-D model of sedimentary rock layers based on page 27</td>
<td>3 days</td>
<td>Real samples of sand and fine soil</td>
</tr>
<tr>
<td></td>
<td>geologic time, processes that form crust, modeling earth layers</td>
<td></td>
<td></td>
<td></td>
<td>Rope with beads every meter (each bead representing a billion years) – for geologic time activity</td>
</tr>
<tr>
<td>2 – Field Work in California</td>
<td>MS-ESS2.1 – developing models</td>
<td>Tactile Graphic of Map of California and San Andreas fault- page 34 – created using PIAF©</td>
<td>3-D model of Map of California and San Andreas fault based page 34</td>
<td>3 days</td>
<td>World at your Fingers map or other tactile world map with raised latitude and longitude lines.</td>
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<tr>
<td>Investigating faults, modeling fault movement tectonic plates and earthquakes, mapping earthquakes around the world</td>
<td>MS-ESS2.2 - geoscience processes (earthquakes)</td>
<td></td>
<td></td>
<td></td>
<td>Foam stickers for plotting locations of earthquakes</td>
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<tr>
<td></td>
<td>MS ESS2.A – material and systems</td>
<td></td>
<td></td>
<td></td>
<td>Talking calculators</td>
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<tr>
<td></td>
<td>MS-ESS2.B – plate tectonics</td>
<td>Tactile graphic of Shield vs stratovolcanos - created using PIAF©</td>
<td>3-D models constructed using papier mache.</td>
<td>3 days</td>
<td>Braille rulers</td>
</tr>
<tr>
<td>3 – Field Work in Hawaii</td>
<td>MS-ESS2.1 – developing models</td>
<td>Tactile graphic of Shield vs stratovolcanos - created using PIAF©</td>
<td>3-D models constructed using papier mache.</td>
<td>3 days</td>
<td>Accessible timer</td>
</tr>
<tr>
<td>Tectonic plates and shield</td>
<td>MS-ESS2.2 - geoscience</td>
<td></td>
<td></td>
<td></td>
<td>World at your Fingers map or other tactile world</td>
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<tr>
<td>Activity</td>
<td>Resources</td>
<td>Time</td>
<td></td>
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<tr>
<td>4 – Field Work in Japan tectonic plates and stratovolcanoes and modeling subduction zones, mapping stratovolcanoes around the world</td>
<td>MS-ESS2-1 – developing models MS-ESS2-2 - geoscience processes (volcanos) MS ESS2.A – material and systems MS-ESS2.B – plate tectonics MS-ESS1.C - subduction Tactile graphic of Shield vs stratovolcanos using PIAF© Tactile graphic of convergent boundary with subduction zone page 10 of field notebook – create using Piaf©</td>
<td>3D models constructed using papier mache. 3-D model of convergent boundary with subduction zone based upon page 10 of field notebook</td>
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<tr>
<td>Wrap-up and review Answer final field study questions</td>
<td>World at your Fingers map or other tactile world map with raised latitude and longitude lines. Foam stickers for plotting locations of stratovolcanoes</td>
<td>1 – 2 days</td>
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Appendix C: Student Documents

Field Study Questions

California Questions

1. Explain the occurrence of earthquakes along the San Andreas Fault.
2. Where in the world besides California are there frequent earthquakes.
3. How do movements along California’s San Andreas Fault relate to tectonic plates?

Hawaii Questions

4. Are magmas erupted at Hawaiian volcanoes highly viscous?
5. Are magmas erupted at Hawaiian volcanoes high in silica?
6. What does the silica of these magmas say about their origin?
7. What is the name of the type of volcano found in Hawaii?
8. Why are Hawaiian shield volcanoes so gently sloped?
9. Where are some other shield volcanoes located on Earth?
10. How does the location of shield volcanoes relate to tectonic plates?

Japan Questions

11. Is magma erupted from volcanoes in Japan highly viscous?
12. Why are strato volcanoes so steep?

13. Where are some other strato volcanoes located on Earth?

14. How does the location of strato volcanoes relate to tectonic plates?

Weekly Journal Response

Summarize what you have learned so far about volcanoes, earthquakes and plate tectonics. Be sure to describe your understanding of how volcanoes and earthquakes are related to plate tectonics. You may include a drawing to illustrate your understanding, if possible.

(Cuff, Carmichael & Willard, 2013)