Commentary: A Summary and Analysis of Twenty-Seven Years of Geoscience Conceptions Research

Kim A. Cheek[1]

ABSTRACT

Seventy-nine studies in geoscience conceptions appeared in peer-reviewed publications in English from 1982 through July 2009. Summaries of the 79 studies suggest certain recurring themes across subject areas: issues with terms, scale (temporal and spatial), role of prior experience, and incorrect application of everyday knowledge to geoscience phenomena. The majority of studies reviewed were descriptive and employed only one method of data collection and response type. Eleven-fourteen-year-olds and university undergraduates were most commonly represented in the samples. A small percentage of studies of geoscience conceptions of K-12 students made reference to standards documents or a curriculum as justification for the research design. More directed descriptive studies, along with greater parity between descriptive and intervention studies is needed. Greater attention to developmental theories of concept acquisition, national standards documents, and intersection with cognitive science literature are warranted.

INTRODUCTION

Research into students' conceptions in science has been going on for several decades. There is a large body of scientific conceptions literature, though there is comparatively less in the geosciences than in other scientific disciplines (Libarkin, S. Anderson, Science, Beilfuss, & Boone, 2005; Dodick & Orion, 2003a). Nevertheless, a substantial body of research into students' geoscience conceptions has appeared within the past twenty-seven years. It is prudent to periodically review the available research literature within a discipline and summarize what has been done to date. Reviews provide direction for future research, curricular and instructional decisions, and educational policy.

Two prior literature reviews provide a foundation for this paper. Dove's (1998) narrative review dealt with students' ideas about rocks, volcanoes, earthquakes, Earth's structure, landforms, weathering, erosion, and soil. The focus of her summary and conclusions was on commonalities among studies' results. She found that students tended to:

- Use everyday terms such as "pebble" in scientific contexts
- Confuse concepts that are closely related or are taught together
- Rely on insignificant features such as color to identify specimens
- Ascribe human or animal characteristics to objects or events
- Have trouble visualizing changes in Earth's surface features over time
- Generalize too broadly (all igneous rocks come from volcanoes)
- Lack sufficient background knowledge to acquire new geoscience concepts
- Hold explanatory ideas that mirror those held by earlier generations of scientists (Dove, 1998)

Dove noted that textbooks and teaching methodologies can be partly blamed for students' conceptual difficulties. In a desire to simplify concepts for novices, definitions and stereotypical schematics can lead students to erroneous conclusions about geoscience phenomena. Much of the research on student conceptions of geologic time and plate tectonics has been conducted since her review. It is important to determine whether her earlier conclusions apply to newer research and novel topics. Dove did not discuss methodologies of the studies she reviewed. With the research base that has developed in the eleven years since her review, a discussion of methodological trends is warranted.

King's (2008) more recent geoscience education review provides a broad overview of factors important in geoscience education, including geoscience conceptions. Like Dove, King's review did not discuss studies' methodologies. This paper updates the synthesis of Dove and King while also providing an overview of methodologies employed in these studies.

Seventy-nine studies dealing with geoscience conceptions that appeared in the literature between 1982 and July, 2009 were reviewed. An initial electronic database search was conducted. Additional articles were found through reference lists within articles and a hand search of major science education journals in which geoscience conceptions research appears. The review was limited to peer-reviewed journal articles in English. In a few instances, two articles by the same author(s) described one study albeit different aspects. In those cases, the two articles were reported together. Articles that argue for a particular teaching methodology but provide no data that tests the effect of the strategy on conceptual change were not included. Following the precedent of King (2008) and Dove (1998), the review was limited primarily to articles dealing with what has traditionally been seen as Earth science. Studies that would fall under the heading of Earth system science--oceanographic, astronomical, or atmospheric processes--were excluded with one exception. Climate change issues are frequently covered by the mainstream news media. They are some of the most significant geoscience issues of which the general public is aware, have implications for the entire Earth system, and particularly relate to human interactions with the Earth system. Understanding these issues is important for the development of an educated citizenry that can make wise decisions regarding sustainability. Thus, articles dealing with students' conceptions of climate

[1]Valley Forge Christian College, Department of Education; kacheek@vfcc.edu

change issues have been included in this review.

The seventy-nine studies were sorted into subject areas based upon their primary emphasis (Table 1). This was done to facilitate discussion of common themes across studies while generating a manageable number of categories. Sorting was done from a developmental perspective according to when a student would likely first be exposed to a particular topic in the U.S. (American Association for the Advancement of Science, 1993). This may not correspond to curriculum progressions outside the U.S. The choice of subject areas was based upon the primary emphasis of the study as stated by the authors. Findings that apply in another area are reported there as well. The *general geoscience* subject area includes studies whose aim was to probe conceptions across a range of geoscience topics. Findings reported in those studies were sorted into the remaining subject areas and added to the already tabulated studies to create column three of Table 1. Since many in this group describe results for multiple subject areas, the total number of studies listed in column three is greater than 79.

SUMMARY OF FINDINGS BY SUBJECT AREA

Key findings for each subject area are summarized. Results of the eleven general geoscience studies are discussed under the particular topic areas to which they apply. Summaries focus on recurring themes across studies.

Earth Materials & Structures

This section includes studies on rocks, minerals, clays, soil, renewable and nonrenewable energy sources, water, groundwater, & watersheds. Students at a variety of ages had difficulty identifying rock types or specific rocks and minerals (Finley, 1982; Stofflett, 1993; Blake, 2004). Identification frequently focused on surface features such as color. However, both Finley and Blake found that students developed more scientific understanding of minerals and rocks, respectively as a result of instruction. Across studies, broad generalizations were common. For example if a mineral can scratch glass it must be a diamond (Schoon, 1992; Schoon & Boone, 1998). Sometimes even university students ascribed human causality to geologic events or viewed rocks as if they are living things, e.g., pebbles grow to form rocks (Kusnick, 2002). Some preservice teachers (those preparing to teach 5-14-year-olds) believed that soils are put down as rock layers (Gosselin & Macklem-Hurst, 2002) perhaps because they focus on the horizons in a soil profile.

A contributing factor to these broad generalizations was a misunderstanding of terms. Word pairs such as minerals and rocks or soil and dirt were viewed as synonymous. Terms with multiple meanings were problematic, particularly those with vernacular as well as scientific meanings (Kusnick, 2002; Happs, 1984, 1985; Rule, 2005; Gosselin & Macklem-Hurst, 2002). For example, both preservice teachers and 11-12-year-olds tended to ascribe common everyday terms and meanings to phenomena rather than scientific ones, i.e., clay is something you use to make pottery (Rule, 2007), texture means "rough," "bumpy," or "sharp" (Ford, 2005, p. 286), or rocks are found in nature but are not building materials (Dove, 1996). Even 11-12-year-olds could supply a school definition of a term like "rock" after instruction. This didn't always mean that they had good conceptual understanding, however. Those same children tended to view the rock cycle as the cause of rock formation rather than a description of possible pathways through which lithospheric materials might pass (Ford, 2003). In one instance, learners did not generalize broadly enough. Oversby (1996) found that a majority of preservice teachers thought a footprint preserved in rock and a mammoth frozen in ice were not fossils.

Participants in these studies tended to view Earth as static and unchanging and believed many geologic processes require far shorter periods of time than they actually do. Kusnick (2002) says, "Students can quote the age of the Earth, but they still cite surprisingly short time scales in describing rock formation" (p. 35). Rule (2005) found that a significant number of preservice elementary teachers thought petroleum forms in hundreds of years or less. Similarly, some 11-17-year-olds and university students in Happs' (1984) study estimated the age of soil as less than 20 years. Others in the same sample said up to 100 million years. The latter figure may suggest that some students have little concept of the amount of time represented by 100 million years.

Studies dealing with groundwater and watersheds mirror the results of the research just reported. Students apply ideas about water storage and movement that apply at Earth's surface to groundwater. Several authors mention that students thought groundwater exists in

TABLE 1. NUMBER OF STUDIES BY SUBJECT AREA

Subject Area	Number of Studies	Number of Studies Reporting Data in Area
Earth materials & structures (rocks, minerals, groundwater, & watersheds)	17	21
Earth processes (water & carbon cycles, eutrophication, weathering, & erosion)	7	8
Earth's structure, plate tectonics, rock cycle, earthquakes, & volcanoes	14	22
Geologic time	10	18
Climate change processes (greenhouse effect, global warming, & stratospheric ozone depletion)	20	21
General geoscience	11	N.A.
Total	79	90

pools, lakes, and streams (Dickerson & Dawkins, 2004; Dickerson, Callahan, Van Sickle, & Hay, 2005; Ben-zvi-Assarf & Orion, 2005; Gosselin & Macklem-Hurst, 2002). The application of surface notions to subsurface features results in confusion regarding scale. Some students imagine that these underground storage features mirror the sizes of similar structures at Earth's surface For example, those who said groundwater is stored in underground pipes described them as of similar size to pipes in homes. This was not universally true; however, as others thought the sizes of underground structures are very different from comparable features at the surface (Dickerson et al., 2005).

Studies on watersheds suggest that children associate a watershed with a mountainous, rustic area rather than a more developed region (Shepardson, Wee, Priddy, Schellenberger, & Harbor, 2007). This "natural" view was also demonstrated in a study in which students were asked to draw a river basin (Dove, 1999). Many children drew pictures that indicated a largely rural view of river basins with no man-made features included. Whether this means that children think watersheds and river basins only exist in rural areas, or if it is indicative of something else such as an attempt to reproduce drawings they may have seen in textbooks is speculative. Dove also found most drew rivers flowing down the page or from left to right consistent with the way students in the UK read. It is not clear if these children think rivers can only flow in one direction, though undergraduate geology majors in a study on eutrophication believed that all rivers run north to south (Sell, Herbert, Stuessy, & Schielack, 2006). It would be interesting to see if this idea holds true across cultures, particularly those that read from right to left.

As in other studies in this section, misunderstanding of terms related to watersheds was evident. When asked to draw a watershed, a significant minority drew a shed that they said was used to hold water (Shepardson, Harbor, & Wee, 2005; Shepardson, Wee, Priddy, Schellenberger, & Harbor, 2007). Students in these studies tended to focus on atmospheric rather than surface or underground movement of water through a watershed, consistent with the research on groundwater in which subsurface movement and storage of water was poorly understood.

There were two intervention studies in this group. One was designed to determine whether using cartoons to teach 11-12-year-olds about rocks and minerals would result in increased performance on a post-test of their understanding (Rule & Auge, 2005). Students who were taught with the cartoons performed better than those in the control group (average gain of ten points vs. five points from pre- to post-test), and the effect size was large. The authors note the role played by student motivation in their results. Students in the experimental group demonstrated a high degree of excitement about the unit while some in the control group said it was "unfair" that other students were learning via cartoons and they were not (p. 555).

A second intervention study (Fortner, 2009) explored the effect of inquiry instruction on 4th and 5th graders' understanding of the problems associated with nonrenewable sources of energy and one possible source of renewable energy (solar power). Children's scores improved significantly from a pre- to post-test of their knowledge of renewable and nonrenewable energy sources. No control group is identified so it is not possible to comment on whether this particular series of lessons was more effective than another. The author does provide an extensive description of the lessons which could easily be replicated with another sample to provide additional data about their effectiveness.

Earth Processes

Studies in this section include the hydrologic and carbon cycles, weathering, erosion, and eutrophication. The rock cycle is discussed in the next section rather than here.

In his research with 5-14-year-olds, Bar (1989) reported that understanding of the hydrologic cycle develops as children around the age of 8 or 9 come to realize that water and then air are conserved (p. 495). Conversely, Ben-zvi-Asarf and Orion (2005) found that 12-15-year-olds in their study generally did not realize that matter is conserved in the Earth system. The discrepancy between these two studies regarding the age at which conservation of matter is grasped can be partly explained by the experimental designs. Students in Ben-zvi-Asarf and Orion's study were asked to agree/disagree with a series of statements. Less than half knew that the amount of water in the world's oceans was not increasing due to the flow of water from rivers to the ocean. In contrast, Bar viewed statements that attributed the existence of clouds to water vapor that had evaporated from puddles as evidence of conservation of water. While the age at which children understand conservation of matter is important, both studies agree that the concept is crucial to a full understanding of the hydrologic cycle. An incomplete understanding of conservation of water may also be evident in the responses of university students who failed to connect condensation of water vapor with precipitation (Sibley et al., 2007).

Belief in non-natural causes for the hydrologic cycle was also found. While 10-14-year-old children from Botswana (Taiwo, Ray, Motswiri, & Masene, 2001) held some scientific conceptions, they often simultaneously attributed aspects of the hydrologic cycle to actions of the gods or thought that precipitation was due to melting clouds. In another study, humans were seen to play a far greater role in the hydrologic cycle than they actually do. Confusion regarding scale was evident in this notion as students thought the total amount of water in the human body comprises a significant percentage of the total water on Earth (Ben-zvi-Assarf & Orion, 2005).

Students held more accurate conceptions of atmospheric aspects of the hydrologic cycle than movement of groundwater (Ben-zvi-Assarf & Orion, 2005; Shepardson, Wee, Priddy, Schellenberger, & Harbor, 2009). Sibley, et al. (2007) found that slightly more than one-fourth of the undergraduates they studied did not include groundwater in a diagram of the hydrologic cycle. As was mentioned in an earlier section, there was a tendency across studies to apply ideas about water storage and movement that apply at the surface to groundwater. Conceptions appear to be highly influenced by textbook drawings and not personal experience. When urban and suburban 9-18-year-olds were asked to draw the hydrologic cycle many drew mountainous landscapes rather than ones that would depict the hydrologic cycle in their local area (Shepardson et al., 2009). These findings are very similar to what was described in the previous section for watersheds.

Misapplication of terminology was identified as an issue in studies dealing with *Earth materials*. It also appears to be a factor in *Earth processes.* A study in which students were asked to distinguish between weathering and erosion illustrates (Dove, 1997). While weathering encompasses the breakdown of Earth materials by both physical and chemical means, students in Dove's study thought that chemical processes alone were examples of weathering. Weathering was associated with weather elements such as wind and rain. In contrast, erosion was seen as a physical process not related to weather elements. Students appeared to be reasoning on the basis of the common etymology of weather and weathering.

As described previously, students have a poor conception of scale when something is outside their ability to observe it directly such as groundwater. This difficulty with scale creates a conceptual barrier for a student who thinks that an oil molecule is larger than a bacterial cell (Sell et al., 2006).

Earth's Structure, Plate Tectonics, Rock Cycle, Earthquakes, and Volcanoes

It is difficult for students to make sense of Earth's changing surface without an understanding of plate tectonics, Earth's layered structure, heat transfer and the movement of material through the geosphere, the rock cycle, and visible results of tectonic activity such as earthquakes and volcanoes. In several studies (Blake, 2005; Lillo, 1994; DeLaughter, S. Stein, C. Stein, & Bain, 1998; Libarkin et al., 2005) students were asked to draw or describe what they would see if they could cut the Earth in half. Some 7-15-year-olds (Blake, 2005; Lillo, 1994) drew animals, humans, or an individual rock in the Earth's interior indicating no real conception of Earth's internal structure. Some university students as well as younger pupils drew flat layers inside a spherical Earth (Lillo, 1994; DeLaughter et al., 1998). Commonly, students drew concentric layers (Libarkin et al., 2005). Even children were able to create drawings with concentric layers as 89% of the 10-12-year-olds in Gobert's (2000) sample drew spatially correct interior models of the Earth. However, the authors point out that this does not indicate students have a clear understanding of Earth's internal structure. Layers were often drawn to exaggerate the size of the crust relative to other layers (Gobert, 2005). Even though terms such as crust, mantle, and core were used by students to explain their drawings, several of the authors report students appeared confused by those terms. At least a significant minority believed magma originates in Earth's core (Bisard, Aron, Francek, & Nelson, 1994; Dahl, S. Anderson, & Libarkin, 2005; Libarkin & Kurdziel, 2006). The standard drawing of convection cells found in many introductory geology textbooks could lead to such an interpretation. Sometimes, students may be misinterpreting information provided to them within a study itself. Gobert (2000) had 10-12-year-olds draw pictures "of the movement in the different layers of the Earth when volcanoes are erupting" (p. 941). Many of the children drew pictures with magma originating in the core. It is conceivable that they were interpreting the following prompt based upon a misunderstanding of what was meant by "currents."

> *As mentioned before, the core of the earth is very hot. The heat creates currents that rise up through the mantle. When these currents get near the top of the mantle, they push on the plates and force the plates to move in many directions.* (Gobert, 2000, p. 971)

While this statement in clear to a geoscientist, it is possible children may have thought of the word "currents" in light of currents of water in streams, rivers, or oceans. If this were the case, children may well have envisioned currents of magma moving from the core through the mantle and out a volcano.

Teachers as well as students hold alternative conceptions regarding Earth's structure. Their conceptions, like those of their students, sometimes demonstrate the incorrect application of everyday ideas and terms to a geoscience context. King (2000) found that more than 80% of 61 secondary science teachers thought the mantle was liquid. King gives examples of several textbooks containing erroneous information that indicates the mantle is molten. Some confusion may result not from incorrect information *per se* but from a misinterpretation based upon everyday experience. A widely used undergraduate geology textbook states, "Despite their strength, the rocks of the mesosphere [lower mantle] are still very hot and capable of very gradual flow" (Tarbuck & Lutgens, 2005, p. 21). A student with fairly minimal background knowledge in geoscience could easily infer from this that the mantle is liquid. The notion that rocks exhibit ductile flow under the right temperature and pressure conditions does not fit with an everyday experience with solids.

Commonsense ideas, some of which mirror former scientific views also abound. Marques and Thompson (1997a) found almost one-half of the 16-17-year-olds in their sample believed the deepest part of the oceans and the highest parts of the continents are in the center. They also believed that continental boundaries are plate boundaries. The view that the deepest parts of the oceans are in the center and continental boundaries are plate boundaries can be found in the scientific literature in the not too distant past.

Confusion regarding the location of tectonic plates (Libarkin et al., 2005), how plate tectonics relates to the present location of continents (Libarkin & Kurdziel, 2006), and an inability to accurately draw what occurs at plate boundaries (Sibley, 2005) has been reported among university students, including geology majors and graduate students. Sibley found some correlation between students' ability to produce accurate drawings and their scores on a visualization test. Although this connection was not explored in earlier studies within this group, the visual-spatial nature of geoscience is well-known (King, 2008) and may account for students' conceptual difficulties.

The only plate tectonics intervention study underscores the role of visual-spatial tasks in geoscience conceptions. Gobert and Clement (1999) investigated the effect of student—generated diagrams vs. student-generated summaries on conceptual understanding of plate tectonics. Ten-twelve-year-olds were divided into three groups. All read a short informational text about plate tectonics. The control group simply read the information. One experimental group read the information and wrote summaries of what they read, while the other experimental group read the information and drew diagrams about plate tectonics. Children wrote summaries and created drawings at several points while reading and all groups completed a post-test of their knowledge of the location of Earth's layers and heat transfer through the layers after reading. During reading the summary group's writings contained more content information than those in the drawing group. The diagram group outperformed both the summary and control groups on the post-test.

Three studies assessed the effectiveness of a particular intervention on students' understanding of the rock cycle. Stofflett (1994) investigated the effect of four different pedagogical strategies, one of which was a conceptual change strategy, on preservice elementary teachers' understanding of the rock cycle. Blake (2001, 2004) described the effect of using an aluminum can recycling analogy for the rock cycle on 9-11-year-olds' understanding. Students in the conceptual change group in Stofflett's study and those in the analogy group in Blake's research performed better on a post-test than students in other groups; however, their understanding was still incomplete. Stofflett notes that even though some students employed scientific vocabulary, they used it incorrectly.

One difficulty with the aluminum can recycling analogy is that there is a fixed path through which the aluminum can passes as part of the recycling process. This is not true with the rock cycle in which many paths are possible. Kali, Orion, and Eylon (2003) sought to help 12-13-year-olds develop the systems thinking necessary to understand the rock cycle with its multiple pathways. Students worked in small groups with a magnetic board to which they could affix cards to answer questions regarding a possible path of Earth materials through the rock cycle, e.g. the processes necessary to produce granite from exposed rhyolite (p. 554). Approximately three-fourths of the participants improved in their ability to apply systems thinking from the pre- to post-test.

Three studies probed earthquake conceptions. Ross and Shuell (1993) found that 5-12-year-old children lacked an understanding of tectonic processes responsible for earthquakes whether or not they had ever experienced one. University students in another study (Barrow & Haskins, 1996) who got their information about earthquakes from the mass media appeared to have a broader understanding than those who had experienced an earthquake themselves. Some Taiwanese 11-and-12-year-olds held mythical explanations for earthquake occurrence while others held both mythical and scientific ideas in tandem (Tsai, 2001). Tsai's study on earthquakes and Blake's (2005) on Earth's structure share a common theme. Supernatural forces were ascribed causality in the first and humans were seen as causal agents for volcanoes and mountains in the second. When dealing with children, this tendency to anthropomorphism must be acknowledged.

Students were also unclear as to why earthquakes and volcanoes are often studied together suggesting an unawareness of how both are related to plate movements (Libarkin et al., 2005). Many students hold very stereotypical views of the locations of earthquakes and volcanoes. They frequently equated volcanoes (and earthquakes in one study) with warm climates (DeLaughter et al., 1998; Libarkin & Kurdziel, 2001; Dahl et al., 2005).

Geologic Time

Understanding geologic time encompasses two distinct ideas. The first has to do with the ability to place events in Earth's history on a sufficiently large timescale in both relative and absolute positions on the scale. The second deals with the ability to conceive of processes that occur at very slow rates and therefore require very long periods of time. Most research into students' conceptions of geologic time has dealt with the former rather than the latter.

Ault (1982) was one of the first to explicitly probe children's conceptions of geologic time. He found that children who were able to accurately complete a sequencing task with a hypothetical compost pile were unable to transfer those ideas to rock outcrops in the local area. Even children who said the oldest rock layer was at the bottom (correct) often did so based on surface features such as "crumbliness." Some children in the sample held to an accretionary view of rock formation and said that the oldest rock layers were in the center. Both ideas underscore the role of everyday experience in students' conceptions. Many children may have noticed that older sidewalks are more likely to be crumbly than newer ones. Thus, in everyday experience, crumbliness could be indicative of age. An accretionary view fits with the experience of making a paper maché mask in which the first (oldest) layer of paper and paste is in the center.

Trend (1998, 2000, 2001a, 2001b) has investigated geologic time conceptions of 10-11-year-olds, 17-year-olds, primary teacher trainees (elementary preservice teachers), and in-service teachers. All groups hold similar ideas. They do well placing events in relative sequence on a time scale but have considerable difficulty with an absolute scale. In fact, when asked to specify an age for the Earth, estimates ranged from thousands of years to much older than the age of the universe. Similar confusion about the absolute age of the Earth by a wide variety of ages was documented by Oversby (1996). Trend says that individuals at all ages tend to think it terms of broad time categories. Adults have more well-defined ideas of long time periods than children, but still think in very broad, amorphous categories.

Hidalgo and Otero (2004) found that 16-year-olds and 19-20-year-olds were generally able to locate a geologic event in its correct temporal category, but they were less accurate the older the event. When asked to place four pictures in correct temporal order (invertebrate marine life, dinosaurs, mammals and birds, hominids), students completed the ordering tasks successfully. The authors note that this did not necessarily mean they had a good sense of the temporal order of these events. Rather, they used any and all clues available to them in the pictures to reason their way to the correct sequence. They also experienced great difficulty in assigning temporal labels to the events, a finding that is very consistent with Trend's work (1998, 2000, 2001a, 2001b).

Others have found that although conceptions of relative time are better than absolute, there are still difficulties (Dahl et al., 2005; Libarkin, Kurdziel, & S. Anderson, 2007; Petcovic & Ruhf, 2008). People equated the formation of the universe with the formation of Earth (Marques & Thompson, 1997b), believed a supercontinent existed at Earth's formation (Libarkin & S. Anderson, 2005), and alleged that life was present at or before Earth's formation (DeLaughter et al., 1998; Libarkin et al., 2005). They also thought that dinosaurs and cavemen lived contemporaneously (Schoon & Boone, 1998; Schoon, 1992), and that carbon-14 is the best method to determine the Earth's age (Rule, 2005).

There are hints in a number of these studies that a poor understanding of large numbers could partially explain why students have so much difficulty understanding geologic time (Trend, 1998, 2001b). In some cases, participants appeared to be merely mentioning the largest number they can think of with no real sense of the amount of time it represents, a point alluded to earlier in the section on *Earth materials.*

Dodick and Orion (2003a, 2003b) explored how Israeli adolescents understood geologic changes over time and the temporal relationships between adjacent strata in an outcrop. Their work is unique with its focus on the temporal order of geologic processes rather than the order of events on a timescale. They found that students had difficulty placing a series of geologic events in the correct temporal sequence. Generally older students outperformed younger ones though age was not always the best predictor of performance.

Duration in geologic time has been studied far less than temporal succession. Dodick and Orion (2003a, 2003b) utilized two tasks that probed adolescents' understanding of the duration of geologic events. In both cases students overwhelmingly concluded thicker strata require more time than thinner strata, and that if two layers were the same size the processes that gave rise to them must have required the same amount of time. Thus, there may be a spatial component to how students understand geologic time. Hidalgo and Otero (2004) found that students attributed folds to earthquakes, volcanoes, and tectonic plate collisions. Even those who said plate collisions were responsible for folds appeared to view such processes as requiring very short periods of time.

There is an issue that emerges when discussing students' conceptions of geologic time that is not mentioned in other areas. Some students may not misunderstand geologic time as much as they refuse to acknowledge it due to deeply held personal beliefs (Libarkin et al., 2007). This may be more of a concern in the U.S. as it is not mentioned in studies conducted in other countries. This, in turn, has implications for conceptions in other areas of geoscience. These students view processes and events as requiring far less time than they actually do.

Climate Change Processes

Twenty studies dealt with some facet of climate change, the greenhouse effect, or stratospheric ozone depletion. As has been noted in previous sections, students tended to generalize too broadly, assuming that one causes the other or all have the same underlying cause. A common view was that depletion of the ozone layer is responsible for the greenhouse effect (Boyes & Stanisstreet, 1993; Francis, Boyes, Qualter, & Stanisstreet, 1993; Dove, 1996; Rye, Rubba, & Wiesenmayer, 1997; Koulaidis, & Christidou, 1999; Spellman, Field, & Sinclair, 2003; Papadimitriou, 2004; Lee, Lester, Ma, Lambert, & Jean-Baptiste, 2007; Schuster, Filippelli, & Thomas, 2008; DeLaughter et al., 1998). Responses of this type were similar regardless of the age of the sample.

Perhaps these ideas become fused in students' minds because ozone depletion, global warming, and the greenhouse effect are often discussed together (Rye et al., 1997; Boyes, Stanisstreet, & Papantoniou, 1999). The melding of these ideas in students' minds means that they have inaccurate ideas about what causes each of these phenomena. Car emissions are viewed as causes of ozone depletion (Boyes & Stanisstreet, 1997; Mason & Santi, 1998; Leighton & Bisanz, 2003). Others think solid waste disposal contributes to global warming (Boyes & Stanisstreet, 1993; Francis et al., 1993; Koulaidis, & Christidou, 1999; Jeffries, Stanisstreet, & Boyes, 2001). Students are also confused about how the greenhouse effect and/or ozone depletion affects individuals and societies or other facets of the Earth system (Andersson & Wallin, 2000; Leighton & Bisanz, 2003; Dove, 1996).

Implicit in the results of many of these studies is the underlying notion that Earth is heated from above by incoming solar radiation rather than from long-wave radiation emitted from Earth's surface (Boyes & Stanisstreet, 1992; Mason & Santi, 1998; Koulaidis, & Christidou, 1999; Jeffries et al., 2001). This notion underscores the impact of everyday perceptual experience on students' conceptions, a theme found in earlier sections. This view accords well with the everyday experience of feeling warm on a hot, summer day.

Several authors note that students held scientific and nonscientific ideas in tandem (Boyes & Stanisstreet, 1998; Gautier, Deutsch, & Rebich, 2006; Lee et al., 2007). Determining the appropriate meaning for a word with multiple meanings or interpreting a term literally were both problematic. Österlind (2005) describes a Swedish student who confused a catalyst with a catalytic converter (identical terms in Swedish) and therefore failed to understand chlorine's role as a catalyst in stratospheric ozone depletion. Children (11-years-old or younger) sometimes interpreted the hole in the ozone layer as a tear in the sense that one might tear a piece of cloth (Leighton & Bisanz, 2003) or a hole that was burned by the Sun (Boyes & Stanisstreet, 1997). Of particular concern is the fact that students in several studies appeared to assign very short time periods to processes responsible for global warming (Papadimitriou, 2004) or how rapidly a drastic reduction in CO_2 emissions could be accomplished (Andersson & Wallin, 2000).

There was one intervention study in this group. A portion of a 12-lesson unit entitled, *The Living Planet,* was used to improve 10-11-year-olds' conceptions of the greenhouse effect and global warming (Lee et al., 2007). Students responded to a writing prompt about the greenhouse effect and global warming both before and after instruction. The authors describe the intervention as "partially effective" (p. 124) in that scientific conceptions increased from the pre- to post-assessment, but confusion persisted. Even after instruction, some children thought the greenhouse effect referred to a literal greenhouse. This is similar to results previously seen in studies of watersheds reported in an earlier section.

RECURRING THEMES

There are a number of themes that recur across studies that can provide direction to researchers and practitioners alike. First, Dove's (1998) conclusions hold true and indicate that little has changed in the intervening decade. Many of her conclusions relate to the idea that students apply everyday notions to geoscience phenomena. In some cases, that works well and their knowledge supports new understanding. In other instances, those everyday ideas serve as barriers to the acquisition of accurate geoscience knowledge. In addition to those conclusions, several other themes are apparent in more recent literature.

First, students appear to have a poor understanding of spatial and temporal scale. One reason for their confusion with spatial scale may relate to the incorrect application of everyday knowledge and experience. Students commonly think that subsurface features are similar to those that occur at the surface. When they are outside the realm of personal experience, their knowledge is particularly weak. A series of studies dealing with spatial scale has demonstrated this with many scientific concepts across disciplines (Tretter, Jones, & Minogue, 2006; Tretter, Jones, Andre, Negishi, & Minogue, 2006; Jones, Taylor, & Broadwell, 2009; Jones, Tretter, Taylor, & Oppewal, 2008).

A similar problem exists with temporal scale. Many individuals in these samples seriously underestimate the amount of time required for many geologic processes to occur. In fact, a poor understanding of long time periods impacts every area reviewed above not just those studies dealing specifically with geologic time. They also lack a sufficiently large enough time scale to deal with events in Earth's history. It is not clear what may account for this problem. It may well be that the problem reflects a difficulty with large quantities of any type and is not peculiar to time. There are hints that this may be the case. The underlying role of a concept of large numbers in geoscience conceptions is an area that warrants further investigation.

Dove found that students often ascribe animate characteristics to natural objects and events. Some students also view human and supernatural agents as the causes of geoscience events. Humans are seen as more influential than they are. Students who adopt these views generally also have trouble comprehending geologic time. Ideas of this type tend to be less prevalent among older learners than younger ones, suggesting the presence of a lower age limit at which certain concepts can be feasibly grasped.

There are hints that authors have some questions about the robustness of student conceptions. Shepardson, et al. (2007b) state, "It is possible that an individual student, under a different context, might convey a different conception" (p. 570). Kusnick (2002) expressed similar concerns. Minimally, this should cause caution in data interpretation.

METHODOLOGICAL ANALYSIS

A summary of conceptions research findings is important, but it is incomplete without some investigation of the methodologies used and how they may impact results. All research methodologies have trade-offs. A comprehensive research program in geoscience conceptions will need to be broad, not merely in terms of the topics investigated but also in the methodologies and samples used. Thus it is reasonable to map the types of studies that have been conducted, their data collection methods, and the age range of their samples. This can help point to directions for future research.

Type of Study

Studies were initially sorted based upon whether their primary aim was to describe conceptions in a particular area (descriptive) or to determine the effectiveness of a particular teaching strategy on student achievement and/ or compare achievement as a result of two or more teaching strategies (intervention). A few studies classified as descriptive mentioned an intervention but did not appear to test its efficacy. Of the 79 studies reviewed, only seven (9%) could be classified as intervention studies, making the remaining 72 (91%) descriptive. One study was primarily descriptive so it was included in that group, but it did contain an intervention component (Gobert, 2005). It is not surprising that much of this research is descriptive since the central goal has been to map the nature of student conceptions in the geosciences.

Method of Data Collection

The subject area of the study (as described in Table 1) was mapped against the method of data collection. Results of this analysis can be found in Table 2. Some studies used one method alone while many used multiple methods. Studies that used one type of response for the majority of the sample but used a second methodology for a subset were classified as multiple methods. Due to the use of standard rounding procedures, percents in the final column do not equal 100. Table 2 demonstrates an apparent preference for written data collection in *Earth materials, general geoscience*, and c*limate change processes* while in other areas methods were more evenly utilized. The preference for written responses in some areas may reflect the fact that the same author(s) conducted several studies and used a similar research design multiple times. The advantage to this approach is that data is collected across a wide range of sample populations, increasing confidence in the generalizability of findings. The danger is that the data collection method itself can influence results.

Overall forty-six percent of the studies employed written responses exclusively, either forced-choice or open -response. An additional 36% paired written responses with at least one other data collection method. This means that over 80% of the findings reported in the summary of studies come all or in part from written responses. Written responses make it easier to collect data from large samples, but make it difficult to probe more deeply unless they are paired with another response type. Facility with written expression is an important variable in the trustworthiness of results especially with younger participants. It cannot be assumed that all participants are equally proficient with written communication. Conversely, since geoscience conceptions research is relatively young compared to conceptions work in other science domains, large data sets provide a sense of the range of responses that can be found and enable researchers to follow up with more targeted research with smaller samples using other data collection methods.

Oral interviews were used exclusively in 14% of the studies while they were coupled with one or more other methods in an additional 23% of studies. Well-designed interviews facilitate the uncovering of students' thinking processes, at least at that moment in time. Coding and interpreting responses can be challenging. Fiscal, personnel, and time constraints make large scale studies of this type more difficult to conduct than those that rely solely or primarily on written responses.

Others (e.g., Orion and Ault 2007; King 2008) have noted the importance of spatial skills to success in the geosciences. Drawings can be useful in geoscience conceptions research for that reason. Interestingly, only 15% of the studies reviewed employed drawings and, then, always in concert with another data collection method. Eight studies (10%) utilized some type of performance task alone or in combination with another form of data collection. One (Finley, 1982) was a mineral identification task while the others used card sorts or concept maps.

Age Range of Sample

Studies were sorted by the age group of the sample, a difficult enterprise as some authors report participants' grade levels while others report ages. An attempt was made to normalize the data by converting grade levels to ages. Table 3 lists the grade level to age conversions used. There are several potential sources of error in this conversion. The first is that in a given class of students there are likely to be one or more students who are older or younger than the majority of their peers. While *most* U.S. first graders are six or seven-years-old, these classes

TABLE 2. METHODS OF DATA COLLECTION EMPLOYED

Response Type	Earth Materials	Earth Processes	Plate Tectonics, Earth's Shape	Geologic Time	General Geoscience	Climate Change Processes	Percent of Studies
Written only	**8**	**2**	4	2	**8**	12	46
Interviews only	2	1	3	0	1	4	14
Written & interviews	2	1	0	3	2	2	13
Written & drawings	2	1	3	0	0	0	8
Written, drawings, & interviews	0	2	3	0	0	0	6
Drawings & interviews	1	0	0	0	0	0	1
Written & observations	1	0	0	0	0	1	3
Task only	1	0	0	0	0	0	1
Written & task	0	0	1	4	0	0	6
Interviews & task	0	0	0	1	0	1	3
Total studies	17	7	14	10	11	20	

TABLE 3. GRADE TO AGE LEVEL CONVERSIONS FOR U.S. SCHOOLCHILDREN

Grade	Age level conversion	Grade	Age level conversion
Kindergarten	5-6 years	7th grade	12-13 years
1st grade	6-7 years	8th grade	13-14 years
2nd grade	7-8 years	9th grade	14-15 years
3rd grade	8-9 years	10th grade	15-16 years
4th grade	9-10 years	11th grade	16-17 years
5th grade	10-11 years	12th grade	17-18 years
6th grade	11-12 years		

contain an occasional five or eight-year-old. The second difficulty is that the age of the students within a class is dependent upon the time of year in which data was collected. If a study was conducted during the spring it is entirely possible that there are no longer any six-year-olds in the class. Grade level and age conversions match the normal ages of students in a particular grade in U.S. schools. Grade and age levels outside the U.S. may not correspond. Nonetheless, the conversion of grades to age levels permits a comparison of studies that is not as easily accomplished if information is left as reported by the authors. Table 3 allows readers outside the U.S. to make appropriate application to students in their country. Despite the possible sources of error, information about age ranges that may be over or underrepresented in geoscience conceptions research can be ascertained.

Figure 1 demonstrates the wide distribution of ages sampled across the studies. Since some of the studies were cross-age, no percentages are reported. Data in Figure 1 does not include two studies (Bisard et al., 1994; Schoon, 1992). Those authors report a range of ages within their samples but do not indicate if all ages within that range were represented. For example Schoon (1992) describes his sample as, "elementary, secondary, and adult students" (p. 209). It is not clear if "elementary students" includes children from every grade level within that range or some subset.

A preponderance of studies sampled 10-14-year-olds and university undergraduates. Preservice teachers are reported separately from the general undergraduate population. If the two categories had been collapsed they would have represented the second highest frequency just after 11-year-olds. In the U.S., Earth science is frequently taught to 11-14-year-olds (middle school). Thus, it is not surprising that many studies investigated conceptions of this population. University undergraduates represent a sample to which researchers have ready access. Additionally, U.S. introductory geoscience courses serve students from across the university so the views of science and non-science majors alike are represented. Those involved in teacher preparation programs (preservice teachers) are an important population since their understanding will impact that of their students.

Reference to Standards Documents

Education in the early 21st century is a content standards and assessment focused enterprise. In the U.S., the Project 2061 Benchmarks for Science Literacy

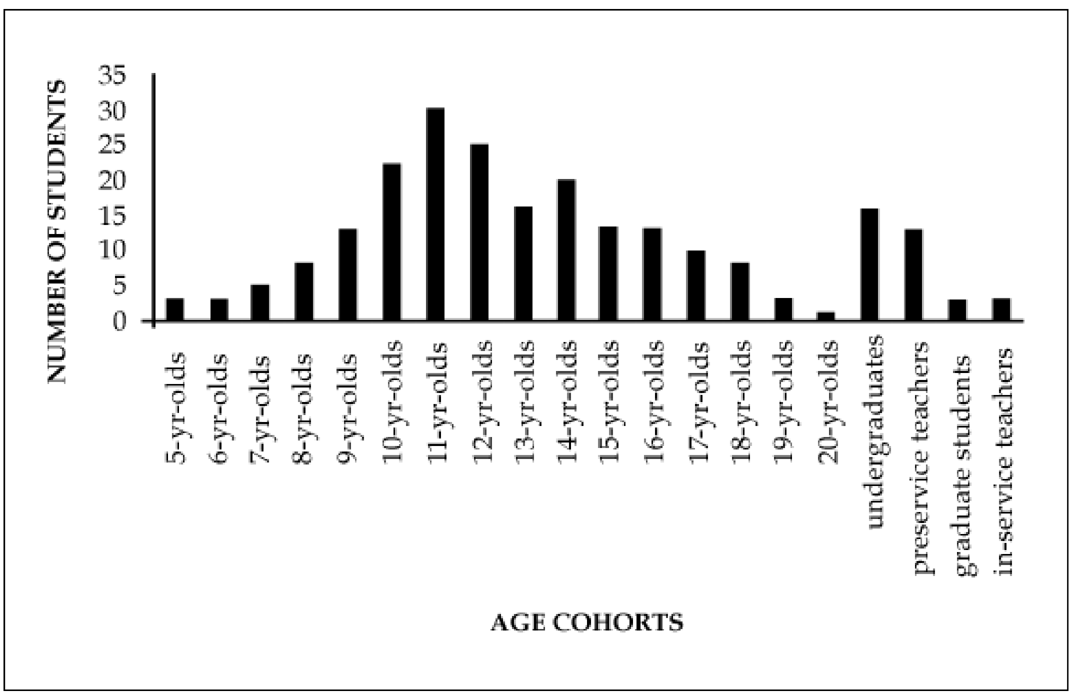

FIGURE 1. Age cohorts represented in samples.

(American Association for the Advancement of Science, 1993) and the National Science Education Standards (Center for Science, Mathematics, and Engineering Education, 1996) were written to articulate what students at various ages should know and be able to do. Although individual state standards documents currently guide state assessments, many are based to some degree upon one of the two national documents. Geoscience occupies various places in the curriculum in different countries, in some cases as part of an articulated national curriculum (see King 2008). It is reasonable to ask whether studies consult standards documents in the development of their research questions. Some studies reviewed for this paper predate the standards movement and evaluating them on that basis would be unfair. They were evaluated on whether or not they referenced a school curriculum as justification for their study's design. Papers that referenced standards documents or a curriculum and contained some explanation of why items in the instrument were chosen were rated "yes" on this criterion. If standards were mentioned in a general way, but no connection was made to the study design, that paper was rated "no." For example, a "no" was assigned if an author said national standards indicate more attention should be paid to geoscience topics in the K-12 curriculum, but said no more than that.

Studies exploring conceptions of preservice or in-service teachers can validly be assessed by their reference to standards documents since teachers should minimally be expected to possess the conceptual knowledge they are required to teach. There have been several recent attempts to articulate what an educated citizenry should understand about geoscience topics, most recently the Earth Science Literacy Initiative ("ESLI Home," n.d.). However, since there is not clear consensus on the essential geoscience knowledge for the general university population, studies focused on undergraduates were not included in this tabulation.

Although the standards movement has been a force in science education for at least two decades, its effect upon conceptions research in the geosciences has not been as great as one might expect. Thirty-five percent of the studies that had samples comprised exclusively or partially of K-12 students, preservice or in-service teachers made reference to standards documents (or a curriculum if the study predates the standards movement), while 65% did not.

CONCLUSIONS AND IMPICATIONS FOR FUTURE RESEARCH

As a whole, it appears we are still struggling to help students move from their everyday, perceptual notions about geoscience phenomena to more scientific conceptions. Problems with spatial and temporal scale appear to cut across subject areas. Scientific terminology is often used inaccurately or with minimal understanding. There are strong hints that inaccurate information or prototypical images in textbooks could be responsible for some erroneous conceptions. These underlying themes along with the results of the methodological analysis suggest avenues for future research.

The overwhelming majority of studies in geoscience conceptions have been descriptive rather than evaluating a particular intervention. Descriptive studies continue to have a place but perhaps with a different focus. It would be useful to explore the relationship among underlying ideas across topic areas. For example, how do concepts of spatial scale relate to how students understand a variety of geoscience topics? Do students with a poor understanding of large numbers have more difficulty understanding geologic time than those whose grasp is better?

Individuals at a variety of ages hold similar conceptions about geoscience topics. Instruction appears to have a minimal impact upon geoscience conceptions (Orion & Ault, 2007). Yet, constructivist teaching practices have been articulated and employed in many classrooms for several decades. What can explain why students still struggle to master the content?

One explanation may lie in the need to tie research design and curriculum more closely to developmental theories of concept acquisition. Early adolescents (ages 11-14) are often introduced to plate tectonics, but what should they be expected to master? If they understand that heat is unequally distributed within the Earth but are unclear about how that drives plate motion, is that a serious problem? This is not a trivial point. One of the difficulties in science instruction is that we spend considerable time reteaching concepts that were covered in earlier grades but not mastered. We must think seriously about what is developmentally appropriate, a concern that was raised decades ago in the larger science education research literature (Shayer & Adey, 1981).

It is easy to focus discussion on what students don't know (this review included). We must focus on what they *do* know. *How* do students acquire a particular scientific concept? Many inaccurate conceptions appear to be based upon everyday perceptual experiences. Students frequently hold scientific and nonscientific ideas in tandem and appear unconcerned about contradictions. But what causes their understanding to improve? Cross-age studies and longitudinal research can improve understanding of geoscience conceptual thinking across the K-16 span. Research by Vosniadou and her colleagues (e.g., Vosniadou & Brewer, 1992; Vosniadou, Skopeliti, & Ikospentaki, 2004) on young children's ideas about Earth's shape provides a model for a systematic research program on conceptual change in a specific area. The bodies of research on geologic time and climate change processes have made the greatest strides in this area, but there is still much we do not know. Recent discussion about learning progressions, or the ways thinking about a subject becomes more sophisticated with age, provides a framework for future geoscience conceptions research (Hmelo-Silver & Duncan, 2009). Ideally, geoscience education researchers will combine their expertise with developmental and cognitive psychologists to develop a fuller picture of how students acquire geoscience concepts.

Geoscience education varies considerably in different countries (King, 2008) and within countries. Exposure to specific topics happens at different ages and means that students in one place may bring significantly more background knowledge to a task than those in another location. A few nations dominate the existing literature. Thirty-nine of the 79 studies reviewed here had samples comprised exclusively of U.S. students and an additional 20 had samples solely from the UK. The use of similar experimental designs with students from different countries like that done in the area of climate change (Boyes & Stanisstreet, 1993; Boyes et al., 1999) can provide data about broad patterns of thinking that go beyond specific cultures.

Intervention studies can usefully test theories that emerge from the more targeted descriptive studies outlined above and can influence how geoscience is taught. Well-designed intervention studies that demonstrate the effectiveness of a particular curriculum or pedagogical strategy can improve the quality of instruction in classrooms. Intervention studies can test out the possible role played by prototypical textbook drawings on students' conceptions. Concerns about their role are only anecdotal at present and need to be tested. Information of this type could be especially useful to educational policy makers, who make textbook adoption decisions, although this will necessitate increased dialog between geoscience education researchers and practitioners.

Conceptions research in the geosciences should be more closely tied to standards documents. Rock and mineral units are part of many elementary school science programs in the U.S. Research on how 5-11-year-old children understand rocks and minerals should focus on the content they are expected to master. If a particular concept is not part of the curriculum for that age level, we cannot expect large numbers of children to understand it.

Much of the reviewed research has collected data via written responses. Drawings, tasks, and other visual means of data collection are underused. This is surprising in a discipline in which visual-spatial reasoning is so important. The use of computer animations as a means of data collection could be useful in allowing students to "experience" geoscience events that would otherwise be impossible. The effectiveness of computer animations and 3D images as teaching tools should also be explored since a common theme across subject areas is that students have difficulty with geoscience concepts with which they have no direct experience.

The positive news is that we know far more about student conceptions in geoscience than we did 27 years ago. Yet, there is still much to learn. Improving the linkages between standards documents and developmental theories of concept acquisition, along with an increased focus on intervention studies, will increase the utility of the research for the research community, public policy makers, and practitioners.

REFERENCES

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

Andersson, B., & Wallin, A., 2000, Students' understanding of the greenhouse effect, the societal consequences of reducing CO_2 emissions and the problem of ozone layer depletion: Journal of Research in Science Teaching, v. 37, p. 1096-1111.

Ault, C., 1982, Time in geological explanations as perceived by elementary-school students: Journal of Geological Education, v. 30, p. 304-309.

Bar, V., 1989, Children's views about the water cycle: Science Education, v. 73, p. 481-500.

Barrow, L., & Haskins, S., 1996, Earthquake knowledge and experiences of introductory geology students: Journal of College Science Teaching, v. 26, p. 143-146.

Ben-zvi-Assarf, O., & Orion, N., 2005, A study of junior high students' perceptions of the water cycle: Journal of Geoscience Education, v. 53, p. 366-373.

Bisard, W., Aron, R., Francek, M., & Nelson, B., 1994, Assessing selected physical science and earth science misconceptions of middle school through university preservice teachers: Journal of College Science Teaching, v. 24, p. 38-42.

Blake, A., 2004, Helping young children to see what is relevant and why: Supporting cognitive change in earth science using analogy: International Journal of Science Education, v. 26, p. 1855-1873.

____, 2005, Do young children's ideas about the Earth's structure and processes reveal underlying patterns of descriptive and causal understanding in earth science? Research in Science & Technological Education, v. 23, p. 59-74.

____, (2001). Developing young children's understanding: An example from earth science. Evaluation and Research in Education, v. 15, p. 154-163.

Boyes, E., & Stanisstreet, M., 1993, The 'greenhouse effect': children's perceptions of causes, consequences and cures: International Journal of Science Education, v. 15, p. 531-552.

____, 1997. The environmental impact of cars: Children's ideas and reasoning: Environmental Education Research, v. 3, p. 269-282.

____, 1992, Students' perceptions of global warming: International Journal of Environmental Studies, v. 42, p. 287-300.

____, 1998, High school students' perceptions of how major global environmental effects might cause skin cancer: The Journal of Environmental Education, v. 29, p. 31-36.

____, 1997, Children's models of understanding of two major global environmental issues (ozone layer and greenhouse effect): Research in Science & Technological Education, v. 15, p. 19-28.

Boyes, E., Stanisstreet, M., & Papantoniou, V. S., 1999, The ideas of Greek high school students about the "ozone layer": Science Education, v. 83, p. 724-737.

Center for Science, Mathematics, and Engineering Education, 1996, National Science Education Standards: Washington, D.C., National Academy Press.

Dahl, J., Anderson, S., & Libarkin, J., 2005, Digging into earth science: Alternative conceptions held by K-12 teachers: Journal of Geoscience Education, v. 12, p. 65-68.

DeLaughter, J., Stein, S., Stein, C., & Bain, K., 1998, Preconceptions abound among students in an introductory earth science course: Eos, v. 79, p. 429-436.

Dickerson, D., Callahan, T., Van Sickle, M., & Hay, G., 2005, Students' conceptions of scale regarding groundwater: Journal of Geoscience Education, v. 53, p. 374-380.

Dickerson, D., & Dawkins, K., 2004, Eighth grade students' understandings of groundwater: Journal of Geoscience Education, v. 52, p. 178-181.

Dodick, J., & Orion, N., 2003a, Cognitive factors affecting student understanding of geologic time: Journal of Research in Science Teaching, v. 40, p. 415-442.

____, 2003b, Measuring student understanding of geological time: Science Education, v. 87, p. 708-731.

Dove, J., 1998, Students' alternative conceptions in Earth science:

A review of research and implications for teaching and learning: Research Papers in Education, v. 13, p. 183-201.
____, 1996, Student teacher identification of rock types: Journal of Geoscience Education, v. 44, p. 266-269.
____, 1999, Exploring a hydrological concept through children's drawings: International Journal of Science Education, v. 21, p. 485-497.
____, 1997, Student ideas about weathering and erosion: International Journal of Science Education, v. 19, p. 971-980.
____, 1996, Student teacher understanding of the greenhouse effect, ozone layer depletion and acid rain: Environmental Education Research, v. 2, p. 89-100.
ESLI Home, (n.d.), http://www.earthscienceliteracy.org/.
Finley, F., 1982, An empirical determination of concepts contributing to successful performance of a science process: A study of mineral classification: Journal of Research in Science Teaching, v. 19, p. 689-696.
Ford, D., 2005, The challenge of observing geologically: Third graders' descriptions of rock and mineral properties: Science Education, v. 89, p. 276-295.
____, 2003, Sixth graders' conceptions of rocks in their local environments: Journal of Geoscience Education, v. 51, p. 365 -372.
Fortner, S. K., 2009, Fourth and fifth grade students learn about renewable and nonrenewable energy through inquiry: Journal of Geoscience Education, v. 57, p. 121-127.
Francis, C., Boyes, E., Qualter, A., & Stanisstreet, M., 1993, Ideas of elementary students about reducing the "greenhouse effect": Science Education, v. 77, p. 375-392.
Gautier, C., Deutsch, K., & Rebich, S., 2006, Misconceptions about the greenhouse effect: Journal of Geoscience Education, v. 54, p. 386-395.
Gobert, J., 2000, A typology of causal models for plate tectonics: Inferential power and barriers to understanding: International Journal of Science Education, v. 22, p. 937-977.
____, 2005, The effects of different learning tasks on model-building in plate tectonics: Diagramming versus explaining: Journal of Geoscience Education, v. 53, p. 444-455.
Gobert, J., & Clement, J., 1999, Effects of student-generated diagrams versus student-generated summaries on conceptual understanding of causal and dynamic knowledge in plate tectonics: Journal of Research in Science Teaching, v. 36, p. 39-53.
Gosselin, D., & Macklem-Hurst, J., 2002, Pre/post-knowledge assessment of an earth science course for elementary/ middle school education majors: Journal of Geoscience Education, v. 50, p. 169-175.
Happs, J., 1984, Soil genesis and development: Views held by New Zealand students: Journal of Geography, v. 83, p. 177-180.
Happs, J., 1985, Regression in learning outcomes: Some examples from the earth sciences: European Journal of Science Education, v. 7, p. 431-443.
Hidalgo, A., & Otero, J., 2004, An analysis of the understanding of geological time by students at secondary and post-secondary level: International Journal of Science Education, v. 26, p. 845-857.
Hmelo-Silver, C., & Duncan, R. G. eds, 2009, Special issue: Learning progressions: Journal of Research in Science Teaching, v. 46, p. 605-737.
Jeffries, H., Stanisstreet, M., & Boyes, E., 2001, Knowledge about the 'greenhouse effect': Have college students improved? Research in Science & Technological Education, v. 19, p. 205-221.
Jones, M. G., Taylor, A., & Broadwell, B., 2009, Concepts of scale held by students with visual impairment: Journal of Research in Science Teaching, v. 46, p. 506-519.
Jones, M. G., Tretter, T., Taylor, A., & Oppewal, T., 2008, Experienced and novice teachers' concepts of spatial scale: International Journal of Science Education, v. 30, p. 409-429.
Kali, Y., Orion, N., & Eylon, B., 2003, Effect of knowledge integration activities on students' perception of the Earth's crust as a cyclic system: Journal of Research in Science Teaching, v. 40, p. 545-565.
King, C., 2008, Geoscience education: An overview: Studies in Science Education, v. 44, p. 187-222.
____, 2000, The Earth's mantle is solid: Teachers' misconceptions about the Earth and plate tectonics: School Science Review, v. 82, p. 57-64.
Koulaidis, V., & Christidou, V., 1999, Models of students' thinking concerning the greenhouse effect and teaching implications: Science Education, v. 83, p. 559-576.
Kusnick, J., 2002, Growing pebbles and conceptual prisms--understanding the source of student misconceptions about rock formation: Journal of Geoscience Education, v. 50, p. 31 -39.
Lee, O., Lester, B., Ma, L., Lambert, J., & Jean-Baptiste, M., 2007, Conceptions of the greenhouse effect and global warming among elementary students from diverse languages and cultures: Journal of Geoscience Education, v. 55, p. 117-125.
Leighton, J., & Bisanz, G., 2003, Children's and adults' knowledge and models of reasoning about the ozone layer and its depletion: International Journal of Science Education, v. 25, p. 117-139.
Libarkin, J., & Anderson, S., 2005, Assessment of learning in entry-level geoscience course: Results from the Geoscience Concept Inventory: Journal of Geoscience Education, v. 53, p. 394-401.
Libarkin, J., Anderson, S., Science, J. D., Beilfuss, M., & Boone, W., 2005, Qualitative analysis of college students' ideas about the Earth: Interviews and open-ended questionnaires: Journal of Geoscience Education, v. 53, p. 17-26.
Libarkin, J., & Kurdziel, J., 2006, Ontology and the teaching of Earth system science: Journal of Geoscience Education, v. 54, p. 408-413.
____, 2001, Research methodologies in science education: Assessing students' alternative conceptions: Journal of Geoscience Education, v. 49, p. 378-383.
Libarkin, J., Kurdziel, J., & Anderson, S., 2007, College student conceptions of geological time and the disconnect between ordering and scale: Journal of Geoscience Education, v. 55, p. 413-422.
Lillo, J., 1994, An analysis of the annotated drawings of the internal structure of the Earth made by students aged 10-15 from primary and secondary schools in Spain: Teaching Earth Sciences, v. 19, p. 83-89.
Marques, L., & Thompson, D., 1997a, Misconceptions and conceptual change concerning continental drift and plate tectonics among Portuguese students aged 16-17: Research in Science & Technological Education, v. 15, p. 195-225.
____, 1997b, Portuguese students' understanding at ages 10-11 and 14-15 of the origin and nature of the Earth and the development of life: Research in Science & Technological Education, v. 15, p. 2-22.
Mason, L., & Santi, M., 1998, Discussing the greenhouse effect: Children's collaborative discourse reasoning and conceptual change: Environmental Education Research, v. 4, p. 67-85.
Orion, N., & Ault, C., 2007, Learning Earth Sciences, *in* Handbook of Research on Science Education, p. 653-687, Mahwah, NJ, Lawrence Erlbaum Associates.
Österlind, K., 2005, Concept formation in environmental education: 14-year olds' work on the intensified greenhouse effect and the depletion of the ozone layer: International Journal of Science Education, v. 27, p. 891-908.
Oversby, J., 1996, Knowledge of earth science and the potential for its development: School Science Review, v. 78, p. 91-97.

Papadimitriou, V., 2004, Prospective primary teachers' understanding of climate change, greenhouse effect, and ozone layer depletion: Journal of Science Education and Technology, v. 13, p. 299-307.

Petcovic, H., & Ruhf, R., 2008, Geoscience conceptual knowledge of preservice elementary teachers: Results from the Geoscience Concept Inventory: Journal of Geoscience Education, v. 56, p. 251-260.

Ross, K., & Shuell, T., 1993, Children's beliefs about earthquakes: Science Education, v. 77, p. 191-205.

Rule, A., 2005, Elementary students' ideas concerning fossil fuel energy: Journal of Geoscience Education, v. 53, p. 309-318.

____, 2007, Preservice elementary teachers' ideas about clays: Journal of Geoscience Education, v. 55, p. 210-220.

Rule, A., & Auge, J., 2005, Using humorous cartoons to teach mineral and rock concepts in sixth grade science class: Journal of Geoscience Education, v. 53, p. 548-558.

Rye, J., Rubba, P., & Wiesenmayer, R., 1997, An investigation of middle school students' alternative conceptions of global warming: International Journal of Science Education, v. 19, p. 527-551.

Schoon, K., 1992, Students' alternative conceptions of earth and space: Journal of Geological Education, v. 40, p. 209-214.

Schoon, K., & Boone, W., 1998, Self-efficacy and alternative conceptions of science of preservice elementary teachers: Science Education, v. 82, p. 553-568.

Schuster, D., Filippelli, G., & Thomas, C., 2008, Secondary students' subject matter representations of climate change: Journal of Geoscience Education, v. 56, p. 307-316.

Sell, K., Herbert, B., Stuessy, C., & Schielack, J., 2006, Supporting student conceptual model development of complex earth systems through the use of multiple representations and inquiry: Journal of Geoscience Education, v. 54, p. 396-407.

Shayer, M., & Adey, P., 1981, Towards a science of science of science teaching--Cognitive development and curriculum demand: London, Heinemann Educational Books.

Shepardson, D., Harbor, J., & Wee, B., 2005, Water towers, pump houses, and mountain streams: Students' ideas about watersheds: Journal of Geoscience Education, v. 53, p. 381-386.

Shepardson, D., Wee, B., Priddy, M., Schellenberger, L., & Harbor, J., 2007, What is a watershed? Implications of student conceptions of environmental science education and the National Science Education Standards: Science Education, v. 91, p. 554-578.

Shepardson, D., Wee, B., Priddy, M., Schellenberger, L., & Harbor, J., 2009, Water transformation and storage in the mountains and at the coast: Midwest students disconnected conceptions of the hydrologic cycle: International Journal of Science Education, v. 31, p. 1447-1471.

Sibley, D., 2005, Visual abilities and misconceptions about plate tectonics: Journal of Geoscience Education, v. 53, p. 471-477.

Sibley, D., Anderson, C., Heidemann, M., Merrill, J., Parker, J., & Szymanski, D., 2007, Box diagrams to assess students' systems thinking about the rock, water, and carbon cycles, Journal of Geoscience Education, v. 55, p. 128-146.

Spellman, G., Field, K., & Sinclair, J., 2003, An investigation into UK higher education students' knowledge of global climatic change: International Research in Geographical and Environmental Education, v. 12, p. 6-17.

Stofflett, R. T., 1993, Preservice elementary teachers' knowledge of rocks and their formation: Journal of Geological Education, v. 41, p. 226-230.

Stofflett, R. T., 1994, Conceptual change in elementary school teacher candidate knowledge of rock-cycle processes: Journal of Geological Education, v. 42, p. 494-499.

Taiwo, A., Ray, H., Motswiri, M., & Masene, R., 2001, Perceptions of the water cycle among primary school children in Botswana: International Journal of Science Education, v. 21, p. 413-429.

Tarbuck, E., & Lutgens, F., 2005, Earth: An introduction to physical geology, 8th ed., Upper Saddle River, NJ, Prentice Hall.

Trend, R., 1998, An investigation into understanding of geological time among 10- and 11-year-old children: International Journal of Science Education, v. 20, p. 973-988.

____, 2000, Conceptions of geological time among primary teacher trainees, with reference to their engagement with geoscience, history, and science: International Journal of Science Education, v. 22, p. 539-555.

____, 2001a, An investigation into the understanding of geological time among 17-year-old students, with implications for the subject matter knowledge of future teachers: International Research in Geographical and Environmental Education, v. 10, p. 298-321.

____, 2001b, Deep time framework: A preliminary study of U.K. primary teachers' conceptions of geological time and perceptions of geoscience: Journal of Research in Science Teaching, v. 38, p. 191-221.

Tretter, T., Jones, M. G., Andre, T., Negishi, A., & Minogue, J., 2006, Conceptual boundaries and distances: Students' and experts' concepts of the scale of scientific phenomena: Journal of Research in Science Teaching, v. 43, p. 282-319.

Tretter, T., Jones, M. G., & Minogue, J., 2006, Accuracy of scale conceptions in science: Mental maneuverings across many orders of spatial magnitude: Journal of Research in Science Teaching, v. 43, p. 1061-1085.

Tsai, C., 2001, Ideas about earthquakes after experiencing a natural disaster in Taiwan: An analysis of students' worldviews: International Journal of Science Education, v. 23, p. 1007-1016.

Vosniadou, S., & Brewer, W., 1992, Mental models of the Earth: A study of conceptual change in childhood: Cognitive Psychology, v. 24, p. 535-585.

Vosniadou, S., Skopeliti, I., & Ikospentaki, K., 2004, Modes of knowing and ways of reasoning in elementary astronomy: Cognitive Development, v. 19, p. 203-222.