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Elementary Children's Retrodictive Reasoning about Earth Science

Julie C. LIBARKIN*
Michigan State University, East Lansing MI, USA

Matthew H. SCHNEPS
Harvard-Smithsonian Center for Astrophysics, Cambridge MA, USA

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Abstract

We report on interviews conducted with twenty-one elementary school children (grades 1-5) about a number of Earth science concepts. These interviews were undertaken as part of a teacher training video series designed specifically to assist elementary teachers in learning essential ideas in Earth science. As such, children were interviewed about a wide array of earth science concepts, from rock formation to the Earth's interior. We analyzed interview data primarily to determine whether or not young children are capable of inferring understanding of the past based on present-day observation (retrodictive reasoning) in the context of Earth science. This work provides a basis from which curricula for teaching earth and environmental sciences can emerge, and suggests that new studies into the retrodictive reasoning abilities of young children are needed, including curricula that encourage inference of the past from modern observations.

Keywords: Earth Science, Reasoning, Retrodiction.

Introduction

This paper discusses the nature of children's reasoning about earth phenomena and processes, and specifically the extent to which retrodictive reasoning is evident in their discourse. We utilize a set of twenty-one interviews with elementary-aged children as the data set from which evidence of retrodictive reasoning emerged. We also documented the presence of alternative conceptions about the earth and considered the extent to which these alternative conceptions interfered with reasoning.

Retrodictive Reasoning in Earth Science

Retrodiction, the interpretation of present-day evidence to infer ancient processes, lies at the heart of much of earth science (e.g., Ault, 1998). While prediction has a role in earth science (e.g., for forecasting natural hazards or extrapolating the impact of human actions on natural

* ✉ Center for Integrative Studies in General Sciences & Dept. of Geological Sciences, Michigan State University, 288 Farm Lane, 206 Natural Science, East Lansing, MI USA 48824, Phone: 011+1+517-355-8369, E-mail: libarkin@msu.edu

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systems), retrodiction lies at the heart of all fields associated with paleo-processes, including geology, evolutionary biology, and cosmology. Interestingly, the concept of retrodiction is not commonly found in discourse about scientific reasoning that emerges from the science education community (Sibley, 2009), perhaps because predictive domains of science dominate the field. At the same time, retrodictive reasoning is of vital importance because of the role it plays in public debate about topics such as evolution, the creation of the universe, and the age of the Earth.

What are the unique characteristics of retrodictive reasoning? Retrodictive reasoning requires the understanding that patterns present in the modern world are the imprints of processes that have already occurred. As a consequence of this recognition, retrodictive reasoners must be able to extrapolate possible causes for these patterns, balance the probability of one specific cause against the likelihood of another, and rationalize a preference for one particular event resulting in an observed pattern. In this way, retrodictive reasoners recognize the role of causation in the production of patterns; interestingly, not all people are able to link processes and patterns together (Libarkin & Kurdziel, 2006). Within this ontology also lies the need for using narrative to explain phenomena (Norris et al., 2005) as well as reasoning about time.

Retrodictive reasoning about earth systems is inherently connected to systems thinking (Kali et al., 2003; Lawton, 2001). Systems thinkers must recognize that processes, the events that result in observable patterns, often interact to produce surprising results. Recognizing not only singular events but also the confluence of events is the hallmark of an effective systems thinker. Systems thinking also requires an understanding that processes, particularly within complex system like the Earth, do not always interact in linear ways. Non-linear processes, including negative and positive feedback loops, are important components of Earth systems thinking for both modern and ancient Earth. Retrodictive reasoning is inherently different from predictive reasoning. Both a process and its result are observable when they are occurring in real time, thus allowing a prediction to be tested. A process that has already occurred is not observable; one can only engage in experiments, in the lab or through observable natural systems, which replicate the process and look for results consistent with the original observation. In retrodiction, one can never actually observe the original process in action. This results in interesting problems from a scientific perspective; one can never completely disprove a hypothesis about a process that has long since occurred. One can only engage in a "more likely than not", or vice versa, standard.

Curricula that explicitly address retrodiction, even in its simplest forms, are surprisingly uncommon in the earth sciences especially for young children, although inquiry in Earth science education requires attention to retrodiction (Pyle, 2008). Existing studies demonstrate that middle and high school students can engage in retrodictive reasoning about possible evolutionary pathways through inquiry with hominid skulls and radiometric data (Thomson & Chapman Beall, 2008). Similarly, geology majors in a capstone course specifically oriented towards retrodiction in global systems reported better understanding of Earth's spheres after engaging in the course as well as more confidence in their ability to retrodict patterns based on observable modern processes (Sunderlin, 2009).

Alternative Conceptions in Earth Science

Although alternative conceptions are not the focus of this study, the students in our interviews present a number of non-scientific ideas that warrant discussion of alternative conceptions here. A growing body of literature has documented the alternative conceptions about Earth's systems held by elementary, secondary, and advanced students (see reviews of Cheek, 2010; Dove, 1998; King, 2008). These conceptions provide a window into the reasoning that might be occurring as students interact with Earth science concepts and phenomena, as well as insight into the potential difficulties students may face in the classroom. An understanding of alternative conceptions is vital for teachers interested in aligning curriculum with student needs, and exposure to the ideas of others can provide students themselves with a gateway into learning complex material.

Alternative conceptions about Earth science have been documented across the Earth system and across age groups. For the purposes of this paper, we focus on alternative conceptions related to the topics covered in our study, including geologic time, particularly as it relates to the timing and rate of Earth processes, rock and soil formation, and deep Earth processes related to, for example, plate tectonics and magma formation. Studies of student ideas about Earth science are much rarer than in other disciplines. Where possible, we report on studies of young children, and include studies of older students (high school, college) where relevant studies of young children are not available.

Student conceptions about Earth's surface processes are often related to their personal observations of the natural world. For example, alternative conceptions about rock formation mechanisms can be understood in the context of observable surficial processes. College students in two studies (Kortz & Murray, 2009; Kusnick, 2002) articulated the idea that rocks form when water dries up or when water deposits material into piles; the simple acts of drying and depositing generate aggregate rocks. Younger students also describe rocks as growing from smaller objects or pebbles (Ault, 1984; Blake, 2005; Dal, 2007), an idea that may also be present in older students (Kusnick, 2002). The relationship between rocks and soils is also sometimes misunderstood, with some teachers believing that soils are deposited as rock layers (Gosselin & Macklem-Hurst, 2002). Happs (1984) noted particularly the importance of geologic time in understanding soil formation, and many of the aforementioned studies note difficulty students have in conceptualizing deep time.

Conceptions about deep Earth processes may more often be driven by instruction, rather than personal experience. Phenomena that are not directly tangible but are rather recognized by their effects, such as plate tectonics, geomagnetism, and gravity, can be particularly difficult for students in Earth science courses to understand (Libarkin & Kurdziel, 2006). This can result in confusion at basic levels, such as with simple terminology used to explain deep Earth processes (e.g., Libarkin et al., 2005), and at more conceptual levels. For example, students may believe that earthquakes push tectonic plates (Barrow & Haskins, 1996; Ross & Shuell, 1993), that mountains simply grow (e.g., Muthukrishna et al., 1993; Trend et al., 2000), or that volcanic magma originates at the Earth's core (Nelson et al., 1992). Students also draw a surprising array of models of the Earth's interior when asked to imagine cutting the Earth in half, including an Earth containing flat or no layers (e.g., Blake, 2005; DeLaughte et al., 1998; Libarkin et al., 2005; Lillo, 1994). The physical location of tectonic plates and the physical state of Earth's interior are also areas of significant confusion.

Student ideas about geologic time have focused on understanding of the order of events as well as the long timescales ('deep time') inherent to many Earth processes. Ault (1982) recognized that young children are able to reason about relative time, an ability that is found across age ranges (e.g., Dahl, Anderson, & Libarkin, 2005; Libarkin et al., 2005; Trend, 1998, 2000, 2001). A number of alternative conceptions about the relative ordering of events have been identified, including that man and classical dinosaurs co-existed (Schoon, 1995), life and supercontinents existed when Earth first formed (Libarkin et al., 2005), and similar ideas related to the misunderstanding of the order and scale of geologic events. The idea that temporal reasoning is unique from other abilities (Montangero, 1996) has also been applied to studies of high school students, with the conclusion that difficulties in reasoning about deep time may be related to deficiencies in diachronic thinking (Dodick & Orion, 2003). Similarly, Trend (1998) suggests that mathematical difficulties associated with understanding large numbers may inhibit understanding of deep time.

Aim of the Study

The Earth sciences have generally not received as much attention within science education as biology, chemistry, and physics have, although a growing recognition of the importance of Earth science in schooling and global discourse is increasing the attention paid to it and related disciplines by science educators (Lewis & Baker, 2009). Our goal in undertaking this study is to further the understanding that teachers and researchers have about the ways in which children reason about Earth processes. To further this goal, we analyzed student ability to engage in simple retrodictive reasoning, as reflected in their discourse about Earth processes, and utilized this opportunity to also document the presence of alternative conceptions.

Based on existing work that clearly shows predictive reasoning ability among children (i.e., Zimmerman, 2000), we hypothesized that elementary students would be capable of engaging in the aspects of simple retrodictive reasoning needed to reason in Earth science. We present evidence of retrodictive reasoning as suggested by student discourse, and considered the role that age might play in student reasoning ability. Secondarily, we hypothesized that, given the limited research into children's alternative conceptions about Earth science, confirmation of existing studies and new alternative conceptions about Earth processes and phenomena would be evident in student responses.

Methods

Context

Interviews with twenty-one elementary students were analyzed for this study. These data originated from a series of interviews conducted during the creation of a video series created to support teacher-education, published in 2004 (Argow, Reilly, & Schneps, 2004). This video series, containing edited components of the interviews analyzed here, is accessible online (http://www.learner.org/resources/series195.html) and was designed to help elementary-grade teachers develop deep understanding of the science concepts needed to effectively address standards in Earth and Space Science. Interviews with children were used to engage teachers about the prevalence of student misconceptions, and were coupled with in situ interviews with real geologists, explanatory simulations, and online activities. Students were interviewed singly and in pairs, and some students were interviewed more than once.

Participants (and guardians) provided written informed consent for this study. Nevertheless, we delayed publication of these data expressly because some of the children discussed here are shown in the video series – we wanted enough time to pass between publication of the series and analysis of these data to ensure that neither we nor readers would be able to identify specific participants. That is, given the nine-year delay between these interviews and this analysis, we are now unable to link any de-identified interview transcripts with specific children. Finally, while we present general demographic information below, we have explicitly limited the information provided to ensure interviewee anonymity.

Procedures

Recruitment. Participants were twenty-one elementary-aged children recruited from classrooms in a large, North American city. Given that the interviews were conducted to provide source material for teacher education, participants were selected on the basis of their interests in science and their willingness to appear on camera, as gauged by their teachers. Ethnicities represented a broad diversity as expected for a large city; we do not provide specific ethnicity information. Children were enrolled in first through fifth grade and were 62% (n=13) female (Table 1).

Table 1. *Grade and Gender Distribution of Interviewees*

Grade	*Gender**	*General Topics Covered*
1st	1 F, 1 M	Soil, earth's interior, air
2nd	2 F, 1 M	Rock formation, soil, volcanoes, earth's interior, plate tectonics
3rd	5 F, 2 M	Rock formation, soil, volcanoes, earth's interior, plate tectonics
4th	3 F, 3 M	Rock formation, volcanoes, earth's interior, erosion
5th	2 F, 1 M	Rock formation, soil, volcanoes, earth's interior

* F=Female, M=Male.

Semi-Structured Interviews. All interviews were conducted in the same room. Interviews were audio- and video-taped, with up to three video technicians present to manage multiple cameras and the audio recording. The first author conducted all but three of the interviews, and the second author observed all of the interviews. During most of the interviews, the second author was able to speak to the interviewer through an earpiece; this allowed the second author to make suggestions for the interviews without interfering with the interview process directly. Care was taken to ensure the interviewer did not to introduce verbal or non-verbal cues that would direct or lead the participant's response. In particular, a set of predetermined interview prompts was used with all subjects and any interview probes were derived from the interviewees' own language during the interviews.

Each interviewee was given a unique identifying code prior to analysis; the second letter and the number indicate gender and grade level, respectively, while the first letter makes each code unique. Most of the children were interviewed alone; eight children were interviewed in pairs and two participants were interviewed more than once. Interviews started with general topics related to rocks, soil, mountains, and water, although interviewees ultimately discussed a variety of other topics with interviewees (Table 1). Each interview started with a visual or drawing prompt. At the start of each interview, children were asked to draw pictures and/or were shown rocks (e.g., Fig. 1), a bucket of soil, a rain stick, or photos to prompt their thinking. These probes were used as needed throughout the interview, and interviewees were encouraged to draw out their ideas. The interview protocol was semi-structured. The interviewer began each interview with a few scripted questions, and these questions were used throughout the interview to redirect the discussion, as well. As the interview progressed, probes were generated in response to interviewee discourse and drawings. This resulted in a wide variety of topics being covered across the entire sample.

Coding. Transcript analysis focused on retrodictive reasoning patterns, with a secondary purpose of documenting alternative conceptions. First, we analyzed transcripts for the presence or absence of basic retrodictive reasoning. This coding scheme does not represent retrodictive reasoning in its entirety, but rather models the most simple aspects of retrodictive reasoning that are necessary for effective reasoning about the Earth:

1) Links are made between observations and processes as evidenced by an understanding that patterns present in the modern world are the imprints of processes that have already occurred.
2) Multiple working hypotheses are raised (multiple possible causes for these patterns are held simultaneously).
3) Preference for one hypothesis over others are rationally explained.
4) Reasoning references time beyond human timescales.

Reliability. Inter-rater reliability for codes was established through concurrent coding of ~10% of the responses by the first author and a colleague (a geologist and former high school teacher). The raters calculated the single measures intraclass correlation across all retrodictive codes evaluated by both authors. The average measures intraclass correlation was 0.92 (min.=0.82 and max.=0.96). An intraclass correlation of 1.0 implies perfect reliability; a correlation of 0.92 indicates that both raters were in strong agreement. Disagreement related to the similarity in two codes, one that related to interacting events and the other associated with feedback; this disagreement was clarified through recognition that neither was fundamental to retrodictive reasoning and both were removed. This high reliability for the coded subsample allowed one author to complete the coding with a reasonable assumption of reliability for all analyses.

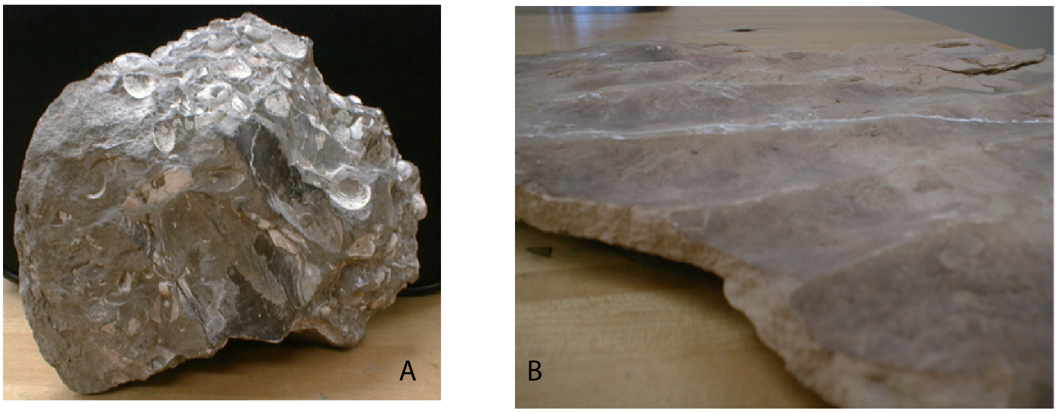

Figure 1. Examples of rocks used to engage students during interviews. A) Fossil-rich limestone. B) Fine-grained sandstone with ripple marks.

Results and Discussion

The structure of students' retrodictive reasoning patterns is intertwined with the presence of alternative conceptions about Earth phenomena. As such, we discuss retrodictive reasoning patterns in significant detail, and note where alternative conceptions are also evident in the student discourse. We particularly focus on evidence that highlights the presence of retrodictive reasoning in students.

The elementary students interviewed in this study exhibited varying degrees of retrodictive reasoning. Nearly every interviewee recognized that Earth materials and patterns present today are the result of prior events. This reasoning was evident most commonly when students were presented with tangible materials, such as dirt or rocks, or when students were drawing pictures of structures they had seen or learned about, such as volcanoes or the Earth's interior. Most students were also able to articulate a possible process that could have created a specific observed pattern, although not all students were able to articulate non-anthropogenic processes. That is, only a subset of students recognized that processes occur on Earth that are independent of human action. In addition, a few students articulated more than one possible process, demonstrating that young children are able to generate multiple working hypotheses about Earth processes.

Links Between Observations and Processes

All interviewees (n=21) recognized that processes leave traces, and that these traces can be used to reason about processes themselves. This is the most fundamental component of retrodictive reasoning and was evident in student discourse about both simple and complex phenomena. In addition, students were generally able to articulate reasoning for why a process would create a specific outcome. To demonstrate this, we provide examples related to students' ideas about rock formation as well as more complex ideas about why some rocks are found in seemingly unlikely places. Students most often called upon processes that were familiar from everyday life, and less commonly called upon processes that had clearly not been experienced directly.

Many of the children interviewed about Earth's interior held the previously documented idea that the Earth contains a layer of magma, often with that layer at the Earth's center, and that this layer is the source of lava that is extruded by volcanoes. Interviewees who discussed the Earth's interior all expressed an idea that the center of the Earth is very hot. One fourth grader (JF4) explained that, in addition to other reasons, the inside of the Earth is hot because neither water nor air could get inside the Earth to cool it off. She compared a hot, stuffy room to the Earth's interior, explaining that:

> *JF4: If no air can be in [a] room, it gets horribly hot.*
>
> *Q: Why does it get really, really hot in that room?*
>
> *JF4: Because no fresh air from the outside can get in here and make us feel nice and cool. So that's why.*

This student is clearly calling upon familiar experiences with fire and stuffy rooms in building her explanations about Earth phenomena, and may related to the alternative conception that insulation by itself is a source of heat (e.g., Wiser & Amin, 2001).

Another example of everyday explanations is found in a student's model for the formation of dirt and rocks included in a model in which the rotation of the Earth resulted in the mixing of materials that form dirt. For example, a 1st grade female indicated that dirt forms because "*the earth is spinning so fast, that kind of mixes everything together*" (EF1). This student used the mixing that occurs when she makes cookies as an explanation for why this mixing would result in a solid rock. Although not based on everyday experience, a fourth grade female presented a disconnected set of ideas for how shells might form a rock (Fig. 1A) that included Earth's rotation: "*the weather or the sun or you know how the earth sort of rotates around, maybe they got hardened and that's how this thing was made*" (ZF4). Experience with heat and the Sun's impact on materials at Earth's surface likely also influenced the processes students called upon to explain rock formation. One third-grade student believed that rocks would harden because "*the sun probably was looking at it for a long time, like a lot of heat was on it for a lot of years and then it finally just hardened*" (EF3). A fourth grader (MF4) expressed the partially correct idea about sedimentary rock formation, stating that, "*sand rocks, they're made from sand crushed under the ground for many years*"; it is unclear in this case whether 'crushing' refers simply to pressure pushing sand together (a scientific idea) or whether it indicates the formation of sand from rocks underground (an alternative conception).

Beyond simple explanations of rock formation, students were asked to reason about seemingly contradictory information. A rock containing shells (Fig. 1A) was presented to some students as having been discovered beneath the ground within the interior of the USA. The students were generally adamant that the rock formed near a beach, and also recognized that the interior USA is far from beaches. This cognitive dissonance provided an opportunity for students to reason retrodictively. For example, a third-grade student (OF3) provided an explanation for the contradiction of a shell-containing rock far from a beach that relied upon her prior knowledge:

> *Q: …How could this [rock in Fig. 1A], that you said came from a beach, end up in the middle of Kansas?*

OF3: Maybe a long time ago…maybe that was formed when the dinosaurs, where the United States wasn't all together…it was probably next to the ocean once, but then it got in while the states formed together to make United States of America. Probably just stayed there until you guys dug it up.

With prompting, OF3 provided a drawing of the process that would result in the "*states form[ing] together to make United States of America*", with each state representing a unique tectonic plate (Fig. 2). She clearly articulated that the rock needed to form near the ocean, and recognized that while an ocean did not currently exist in the region an ocean may have existed in that location in the past. Several researchers have noted that students often mistake continental boundaries for plate tectonic boundaries (e.g., (Marques & Thompson, 1997). The above-mentioned student as well as others in this study similarly suggested that tectonic plates are delineated by non-related external boundaries. In this case, OF3 confounded geopolitical boundaries associated with the borders of states within the USA with physical boundaries separating tectonic plates. Despite this confounding, OF3's hypothesis of tectonic plate movement is a good explanation for the presence of shells at great heights such as in the Alps, although a rock in the USA's interior likely resulted from a different mechanism (an intracratonic ocean).

Figure 2. Drawing of the "State Tectonics" process made by a third-grade student (OF3).

Each landmass, outlined in brown, was drawn as a different state (e.g., Kansas, Minnesota). The brown dot represents the location in the interior of the USA where the interviewer indicated the rock in Fig. 1A was discovered. Blue represents ocean locations during the time of the rock's formation.

A second third-grader (TF3) provided an alternative, human-based cause for the rock's location in the continent's interior. She also recognized the necessity that the ocean must have existed in the rock's place of origin in the past. Her model appears to be based on prior exposure to beach replenishment strategies undertaken by municipalities to combat beach erosion.

Q: …How could this [rock in Fig. 1A], that you said came from a beach, end up in the middle of Kansas?

> *TF3: …I've heard that they took dirt or sand or stuff and dumped it into the ocean, so* the ocean got smaller and smaller and smaller, like somewhere over there, and then it became land. So maybe…they put dirt and sand in the water to make land, like extra land.
>
> Q: So who did that?
>
> TF3: People that were there…not necessarily people today, because they would be long gone by now, but like people that existed a long time ago.

In this exchange, the student still recognizes that the process must have been an ancient one. This requires her to call upon peoples who are "*long gone by now*", rather than requiring the process to be modern. Both of these exchanges, that of OF3 and TF3, suggest that these students are using retrodictive reasoning to combine disparate pieces of information (i.e., state boundaries, ancient peoples, beach replenishment) into a single explanatory model that still allows for earth processes to have occurred in the past.

Presence of Multiple Working Hypotheses

In most cases, interviewees provided only one explanation for their observations or ideas; that is, most of the interviewed students did not offer more than one process that would result in an observed material or pattern. However, a subset of students (n=8) did exhibit the ability to consider more than one explanation for their observations. Most often, these ideas were presented in response to interviewer prompts over time, rather than as a set of possible mechanisms presented in tandem. This is an important distinction in that we cannot always know if these children abandoned one idea before presenting a new idea, or if ideas were truly held as multiple working hypotheses simultaneously.

Returning to the idea of rock formation, a fifth grade girl (OF5) provided two possible mechanisms for the formation of a shell-filled rock (Fig. 1A). Her first explanation revolved around lava mixing with seashells:

> *Q: You said that the seashells were in the rock; how did the seashells get in the rock?*
>
> *OF5: Well, maybe if a volcano erupted or something, maybe the lava mixed in the sea shells and became a rock.*

The interviewer prompted the student to provide other explanations in an attempt to identify multiple hypotheses. Although many students articulated just one mechanism, OF5 provided a second explanation similar to ideas other students held about the Sun baking rocks:

> *OF5: Maybe it's clay and seashells hardened.*
>
> *Q: How would that happen?*
>
> *OF5: Maybe it was just left out in the sun with sea shells and it just became really hard and you couldn't get the sea shells out of it anymore.*

Other students provided multiple explanations without significant prompting. A third-grade boy (JM3) presented a suite of possible mechanisms for the formation of mountains that included meteor impacts, earthquakes, pressure from underground, volcanoes, and wind deposition. This represents many of the common alternative conceptions about mountain formation documented in the literature (e.g., Muthukrishna et al., 1993). In the case of JM3, he articulates quite clearly that different mountains are formed in different ways, clearly demonstrating his ability to work with multiple hypotheses at once. In the following exchange, JM3 is explaining how mountains can form from meteor impacts, volcanoes pushing up from underground, or from the remnants of old volcanoes:

> *Q: You said earlier you think Mount Everest formed when a crater hit the earth; can you tell me more about that?*
>
> *JM3: If it were formed by a crater, it must have been a whole bunch of craters… A crater is a giant hole in the ground that was formed by a meteorite …[the mountains are] in between most of the craters.*
>
> …
>
> *Q: Do you think all mountains form that way?*
>
> *A: No, I don't.*
>
> *Q: How can you form other mountains?*
>
> *A: …something happening underground, so it pushes all the layers of land up so it forms a mountain.*
>
> *Q: What's happening to push that land up underground?*
>
> *A: Maybe it was when a volcano was erupting, or many at the same time. Or maybe it was just an old volcano that was made in the sea and then after years, it wasn't a volcano anymore, because the rocks change over time, so it becomes a mountain instead of a volcano.*

The student did not change his mind when subsequently probed, but rather stuck with the idea that multiple processes can produce the same effect. This is indicative of reasoning with multiple hypotheses.

Preference for One Hypothesis Over Others

As explained above, all students possessed the ability to identify processes that must have occurred to produce modern observations, and some students were able to generate and hold at once multiple explanatory processes. However, students generally did not reason about which possible cause was the most likely cause, an important aspect of retrodictive reasoning, and perhaps the most difficult. Students were comfortable providing explanations for their own ideas, and were willing to argue with others. However, we were unable to identify any discourse in which these children rationalized a preference for one idea over another. This may suggest that elementary-aged children see no need to choose one hypothesis over another or may simply be an artifact of the type of interviews conducted here.

Reasoning References Time Beyond Human Timescales

Almost every student (n=19) explicitly discussed the importance of time in their explanations. Students generally recognized that geologic processes take a long time, although the exact nature of "long" was unclear. Because elementary children are unlikely to understand the meaning of specific large numbers, we chose to focus on relative temporal descriptions (i.e., long, short) rather than on absolute ages. In essence, we believe that the absolute numbers stated by interviewees were generally meaningless and should not be over interpreted. As an example, we consider the discussion of how long students thought it would take for dirt to form. This question was posed after a discussion of the formation of dirt from solid rock, initiated either by the interviewee or as an interviewer prompt. Not surprisingly, students' perspective about how long this process might take ranged from a few days to thousands of years. Interestingly, students' ideas were generally well aligned with the actual amount of time it takes for soils to form. We suggest that this does not indicate strong conceptual understanding of the temporal nature of soil formation, but rather that soil happens to form over timespans that align quite well with the numbers the interviewed students happened to know.

Although humans can impact the Earth system, as evidenced by modern climate change, most Earth processes occur without human intervention and certainly the vast majority of Earth history passed before humans evolved. As noted above and by other researchers (e.g., Blake, 2005), some students were unable to recognize that humans play almost no role in most Earth processes. A particularly good example of this is reflected in a discussion between the interviewer and a first-grade student (LM1). In this exchange, the student has explained that a rock looks like it has been "*knocked around*":

> *Q: How would a stone like this get knocked around?*
>
> *LM1: Humans kicking it, maybe. It came out of a volcano, or something, and it'll hit and crash apart because it came down with such force.*
>
> *Q: Is there any other way it can get knocked around?*
>
> *LM1: Yeah, by humans kicking it.*

This student is clearly most comfortable with a human cause for the rock's movement, although a geologic event (volcano) is mentioned in passing. This is similar to TF3 explaining shells found in the interior USA through humans filling up the ocean with sand.

The idea that humans cause some geologic events is not limited to the youngest children. For example, a fifth grade student (TF5) is discussing dirt as an unchanging material:

> *Q: Is the dirt in the dinosaur period the same dirt that we find today?*
>
> *TF5: Yes, I think so. It's possible for dirt to live that long, because…Like people, they will get killed and stuff, and they might just die. And plants, anybody could smoosh it, or a tree, they could cut down. But dirt's so small, nobody would really want to do anything to it. And if they do anything, nothing would really happen. You can't kill dirt. It's just there forever.*

This student views at least some aspects of the Earth as being static and unchanging. This discourse also reflects a notion that humans must be involved in changing or destroying dirt. Generally, those students who called upon human activities to explain changes, or lack of changes, to the Earth were least likely to recognize the importance and scale of geologic time. However, most of the young children interviewed here recognized the importance of time in creating Earth phenomena, as evidenced by the data presented in preceding sections, suggesting that deep time in an abstract sense is not outside the reach of young children.

Conclusion

The children interviewed here showed themselves to be remarkably capable of some aspects of retrodictive reasoning, despite the presence of a number of interesting alternative conceptions about Earth processes. All interviewed students present evidence of an understanding that patterns present in the modern world are the imprints of processes that have already occurred, and most also explicitly reasoned about geologic time. This reasoning was more nuanced than the simple idea that processes take time to occur. Rather, these young students recognized that geologic processes resulting in modern features generally occur in the past and often before humans, or at least modern humans, were living in the same areas as modern features. This understanding of the relationship between modern observations and past events is the first prerequisite for retrodictive reasoning, and its presence indicates that young children are capable of making this type of inference about the past from modern evidence.

Children in this study were often able to describe specific events that might result in modern features and demonstrated the ability to use a variety of knowledge types in the context of their retrodictive reasoning. In some cases, children were drawing analogies from their own observations. This is particularly well exemplified by the young student who reasoned that the hot center of the Earth might result from a lack of air, as might occur in a stuffy room on a hot day. Similarly, an analogy of ingredients mixed together with a beater to form cookie dough was used to support the idea that the Earth's rotation results in materials mixing together to form rocks. These analogies clearly result from everyday experience. Everyday experiences often aligned with domain-general types of information, such as the idea that rocks will harden in the Sun; we suggest that this notion comes from physical experience with materials, such as mud, drying and hardening, rather than from instruction.

In other cases, such as with the model of states as tectonic plates or people infilling the ocean, the child was clearly pulling from an idea they had been taught in school or heard from the media, an authority, or friend. Most of these ideas were quite domain-specific. For example, students had very specific ideas about the ways in which mountains form that were unlikely to derive from everyday observations, such as the idea that meteors generate craters that are mountains. While children might experiment in the classroom with craters in simple experiments using for example flour and golfballs, meteor impacts are not likely a phenomenon directly observed by these students. The role of everyday experience and learned ideas in influencing a child's ability to reason retrodictively warrants further research. Most importantly, the ways in which everyday experience could be used to encourage retrodictive reasoning should be explored.

The presence of alternative conceptions about Earth systems, of which there were many documented in even this relatively small number of interviews, did not seem to interfere with the ability to reason retrodictively. Certainly, alternative conceptions will interfere with the ability to ascertain an accurate reason for Earth features and processes. However, the ability to reason despite significant alternative conceptions suggests that retrodictive reasoning in young students can be fostered even when children are cognitively unable to grasp some of the more complicated principles underlying strong scientific literacy. Gaining deep understanding of the fundamental laws and principles that govern the Earth system is vital for the reasoning, both retrodictive and predictive, that is needed for decision-making about human impacts on Earth.

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Julie LIBARKIN is an Associate Professor of Geological Sciences at Michigan State University and Director of the Geocognition Research Lab. She specializes in assessment of student ideas and communication of science, with a specific focus on Earth Science.

Matthew SCHNEPS is the Director of the Laboratory for Visual Learning at the Harvard-Smithsonian Center for Astrophysics. His interests include science education, student ideas, educational media, learning differences, and cognitive psychology, with a focus on non-verbal learning.

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