Examining the Features of Earth Science Logical Reasoning and Authentic Scientific Inquiry Demonstrated in a High School Earth Science Curriculum: A Case Study

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ABSTRACT

The purpose of this study was to investigate the inquiry features demonstrated in the inquiry tasks of a high school Earth Science curriculum. One of the most widely used curricula, Holt Earth Science, was chosen for this case study to examine how Earth Science logical reasoning and authentic scientific inquiry were related to one another and how they were reflected in the curriculum. The framework for data collection and analysis used in this case study included logical reasoning, hermeneutics, and historical method , and authentic inquiry. Two raters validated the framework's adoption in this study, looking at the content validity and reliability after the training. Each rater rated the sample curriculum independently and compared results to see if or how they agreed and disagreed. This process included questions, discussions, and clarifications about items of each framework. For inquiry tasks, results showed that induction (37.6%) and abduction (47.7%) were mainly used for logical reasoning; in hermeneutics, the process termed "forestructures of understanding" (82.7%) was mainly used, and "recursive reasoning" (12.0%) and the "historical nature of human understanding" (5.3%) were minimally used; and in the historical method, "adhering to the modern principle of uniformitarianism" (48.8%) and "constructing proper taxonomies" (34.2%) were mainly used. However, the curriculum included little use of what is typically represented, in high school Earth Science, as the features of authentic scientific inquiry. These features are "making multiple observations" and "developing theories about mechanisms." This study also analyzed the relationships among three types of logical reasoning and the features of authentic scientific inquiry. Based on these findings on logical reasoning and authentic inquiry features, we discuss the implications for inquiry-based Earth Science curriculum development. © *2013 National Association of Geoscience Teachers*. [DOI: 10.5408/12-360.1]

Key words: Earth Science logical reasoning, authentic scientific inquiry

INTRODUCTION

In many countries for more than a decade, scientific inquiry has been a central theme for science curriculum development, including its representation in textbooks (Abd-El Khalick et al., 2004; Anderson, 2007). For example, in 2004, Finland adopted the notion of scientific inquiry being a core idea of science curriculum in its *National Core Curriculum* (Finnish National Board of Education [FNBE], 2004); in 2007, Singapore made scientific inquiry central to its curriculum framework (Ministry of Education [MOE], 2007); in 2001, the United States developed a new high school Earth Science curriculum based on the essential features of scientific inquiry, calling it Earth System Science in the Community (EarthComm) (Smith et al., 2001).

Each of these countries may have faced different challenges and found its own solution in developing inquiry-based curriculum (e.g., professional development, assessment, and instructional materials). Nonetheless, the common goal of scientific inquiry is to help students understand accurate ideas of science by engaging them in authentic science learning (cf. NRC, 1996, 2012). Current science education emphasizes that students should understand science as a creation of knowledge and a process, rather than acquiring their content knowledge from textbooks. Scientific inquiry appears to achieve this goal by providing opportunities for students to creatively seek knowledge to solve problems in their everyday lives (cf. Minner et al., 2010; Chinn and Malhotra, 2002). In this sense, scientific inquiry serves as a viable means of and an end in science curriculum development.

The *National Science Education Standards* (NSES; NRC, 1996) provided bases for understanding scientific inquiry, defining it as "... the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world" (p. 23). This vision of scientific inquiry has recently shifted, bringing a renewed focus to "the practices of scientific inquiry" in a new *Framework for K–12 Science Education* (NRC, 2012). The framework emphasizes engaging students in scientific inquiry and teaching them how to reason in a scientific context. Within this framework, eight practices are suggested as essential elements of K–12 science curriculum (NRC, 2012, p. 49). The new framework for K–12 became central to the development of the Next Generation Science Standards (NGSS) published in April 2013 (Achieve, Inc., 2013).

In reality, however, much of the inquiry work done by students in K–12 school sciences mirrors little of the practical work in real science (Crawford, 2007). In particular, students' inquiry experiences in the Earth Sciences are often indirect, because, in many cases, immediate and direct experimentation is impossible (NRC, 1996). Typically, Earth materials are rarely available for experimentation in a laboratory because

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of too many variables to control, and the immense quantities of time and space required for Earth processes to operate. Despite these challenges of Earth Science inquiries, NGSS and NSES have recommended Earth and Space Science to be one of the school science curricula that provide opportunities to practice authentic inquiry and achieve scientific literacy. One way to help students accomplish the goal envisioned by NGSS is to have them study Earth Science through *authentic inquiry*. Through unique, authentic inquiry activities in the Earth Science curriculum, students need to acquire scientific reasoning and become competent at inquiry in Earth Science if they are to carry out investigations in meaningful, relevant, and personal ways (Park et al., 2005). Authentic inquiry activities have continually served as an influential resource in the science curriculum (AAAS, 1993). In the inquiry activities of the Earth Science curriculum, therefore, it is significant to investigate the extent to which logical reasoning and authentic scientific inquiry are utilized.

In this case study, we analyze scientific inquiry tasks demonstrated in an Earth Science curriculum by utilizing two frameworks: Earth Science logical reasoning and authentic scientific inquiry (see Appendices 1 and 2). These help clarify the ways in which the inquiry activities are reflected in the curricula. Moreover, they illuminate the relationship—as presented in the Earth Science curricula—between science logical reasoning and authentic scientific inquiry. The following section explains in detail how scientific inquiry is demonstrated in these two frameworks.

THEORETICAL FRAMEWORK

Earth Science Logical Reasoning

Scientific inquiry is deemed to be context specific, as it is used differently in different disciplines (AAAS, 1989). The context, described as the scope of study and techniques of each discipline, is acknowledged in reform documents: "science disciplines differ from one another in what is studied and techniques used" (AAAS, 1993, p. 19). Though scientific inquiry is described as having many faces in different contexts, the reform document defines scientific inquiry as referring "to the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work" (NRC, 1996, p. 23). As such, it is adopted by science disciplines in diverse ways, each having its own unique methodology. Research in Earth Science has long adopted a method of both descriptive logic and interpretive approach (Frodeman, 1995; Pyle, 2008). A study of Earth tends to rely on time and spatial reasoning. For one to understand how Earth worked in the past, one must know about retrodiction. Retrodiction is one of the inference methodologies used for Earth Sciences. Retrodiction can, for example, "use appropriate current facts to reconstruct conditions and events of the Earth's past" (Engelhardt and Zimmermann, 1988, p. 213). This unique facet of research in Earth Science offers the distinctive characteristic of "seeing through the landscape and through time" (Orion and Ault, 2007).

Traditional scientific research methodology is commonly carried out in a well-controlled experimental context. Scientists studying Earth, however, must take on a distinctive research methodology. It often involves a complicated system of deep time and abyssal space (Ault, 1998). Logical inference can thus be readily used in its research methodology. The inductive, deductive, and abductive nature of this methodology is well documented (Engelhardt and Zimmermann, 1988; Magnani, 2001; Kim et al., 2005). A distinctive methodology of Earth Science study, adopted through an inquiry analysis framework of Earth Science education, is logical inference.

The methodology of Earth Science study is divided into logical inference, hermeneutics, and historical method (Engelhardt and Zimmermann, 1988; Frodeman, 1995; Kim et al., 2005). Each method is defined in detail with examples in Appendix A. First, logical inference includes inductive, deductive, and abductive reasoning. Second, hermeneutics consists of recursive reasoning, forestructures of understanding, and the historical nature of human understanding (see the Instrumentation and Modification section and Appendix A for definition and examples of each concept). For the word "recursive," Frodeman (1995) calls it "circular," but here we will henceforth use "recursive" to reduce the readers' confusion. "Recursive (circular) reasoning" is a logical growth in a recursive pattern that helps construct the whole reasoning of an event in the natural world (Frodeman, 1995, p. 963). The whole reasoning of an event is summed up based on a discrete understanding of each form of data or proof. The discrete understanding is based on the relationship among the natural phenomena. In this way, an understanding delves deeper and deeper into the curriculum. The forestructures of understanding play a role in helping to solve inquiry tasks that require a preconception and/or in understanding the cause and process of an event or phenomenon in the natural world only when the observable results are available. Frodeman (1995) adopted the idea of "forestructures" from Heidegger (1927, 1962), who called it "prejudgments." According to Heidegger, we usually bring three types of prejudgments to every situation, including preconceptions, foresight, and a set of practices we have in advance. Preconceptions are, as Heidegger defined, the ideas and theories that we rely on when thinking about an object. They tend to affect what we see in the field. Foresight is the idea of the presumed goal of one's inquiry and one's senses of what will count as an answer. In other words, without some rough sense of the type of answer that we are seeking, we would not recognize it when we actually came across it. Third, a set of practices we have in advance is often used when we study an object, which is called our "fore-having." These practices can be the culturally acquired set of skills and knowledge that we bring to the object of investigation (Frodeman, 1995, p. 964). As one inquires about a subject, the historical nature of human understanding is an important aid in increasing one's understanding of a relevant concept about that particular phenomenon. Last, the nature of human understanding may never avoid producing different ways and amounts of understanding. However, the historical nature of human understanding in Earth Science research helps us, in more relevant and effective ways, understand and account for natural events (see the Instrumentation and Modification section and Appendix A for more details on definition and examples of each concept). Earth scientists explore the history of the Earth by means of historical methodology. These methods include "adhering to the modern principle of uniformitarianism," "place substituting for time in stage-theorizing," "relic interpretation," "constructing proper taxonomies," and "evaluating independent lines of inquiry for convergence" (Ault, 1998) (see the Instrumentation and Modification section and Appendix A for more details on definition and examples of each concept).

Authentic Scientific Inquiry

In recent literature, authentic scientific inquiry (ACI) is often described as the practicing of science in a fashion that reflects what real scientists actually practice in their professional work (Atkin and Black, 2003; Hume and Coll, 2010; Wong and Hodson, 2010). During the practicing of science, scientists interpret, support, negotiate, argue, and justify their inquiry approaches or assertions based on evidence and logical argument to develop knowledge of the natural world (NRC, 1996; Hofstein and Lunetta, 2003).

Recently, *A Framework for K–12 Science Education* emphasized "the practices of scientific inquiry" by engaging students in scientific inquiry and teaching them how to reason in a scientific context (NRC, 2012). The framework suggested eight practices that should be essential elements of K–12 science curriculum. These eight were "asking questions and defining problems; developing and using models; planning and carrying out investigations; analyzing and interpreting data; using mathematics and computational thinking; constructing explanations and designing solutions; engaging in argument from evidence; and obtaining, evaluating, and communicating information" (NRC, 2012, p. 49; NRC, 1996). Along this vision of scientific inquiry (NRC, 1996), Chinn and Malhotra (2002) investigated the features of "authentic scientific inquiry" based on the psychology of science, the sociology of science, the philosophy of science, and the history of science. They divided scientific inquiry into authentic scientific inquiry and simple school inquiry tasks. This division was based on terms of the epistemology reflecting the nature of science and the cognitive process of inquiry. They went on to assert that the inquiry processes of textbook inquiry activities were so simple that they could deteriorate the epistemological quality of authentic science. Thus, they separately provided the features of authentic scientific inquiry that can serve as analytic tools in the aid of evaluating science inquiry tasks.

Research Questions

Using the framework of logical reasoning and authentic scientific inquiry described here, this case study analyzed the inquiry tasks included in the textbook *Earth Science: Holt Science & Technology* (Berry et al., 2007; abbreviated here as Holt Earth Science). The following questions guided the study:

(1) To what extent is the feature of authentic scientific inquiry reflected in Earth Science curriculum for inquiry activities?
(2) How is the feature of authentic science related to Earth Science logical reasoning?

METHODOLOGY

Research Design

As a case study of high school Earth Science curriculum, we analyzed all the inquiry tasks presented in *Earth Science: Holt Science & Technology* (Berry et al., 2007). We used two inquiry analysis frameworks based on the key features of "Earth Science logical reasoning" and "authentic scientific inquiry." This high school textbook was chosen for two reasons. First, Holt Earth Science is one of the most widely used curricula in the U.S. (Park, 2005). Second, it was published after the advent of the National Science Education Standard (NRC, 1996) where "inquiry" was a focal theme in the reform of science education. The main inquiry features of the curriculum consisted of objectives, materials, safety information, asking questions, forming and testing a hypothesis, analyzing the results, and drawing a conclusion. Excluding the objectives, materials, and safety information, our analysis only focused on the questions and sentences that guided students in their performance of inquiry tasks. The content of the text covered all areas of Earth Science, including geology, astronomy, meteorology, oceanology, environmental science, and the inquiry method. In our analysis, we included environment because it encompassed global climate change, global scale of cycle, and environment-related activities.

Sample

If the total text exceeds 500 pages, Lowery and Leonard (1978) recommend a random sample of 5% of that total for analysis of a text. In our case, that rule yielded a sample of 43 pages from *Earth Science: Holt Science & Technology* (851 pages in total). A table of random numbers (1–851) was used to select these pages. A randomly selected page was disregarded (and another selected) if its sentences made up less than half the page, and the next page was included if the activity continued on the following page.

Instrumentation and Modification: Earth Science Logical Reasoning

We modified the inquiry analysis framework (Chinn and Malhotra, 2002) by selecting key features of Earth Science methodology. We did so to help examine distinctive Earth Science inquiry methodologies reflected in the current Earth Science curricula across the U.S. In our analysis of curricula, we used the inductive method to identify the attributes of, discover the similarities with or differences between, and recognize the relationships of observed objects. We used the deductive method when applying a general scientific conclusion to concrete events or setting up a strategy to test a hypothesis. Last, we utilized the abductive method to understand the cause or formation process of Earth Science events or phenomena. In the case study, we also used the framework of hermeneutic and historical methodology to analyze the inquiry features demonstrated in the authentic inquiry activities and methodology of all disciplines of Earth Sciences, i.e., geology, astronomy, oceanology, and meteorology. Historical methodology is appropriately used in logical reasoning inquiries that require extrapolation from the observable events across time and place on an unobservable scale (Gould, 1986). This is especially good when we need to infer, based on observable phenomena in one or more areas, an event that is not directly available for observation.

Authentic Scientific Inquiry

In our analysis of the curriculum, we redefined each of the procedures required in Earth Science research as follows. "Adhering to the modern principle of uniformitarianism" refers to the activities that help solve inquiry problems based on the assumption that "the present is a key to the past," and it demonstrates the assumption that current natural phenomena occur through the same process(es) as they do in an experimental model. "Place substituting for time in stage theorizing" indicates that inquiry activities decide a time sequence in several independent places given data in different ages. "Relic interpretation" refers to all inquiry activities in which students infer the process acting on the present relics that have come to remain until now. "Constructing proper taxonomies" refers to inquiry activities that use the appropriate Earth Science terms when making inferences about or categorizing the natural phenomena based on a certain criterion. "Evaluating independent lines of inquiry for convergence" indicates inquiry activities that practically use evidence—from several sources—to solve, using convergent reasoning, problems regarding the same topic (see Appendix A for more details on definition and examples of each concept). When we examined the framework for the features of authentic scientific inquiry (Appendix B), we found that 11 of 14 features fell into those of authentic scientific inquiry. In this study, we modified the framework in order to help us interpret features more appropriately, since, depending on the situation, some features could be vague or interpreted differently. We grouped together all multiple observations having the goal of approaching the object through authentic scientific inquiry. In consideration of methodological flaws, we counted the strengths and weaknesses (or the efficiency) of a methodology. Such consideration reflected the fact that scientific evidence could be biased in interpreting, recording, or reporting the data, or even in the choice of which data to consider in the first place (AAAS, 1989). Therefore, it was worth including them in this authentic scientific inquiry category. On the other hand, we broadly interpreted the "developing theories about mechanisms" and included the process of students' reasoning by generating rules or principles. That is, we included the process of abductive inference, a process students may be able to utilize by means of experiment and data interpretation.

Data Collection and Interrater Reliability

Data collection was verified as reliable by two science educators with expertise in Earth Science education. To rate each category of the twofold framework, both raters had a 1 h training session. The sample sentences were used to see how each category of the framework applied. The session involved questions, discussions, and clarifications. The goal was to ensure that the two raters shared the same interpretations and understanding of the language connotations. For example, they both needed the same understanding of the meaning of "simple vs. complex transformation of observation" and "methodological flaws" (see Fig. 3). Before moving on to the next rating phase, the training went on until the two raters had reached, for analysis of all selected texts, 85% to 90% agreement. After the pilot training, the raters analyzed, individually, the inquiry tasks included in the sample selection of pages. We compared their analyses to the extent to which they agreed. In the end, for the Earth Science inquiry methodology, their agreement rate was 87.5% and 89% for the authentic scientific inquiry.

Data Analysis

The details of the analytical process are as follows. First, the inquiry features demonstrated in the inquiry tasks of the textbook were coded according to the logical, hermeneutic, and historical methods. These three methodologies represent the framework of Earth Science logical reasoning methodology (see Appendix A). We then calculated the frequency of each method relative to the total number of features by analyzing each unit of the sentence (i.e., one complete sentence including a question). The result of each inquiry methodology analysis is illustrated in frequencies of all methodologies (see Fig. 2). Second, we coded the inquiry features demonstrated in inquiry tasks of the textbook by analyzing the sentences according to the framework of authentic scientific inquiry (see Appendix B). As we did in the Earth Science inquiry methodology, again we used each sentence as a unit of analysis. To analyze the features of authentic scientific inquiry, all the inquiry tasks were analyzed according to the number of features of authentic scientific inquiry that appeared in each of the inquiry tasks. The results are illustrated in percentages of the total number of authentic scientific inquiries (see Fig. 3). Third, we compared the features of authentic science with Earth Science methodologies in order to find out how each feature of the framework aligned with the recommendations made by the National Science Education Standards and *A Framework for K–12 Science Education*. We did so through an assessment of inquiry tasks by calculating the number of features, in the inquiry tasks, of Earth Science methodology to those of authentic science. The result is presented as a percentage (see Table I). In addition, textbook examples of the inquiry task that we used for analysis according to the framework are shown in Table II.

RESULTS

The results of analysis of the Earth Science inquiry methodology are presented in Figs. 1 and 2; those of the authentic scientific inquiry can be found in Fig. 3; those of comparison of both entities are shown in Tables I and II; some of the textbook content examples of both entities can be found in Table II.

Features of Earth Science Inquiry Methodology

The results of analysis of inquiry tasks using a framework of Earth Science inquiry methodology are shown in Figs. 1 and 2. The distribution of use of logical methods in the sample of the high school Earth Science textbook is 15% historical, 37% logical, and 48% hermeneutic methods. Abductive methodology was used 42 times (38.1%) in the inquiry tasks we analyzed, deductive methodology was used 23 (21.9%) times, and inductive methodology was used 42 (40%) times (see Fig. 2). As shown in Fig. 2, the inquiry tasks in the Earth Science curriculum involved only a small amount of the deductive method in comparison to the inductive method. This is likely due to most of the inquiry tasks guiding the students to observe and infer how and why Earth phenomena occurred. They were not asked to apply a theory to a specific phenomenon and to abductively explain how and why it happened. As for the hermeneutic method in inquiry tasks, the Holt science and technology text predominantly used "forestructures of understanding." It was used 110 times (82.7%) in the inquiry tasks. "Recursive

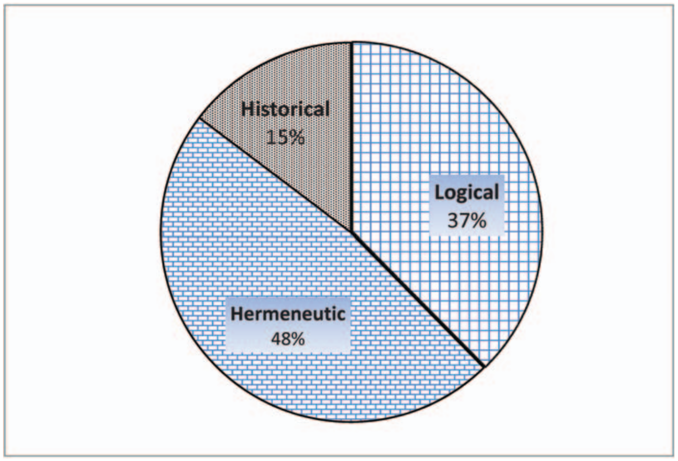

FIGURE 1. Percentage of use of logical method.

reasoning" was used in 16 (12.0%) of them, and "historical nature of human understanding" was used in 7 (5.3%) of them (see Fig. 2). The predominant use of "forestructures of understanding" may be due to the fact that students are most likely to use their preconception, foresight, and fore-having when they start doing inquiry tasks. Students tend to already have prior knowledge and experience about the given topic of an inquiry task, though it is not necessarily scientifically correct or current (Driver and Oldham, 1986; Bransford et al., 2000). When required to, for example, students might be able to form a hypothesis based on their preconception and foresight. The minimal use of "historical nature of human understanding" may be due to most inquiry tasks consisting of one short unit or of making a model to grasp the historical aspects. Therefore, it is likely difficult for students to increase their understanding about natural phenomena having historical effects, e.g., climate change and global warming.

Finally, as for the historical method, nearly half the inquiry tasks used the "adhering to the modern principle of uniformitarianism" (20 times, 48.8%). "Constructing proper taxonomies" made up 14 (34.2%) of the inquiry tasks; "relic interpretation" made up 5 (12.2%) of them, and "place substituting for time in stage theorizing" made up 2 (4.9%) of them. "Evaluating independent lines of inquiry for convergence" was not represented at all in the inquiry activities. The historical method was mainly applied to that domain of geology that studies and understands the past through Earth's present phenomena. Because of this, many inquiry tasks took no account of the historical method. Also used only rarely were two other methods: "place substituting

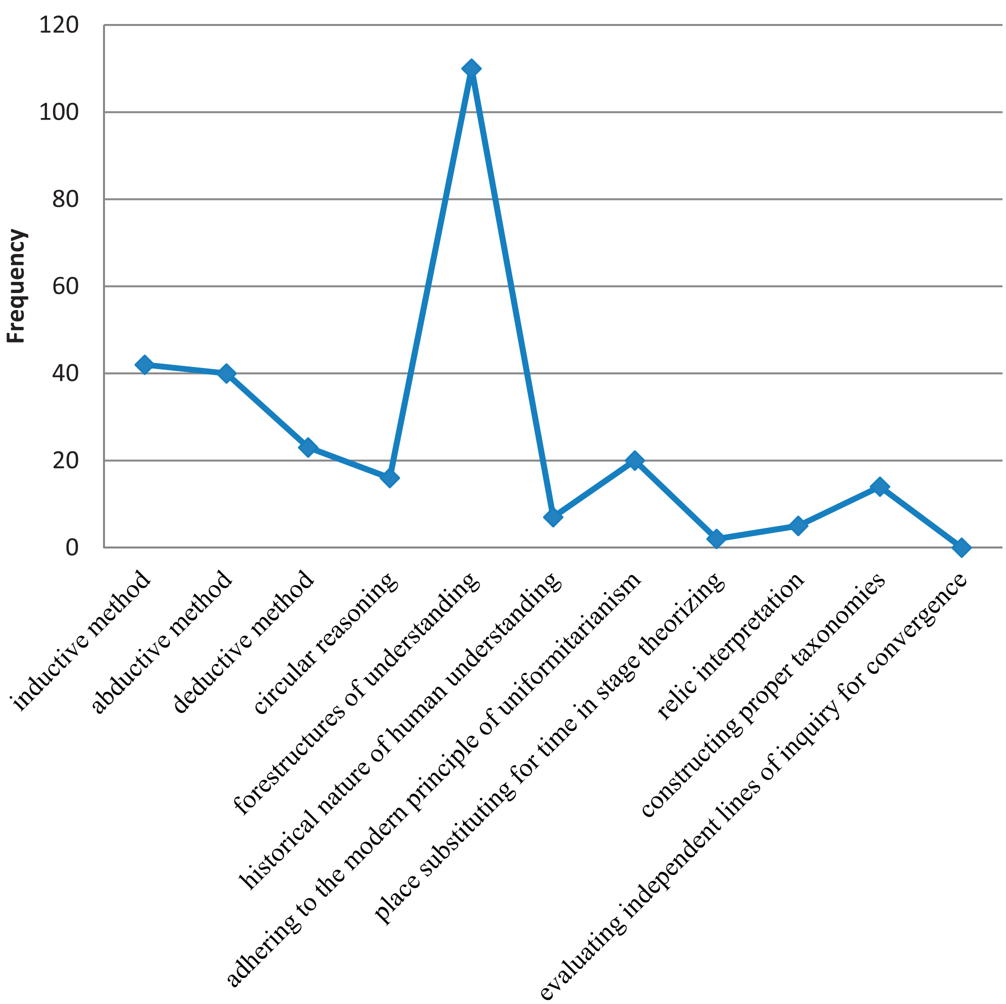

FIGURE 2. Frequency of use of each element of logical reasoning.

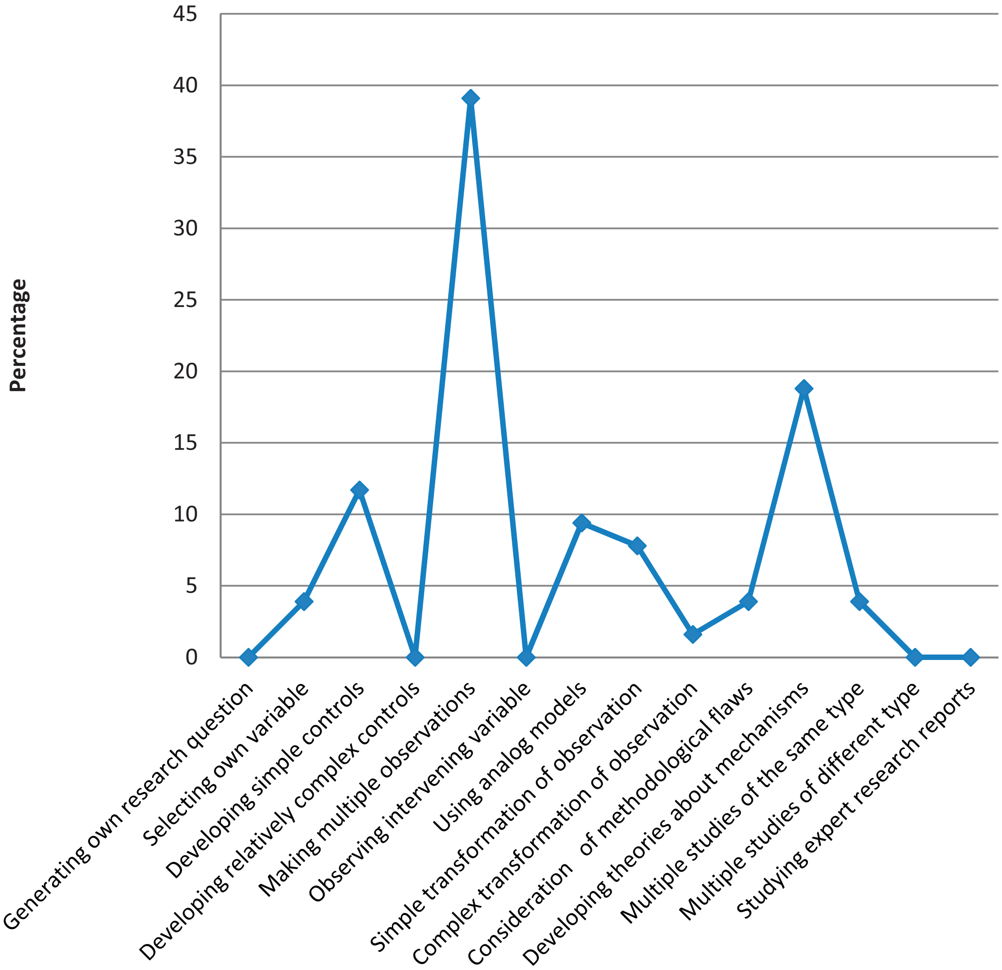

FIGURE 3. Percentage of use of authentic science inquiry.

for time in stage theorizing" and "evaluating independent lines of inquiry for convergence."

Features of Authentic Scientific Inquiry

Figure 3 presents the results of analysis of inquiry tasks included in the Earth Science textbook regarding authentic scientific inquiry. In total, 22 inquiry tasks ($N = 22$) were included in the selected sample pages as selected by Lowery and Leonard's (1978) recommendation. As can be seen, one noteworthy feature is that there was much more use of "making multiple observations" and "developing theories about mechanisms" than that found in the research results of Chinn and Malhotra (2002). One of the reasons for this is that our analysis defined more broadly "developing theories about mechanisms." Also, we counted multiple observations by including most of the restricted observations. In the high school Earth Science curriculum, however, there is none of the following: "generating own research question," "developing relatively complex controls," "observing intervening variable," "multiple studies of different type," or "studying expert research reports."

The analysis of "selecting own variable," a feature associated with the planning of an experiment, showed low usage—0.2 times per inquiry activity (11.7%). This may be due to every set of experimental procedure already being provided; students had little opportunity to select their own variables in performing the given inquiry tasks. Take for example the making of a building structure model that can withstand an earthquake. Guiding students to select related variables falls into the category of "selecting own variable."

Among the features of authentic scientific inquiry, the one used most often was making multiple observations (39.1%; 2.3 times per inquiry task). This feature was used 50 times during the activities of 22 inquiry tasks. Many activities require students, when explaining by experimenting and modeling, to draw a pattern or theme through observations. Students can, for example, make multiple observations to recognize patterns or differences and tendencies embedded in the upper and lower depositional materials of sedimentary layers.

For the feature of "using analog models" (9.4%), many activities asked students to create actual models to explain Earth Science phenomena. An example of "using analog model" is to let students explain the movement of the continents based on the similarity between the real convection of mantle and a model of convection currents (see "convection connection" in Table II). An example of "complex transformation of observation" is the activity of transforming data of outcrops and determining time order in the interpretation of a geologic column (see Table II).

In authentic scientific inquiry, according to Chinn and Malhotra (2002), before any data are produced, observation

TABLE I: Comparison of authentic scientific inquiry with Earth Science inquiry.[1]

Feature of Earth Science Methodology	Feature of Authentic Scientific Inquiry[3]													
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
Methodology														
Frequency[2]	0	5	15	0	50	0	12	10	2	5	24	5	0	0
Method of Logical Reasoning														
Inductive method		1			23		1	4		1	8			
Abductive method		3			2		8			1	15			
Deductive method					4		1		2		4			
Hermeneutic Method														
Recursive reasoning					8		1	1	1		4			
Forestructures of understanding		4			25		9	4	2	2	24			
Historical nature of human understanding					2		2				1			
Historical Method														
Adhering to the modern principle of uniformitarianism					4		9		2		8			
Place substituting for time in stage theorizing					3				2					
Relic interpretation					2						1			
Constructing proper taxonomies		1			4		2	2	1		5			
Evaluating independent lines of inquiry for convergence														

[1]Blank cells mean that no features were used in the given inquiry tasks.
[2]The frequency of authentic scientific inquiry (see also Fig. 3) was calculated using the number of features in the inquiry tasks. The frequency of Earth Science logical reasoning methodology usage was calculated by counting the number of each methodology used within each feature of the authentic scientific inquiry. For example, B has five occurrences of authentic scientific inquiry, and three occurrences of the abductive method of Earth Science logical reasoning. The interpretation of this relationship reads that three of five Bs (selecting own variable) are related to the abductive method.
[3]Alphabetical symbols in Table I represent the features of authentic scientific inquiry as follows: A = generating own research question; B = selecting own variable; C = developing simple controls; D = developing relatively complex controls; E = making multiple observations; F = observing intervening variable; G = using analog models; H = simple transformation of observation; I = complex transformation of observation; J = consideration of methodological flaws; K = developing theories about mechanisms; L = multiple studies of the same type; M = multiple studies of different type; N = studying expert research reports.

is likely to be transformed during the process of reasoning into the form of code, table, summary, mathematical change, and statistical analysis. However, our analysis showed that most inquiry activities in school science largely facilitated the use of simple levels of mathematical transformations, such as tables and graphs.

Regarding the feature of the "consideration of methodological flaws" (3.9%), the Holt Earth Science curriculum included a number of inquiry activities that encouraged students to develop a critical point of view about the methodology used. This helped students evaluate, while conducting experiments, methodological flaws or efficiencies. When measuring the circumference of a ball, for instance, students were encouraged to think about methodological flaws by inquiring into why a difference existed between the circumference as calculated from Eratosthenes' method and that directly measured with a ruler.

The second most often used feature of authentic scientific inquiry was the feature of "developing theories about mechanisms" (18.8%; 1.1 times per inquiry task). Students were encouraged, for example, to develop theories about the relationship between the continents' movement and the mantle convection. Their theories were based on a similarity found in the real natural phenomena in an activity using a convection currents model (see Table II). Through this type of activity, the students learned how a theory is developed and applied to explain the mechanistic process of natural events.

For "multiple studies of the same type" (3.9%), the curriculum offered a chance to conduct a separate study from the main inquiry tasks. An example of "multiple studies of the same type" was students being required to suggest a substance other than water that could be used to model convection of the mantle.

Finally, the selected samples of the curriculum exhibited no features of "generating own research question," "developing relatively complex controls," "observing intervening variable," and "studying expert research reports." This does not preclude the possibility of their existence, though the chances seem quite low. One reason for this is that students were given no opportunities to plan out an inquiry project that would call for such features as "generating own question," "selecting own variable," and "developing relatively complex controls."

Relationship between the Features of Authentic Scientific Inquiry and the Features of Earth Science

Authentic Science and Abductive Methodology

As seen in Table I, the results of our analysis show the features of authentic scientific inquiry compared to the Earth Science inquiry methodologies. On three out of five occasions (60.0%), use of the "selecting own variable" feature was related to the abductive methodology. The inquiry tasks offered students opportunities to perform abductive reasoning by having them generate an idea based on previously known situations. The objective was to "select their own variable" that could be a factor in natural events.

TABLE II: Comparing and Analyzing Examples of the Features of Authentic Scientific Inquiry and Earth Science Inquiry.

Title of Inquiry Activity	Content of Inquiry Activity	Result of Analysis	
		Features of Authentic Scientific Inquiry	Features of Earth Science Logical Reasoning Methodology
Under pressure	What atmospheric factors affect how your barometer works? (Explain your answer)	Selecting own variable	To explain a cause of phenomena based on prior experiences—abductive method
			To approach a problem with preconception about a relationship between air pressure and atmosphere components—forestructures of understanding
			To use proper taxonomies to help reason cause and effect of the change of air pressure using Earth Science term—constructing proper taxonomies
Gliding glacier	Compare the patterns formed by three models of glaciers with the features carved by alpine glaciers or by continental glaciers	Making multiple observations	To grasp the similarity between real and experimental situations through observations—inductive method
			To explain real glacial features based on the preconception, and the features of glacial erosion that are learned from experimental activity—forestructures of understanding
			To explain real natural phenomena based on an assumption that the experimental situation is similar to real Earth Science situation—adhering to the modern principle of uniformitarianism
Convection connection	How does the mantle convection model relate to the theory of plate tectonics and continental drift?	Using analog models & developing theories about mechanisms	To reason the principle of real natural phenomena based on similarities to experiment—abductive method
			Preconception about the mantle convection, and foresight, being able to reason the unobservable process of phenomena, are needed—forestructures of understanding
			To explain the principle of real phenomena based on the assumption that the experimental model is similar to real Earth Science situation—adhering to the modern principle of uniformitarianism
How do you stack up?	Which is the oldest layer in your column? Which rock layer is the youngest? How do you know?	Complex transformation of observation & making multiple observations	To decide a time sequence by applying the principle of superposition to the actual geologic column—deductive method
			To decide a time sequence by comparing the individual outcrop with the whole outcrops—recursive reasoning
			To find a time sequence of the past occasions by exploring the present deposition of different places—place substituting for time in stage theorizing
			To infer a formation of the environment using the appropriate names of fossils and rocks—constructing proper taxonomies
Quake challenge	What are some limitations of your earthquake model?	Consideration of methodological flaws	To apply to a building structure that the students made and recognize its limitation in withstanding an earthquake—inductive method
			To approach the object with foresight to reason the process and cause through observation of experimental results—forestructures of understanding
Let's get sedimental	Explain how these features might be used to identify the top of a sedimentary layer in real rocks and to decide if the layer has been disturbed	Developing theories about mechanisms	To infer the past occasion from the present relic—abductive method
			To approach the object with preconception about the deposition structure and with foresight obtained from the experimental process—forestructures of understanding
			To infer the past occasion based on observation of the present relic—relic interpretation

In 23 out of 50 instances (46.0%), "making multiple observations" was associated with the inductive method. This is because when we create a theme or pattern by comparing a similarity or difference among observed phenomena, this particular feature (making multiple observations) may be associated with inductive reasoning. On eight out of twelve occasions (66.7%), "using analog models" was related to the abductive method. When students explain a cause of events, they need to reason abductively based on how similar it is to models used. In Earth Science, the use of models figures into many inquiry activities that call for students to explain natural phenomena. It is of course a fact that we cannot directly experience most Earth Science events, e.g., Earth's internal behavior. This feature of using analog models becomes valuable in carrying out inquiry tasks that maintain the integrity of authentic scientific inquiry. Indeed, students herein strengthen and develop an inquiry skill, making it important that this kind of inquiry activity be included in the curriculum.

Chinn and Malhotra (2002) argued that inductive and analogical reasoning are included in the models of real science. Our results also illustrated that school science curriculum largely used inductive and abductive methods when experimenting with a model. In fact, 15 of 24 (62.5%) instances of "developing theories about mechanisms" were associated with the abductive method. Eight of them were related to the inductive method. To draw a conclusion or explain the cause of an event through inquiry tasks, students generally use the abductive method. In this manner, they develop theories about mechanisms based on the similarity of a real event to that of a model.

Associated with the deductive method was the feature of "complex transformation of observation." For example, students were to reason deductively by applying the principle of superposition to an actual geologic column. At that time, transformation of data needs to be done to interpret geologic events from different places (see also Table II). Associated with both inductive and abductive methods was the feature of "consideration of methodological flaws." When an experiment ends with a result different from others, we should figure out why we needed to employ abductive reasoning. If, on the other hand, students are to observe and understand the critical point of a structure being able to withstand an earthquake, then they need to employ inductive reasoning (see Table II).

The result of this curriculum analysis demonstrated that both inductive reasoning and abductive reasoning are associated with more than 60% of cases involving "making multiple observations," "selecting own variable," "using analog models," and "developing theories about mechanisms." Neither type of reasoning, however, was associated with any of the following features of authentic scientific inquiry: "generating own research question," "observing intervening variable," "developing relatively complex controls," and "studying expert research reports."

The three features of authentic scientific inquiry—"selecting own variable," "using analog models," and "developing theories about mechanisms"—that are closely related to Earth Science logical reasoning are all key elements of setting and testing a hypothesis. Setting and testing a hypothesis is a critical and creative job of scientists (AAAS, 1993). On other hand, the abductive method was most often associated with the features of authentic scientific inquiry. The exceptions were "making multiple observations" (associated with inductive methodology) and "complex transformation of observation" (associated with deductive methodology). Therefore, regarding curriculum development, it is suggested that the Holt Earth Science curriculum include inquiry tasks that promote and develop students' abductive reasoning abilities.

Authentic Science and Hermeneutic Methodology

As displayed in Table I, most of the features of authentic scientific inquiry were associated with the hermeneutic methodology's "forestructures of understanding." These forestructures include preconception, foresight, and forehaving and are necessary to solving most inquiry problems.

When they select their own variable for a design of inquiry, students need preconception and foresight. They approach the object, when making multiple observations, with their preconceptions. "Using analog models" enables us to explain real natural phenomena. In using this to connect phenomena to a model and to explain the process and the cause, students need foresight. To perform a "complex transformation of observation," students can transform data with their preconception of the goal they want. For "consideration of methodological flaws," students wanting to "develop theories about mechanisms" need foresight and fore-having including skills and instruments. In addition, to observe and evaluate research outcomes and products, students need foresight to infer a cause and process.

Recursive reasoning in the hermeneutic method was associated with the following features: "complex transformation of observation," "making multiple observations," and "developing theories about mechanisms." When deciding sequence of time by comparing individual outcrops with whole outcrops, students could reason recursively. At that moment, students drew conclusions about the sequence of time by "making multiple observations" and "comparing through transformation of data" (see Table II). Through their use of recursive reasoning to compare a part with a whole, students could "develop theories about mechanisms."

As seen in Table I, the results of comparing the two frameworks showed that forestructures of understanding were associated with more than 80% of "selecting own variable," 50% of "making multiple observations," 75% of "using analog models," 100% of "complex transformation of observation," and 100% of "developing theories about mechanisms." Recursive reasoning was related to 50% of "complex transformation of observation," 16% of "making multiple observations," and 17% of "developing theories about mechanisms." The historical nature of human understanding was associated with 17% of "using analog models." Regarding the hermeneutic method, no relationship was found with the other features of authentic scientific inquiry; these included "generating own research question," "developing relatively complex controls," and "observing intervening variable."

Authentic Science and Historical Methodology

"Adhering to the modern principle of uniformitarianism" in the historical method was associated with "using analog models," "complex transformation of observation," and "developing theories about mechanisms." The other two features, "place substituting for time in stage theorizing" and "constructing proper taxonomies," were associated with "complex transformation of observation." When we make a "complex transformation of observation" to a time sequence of past Earth phenomena, the premise of uniformitarianism, that the present is similar to the past, is used (see Table II). When students are told to explain, by using an experimental model, why some areas of the ocean do not circulate, they have to "develop mechanisms" about the ocean circulation by "using analog models." Then, they perform the inquiry tasks based on the premise that the process of experiment is similar to that of the real ocean.

Recall that "place substituting for time in stage theorizing" and "constructing proper taxonomies" are associated with "complex transformation of observation." This means that when we sequence a past event after watching deposition in the present, or when we think about formation of the environment using the names of fossils and rocks, then we arrive at a conclusion through transformation of observation (see Table II). Relic interpretation is when we understand the process(es) acting upon a relic based on what remains from a present relic. This process is associated with "making multiple observations" and "developing theories about mechanisms." For example, students discover, through multiple observations, whether or not there was an inversion of a past occasion based on the relic of sedimentary structure in a bottle. When students develop theories to draw conclusions about the inversion based on the experimental observations, the activity corresponds to "developing theories about mechanisms" (see Table II). "Constructing proper taxonomies" is associated with the "selecting own variable." When they are asked to decide what atmospheric factors affect the action of a barometer, students use proper taxonomies to help perform cause-and-effect reasoning by using the Earth Science term "change of air pressure" (see Table II).

The result of our curriculum analysis shows that the "modern principle of uniformitarianism" and the "stage theorizing" were associated with over 60% of "using analog models" and "making multiple observations." "Constructing proper taxonomies" was related to 20% of "selecting own variable." However, we cannot confirm the relationship of the historical method to the other features of authentic scientific inquiry, including "generating own research question," "developing relatively complex controls," "observing intervening variable," and "consideration of methodological flaws."

DISCUSSION AND IMPLICATIONS

As a nation reforms science education by recommending a vision of what and how students should learn in science, it is worth analyzing the current science curricula to find out how they align with that vision. Scientific inquiry has been adopted to develop Earth Science curricula, and the Next Generation Science Standards (Achieve, Inc., 2013) recommend Earth and Space Science as one discipline for teaching scientific inquiry in K–12 grades.

This case study found that inquiry tasks in the U.S. high school Earth Science curriculum mainly used inductive and abductive methods of logic, and "forestructures of understanding" was overwhelmingly used (Park et al., 2009), while there are a few cases of "recursive reasoning" and "historical nature of human understanding" used in the hermeneutic method. Given the fact that students have many experiences making multiple observations on various field trips, this result implies that students of Earth Sciences may perceive science as a process of making multiple observations about objects and events of Earth and inductively making a conclusion, which is far from what current science education reform documents are aiming towards. Rather, students are to be trained to do science, continuously and recursively, going back and forth in investigating, gathering data, interpreting, and communicating to other people until they come to an agreement among the community members of a discipline area. For the historical method, inquiry tasks of the curriculum largely used the "modern principle of uniformitarianism" and "constructing proper taxonomies." From the hermeneutic method, the "historical nature of human understanding" was lacking in the features of Earth Science inquiry methodology. This feature helps students to increase their understanding of real Earth Science phenomena as they do experiments about an Earth Science topic observed in the physical world. Inquiry tasks that reflect this aspect would help students to develop and strengthen their skills and abilities to use the feature of "historical nature of human understanding." Concerning the historical method, our study results imply that high school Earth Science curriculum needs inquiry tasks that reflect features of scientific inquiry, including "stage theorizing," "relic interpretation," and "evaluating independent lines of inquiry for convergence." One way to reflect these features would be to include inquiry activities that draw independent conclusions and converge into one theory.

Two features of authentic scientific inquiry often presented in this high school curriculum were "making multiple observations" and "developing theories about mechanisms." These were found to exist in greater frequency than they were in prior research by Chinn and Malhotra (2002), in which they expected inquiry tasks to reflect more features of authentic scientific inquiry. We found that this particular feature of high school Earth Science curriculum bore a resemblance, in terms of the features of authentic scientific inquiry, to secondary school science curricula. Still, some of the features of authentic inquiry emphasized in the National Science Education Standards (NSES; NRC, 1996) were absent. NSES recommends for all 9th–12th grade students the "abilities necessary to do scientific inquiry" (p. 175). Among the features of authentic scientific inquiry that we found to be absent, "generating own research question" is related to "identifying questions and concepts that guide scientific investigations" (p. 175). "Developing relatively complex controls" and "observing intervening variables" are associated with "designing and conducting scientific investigations" (p. 175). Finally, "studying expert research reports" is related to "communicating and defending a scientific argument" (p. 176). These standards are inevitable elements of making a "complete" scientific inquiry, defined as "asking questions and defining problems; developing and using models; planning and carrying out investigations; analyzing and interpreting data; using mathematics and computational thinking; constructing explanations and designing solutions; engaging in argument from evidence; and obtaining, evaluating, and communicating information" (NRC, 2012, p. 49). Therefore, by not including all the authentic scientific inquiry features, the Earth Science curriculum makes it difficult for 9th–12th graders to strengthen and develop all the "abilities necessary to do scientific inquiry." A number of inquiry tasks that espouse the NSES's recommendations would certainly assist promoting "quality learning and the spirit and practice of scientific inquiry" (NRC, 1996, p. 177). Still, opportunities to utilize several other features failed to materialize. These other features included "generating own research question," "developing relatively complex controls," "observing intervening variable," "multiple studies of different type," and "studying expert research reports." The features of authentic scientific inquiry that were little provided are, according to NSES, associated with the "abilities necessary for grades 9–12 to do scientific inquiry" (NRC, 1996, p. 175). Therefore, the current Earth Science curriculum may not be effective at developing the abilities of conducting complete authentic scientific inquiry as opposed to the national reform efforts that continuously help school science to accomplish this.

Our results demonstrated that the method most associated with the features of authentic scientific inquiry was the abductive method. Two exceptions were "making multiple observations," associated with the inductive method, and "complex transformation of observation," associated with the deductive method. The features of "using analog models" and "developing theories about mechanisms" are highly associated with the abductive method. This result is in line with the previous research about the association of students' abductive ability with hypothesis-generation activity. Such research showed that the ability to generate a hypothesis was closely related to logical and creative thinking. Therefore, the strategy of teaching and learning carefully needs to be prepared to nurture students' abductive ability (Kwon et al., 2003). Accordingly, in high school Earth Science curriculum, we need to increase the number of inquiry activities that bring about abductive thinking through authentic scientific inquiry.

The relationship between the hermeneutic method and features of authentic inquiry showed that forestructures of understanding are related to more than 50% of "selecting own variable," "making multiple observations," "using analog models," "complex transformation of observation," and "developing theories about mechanisms." "Recursive reasoning" was associated with, in part, "complex transformation of observation," "making multiple observations," and "developing theories about mechanisms." The "modern principle of uniformitarianism" and "stage theorizing" in the historical method were associated with more than 60% of "using analog models" and "making multiple observations." On the other hand, "constructing proper taxonomies" was associated with 20% of "selecting own variable."

We cannot, however, confirm the relationship of Earth Science logical reasoning to other features of authentic scientific inquiry—features like "generating own research question," "developing relatively complex controls," "observing intervening variable," and "multiple studies of different type." It seems therefore that high school Earth Science curricula need to develop and include a number of inquiry tasks that, through various features of authentic scientific inquiry, utilize the features of hermeneutic and historical methodologies. This way students may be able to practice and acquire the abilities of performing "complete inquiry" (NRC, 2012, p. 49). It may be difficult to design one inquiry activity to include all of the features of Earth Science methodology and authentic scientific inquiry. Nevertheless, our findings suggest that in high school Earth Science curricula, what are needed are inquiry tasks that involve various Earth Science methodologies. Further, these tasks would be of greater value if they reflected different features of authentic science inquiry. For instance, a number of inquiry tasks could provide students with an opportunity through recursive reasoning to generate their own research question, select their own variable, and consider methodological flaws. As for the historical method, curricula could develop, in order to interpret a relic, a number of inquiry tasks that make students generate their own research question, select their own variable, consider methodological flaws, and study expert research reports.

Recommendations for Further Research

These needs of Earth Science curricula may require a full review of the theoretical and practical relationships between Earth Science logical reasoning methodology and authentic scientific inquiry. Doing so may ensure that high school Earth Science teaching and learning are aligned with the *Framework for K–12 Science Education* and Next Generation Science Standards, the focus of which is complete scientific inquiry including "asking questions and defining problems; developing and using models; planning and carrying out investigations; analyzing and interpreting data; using mathematics and computational thinking; constructing explanations and designing solutions; engaging in argument from evidence; and obtaining, evaluating, and communicating information" (NRC, 2012, p. 49). This study analyzed and compared two compelling approaches to studying Earth Science: Earth Science methodology and authentic scientific inquiry. The result of the study illustrated the need for curriculum development that includes a variety of authentic inquiry tasks applying each science logical reasoning methodology. Once the desirable curriculum is developed, the way in which the curriculum generates and maximizes students' meaningful learning in Earth Sciences will be a topic for further study.

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APPENDIX A. The Inquiry Analysis Framework Based on the Features of Earth Science Inquiry

This analysis framework was originally formed by Kim et al.'s work (2005). The examples presented in the table are adapted from Ault (1998), Engelhardt and Zimmermann (1988, English version), and Frodeman (1995).

Logical Inference Methodology

The following statements demonstrate induction, abduction, and deduction by means of three examples, each using or arriving at the same law (Engelhardt and Zimmermann, 1988, p. 81–82).

Example fact: Diamond is invariably produced if and only if carbon or carbon-containing compounds are exposed to pressures of over 55 kbar at a temperature of at least 1000°C in the absence of oxygen.

Inductive method: the process to discover a law as a result of observing and exactly describing controlling state of affairs and phenomena.

(Examples)

First premise (controlling state of affairs): In various experiments, carbon was exposed to various pressures in the absence of oxygen at a temperature of 1000°C.

Second premise (resulting state of affairs): In all experiments in which the pressure exceeded 55 kbar, and only under these conditions, diamond was produced.

Conclusion (law): If carbon is exposed to pressures of over 55 kbar in the absence of oxygen and at 1000°C, diamond will be produced.

Abductive method: the process to infer a principle, a fact, or a law and yield or newly construct an explanatory hypothesis to explain the resulting state of affairs.

(Examples)

First premise (resulting state of affairs): Diamonds were found in volcanic pipes in South Africa.

Second premise (law): Diamonds are produced only from carbon and carbon compounds when the temperatures reach at least 1000°C and when the pressures are at least 55 kbar.

Conclusion (controlling state of affairs): In the formation of the volcanic pipes, material was brought up from depths where the pressure of at least 55 kbar is obtained.

Deductive method: THE process to produce a statement regarding the resulting state of affairs from a universal law or a general assertion.

(Examples)

First premise (law): At pressures of over 55 kbar and at temperatures of over 1000°C, carbon in the absence of oxygen will change into a diamond.

Second premise (controlling state of affairs): In an experiment, carbon is subjected to a pressure of 80 kbar and a temperature of 1200°C.

Conclusion (resulting state of affairs): In the experiment, a diamond will be produced.

The following table presents the "three modes of inference" that are used in research to arrive at scientific explanations.

	Induction	Abduction	Deduction
Premises	A	B	L
	B	L	A
Conclusions	L	A	B

Abbreviations are:

A = controlling state of affairs;
B = resulting state of affairs; and
L = law.

Hermeneutic Methodology

Recursive reasoning: a line of thinking that the meaning of its parts is understood from its relationship to the whole, while our conception of the whole is constructed from an understanding of its parts.

(Examples)

Our understanding of a region is based on our interpretation of the individual outcrops in that region, and our interpretation of an individual bed within an outcrop is based on our understanding of the sediments and structure that make up that bed.

Forestructures of understanding: a tendency to approach our object of study with our preconception and theory, i.e., foresight, which is our idea of the presumed goal of our inquiry and our sense of answer, and fore-having, which is a set of implements, and skills and institutions we bring to the object of study.

(Examples)

When scientists approach the Western Cordillera with concepts like ophiolite complexes and accretionary terrains, the concept will affect what they see in the field.

Historical nature of human understanding: a recognition that our original goals and assumptions result in certain facts being discovered rather than others, which in turn leads to new avenues of research and sets of facts. This particular prejudgment we start with has a lasting effect.

(Examples)

Any scientist can name areas of potential importance that do not get investigated because of the lack of time and resources or the lack of sufficient commitment on the part of the scientific community. As these decisions get multiplied over the decades, the body of scientific knowledge comes to have a strongly historical component.

Historical Methodology

Adhering to the modern principle of uniformitarianism: a method for a scientist to examine small, steady processes of change in the present, and then extrapolate their effects over geological time and predict or reason either forward or backward in time.

(Example)

Just like the method Lyell had used to interpret rock strata, Darwin applied this method to life by extrapolating the process of selective breeding to infer the effects of natural selection over time.

Place substituting for time in stage theorizing: the way that scientists assume that geologic objects in different stages can be arranged by an order of time.

(Example)

When three types of atolls, fringing reef, barrier reef, and atoll, are observed in the present at different places, it is assumed those are the historical consequence of slowly sinking islands over different periods of time.

Relic interpretation: the way to interpret and reason historical changes or new tendencies that relics of past events have, when an object does not have observable clues about their assumed derivation.

(Example)

Since it is exceedingly difficult to directly observe bombardment of a meteorite, scientists can approximately assume the geological history of the Moon by investigating astroblemes remaining on the surface of it.

Constructing proper taxonomies: the method to use explanatory categories that can connote a causal reasoning.

(Example)

The theory of plate tectonics has developed, supported by using descriptive categories such as ophiolite, spreading center, convergent boundary, and arc volcanics, which connote a causal reasoning.

Evaluating independent lines of inquiry for convergence: the method to evaluate the extent to which common answers converge by examining various and independent lines of inquiry results.

(Example)

A continental drift theory could be admitted when independent lines of inquiry, such as when a magnetic stripe is observed to be laid down symmetrically, magnetic anomaly mapping, and the drift of a magnetic pole, converged to the common consequence of continental drift.

APPENDIX B. The Inquiry Analysis Framework of the Features of Authentic Inquiry.[1]

Feature of Reasoning Task	Definition and Examples
Generating own research question	Students are not told what questions to investigate but develop these questions on their own. For example, ask students to formulate a research question of their own about unknown minerals to determine if it is feldspar or quartz or others.
Selecting own variable	Students are not told exactly what the relevant variables are but select and/or define these variables on their own. For example, students are directed to think of and investigate variables that might influence a wind mill they build. They are not told what these variables are.
Developing simple controls	Students must control already-known variables. For example, students test the effects of wind turbine blade length, blade number, blade pitch, blade shape, and blade weight; when testing the effects of one variable, the other variables must be held constant.
Developing relatively complex controls	Students must be concerned about nonobvious controls. For example, students must devise a way to control for the amount of light shining on two plots of land that are differentially shady.
Making multiple observations	Students measure or evaluate measures of multiple variables. For example, students observe several different regions of the world to completely understand global warming or observe population changes in several different species in a lake ecology simulation.
Observing intervening variable	Students measure or evaluate measures of intervening variables. For example, students examine the ways in which the rise of carbon dioxide as an intervening variable mediates the greenhouse effect on global warming.
Using analog models	Students conduct research with simplified analog models intended to represent a real situation. For example, students experiment with rocks and sand in a jar to model sediments in the ocean.
Simple transformation of observation	Students transform observation in simple ways such as averaging data and or graphing results. For example, students are asked to transform a 3-yr-long data set of wind speed collected at a certain local area into a graph.
Complex transformation of observation	Students transform variables in ways that go beyond averaging or graphing. For example, students analyze telescope images of several regions of space, and then use an image processor to make movies of the images in order to determine whether any spots of light change in brightness.
Consideration of methodological flaws	Students reason about possible experimental flaws in the method of the study they are designing or interpreting. For example, students discuss whether a method for measuring sunlight in a 1 m^2 plot of land is accurate, or students note possible flaws in the methods used by scientists to gather data about surface temperature in a unit land of 1 m^2.
Developing theories about mechanisms	Students develop or test theories about mechanism. For example, students develop theories about how magmas are formed and exploded, or students test theories of how folds, faults, and slip occur.
Multiple studies of the same type	Students conduct more than one study as they engage in inquiry on the topic, and the studies are all of the same type. For example, students conduct multiple studies on factors that influence how the discharge of a stream forms different types of meandering rivers, but all the studies apply the same basic procedure of the discharge of a stream.
Multiple studies of different type	Students conduct different types of studies. For example, ask students to study why the water of the ocean turns over yearly or sometimes never turns over and to conduct studies about the distribution of water temperature in relation to El Niño or La Niña.
Studying expert research reports	Students read research reports written by scientist or abbreviated newspaper or magazine-style reports of such research.

[1]Analysis framework is modified from the work of Chinn and Malhotra (2002).