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A Model of Inquiry for Teaching Earth Science

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Abstract

Teachers and administrators have heard recent calls for more inquiry-oriented science instruction at roughly the same time more emphasis has been placed on high-stakes testing in science. While these two factors justify an examination on assessment practices, they also justify a refinement in teaching approaches to science inquiry. At their core, models of inquiry-science teaching attempt to engage student in active processes of science knowledge construction, emulating the process of science itself. But each domain in science has unique, if overlapping, histories, traditions, and conventions that have directed inquiry within those sciences. This paper outlines a model of inquiry science teaching that more accurately reflects the nature of the Earth sciences than do generic or physical science-based models do. This model incorporates elements recognizable for any science domain (question posing, methods definition and application, and solution determination), but also provides specific mechanisms within each element that reflect the nature of the Earth sciences, in current, historical, and classroom contexts. These mechanisms include descriptions of materials, space, and time; observations and modeling; and interpretations and historical representations. Possible pathways for short- and long-term instructional planning are also discussed.
Teaching Earth science in the K-12 classroom presents a challenge compared to other sciences in the curriculum. Earth science is an interdisciplinary science, encompassing ideas from physics, chemistry, and biology, but applied through geology, meteorology, oceanography, and in K-12 curricula, space science and astronomy. Earth science is not a narrow set of ideas, but a synthesis of many concepts, traditions, and disciplines in science.

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Geology, by definition, is the study of the Earth, but how does one systematically inquire about the Earth? Fundamentally, the Earth sciences provide information on (a) *materials* (such as rocks, minerals, water, etc.), (b) *space* (i.e., where the materials are found or how they are distributed), and (c) *time* (i.e., how materials and their distributions have changed and evolved). Historically, studies in each of these areas have been both descriptive and interpretive and have included activities such as isolating a map location for a land feature, determining the length of a river, or suggesting the depth of an oil reserve.

Compared with the other sciences, the Earth sciences are relatively young, and as the science of geology has matured, the role of interpretation has become more important. These interpretations include identifying factors that cause Earth events, interpolations between specific locations, and extrapolations of process beyond available data.

Interpretations are common both in a predictive (forward in time) manner and a "retrodictive" (backwards in time) manner.

Many state curricula place a heavy emphasis on geology content as a part of Earth science courses. Because geologic phenomena are so interconnected, the same basic ideas can be extended to other areas of Earth science. At the same time, many states have also included "inquiry" as a part of these same curricula. As defined by the National Science Education Standards (1996), inquiry instruction can be defined as including both "understanding of scientific inquiry" as well as "abilities necessary to do scientific inquiry." Inquiry experiences in the Earth sciences are often vicarious or indirect, because direct experimentation, such as is used in the physical sciences, is typically not possible (National Research Council, 1996). The natural variability of Earth materials, their broad but often interrupted (or missing) distribution, and the extended time spans required for Earth processes to operate often shape Earth inquiries in such a way that it would be difficult to control all of the variables and represent real world conditions in a laboratory. In addition, the evidence derived from Earth inquiries can be ambiguous and lack opportunities for direct, discrete confirmation.

It has been suggested that educational environments can be ill-structured (Nespor, 1987), and as a result of a mismatch between highly structured curricula against a less well structured content domain and classroom environments, considerable pressure is placed on teachers decision-making capacities (Keys & Kang, 2000; Keys & Bryan, 2001). Because of these factors, it can be inferred that teachers may avoid inquiry altogether in Earth science classes without having more specific means of facilitating student completion of content objectives. This work attempts to define understandings of geoscience inquiry, positioned in a manner that suggests decision-making strategies for teachers to enhance their students' abilities with respect to geoscience inquiry. In this work, many of the examples presented are focused on geology, but have at least some connections with other aspects of Earth science.

Structural Framework

Teasing Apart Problems in Geoscience

An important consideration in Earth inquiries is that students should create "by [their] own effort an independent assemblage of truth," a point made by one of the fathers of American geology, T.C. Chamberlin (1897, p. 848). What becomes apparent early in any Earth inquiry is that the questions are often based on incomplete information about complex, interactive, and (ultimately) uncontrollable events, and thus, these questions defy simple or discrete explanation through any single pathway of inquiry (Ault, 1998; Frodeman, 1995). Getting lost in the details of this complexity is easy, so when teachers fall back on questions that are trivial or limited to confirmation of previous results it is perhaps merely defensive and "safe" in a classroom. Knowledge of how these details are framed in the geosciences is vital in recognizing what are relevant problems in the geosciences, and thus the work below provides a historical and philosophical framework on which teachers might base instructional decisions.

An Inquiry Framework for Instruction

The instructionally defensive strategy is acceptable to a point, but as Chamberlin noted, Earth inquiries should result in an independent construction of the knowledge – the very basis of constructivist learning. Chamberlin's thoughts hold true even if a student is to merely confirm that which is already known. In extending the learning experience beyond confirmation, Monk and Dillon (1995) suggested that classroom inquiries can be broken into three separate components: (a) defining the question, (b) choosing methods, and (c) arriving at solutions. For each of these three stages, one must also determine what the inquiry is about (materials, space, or time?). Given the variability of students' abilities to construct these components, teachers must also control the level of inquiry, deciding the extent to which each of components is pre-defined. Using this basic framework, the instructional sequence can be defined by teachers, sequencing events so as to allow either the introduction (by the teacher) or construction (by the student) of each component. Thus, a large-scale framework of the work described below is based on this basic sequence, incorporating first the nature of geoscience inquiry and subsequently how this nature can be manifested in a classroom setting.

Levels of Inquiry

Teachers have a range of options when deciding the level of structure to be provided to students in any inquiry. Bell and his colleagues (2005) described key aspects of inquiry as (a) *confirmational*, in which students are expected to confirm known (at least by the teacher) information, (b) *structured*, in which students respond to a teacher-specified question and method, (c) *guided*, in which students select procedures and justify answers to a question proposed by the teacher, and (d) *open*, in which students select both the question and the method in a general area devised or suggested by the teacher. These levels become important tools to teachers, who often struggle with their beliefs about what is expected of them by content standards versus their students' capacities (Keys & Bryan, 2001). By planning how much pre-defined information is given to students, it is possible for teachers to begin to reconcile these competing beliefs. Thus a third, finer-grained framework for the work below specifies what appropriate levels of information could look like.

In each of the following sections on questions, methods, and solutions below, corresponding examples from the geosciences are defined, sketching the origins and applications of each and providing an understanding of geoscience inquiries. These examples are further framed with respect to possible levels of classroom inquiry appropriate to student abilities, provided in a table form (see tables I, II, and III). To further illustrate classroom applications of an Earth science-specific model of inquiry, each section also begins with a classroom vignette.

Defining the Question in Geoscience Inquiries

Vignette A

An issue Mrs. Spurrier has always struggled with is getting her students to understand the relationship between landforms and the rock structures underneath the land surface. Her students can identify folds and faults on a test without problem, but they cannot seem to see how this has anything to do with mountains, stream drainage patterns, or landslides. During a topographic map reading exercise, one of her students asks her why the river channels on some maps look like the branches in a leaf, while on other maps the pattern looks like steps or ladders. From cross-sections, Mrs. Spurrier decides that she can structure a student investigation around maps on which she can place known faults and ridges of resistant rock (sandstone, etc.). The question she poses to them is this: What do faults and rocks have to do with the course of rivers?

Inquiries in the Earth sciences are not necessarily about making generalizable statements that go beyond a setting. They can, instead, consist of describing an event that represents a setting and then comparing descriptions for different settings (Ault, 1998). The challenge is to frame these questions in terms of material, space, and time, and then facilitate larger and longer-term understandings by promoting a larger significance, extending to other areas or times.

Time, for example, is not intentionally progressive. As a matter of fact, time in geology is often treated as regressive – that is, what has happened in the past. Geology as a science is dependent on time and place (Toulmin, 1990), and Earth inquiries are fundamentally place bound. Only when taken as a group can one integrate inquiries across locations and time (Kitts, 1977). Hillside creep measurements, for example, start by measuring slope positions in different locations and at different times, and only when a body of data on positions, soil types, vegetative cover, etc., is built up over time can one begin to make generalizations about landslide hazards.

Descriptions of Materials, Space, and Time

At the simplest level, meaningful questions in Earth science center on descriptions (e.g., a description of what a rock or mineral is made of). These questions lend themselves to responses that confirm what is already known, limited to a defined set of minerals or rocks. Finley (1982) further defined descriptions as (a) *classifications* – a characteristic is present or not, such as cleavage, (b) *comparisons* – more or less of a given property, such as hardness, and (c) *quantitative* – fixing a number to some characteristic, such as density or specific gravity. At a guided inquiry level, new or unique materials can be introduced, and questions could center on comparisons and contrasts between the new materials and what is already known. Questions of space, such as where certain minerals can be found, can be posed in a similar fashion involving classification and comparison with where the same mineral can be found, perhaps determining a map location. Time questions can be structured about a sequence of when minerals found together formed, working backwards in time based on the size and shape of mineral grains in a rock.

On the other hand, student observations about Earth phenomena are necessary if they are to generate or accept more open questions. Chin and Brown (2002) speak to the authenticity of student-generated questions, particularly with respect to their direct personal experiences versus those that are teacher-derived and perhaps outside of students' direct experience. Students must be able to define aspects of their own direct or indirect experiences with Earth events, even if they use their own words and not necessarily scientific terminology. Thus, a student-generated question of why a backyard stream floods is as valid as a broader question of why New Orleans flooded during Hurricane Katrina, so long as the questions consider materials, time, and space.

Interpolation and Extrapolation

As one moves from descriptions to interpolations, adding more dimensions adds more complexity to questions, but it also expands the range of questions that can be asked. For example, one could ask how a stream channel changes with respect to time or to changes in water flow. An individual might not be able to observe directly such changes all of the time, but defining a trend from more than one dimension helps to establish a jumping off point from which extrapolations can be drawn. Students may be able to extrapolate what the stream channel might look like during a flood or how those changes differ from lower flow conditions. One could also pose questions of interpolation, in an attempt to describe materials that may have been changed or removed by Earth processes.

Interpolations do not inherently imply the cause of what is changed or how fast it changed. Interpolations and extrapolations, however, become increasingly reliant upon visualizations (Ault, 1994), such as maps, charts, scales, and graphs. Simply drawing the contour lines on a topographic or weather map requires interpolation between three points – the starting point of a line and the two measured points the line is to be drawn between. Verbal descriptions alone cannot adequately convey the necessary patterns that we would have students investigate. Visual representations of the geometry of rock layers, graph patterns of heat flow from the interior of the Earth across various layers, or maps of the ocean floor all provide a taste of the complexity of Earth systems that should frame meaningful questions, especially when projecting across time, space, or material gaps.

A basic idea in Earth science is uniformitarianism, a theory that results in an understanding that Earth processes today allow us to make inferences about similar processes in another place or time. Uniformitarianism relies on pattern recognition, to the extent that Earth processes and the resultant features we observe today can be extrapolated forward or backward in time beyond the information we have at hand. Adding more dimensions enriches questions, such that at least two aspects of a phenomenon must be addressed.

Interactions

Earth phenomena, from the dramatic impact of an earthquake to the subtleties of groundwater flow are complex and multivariate and defy simple explanations. To even begin to understand them, descriptions of materials, space, and time must be defined. Alone, however, these descriptions fall short of providing a fuller, causal explanation of Earth phenomena. When inferring beyond data or across gaps in data, various aspects of Earth phenomena are influenced by other factors that are part of the same overall system. Weather forecasts, for example, offer general projections of future weather conditions for an area, but the actual weather in a location can be influenced by small variations in wind, ground cover, or topography. The interactions of these components raise questions that come even closer to defining the Earth phenomenon of interest. For example, defining what climates would be like on Earth for different plate positions over time would connect all three elements – materials, space, and time – and create a question that is three dimensional in nature. Add to this question the relationship of geographic barriers, and a mechanism for different plant or animal speciation becomes available. This is then a four-dimensional question, one that comes closer to reality.

There is utility in using phenomena to explain other phenomena. The more dimensions added to a question, the closer it comes to reality, with the potential benefit of creating more interconnections between questions. Thus, the availability of water (or lack thereof) from local wells can best be investigated by asking about soil characteristics, slope, recharge areas, and the volume of water extraction over time.

Interactions are scaleable, but with an increase in scale comes an increase in ambiguity or questions for which there would not be enough data for students to develop meaningful questions; that is, a scientific question may be valid and legitimate, but there is no way to pursue it in the classroom. With a sufficiently large scale, however, questions can be based within a "sphere": lithosphere (rock), the hydrosphere (water), atmosphere (air), and cryosphere (frozen). Questions are bounded by the materials present, the ways the materials are distributed across an area, and the ways the materials change over time, giving each sphere a sufficiently limited set of material-space-time considerations that students can define questions within them. Where these spheres interact may offer the most interesting questions, such as how ocean water makes plate tectonics possible.

In Vignette A, Mrs. Spurrier has posed a question structured around an interaction between the underlying geologic structure in an area and the stream patterns for that area. In doing so, she based this question on an interaction between how materials are distributed or oriented and what pattern the streams assume over a larger area. To explore the application range of questions for both the nature of geoscience inquiry and student abilities, sample questions are posed in Table I.

Table I

Sample Earth Science Inquiry Questions

	Confirmation	**Structured**	**Guided**	**Open**
Description	What is the estimated ratio of dark minerals to light-colored minerals in a rock sample?	What is the role of grain size in the settling rates of sediment in a column of water?	What metamorphic minerals form at different temperatures and pressures?	What kind of rocks can be found behind the school?
Interpolations & Extrapolations	From the data provided, construct a graph that shows the negative relationship between grain size and rate of cooling for molten rock	If small grained igneous rocks have a rapid cooling rate and large grained igneous rocks a slow cooling rate, what is the rate of cooling for mixed grains?	What is the lateral extent and thickness of rock unit?	What is the geology of area the town is in?
Interactions	How are the deposits left by glaciers and alluvial fans different?	In what ways are grain sorting and grain size related to the environment in which a rock forms?	How does latitude and proximity to the ocean affect the physical geography of an area?	How does the elevation of the town affect its climate?

Choosing Methods – Observations and Models

Vignette B

Mrs. Spurrier and her students cannot help but observe that the day after a heavy rainstorm her classroom is filled with the overpowering stench of raw sewage. Yet the stream that flows next to the building is usually barely flowing at all. The odor has only become apparent after the growth of the nearby subdivision. Besides the obvious problem the smell represents, Mrs. Spurrier decides that this is something to have her students investigate.

As a part of setting up the investigation, Mrs. Spurrier has her students list factors they believe have caused or are related to the problem. Her students have identified such factors as the amount of rainfall, the frequency of heavy rainfalls, the size of the stream channel, and the number of houses in the subdivision. One student also asks whether the houses were attached to a public sewer line or used septic tanks.

There are obvious public health hazards to which Mrs. Spurrier does not wish to expose her students, so she structures the inquiry carefully, selecting a time that has been without rain for several days to have students take careful measurements of the size and depth of the channel, what they see in the channel, etc. She also assigns students to research the factors they have previously identified. Using these pieces of information, the class constructs a map showing the school grounds, the stream, and the subdivision. Using rainfall data from the local TV station, they construct a model that suggests that if a rainfall is over ¾ in. then the room will smell awful the next day. All they need is a heavy rain to test their model….

Unlike investigations in physics, Earth science investigations seldom include the direct manipulation of variables (Frodeman, 1995; Toulmin, 1990), except in the context of simulating an Earth process under laboratory conditions. Two geologists who profoundly influenced the nature of research in the Earth sciences were Grove Karl Gilbert and Thomas C. Chamberlin, who formulated basic descriptions of not just specific phenomena in geology, but also refined the methodological approaches through which geologists address questions of interest. For physicists, methods are tied to law and theory. But according to Gilbert (1886) method is related to *hypothesis* and *antecedent*. Antecedents in the context of Earth phenomena are factors that are both logical connected to a phenomenon, causal with respect to the nature of the phenomenon, and also linked to the timing and duration of the event. Hypotheses stand in for a set of antecedent conditions that could explain a given phenomenon (Kitts, 1977). For instance, an especially heavy rainfall after days of rain upstream of a location could be linked to floods downstream. The hypotheses resulting from these antecedents, however, are not necessarily the same testable statements one would find in the physical sciences. They are statements of starting conditions of materials in space with respect to some initial time point. This assumption of hypothesis → antecedent becomes the central basis for retrodiction (Ault, 1998).

Hypotheses in geology are different than those for physics, in that many are historical tools rather than straight predictions from a controlled experiment. One can rarely be assured that any two examples of an Earth phenomenon are exactly the same, whether in time or place (Ault, 1998). Although antecedents are interpretative endpoints that contribute to models, hypotheses are the means by which models are tested. According to Kitts (1977), Gilbert believed that rigid theoretical structures, such as those in chemistry and physics, are a threat to the development of progressive histories – that in seeking or even requiring a directionality in a theory was not necessary when generating descriptions from one phenomenon to another. Directionality, particularly with respect to time, implies an increase in diversity and complexity, one with a definable order. One need not assume that a particular Earth phenomenon was in the past less complex or resulted in a simpler to understand result. For instance, when defining what conditions were like in the past or will be in the future, one does not have to assume that a particular Earth phenomenon was less complex in the past. Stream deposits of 400 million years ago are as complex and recognizable as stream deposits today. Any different assumption would imply that uniformitarianism is not a useful tool for Earth science inquiries.

Chamberlin (1897), in applying the idea of multiple working hypotheses contended that since Earth phenomena rarely result from a single cause, a single hypothesis is inadequate. Because there are multiple contributing causes to a single Earth event, multiple hypotheses need to be articulated, explored, and pitted against each other, with the understanding that the multiple hypotheses need not completely account for the phenomenon. Perhaps the flooding in one location is the result of heavy rain on saturated ground upstream, but the flood could also be caused by a blockage of flow downstream. According to Ault (1998), these multiple hypotheses produce “independent, converging lines of inquiry” (p. 207). Thus, an Earth science classroom that is dedicated to a flexibility of methods, such as through guided inquiry, closely matches how Earth science inquiries have been made in the past, using observations to provide specifics of an Earth event, while using *models* to test causal mechanisms.

Observations

Observations in geology are more than just verbal descriptions, although such descriptions provide the “raw material” for the formulation of hypotheses. Were observations limited to measurements of grain size, bed thickness, strike and dip of a rock unit, and geometric relations of folds and faults, they would be largely indistinguishable from measurements of force, voltage, pH, or concentration. What separates geologic observations from chemical observations is the need to consider a range of scales, whether such scales are in the microtextures seen in shocked quartz grains at an impact site, the thickness of the rind on a weathered rock, road cuts with multiple rock layers, or the large-scale map patterns of mountain belts. Such observations are essentially identical, whether the observations are determined by high-tech tools (such as satellite imagery and laser altimetry) or more traditional tools (such as pocket transits and petrographic microscopes). The difference is in the scale of the spatial range and volume of data collected.

The second distinction is made with respect to the terminology used in descriptions. Detailed descriptions of materials include many unusual terms, such as *anticline, subduction zone,* or *hot-spot volcano*. Terms such as these provide not only descriptions of shape or form, but also information on cause, and they provide clues to where other such observations might be made. . These observations are inherently interpretive, rather than experimental (Ault, 1998). Organized into taxonomies, observations are designed to fully represent the Earth phenomena of interest. To the extent that these taxonomies fail to fully account for the events, they lose the level of reproducibility required of scientific inquiries, and therefore lack utility for continued use.

Models

Even though normal modes of inquiry in Earth science do not involve the direct manipulation of variables in the same manner as other sciences, there are circumstances in which the question requires changes in how observations are made. Manipulating how observations are made, however, usually requires a model of some sort with variables that can be changed. Models are dependent on the overlap or cumulative effect of different factors, as well as the boundary conditions in which the model is used (Harrison & Treagust, 2000). For instance, describing an eruption of a volcano requires observations of the temperature of the lava, how much of different chemical elements are available, and how much gas is in the lava. Change any of these variables, and a different eruption will result, which frequently happens across eruptions from the same volcano over time.

Models that are of use in explaining Earth-phenomena in this way fall into one of four categories:

1. A *simulation* model, where one tries to duplicate how the materials change when conditions are changed (e.g., when samples of limestone are immersed in different concentrations HCl to duplicate how rocks containing $CaCO_3$ chemically weather).
2. A *functional* model, in which a measurement is used to make interpolations or extrapolations (e.g., deciding how long a sedimentary layer took to accumulate based on how fast different sediments settle).
3. A *cyclical* model, in which connections between specific materials across time and/or space are explored (e.g., the behavior of solid Earth materials over time in the rock cycle.
4. A *global* or *systems* model, in which the end result is an interpretation based on observations of complex phenomena (e.g., the relationship of rock types to plate margins). (Stevens & Collins, 1980)

In an instructional sense, it is important to ensure that students know when one type of model or another is appropriate, what model components are or can be determined in the context of the question of interest, and how various models for an Earth phenomena can be compared and contrasted (Stevens & Collins, 1980). In answering these questions, models can become more or less sophisticated, with students learning through the refinement of the models. Models that allow for the testing of alternative solutions (as is called for through the multiple working hypotheses structure discussed previously) can also support or refute predictions applied to novel situations. Finally, mapping the distinctions between different models can help prevent models from becoming distorted or made too shallow, a source of misconceptions.

In the context of inquiry, however, there is an inherent danger that when models are created, one can make them overly closed ended and thus reduce their use to a direct confirmation of an Earth event, with limited opportunities for discussing the limits of that model (the investigator found exactly what they were looking for; therefore, the job is done). With limited guidance, students are capable of generating questions for which defining all of the necessary parameters is nearly impossible, thus, leading to ambiguous or misleading results.

In Vignette B, Mrs. Spurrier guided her students in an investigation requiring them to make or collect observations and to use them in the context of a functional model. What the students may find in their investigation is that no one model best fits their situation without sufficient observations. The real source of the odor was determined to be the subdivision's compact "package" water treatment plant, which failed due to increased load from additional homes providing influent. A range of methodological approaches for various problems are presented in Table II.

Table II
Sample Earth Science Inquiry Methods

	Confirmation	**Structured**	**Guided**	**Open**
Observations	Counting the numbers of faces on defined crystals	Comparing the angles between the faces of different-sized crystals of the same material	Determining the permeability of different rocks by immersion in water for different amounts of time	Using the bulk density of a soil sample with pH to determine how weathered local soils are.
Models	Identifying where different rock samples can be found on a diagram of the rock cycle.	Use the percentage of quartz, feldspars, and rock fragments to identify the sedimentary environment in which a rock formed.	Using a stream table with different types of sediment and water flow rates to characterize streams.	Modeling a variety of shoreline forms and slopes to determine tsunami inundation

Arriving at Solutions – Interpretive and Historical

Vignette C

Many of Mrs. Spurriers' students travel to the beach on school breaks. The most popular route to the beach is right down the nearby state highway. Being a fan of the beach herself, Mrs. Spurrier knows the route well, and she poses a descriptive question to her students: Count how many ridges they pass over or through have white sand in the road cut and have short, scrubby little pine trees on them. When the students return from break, some students tell her they saw two or three such ridges; others saw four or five. She asked them how these ridges compared with the beach, and at first, the students were a little confused. When they discussed the parts of the beach and the areas just behind the beach, the lights went on for some of the students. "Those sandy ridges were where the beach was once, weren't they? " asks one of her students.

Given the wide range questions tied to Earth phenomena and the methods used to define them, the next step is to decide what answers make sense. Solutions to questions in Earth science span the range from narrow, prescribed answers based on classification to a broad set of answers capturing the complex and dynamic nature of Earth systems. Frodeman (1995) contended that meaningful answers in geology are either interpretive, using a "truth-seeking" approach, or are of a historical nature (regarding the sequences of Earth events). In this light, they become persuasive arguments. It is not an adequate solution to make observations framed from a single point of view to generate reasonable inferences. One can define a process that describes a phenomenon, such as river flooding, but until the mechanisms producing that process are defined (such as the size of the adjacent floodplain, stream peak discharge, and peak flow duration), the solution remains isolated and incomplete. Once a series of interpretations are made available as a narrative description, they become historical and contribute to larger understandings of groups of Earth events.

Interpretations

In general terms, interpretations in geology are reflective of the variety of geological conditions and the complexity of interactions among these conditions. Interpretations take the raw material of observations and attempt to reconcile one set of observations to another. Interpretations also allow the testing and possible refutation of models. Such "tests" are framed in the context of the original goals (questions) of an investigation, which result in certain discoveries to the exclusion of others (Frodeman, 1995). A case in point is the history of plate tectonics as a theory in geology. Thomas Kuhn (1970) suggested that exceptions supporting an alternative interpretation either never happen at all or occur all of the time when phenomena are explained. The hypothesis of continental drift, as articulated by Alfred Wegener, was a counter instance to the hypothesis that continents were "fixed" in place. Those that saw continents as fixed in place saw the data of the "drifters" as puzzles to be accounted for without continents moving. Data such as "fits" between continental margins, transoceanic similarities of plant and animal fossils, and matched sequences of sedimentary rocks were explainable by now-submerged land bridges.

The resulting crisis was not over continental drift per se, but over methods and interpretations. Drifters wanted a uniform explanation for all of the patterns they observed, but "fixers" preferred an approach that made continental drift one possible theory. It was only when different geophysical data, such as paleomagnetic stripes, gravity anomalies, and heat flow measurements from the sea floor were observed, that the idea of plate tectonics could be developed. This idea did not build directly on continental drift but used different lines of evidence to refute continental fixity successfully and account for the data puzzles introduced by the Drifters (Oreskes, 1999).

Historical Representations

What happened or is found at a particular place and time is a solution that satisfies the need for retrodiction in Earth inquiries. This again is what separates Earth inquiries from that of the other sciences. In the physical sciences, experiments can be set up, controlled, results recorded, and conclusions communicated across the research community for replication in different times and places. Following the described procedures ensures replication of results. In Earth inquiries, one form of solution is a narrative description of the phenomenon or object of inquiry. With detailed descriptions, two main goals can be accomplished: (a) the contribution of a set of ideas to a larger problem of interest, such as the relationship of the porosity and permeability of a limestone layer to how much oil it could contain, and (b) the reconciliation of different descriptions of the same phenomena by different models, such as the description of a lava flow by either the type of rock in the flow or the density of gas bubbles in the flow itself (Frodeman, 1995). Once these narratives are integrated into a larger set of ideas, they have value as a solution to a larger path of investigation. "Expert" groups of students might separately describe the same samples of materials, framed by different models, but collectively their observations would define the Earth phenomenon related to the samples.

Another form of historical solution in Earth inquiries is the analogy. Normally, an analogy in science consists of a target concept and an analogue of the event, object, or phenomenon (Glynn, 1991). For example, glaciers are often described as "rivers" of ice, and can represent several of the same class of phenomena, such as erosion, deposition, etc. The analogy breaks down when one considers the mechanisms of glacial processes, ones that generally do not emerge without a narrative description. These analogies are conceived independent of time and spatial distribution, and often limit themselves to the characteristics and behavior of materials. Analogies applied as historical solutions to Earth inquiries require the consideration of time and space. Uniformitarianism, for example, can be considered in terms of the consistency of physical laws over time, or through the projection of current observations of cause into the past (Gould, 1987). Thus, the narrative allows for any unique phenomenon to be directly and quickly considered by analogy to another similar, well-characterized event. Thus, the Mercalli scale of earthquake intensity can provide a fairly accurate estimate of the energies released in an earthquake event based on the damage caused by the earthquake, even if few seismographs are available where the earthquake occurred.

What should characterize any analogy (and all too often forgotten in the use of analogies) is the definition of the limits of an analogy. There were, for example, conditions on the ancient Earth that do not now currently exist, such as those that produced the Precambrian banded iron formations. Today, there is simply too much oxygen in the atmosphere for exposed iron to exist long in a form other than hematite (Fe_2O_3). There are also the limits imposed by the incongruity between geologic time and human time. We can, by analogy, relate *Skolithos* (an extinct burrowing worm known from preserved burrows in clean sandstones) found fossils of Cambrian quartzites to the worm burrows found on today's beaches, but can we reverse the analogy and anticipate what today's burrows will look like on a preserved Myrtle Beach in the distant future (Frodeman, 1995). Mrs. Spurriers' students saw a great deal of sand when they went to the beach, but they needed structured or guided interpretations to see those sandy ridges as past beach terraces. They also needed guidance to see that the ridges are a historical record of sea level changes. Additional solution examples are found in Table III.

Table III
Sample Earth Science Inquiry Solutions

	Confirmation	**Structured**	**Guided**	**Open**
Interpretations	A determination of the relative movement along a fault plane from map pattern data	Description of a paleoenvironment based on rock and fossil types	An estimate of the past location of a continent, based on rock type, fossils, paleomagnetic information, etc.	Determining the direction of stress for a local area based on mineral orientation and folds/faults, etc.
Historical Representations	A sequence of events for the formation of rocks and structures, developed from a 3-D block diagram.	A determination of the age or timing of a divergent plate margin from the similarities and differences of fossil and rock types.	A reconstruction of past positions of a continent based on a regional stratigraphic column	A sequence of the tectonic events for an area

Discussion of a Complete Model

Much of the information presented above is centered on one aspect of inquiry as defined science standards (NRC, 1996), the understanding of the traditions and conventions of geoscience inquiry, with some support for instructional design. The model is graphically represented in Figure 1. In considering the above model of Earth science inquiry in an instructional sense, a teacher needs to consider the application both within the context of an individual lesson as well as planning for students' conceptual growth. Within the general model of constructing inquiries, teachers guide students through questions, using specific methods to arrive at desired or expected solutions. To support such transitions, the teacher's work centers on facilitating students' opportunities for each inquiry component, providing sufficient information (and materials) for students to proceed. This involves a determination of how much information is specified to students (questions, methods, solutions) to describe the level of inquiry.

Connections Between Nodes

In order to make instructional sense of this model, the transitions between the "nodes," as defined by the structure of geoscience inquiry, can serve to describe specific classroom actions in a manner that informs teachers in commonly used terminology. This terminology should consequently find application in specific lesson plan elements. The 5E Learning Cycle (Center for Science, Mathematics, and Engineering Education, 2000) offers a general framework to which the connections can be overlain. To illustrate this application, there is a school in the Virginia Coastal Plain that has behind it on the school grounds a small stream that cuts through layers of Miocene-age sediments. One of these layers is rich in large shell fossils, including *Chesapecten jeffersonius*, a large scallop that is the state fossil of Virginia. As a result, this fossil is sought after by students (*engagement*). After identifying what fossils are present (usually more than one species) in the layer, the range of individual fossil sizes, layer thickness, and lateral extent can be determined. Reviewing and sorting all of the descriptions helps to frame the observations that characterize the layer (*exploration*). By comparing this layer with other layers that are different, and by researching for other, similar layers, the layer can be interpreted as a shell shoal (*explanation*). Shell shoals are sandy beds that typically form near an active beach, and since this location is approximately 40 miles from the current beach, instructional conditions are ripe for students to engage in a new investigation that uses interpolations to frame further observations to fill in data gaps, or extrapolations of correlation to subsequently test the model that the shelly layer is in fact a shell shoal (*elaboration*). Student knowledge can subsequently be tested by soliciting their supporting evidence for predicting where additional shell shoals might be found (*evaluation*).

Complexity of Inquiry

As students' conceptual understanding grows, Earth science inquiry lessons should reflect a consequent growth in complexity and larger understanding. Recall that while the level of inquiry is based on the amount of information supplied to students, not on the complexity of that information. Starting first with relatively constrained, one-dimensional descriptions linked to observations and consequent interpretations, more dimensions can be added to the questions, leading to more complex modeling and historical descriptions. The shift could take place over time between lessons, but also within the context of a lesson. Complexity in this classroom inquiry can be increased by the introduction of additional dimensions, such as fossil density within the shell shoal, morphological differences in the fossils, and variations in the sediments. Observations can be seen as contributing to models being used as tools for framing subsequent observations, particularly in comparing the shell-rich sediments with other, well documented shell shoals, both contemporary and ancient. Finally, the interpretations made by students of the conditions that led to the deposition of the layer in the first place, as well as layers above the shell shoal, can be used to build a history of the local area. This history can then describe changes in sea level in the past (retrodictions) and make predictions for the future. In this manner, students' inquiries can lead to a deeper understanding of the multivariate reality that make up Earth systems. A graphical description of both the Earth science inquiry model as well as the instructional application can be found in Figure 1.

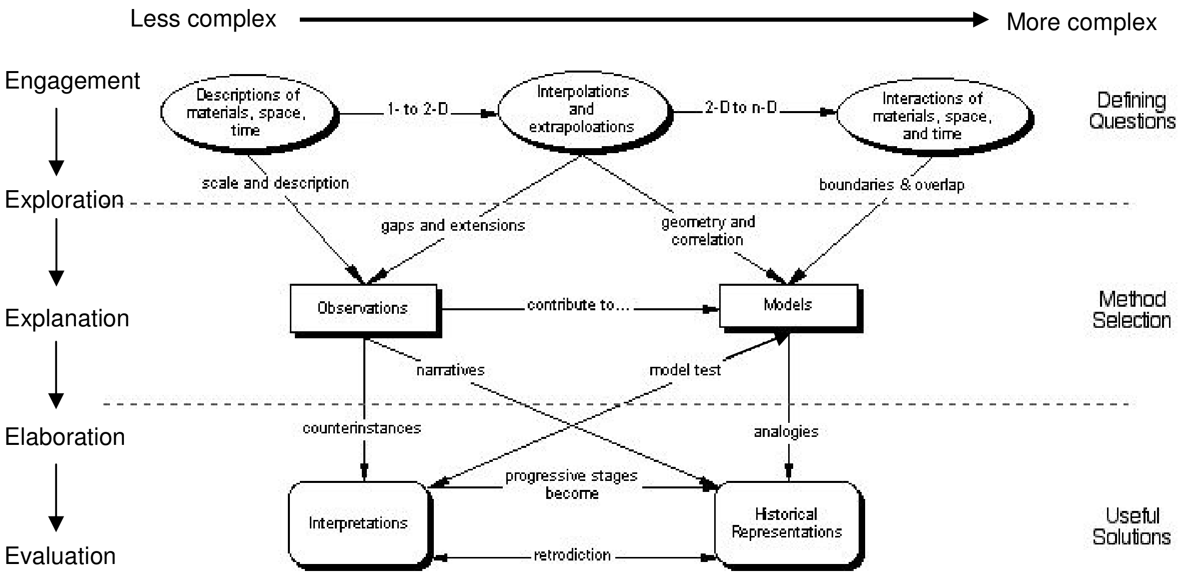

Figure I. Summary Representation of an Inquiry Framework for the Earth Sciences

Selecting the level of complexity is a decision-making process involving teacher professional knowledge, depth of content knowledge, and understanding of student capacities and development. Keys and Bryan's (2001) suggest that this decision-making process is a reflection of the need for teachers to reconcile their beliefs of the both the nature of inquiry as well as the abilities of their students. The documentation of these processes, particularly with respect to this model of geoscience inquiry, is a rich vein of investigation in its own right. With a model that captures both the complexity of instructional planning needs and the nature of inquiry in the Earth sciences, teachers and professional development providers have a tool that supports a richer understanding of science inquiry in general.

Conclusions

It should be readily apparent that even without the same level of control over the conditions of inquiry enjoyed by other sciences, inquiries in Earth science might be structured in a manner that reflects of the nature of the various Earth science disciplines. With the current emphasis placed on inquiry-oriented science instruction, it is important that teachers have a deep understanding inquiry that is reflective of nature and conventions of the discipline. A full instructional explication of the proposed Earth science-specific model of inquiry is beyond the scope of this work, but it should become clear that the central questions, methods, and solutions in Earth science can be defined in instructionally meaningful ways. Furthermore, as recommendations for Earth science curricula embrace an Earth systems approach (Hoffman & Barstow, 2007), it is important to remember that hypothetico-deductive methods of analysis are ill suited to broader descriptions of how the Earth works. Earth science inquiries should be seen as dynamic and are scalable, to meet the demands of individual inquiries while contributing to an overall understanding of Earth systems. With this in mind, it is possible to take Earth science instruction away from simple terminology-based descriptions and build authentic investigations for students to experience.

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