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Kastens, Kim A;Rivet, Ann
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Multiple Modes of Inquiry in Earth Science

Helping students understand the scientific process beyond laboratory experimentation

Kim A. Kastens and Ann Rivet

Laboratory experimentation played only a minor role in the development of many key concepts in Earth science. Earth science researchers have used multiple modes of inquiry to cultivate concepts such as plate tectonics, geological time, the hydrologic cycle, and global climate change. Students who understand the process of science as comprising only laboratory experimentation are at risk of developing a disconnect between the content and process aspects of their Earth science education (Tsai 1999); they may be unable to discern how the process could have led to the concepts. To help teachers enrich their students' understanding of inquiry in Earth science, this article describes six modes of inquiry used by practicing geoscientists (Earth scientists), illustrates each mode with research examples, and provides pointers to investigations that allow high school students to experience each mode.

Inquiry used by geoscientists

The "scientific method" is the primary framework presented to students to explain how science progresses. This method is most commonly conveyed as a sequence of steps by which an experimenter sets up a laboratory apparatus, manipulates one variable at a time, and considers the outcome as a function of the manipulated variables (Edwards 1997; Uthe 2000). Although this is a legitimate characterization of how science is often conducted in many disciplines, laboratory experimentation is only one of several ways in which scientists conduct research in Earth sciences.

Six modes of inquiry widely used by practicing geoscientists include:

- the classic laboratory experiment,
- observation of change over time,
- comparison of ancient artifacts with products of active processes,
- observation of variations across space,
- use of physical models, and
- application of computer models.

Together these modes of inquiry allow geoscientists to address a wide range of questions about Earth structures and processes. In this article, we illustrate each mode of inquiry using examples of seminal or pioneering research and provide pointers to investigations that enable students to experience these modes. By discussing and engaging with multiple modes of inquiry, students should gain a deeper understanding of both science content and science process.

Classic experiment

Earth scientists do, occasionally, conduct classic experiments in which they use laboratory apparatus and manipulate variables. For example, to study water erosion, scientists place sediment in the base of a flume beneath a channel of flowing water (Figure 1a, p. 28). The experimenter varies stream velocity and sediment type, and observes what velocity is required to erode or transport sediment as a function of sediment grain size.

Leavitte (2005) presents a classic experiment that students can conduct to investigate weathering. Students weigh samples of different rock types and place them in a closed, unbreakable container with some water. Students vigorously shake the container and determine the percentage of each sample that has broken off into small particles after being "weathered." By graphing change in sample size and relating this to the rock type, students can evaluate the comparative weathering rates for these types of rocks.

Changes through time

Earth scientists look at changes through time over various timescales. For timescales of minutes to centuries, scientists can use instrumental or historical records. For example, atmospheric scientists used repeated measurements of atmospheric chemistry to detect the human-caused increase in atmospheric carbon dioxide throughout the 20th century (Figure 1b, right, p. 28) (Scripps CO_2 Program 2007). For timescales of thousands to billions of years, Earth scientists rely on traces left in the rock record. For example, by examining the sudden, drastic change in fossils and sediment chemistry at 65 million years before present, scientists inferred a world changed by meteor impact and mass extinctions (Figure 1b, left) (Alvarez 1997).

Regardless of the timescale, there are three common lines of reasoning followed by scientists using the changes through time mode of inquiry. The first line of reasoning focuses on sequence: sequence constrains causality. In essence, if A happened before B, then scientists reason that A can have caused or influenced B, but B cannot have caused or influenced A. The second line of reasoning focuses on rate: rate constrains power. For example, if scientists can show that a meter-thick layer of rock was emplaced nearly instantaneously, they must invoke a more energy-intensive mechanism than if the layer accumulated gradually across many years. The third line of reasoning looks for patterns. For instance: Is the observed parameter increasing or decreasing, accelerating or decelerating, with time? Or does it rise and fall in a regular cycle? Each of these patterns helps scientists explain Earth phenomena by ruling out some causative processes and supporting others. This inquiry mode is powerful for gaining insights about conditions and processes that are not available for study today, such as an ice-free world or a world without photosynthesis.

Students can conduct similar investigations within both shorter and longer timeframes. For example, students can conduct repeated observations of a local creek, correlating documented changes with recorded weather conditions (e.g., Gleason 2001). On a longer timescale, students can consider how the Antarctic sea ice extensions have changed over time as part of a unit on global warming (GMA 2000).

Using modern analogs: Comparison with active processes

"The present is the key to the past" has been one of the guiding principles of geology since the pioneering work of James Hutton in the 1700s (Repcheck 2003). This mode of inquiry hinges on the premise that natural processes operating in the past are the same as those observed operating today. Scientists can compare a physical, chemical, or biological artifact in the rock record with a similar artifact for which the formative processes are still active and observable. Based on similarities between the modern and ancient artifacts, and building on basic principles of physics, chemistry, and ecology, the scientist can infer key aspects of the ancient environment.

For example, by observing recently erupted lavas on the seafloor, scientists learned that pillow basalts (Figure 1c, left, p. 28) erupt only under water, where the high heat capacity of water chills the outer rind of magma quickly. As a result, when scientists observe a sequence of rock strata that contains pillow basalts (Figure 1c, right) they infer that those strata were deposited in a subaqueous setting. Likewise, by observing that sediments rich in organic carbon and pyrite are deposited in anoxic settings in modern wetlands and oceans, scientists infer that oxygen was scarce at times and places where ancient organic-rich, pyrite-bearing sediments were deposited.

A student investigation within this mode of inquiry would be to use modern animals to make inferences about the type of environment in which fossil organisms may have lived (e.g., Flammer 2002). Similarly, students may compare the ratio of the gait and leg length of a modern-day chicken to the distance between ancient dinosaur footprints, to estimate the height of the animal that made the footprints (Olsen).

Variation over space

Earth varies from place to place, on many scales and many dimensions. The variations occur with latitude, altitude, distance onshore-offshore, upstream-downstream, or along urban-rural gradients. Earth scientists use variation over space to generate hypotheses and support inferences about the processes that caused or are causing the observed distributions.

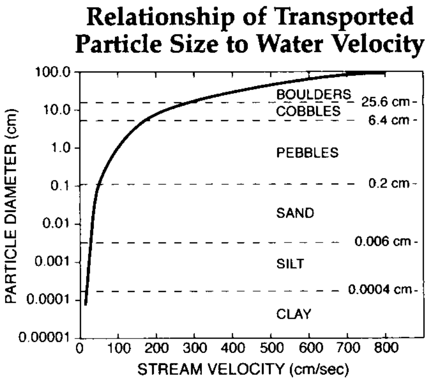
Two common lines of spatial reasoning involve gradients and co-occurrences. When scientists discern a spatial gradient in their data, one possible interpretation is that material has been, or is being, transported in the direction of the gradient. For example, a gradient from coarse-to-fine sediment grain size is often interpreted as showing the direction of sediment transport because finer sediment grains are more easily transported over long distances. When scientists find that two phenomena co-occur spatially, they may consider hypotheses in which one causes the other or both are caused by the same third factor. For example, scientists' observation that earth-

FIGURE 1

Modes of inquiry in the Earth sciences (For all Figure 1 credits, see p. 24 in this issue of *The Science Teacher*.)

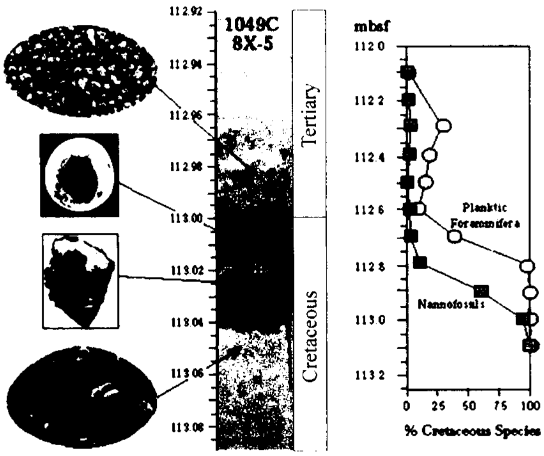
(a) Classic Experiment

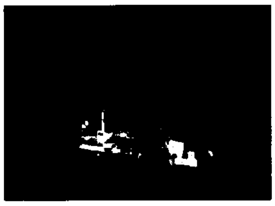
- In a laboratory
- Control one or a few variables
- Collect quantitative data
- Examine outcome as a function of controlled variable(s)



(b) Changes over Time

- Order of events constrains causality
- Rate constrains power
- Pattern of changes through time constrains process





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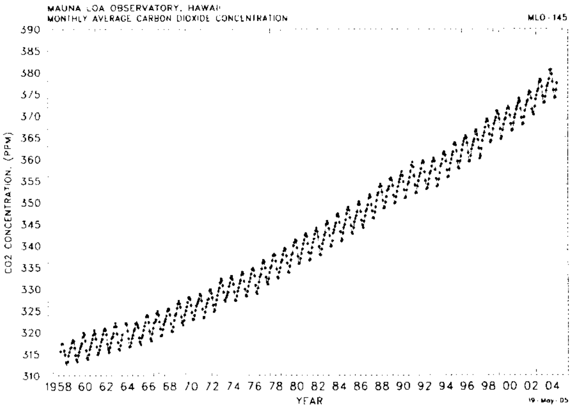


(c) Using Modern Analogs

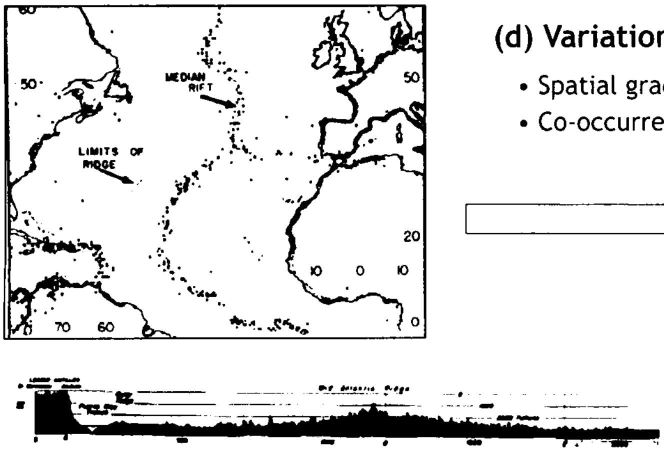
- "The present is the key to the past"

Seafloor

versus

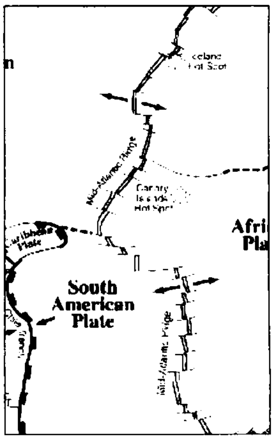
Outcrop

→ Subaqueous eruption



(d) Variation over Space

- Spatial gradient
- Co-occurrence in space

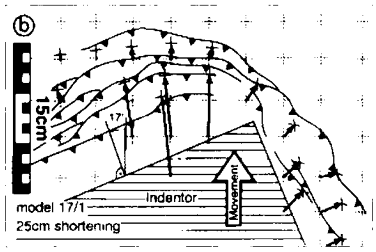


(e) Physical Models

- Build scale model of part of Earth system
- Compare model outcome to observations from nature
- Compare geometry, shapes, trends, patterns, and sequence

Physical Model

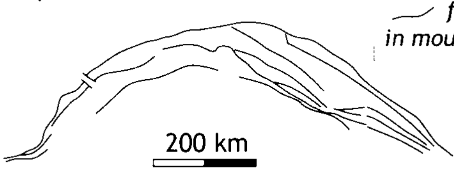
Interpretation of Physical Model

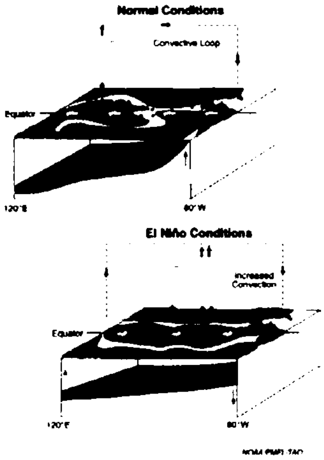


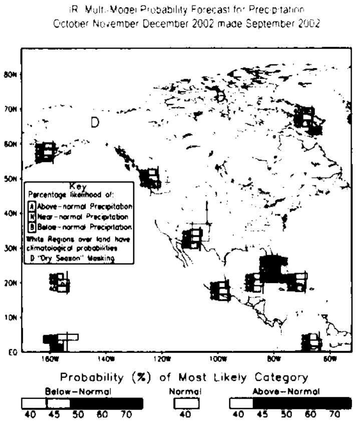
(f) Computer Models

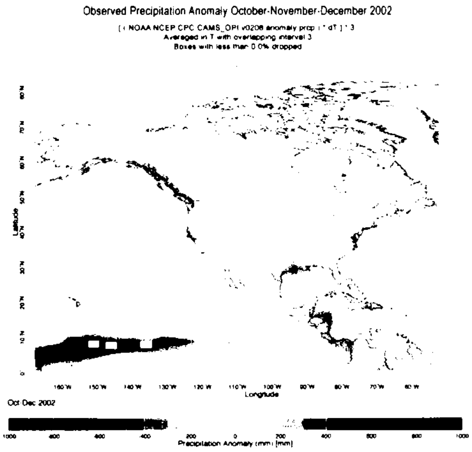
- Begin with conceptual model
- Express hypotheses as equations
- Incorporate equations into computer code
- Compare model output with data from nature

Folds and faults in a real mountain range









quakes coincided spatially with a bathymetric rift along the crest of the Mid-Atlantic Ridge (Figure 1d, p. 29) led to the concept of mid-ocean ridge spreading centers (Kunzig 2000). The co-occurrence of explosive volcanoes, deep earthquakes, and bathymetric trenches around the Pacific "Ring of Fire" gave rise to the concept of subduction zones.

Students can experience this form of inquiry by working either with data they collected themselves or with professionally collected data sets. For example, students from schools along the Hudson River collect data on water chemistry, temperature, and turbidity; pool their data over the internet; and examine upstream-downstream gradients in the river (Hudson River Snapshot Day 2007). Using professionally collected data, students can analyze global patterns of earthquake distribution (e.g., Rissler 2007), evidence of glacial advance and retreat (Jurewicz-Leighton), or the relationship between advancing atmospheric pressure systems and rainfall distribution (e.g., NOAA 2004).

Physical models

A physical model is a manipulatable apparatus that reproduces, at reduced scale, some aspect of the Earth system. For example, in the early days of plate tectonics, scientists used slabs of solid wax floating on molten wax to model the geometry of ridge-transform-ridge plate boundaries (Oldenburg and Brune 1972). To study compressional tectonics, scientists use "sandbox" models in which layers of sand are horizontally compressed (Figure 1e, p. 29). The sequence and geometry of folding and faulting in the model help unravel the deformation history of fold-and-fault mountain ranges.

Although there is some overlap between this mode of inquiry and a classic laboratory experiment, the emphasis in this mode is on comparison between the lab system and the natural system, rather than on comparison across a manipulated variable within the lab. This mode of inquiry is most effective for exploring geometry, shapes, trends, patterns, and sequence, which are attributes that scale well.

An example of student inquiry in this mode is to use a stream table to replicate observations from the local environment. Through this process, students can observe how environmental factors such as stream velocity, stream bed shape, and sediment type impact the shape of their local landscape (e.g, Lillquist and Kinner 2002). Similarly, after collecting data on Moon phases and times of high and low tide over the course of a month, students can manipulate a light source and a large and small sphere to create a physical model that best explains their set of observations from nature (e.g., Westbroek 2005).

When using a physical model in Earth science class, teachers should insist that students explain their findings in terms of the natural system, not just in terms of their methods and observations in the lab. Students should be able to articulate both the similarities and differences between the model and the natural system. Similarities help students understand how the model provides insight into the workings of the natural system, while differences help students understand the limits beyond which the analogy should not be pushed.

Computer models

When scientists build a computer model, they begin with a conceptual model of how some aspect of the Earth system works. They express their hypothesis as equations and implement these equations as computer code such that specific equations will be invoked in specific ways under specific circumstances. Scientists then vary the input circumstances, run the model, and examine the model output. Finally, and most importantly, the scientists test their model by comparing the model output with data from nature (Weart 2007).

For example, climatologists begin with an understanding of ocean-atmosphere interactions such as El Niño (Figure 1f, left, p. 29). They incorporate this understanding into a computer model, which outputs a prediction for how much precipitation should fall at each place on the globe (Figure 1f, center). The scientists compare this model output with actual rainfall data (Figure 1f, right). To the extent that the model output is able to replicate important features of the observational data, scientists gain confidence that the causal relationships used to design the model are indeed likely to be causal relationships that are active in nature.

Of the modes of inquiry discussed in this article, computer modeling is the most recent development and thus has not yet penetrated far into science education. The WorldWatcher visualization software and its predecessors (Edelson, Gordin, and Pea 1999) allow students to examine and interpret global environmental data, and to manipulate certain aspects of the Earth system in the computer. For example, students could remove the atmosphere or the clouds from a hypothetical Earth (Edelson, Gordin, and Pea 1999), or change topography and investigate the consequent change of surface air temperature (GEODE Initiative 2007). In addition to using computer models that have been developed by others, students can also learn by building their own computer models, running them, and comparing the model output to data from nature (Lyneis and Stuntz 2007).

Conclusions

Ideas at the core of the high school Earth science curriculum, including plate tectonics, the hydrological cycle, global climate change, and geological time, were developed through multiple modes of inquiry. Students whose science process studies have covered only classic experimentation will not be able to discern how the process of science could have led to the ideas taught as Earth science content. In the worst case, such students may not even recognize that investigations of Earth *are* science.

On the other hand, if students *can* see the connection between process and conclusion, they may be more likely to have confidence in the content they are learning and be willing to apply these ideas to new settings (Hogan 2000). Students may be able to more fully grasp the explanatory and predictive power of the concept or process. And finally, they may be more likely to understand the limitations of the explanation (Smith et al. 2000). As a result, students gain a richer understanding of the processes and nature of science, beyond a single "scientific method."

Assessments, as well as learning activities, should reflect the multiple modes of inquiry used in Earth sciences. For example, an assessment on concepts such as plate tectonics that were not developed through laboratory experimentation should include questions probing "how do scientists know this?" as well as "what do scientists know?" Likewise, the judging criteria for a science fair or other project should be broad enough to recognize excellence in interpreting data that vary naturally across time or space; there need not be a "manipulated variable" for a project to be good research.

Earth science students should be given opportunities to discuss, experience, evaluate, and reflect on, the methodology, strengths, and limitations of all of the modes of inquiry on which our current (and future) understanding of Earth is based. ■

Kim A. Kastens (kastens@ldeo.columbia.edu) *is a Doherty senior research scientist at Lamont-Doherty Earth Observatory and an adjunct professor in the Department of Earth and Environmental Sciences and Ann Rivet* (rivet@tc.columbia.edu) *is an assistant professor in the Department of Science, Math, and Technology Education, Teachers College, both at Columbia University in New York.*

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