The Challenge: Sequencing

"Sequencing" refers to the process of figuring out what happened, when, and in what order? When detectives or journalists try to establish "What did someone know and when did he know it?" they are using a form of sequencing. Detectives, journalists, and geoscientists all seek this information because sequence constrains causality. Science cares a lot about causality. If we have evidence that A happened before B, then we know that A potentially could have caused or influenced B. But if A happened after B, it could not. For instance, if a climatic trend or bollide impact occurred before an extinction, the change or collision might have contributed to the extinction, but if it occurred after the extinction, then it could not have been a causal factor.

This kind of temporal reasoning is important in the Earth Sciences because it provides insights about events not seen by any humans nor recorded by instruments. So why are we discussing *temporal* reasoning in a series of articles on *spatial* reasoning? Because geoscientists use observations of *spatial* position or configuration to obtain constraints on *temporal* sequence. For example, in a normal stratigraphic sequence, the configuration of layers—which one is below the other—indicates which was deposited first. Similarly, in a cross-cutting relationship, the spatial configuration provides the information about which event preceded the other.

Temporal and spatial reasoning have been identified as two of the most distinctive or characteristic habits of mind of geoscientists (Manduca & Kastens, 2012). As they work on sequencing, your students will thus be mastering two of the kinds of thinking that make geosciences special and fun. Sequencing is one of those skills that seems totally obvious to some students, yet poses a major challenge to others. How can we help the strugglers?

Examples of sequencing are ubiquitous in geology, meteorology, oceanography, astronomy, and other geosciences. Some sequential events are cyclic and predictable, such as seasons, moon phases, and tides. Others are non-cyclic, unpredictable, and cover vast amounts of time, such as the rock and fossil records preserved in stratigraphic profiles.

One of the distinctive practices of geologists is to use spatial information to make inferences from the relative positions and shape of rock layers about a sequence of events and processes over time. Consider the outcrop image in Fig. 1. To a geologist, this shows two distinct sequences. First, in the bottom part, sedimentary layers were deposited, folded, then eroded. Later, different sedimentary rocks were deposited above buried erosional feature to create an unconformity. These processes probably occurred over vast amounts of time, but now produce a composite 'snapshot' of coexisting shape.

Fig. 1. Photographer: Thomas McGuire. http://www.earthscienceworld.org/images/index.html
Photo ID: ho7fk6
http://www.earthscienceworld.org/images/search/results.html?Category=$Category&Continent=$Continent&ImageID=$ImageID#null

Identifying and interpreting changes in the Earth System are of the highest importance, and integral within national and state science education standards. The major guide in developing the Next Generation Science Standards, *A Framework for K – 12 Science Education* (National Research Council, 2011) , states:

> Understanding the different processes that cause Earth to change over time (in a sense, how it "works") therefore requires knowledge of the multiple systems' interconnections and feedbacks. (p. 169-170.)

Pertinent components of the *Earth Science Literacy Standards* include:

Big Idea 1. Earth scientists use repeatable observations and testable ideas to understand and explain our planet.

1.6 Earth scientists construct models of Earth and its processes that best explain the available geological evidence. These scientific models, which can be conceptual or analytical, undergo rigorous scrutiny and testing by collaborating and competing groups of scientists around the world.

Big Idea 3 Earth is a complex system of rock, water, air, and life.

3.4 Earth Systems act over a wide range of temporal and spatial scales.

Big Idea 4 Earth is continuously changing.

4.7 Landscapes result from the dynamic interplay between processes that form and uplift new crust and processes that destroy and depress the crust.

One example of how sequencing informs state science guides comes from the New York State Physical Setting/Earth Science ("Regents Earth Science") Core Curriculum:

> 1.2j. Geologic history can be reconstructed by observing sequences of rock types and fossils to correlate bedrock at various locations.
>
> Age relationships among bodies of rocks can be determined using *principles* of original horizontality, superposition, inclusions, cross-cutting relationships, contact metamorphism, and unconformities. The presence of volcanic ash layers, index fossils and meteoritic debris can provide additional information.

Assessment of this skill often involves diagrams representing stratigraphy. Fig. 2 presents one example. (Note that such drawings often present more complexity than the photograph in the Fig. 1.)

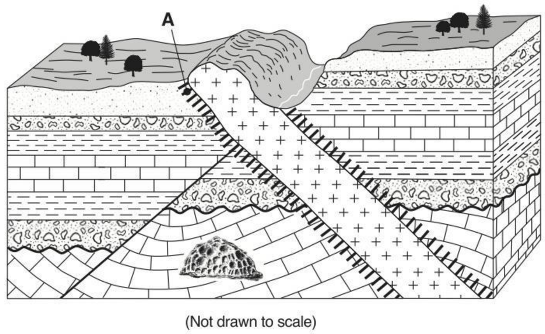

Fig. 2. Source: New York State Education Department "Physical Setting Earth Science" ("Regents Earth Science") Exam, June 2010, question 75.

Too often, students are taught "rules-of-thumb" to answer such questions correctly on high-stakes exams without gaining the critical thinking skills necessary to solve other sequencing problems. In order to reconstruct the Earth processes involved in creating the observed configuration, a student should comprehend such concepts as: deposition of sedimentary layers and superposition; folding, faulting, erosion and unconformities; igneous intrusions or extrusions and cross-cutting relationships; contact metamorphism; and/or index fossils. In addition to understanding each process, students need to grasp the relationship between the process and resulting configuration of rock unit. Spatial representations, such as block diagrams and profiles, need to be mastered to handle such sequencing items. For test items such as Fig. 2, students are also expected to use appropriate parts of the "Reference Tables for Earth Science/Physical Setting" (http://www.p12.nysed.gov/apda/reftable/earthscience-rt/esrt2011-engr.pdf).

Teachers participating in our "Professional Development to Improve the Spatial Thinking of Earth Science Teachers and Students" grant project (http://www.earth2class.org/er/vc/) described difficulties observed as students attempted to answer such questions:

- They are hard because the students don't really understand what the question is asking for, since their experience deals only with the top views, not cross-sections
- Students don't think to use the key or Reference Tables
- Students try to look at the entire picture, find it too busy, and are overwhelmed
- Some find sequencing ('which is older?") relatively easy, but even students who can easily answer questions about order struggle to provide explanation backed up with evidence
- Block diagrams are harder than a pure profile
- Urban kids don't have experience with rocks or mud

Suggested Strategies to Enhance Student Understanding of Sequencing

Many students begin their understanding of sequencing, and intuitively develop the Law of Superposition, from the often-observed experience that in a pile of papers on a desk, the bottom-most were laid down first ("oldest.") If asked to make a sketch to show this, most would be able to do so. Yet expanding this insight to more complex may be intimidating.

Experience geoscientists and some students can start by sketching the earliest events and describe the sequence of events that led to the eventual arrangement. But other students are overwhelmed by the complexity of the image and don't know where to start. Many are hesitant to make drawings ("I'm bad at art.")

To foster understanding of complex stratigraphic problems by all students, we suggest an instructional strategy in which students are taught to take apart a diagram and create of a series of cross-sections for different 'time-slices,' using tracing paper to overcome the discomfort of drawing. They then explain how they would re-construct the sequence, describing the Earth eventsthat transpired between the illustrated time-slices.

This strategy is based on "reverse engineering" in which one de-constructs the events shown in a diagram, working backwards from the final arrangement to the starting point. Reverse engineering is widely used to deduce how something was constructed or assembled from end products without *a priori* knowledge about the procedures involved in the production. It has its origins in the analysis of commercial or military hardware, but is now widely used in many fields.

Such "reverse engineering" may be preferred by many Earth Science learners, especially when they may not yet be familiar with the above-listed kinds of geological processes or such terminology. Our suggested strategy also involves providing plausible alternative scenarios. Students must choose the more likely and provide evidence (give an explanation) for their choice.

To illustrate this strategy, consider what probably happened to create this arrangement of rock structures depicted in a Regents Earth Science exam question:

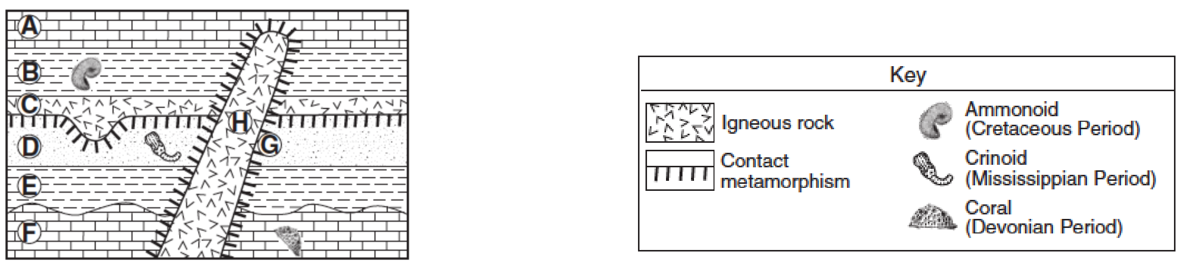

Fig. 3. Source: New York State Education Department "Physical Setting Earth Science" ("Regents Earth Science") Exam, August 2010, question 80.

Using tracing paper and omitting details such as the fossils, students might begin to solve the problem by deciding between the two possibilities presented in Fig. 3. They also should write what evidence supports their view.

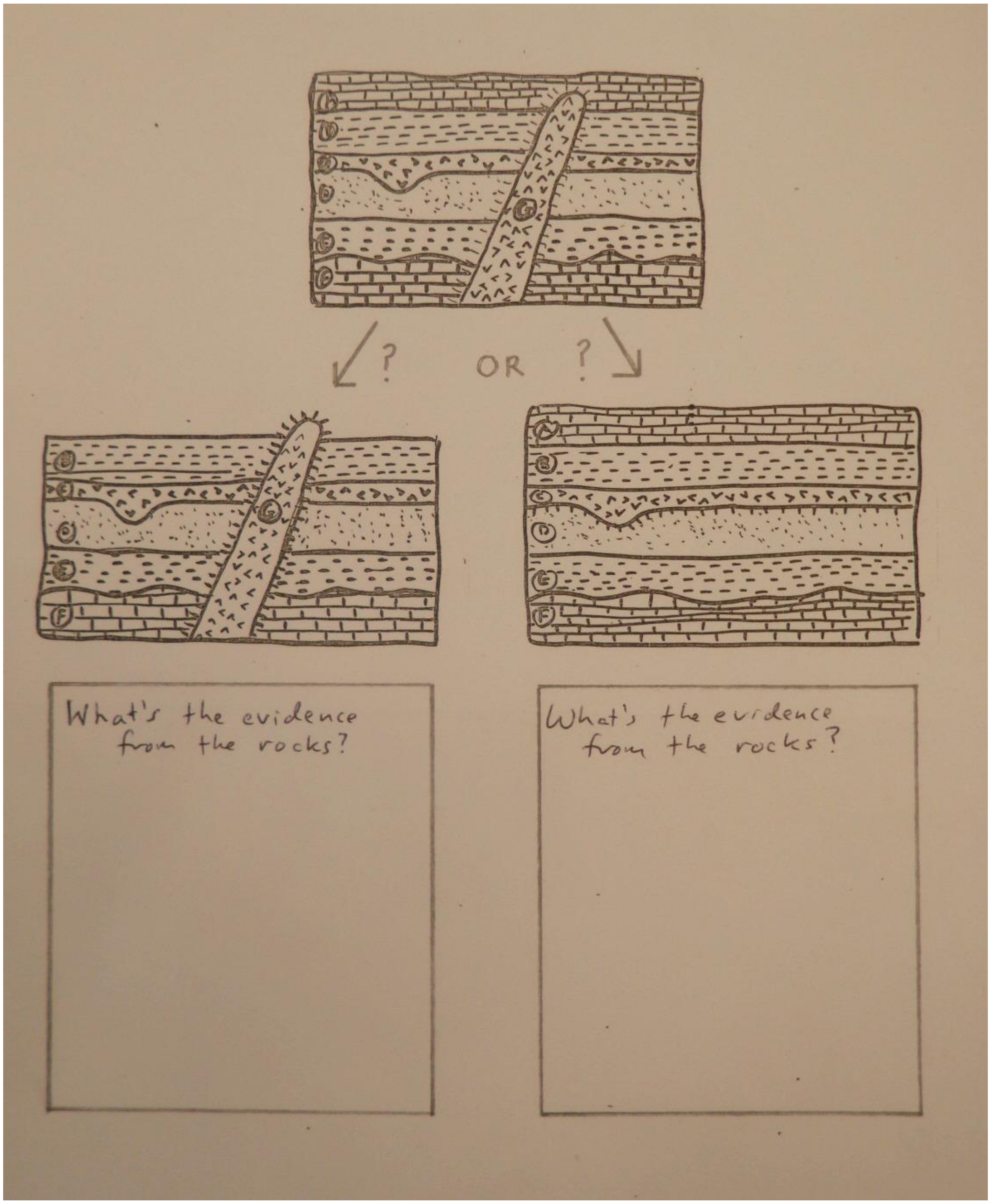

Fig. 4. Alternate possibilities for what happened just prior to the final arrangement. In the left-hand-diagram, layer A is removed; in the right-hand-diagram, intrusion G is removed. Students should realize that, in the absence of layer A, no contact metamorphism would occur where the intrusion extends above the surface. Therefore, the right-hand diagram is correct.

Students might continue the “reverse engineering” process by making a series of drawings and explanations such as those in Fig. 5:

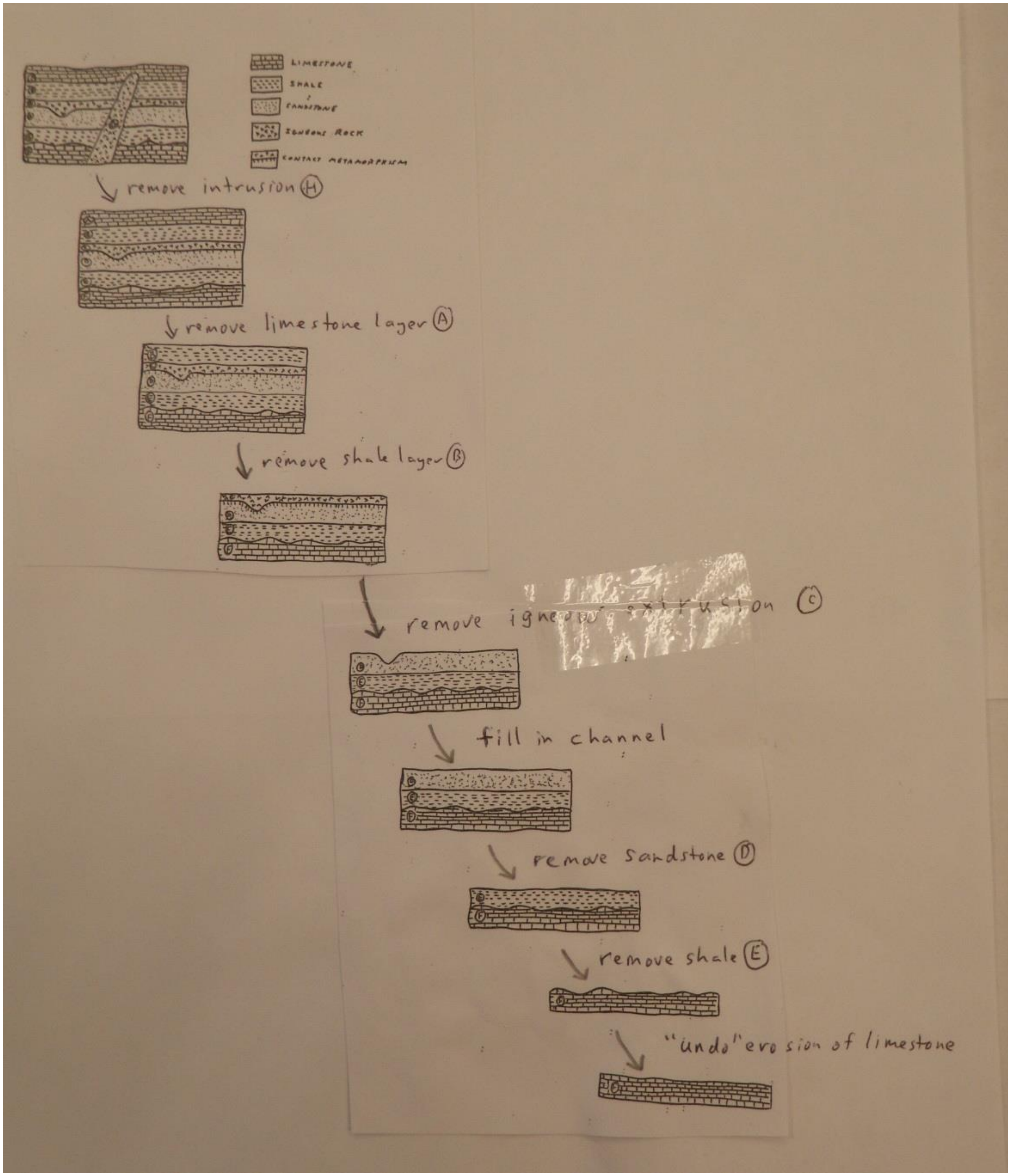

Fig. 5. Sequence of events and explanations which "reverse engineer" the sample arrangement.

Once they have completed the unraveling of the layers, they should better understand how to re-construct the sequence to produce the original arrangement (Fig. 6.)

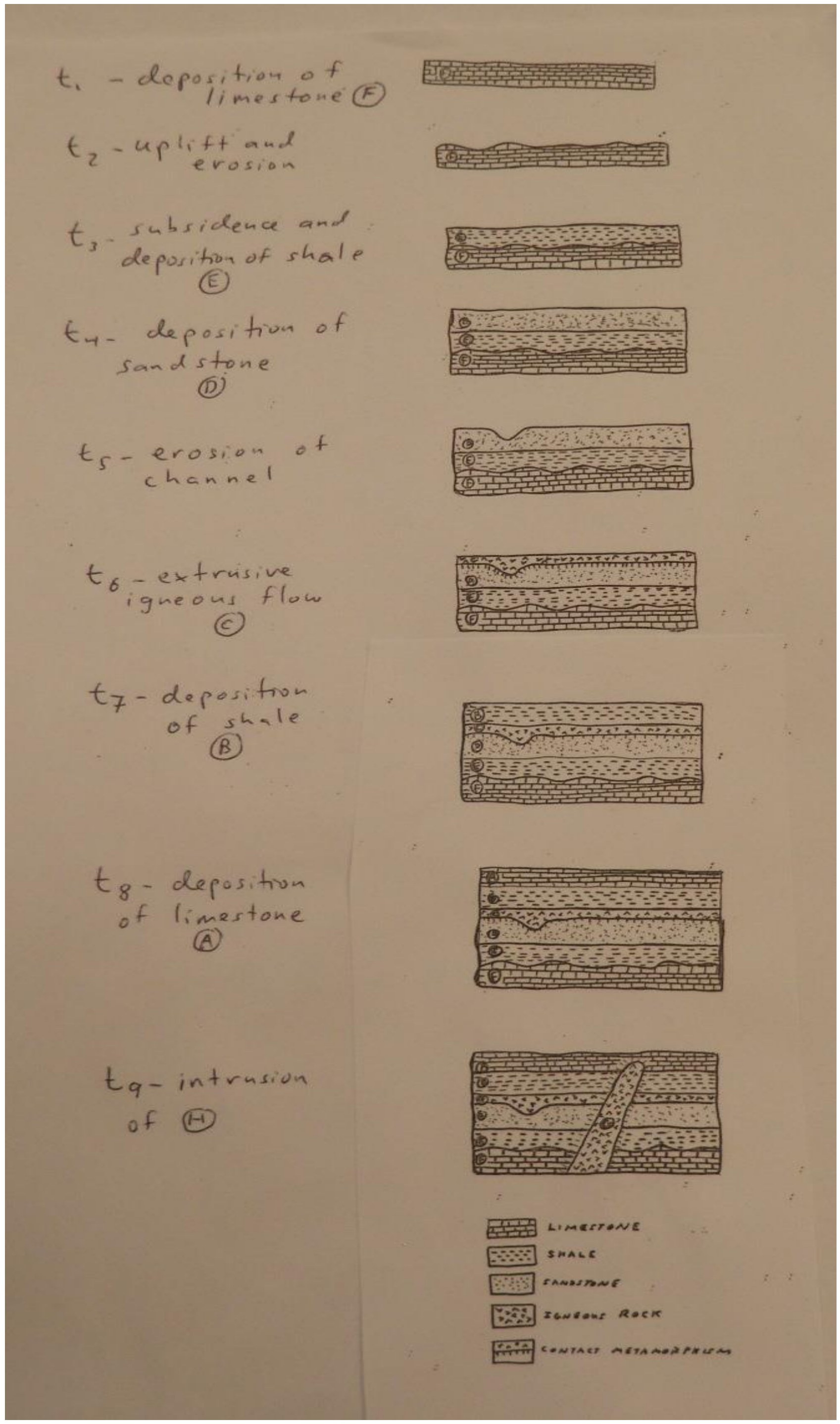

Fig. 6. Example of a re-constructed sequence of events and accompanying explanations of causal Earth processes.

It is important that students be able to talk through or write their reasons behind the choices. This strategy not only strengthens knowledge of geoscience concepts, but also develops other forms of intelligence useful in refining critical thinking skills, such as using multiple hypotheses, graphical representations, and explaining ones thought processes.

In developing lessons that use this strategy, it is essential that representational drawings be connected to actual examples. One resource for suitable images is the American Geological Institute's Earth Science World Image Bank (http://www.earthscienceworld.org/images/index.html).

Sequencing is an important skill, because it takes us from what "is" back to an understanding of what "was" through the steps that produced the arrangement. The ultimate goal is not to help student answer a few more questions on standardized tests. Rather, as teachers we seek to give students the skill so that when they travel to different locations and see real-world outcrops and terrains, they can recognize that variations in the sequence of events produced difference landscapes. In the bigger picture, they can realize that events leave traces and artifacts, and that these traces and artifacts can sometimes be used to reconstruct the events of the past. In fact, this realization can be applied in many other situations, not only in Earth Science.

Acknowledgements and References:

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Previous articles in this series:

Kastens, K.A., and M.J. Passow, 2012, *Opening a Conversation about Spatial Thinking*. The Earth Scientist, v. 28, no. 4, pp. 37 – 40.

Roessel, B., K.A. Kastens, and M.J.Passow, 2013, *Challenge: Seeing Spatial Relationships in Three-Dimensional Physical Models.* The Earth Scientist, v. 29, no. 1, pp. 17 – 20.

Additional References:

Earth Science Literacy Initiative, 2009, *Earth Science Literacy Principles* (http://www.earthscienceliteracy.org/)

Manduca, Cathryn A. and Kastens, Kim A. (2012) *Geoscience and geoscientists: Uniquely equipped to study Eart, h in* Kastens, K.A., and Manduca, C.A., eds., Earth and Mind II: A Synthesis of Research on Thinking and Learning in the Geosciences: Geological Society of America Special Paper 486, p. 1–12, doi:10.1130/2012.2486(01).

National Research Council, 2011, A *Framework for K – 12 Science Education* (http://www.nap.edu/catalog.php?record_id=13165)

New York State Education Department, 2011, "Reference Tables for Earth Science/Physical Setting" (http://www.p12.nysed.gov/apda/reftable/earthscience-rt/esrt2011-engr.pdf)