Figure 1. A photo of the Grand Canyon from the south rim. Photo by E.M. Nelson.

Grand Canyon, USA: Lumping and Splitting to Make Sense of a (Somewhat) Predictable World

Basil Tikoff*,[1] and Thomas F. Shipley[2]

Geology logline: *The exposures of the Grand Canyon allow conceptual lumping and splitting of the space (rocks units) and time (events); different hypotheses for canyon formation illustrate different conceptual temporal lumping and splitting of the erosional events.*

Cognitive science logline: *Predictability underlies two important geological reasoning processes: (1) Presence versus absence and (2) Lumping versus splitting.*

Standing on the rim of the canyon, you viscerally experience the name—it feels big in a way that pictures do not capture. The immensity of absence, which is the Grand Canyon, is conveyed across all of the senses. For instance, the soundscape of the rim is not silence; you can hear the wind. Yet the sound quality is unfamiliar; absent are the common echoes from nearby surfaces. The space of the canyon is so immense that echoes disappear.

The Grand Canyon's ubiquity in geology and popular culture reflects, in part, the clarity with which stories of time are written in its space. At its most basic, it is a very large hole in the ground. The vast amount of missing rock was eroded by the seemingly small river at the bottom of the canyon. Certainly, part of the grandeur of the canyon lies in its ability to illustrate the power of water to erode vast amounts of stone little by little.

The aesthetic appeal is enhanced by the horizontal geological layers that occur at the same elevations on both sides of the canyon. Other canyons offer one or two layers that can be followed across; for example, the Mississippian Redwall limestone generally forms a steep cliff partway up and the Cambrian Bright Angel shale always forms a flat area near the bottom. In contrast, the Grand Canyon offers an entire section of rock with multiple distinguishable units. Because it is all visible, one can easily take the intellectual leap that the

---

* basil@geology.wisc.edu

[1] University of Wisconsin–Madison, Madison, Wisconsin 53706, USA

[2] Temple University, Philadelphia, Pennsylvania 19122, USA

CITATION: Tikoff, B., and Shipley, T.F., 2025, Grand Canyon, USA: Lumping and splitting to make sense of a (somewhat) predictable world: GSA Today, v. 35, p. 4–8, https://doi.org/10.1130/GSATG106GM.1.

horizontal layers were once connected on both sides before the canyon was carved. That symmetry offers a beauty and a predictability, providing an opportunity to think about the past in ways that are both rich and nuanced.

The purpose of this essay, from the cognitive science viewpoint, is to understand how geologists make sense of the world through "unit formation" (lumping) and "segmentation" (splitting; Wertheimer, 1923; English translation in Ellis, 1938). In the cognitive science literature, the terms highlight the creation of a single mental object, or unit, from parts or pieces (i.e., lumping), and the necessary mental cleaving of that object from surrounding things (i.e., splitting). We retain the more informal lumping and splitting categories, because geologists can more likely relate to these terms.

Our life experience and our learned understanding of the physical world indicate the physical world behaves in a regular and predictable way. Here we focus on two psychologically relevant and related dichotomies that arise from that predictability: (1) presence versus absence; and (2) lumping versus splitting. We will address them in order.

PRESENCE VS. ABSENCE

We start with a logical difference between present and absent that has important psychological implications. Every environment contains a finite collection of things that are present, and an infinite set of things that are not present. Wherever you are reading this essay, for example, there are likely no giraffes in sight (as an example of something random). Thus, we have a bias to think about what is present and give little thought to what is absent (i.e., not present) because we could not possibly keep all absent things in mind. However, what is absent can be important, and we do regularly engage with things that are not present if we expect them to be present. We can notice absences, such as no echoes in the soundscape of the canyon's rim, using predictions based on the regularities of the world. For example, we can notice the rocks that are absent at an angular unconformity because rock beds tend to continue. Thus, the abrupt end of sedimentary beds at the unconformity is a place where the pattern of beds would lead us to expect they would continue. In the absence of their continuation, the geometry requires an explanation (Kellman and Shipley, 1992). That explanation is that rocks had been located above the unconformity, but were eroded. What appears as an obvious feature of the world requires the mind noticing a pattern and then picking up on a break in the pattern. For the mind, "adding" results in something being present, which can be directly noticed. In contrast, "removing" results in absence, which can only be noticed if there remain some clues that it would be predicted to be present.

A canyon is an absence of rocks, which are otherwise predicted to be present. In the Grand Canyon, that prediction can be made from the alignment of layers on the walls of the canyon. "Seeing" that the layers across the canyon used to be connected is a form of perceptual lumping (Kellman and Shipley, 1992). Generally, when a collection of objects co-occur, the mind picks up that regularity and forms a memory of that collection (Saffran et al., 1996). That is, the mind is noticing a predictability about the world and "lumping" objects and/or events together.

LUMPING VS. SPLITTING

Just as presence and absence are related but not perfectly reciprocal in the mind, lumping and splitting are related but not mirrors of each other (see Shipley et al., 2013). Lumping versus splitting is likely familiar territory to most geologists. In almost all scientific fields, there is a tension between focusing on the big picture ("lumping") versus the details ("splitting"). Large lumps are composed of a hierarchical nesting of smaller lumps, such that theoretical or practical decisions about how to split have direct implications for the size of the lumps.

Lumping and splitting allow the mind to carve out a piece of the world that is cognitively meaningful and manageable—not too big that it overwhelms the mental resources and not too small that it fails to include valuable information. How to lump and split is a stance adopted by a given scientist that may depend on many variables, including the goal of the study, the complexity of the problem, or preferences of the individual scientist. However, this stance is not arbitrary and it has cognitive roots in the expectations and clues that allow predictions.

> LUMPING AND SPLITTING ALLOW THE MIND TO CARVE OUT A PIECE OF THE WORLD THAT IS COGNITIVELY MEANINGFUL AND MANAGEABLE—NOT TOO BIG THAT IT OVERWHELMS THE MENTAL RESOURCES AND NOT TOO SMALL THAT IT FAILS TO INCLUDE VALUABLE INFORMATION.

Mental lumping and splitting reflect different perspectives on statistical regularities in the world. Things in the world that tend to co-occur can be lumped and things that act independently should be split. The mind lumps concretely as when perception links together glimpses of an object into a whole; the mind lumps abstractly as when we form categories that allow prediction (e.g., working vs. broken machines). Thus, lumping of elements into a group occurs in cases where the elements within that groups are predictable. In contrast, splitting of elements into separate groups occurs in cases where the relationship between groups is unpredictable.

SPATIAL LUMPING AND SPLITTING

Lumping and splitting occur in space and time. We start with spatial lumping and splitting, because it is easier to explain and it may be mentally easier as well (e.g., Zacks and Tversky, 2001). In space, one can lump objects to form groups (e.g., flock of birds), and one can split an object into parts (e.g., the head, wings, and tail of a bird). Note that we can lump parts into a whole object and split groups into individual objects. In the case of the birds, the lumping of a flock reflects the regularities of birds tending to fly in groups, and the lumping into a single bird reflects the regularity of the common velocity of the various parts as they move through space together. Conversely, splitting reflects breakdown in regularity where it may be difficult to predict a feature of one part from another. For example, one may notice when birds do not fly in the same way, or how the wing moves relative to the other parts of the bird. Splitting separates objects from their surroundings, whether it is the flock of birds from the environment or the wing from the rest of the bird.

Because lumping reflects regularities, or predictability, it is a mentally efficient way to manage information. For example, one does not need to represent every bird in a flock if one can predict what many are doing from a few. The geological term “unit” reflects the value of lumping so that careful observations at one outcrop may be applied to other outcrops of the same unit without having to engage in extensive observations at each outcrop. Lumping is based on regularities, but these can be statistical regularities rather than identical matches. Likewise, one splits when splitting leads to better predictions about the properties within the new subgroups.

Everyone can lump and split objects at levels sufficient to pick up and use the regularities. The expert can use observed regularities to lump (such as lumping Africa and South America based on coastal shape) where the novice might split, and split where the novice lumps (such as distinguishing marble and quartzite when faced with a white crystalline rock). The old adage about “the best geologist is the one who has seen the most rocks” likely reflects the skill that develops from seeing variation and regularities in rocks to be adept at lumping and splitting objects into useful categories (Holden et al., 2016).

We return to the Grand Canyon to apply these concepts of lumping and splitting. Figure 2 shows an explicit example of lumping into three categories. In this case, the geologist has lumped all of the flat-lying Paleozoic layers, all of the gently dipping Proterozoic layers, and all of the non-layered units. Splitting, on the other hand, is demonstrated by the recognition of different layers. This example is so obvious to geologists that we do not think about it; we separate rock units even if they have the same lithology or color, by a variety of other criteria that reflect some underlying commonality.

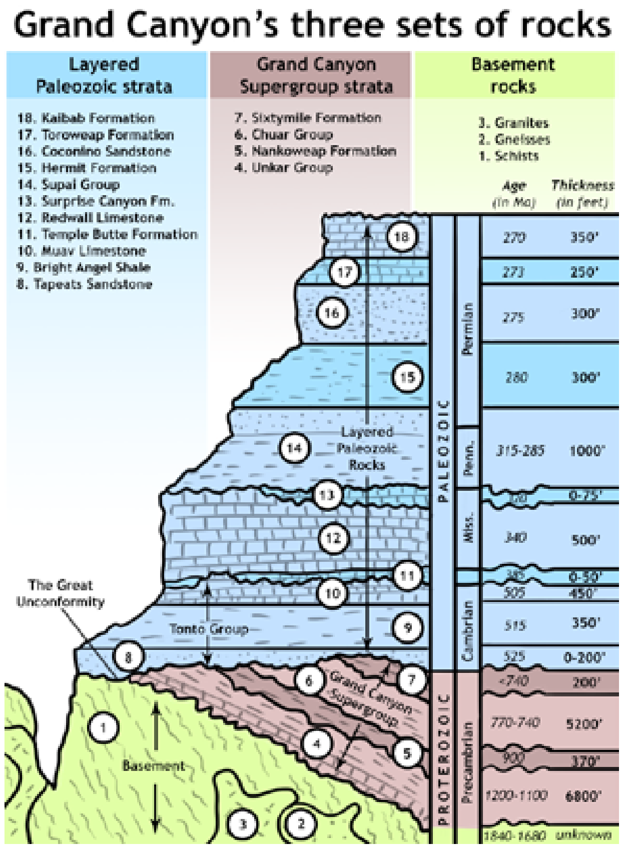

Figure 2. A schematic cross section the Grand Canyon in which lumping of the Paleozoic, Proterozoic, and non-layered Precambrian units was achieved by color coding. From C. Bentley after National Park Service. United States public domain.

Now consider the across-canyon correlations. The spatial filling in of absent layers across the canyon is obvious to geologists and to some, but not all, novices. What is present are distinct lithologies, arrayed as sheets, that align across the canyon. Connecting the pieces—by spatially lumping the layers on either side—is compelled by the geometry of the layers. The geometry of rocks implies predictability of rocks on either side across the divide.

TEMPORAL LUMPING AND SPLITTING

There is an analogous rationale for lumping and splitting over time. Humans do not keep track of time; we keep track of events (Gibson, 1979). For humans, events are things distinct from the surrounding time (Zacks and Swallow, 2007). Practically, what does this mean? Humans combine objects and changes over time to see a sequence of time as belonging together with a beginning, middle, and end. The lumping is based on regularity, where the predictability of what will happen next binds the event into a whole. For example, “doing the dishes” is a temporally bound event, which has internal predictability based on the regularities in the world (e.g., you cannot dry an object until it is wet). The events of gathering, washing, rising, and drying dishes can be collected together because they tend to co-occur. If you see someone apply soap to a dish, you can anticipate they will rinse it next. The internal predictability allows all the sub-events to be mentally gathered together, and also allows the mental coordination between two individuals to gracefully hand a dish from the person doing the washing to the person doing the drying in the middle of the event.

Lumping parts into whole objects can be achieved using internal consistency, which allows filling in the parts that are missing. Similarly, lumping short events into a longer event allows filling in of missing portions of the event. Both objects and events can be filled in using what is present. The evidence to trigger a filling-in inference varies from in-your-face obvious to subtle, with spatial object completion generally being more obvious than temporal event completion (Zacks and Swallow, 2007).

The lumping of time allows efficient reasoning and allows categorization about the Earth system. The geologic timescale is an important example of how spatial and temporal regularity guides identification; in this case, it is the fossil record that guides lumping. A timescale boundary occurs when the old assemblage of fossils is absent and a new assemblage is present; determining this pattern requires splitting. Whether one utilizes era, period, epoch, or stage depends on the problem that is being addressed.

There is rarely an objective instant that is the boundary between the inside and outside of an event. Even when the boundary is extended in time, it is a useful construct so the mind can treat the event as a whole. Nevertheless, the regularity within the event and the reduced predictability across event boundaries is constructively used by the mind and science.

LUMPING AND SPLITTING IN BOTH SPACE AND TIME

A major issue in geology is that lumping and splitting are intimately connected in both space and time. The intermixture of these concepts is ingrained in most geologists. The Cambrian, for example, is both a geological period and a stratigraphic system. Consider the Paleozoic stratigraphy of the Grand Canyon. The different rock units often look different because they were formed at different times, under different environmental conditions, at different latitudes. So when geologists invoke “space for time” substitutions (e.g., the oldest rocks are at the bottom of the canyon), they often mean that conceptual lumping in space inform lumps in time. This approach works because of the predictability, within a specified time interval, of the deposition of the sediments that would become those rocks.

Time and space also clearly overlap in unconformities (e.g., Siccar Point, Scotland; Shipley and Tikoff, 2024). The presence of unconformities, which are spatial features, has temporal implications. They are a record of missing time. Unconformities require splitting in space into different stratigraphic units and splitting in time into different events, separated by events such as uplift and erosion. In other words, both spatial and temporal predictability is disrupted by unconformities.

LUMPING AND SPLITTING IN MODELS

To more clearly show the role of lumping and splitting, we return to the concept of runnable mental models introduced by Shipley and Tikoff (2025). In cognitive science, a mental model is a mental representation of objects with their respective properties. We expand this definition to “runnable mental models” by distinguishing a representation that can be tested by mentally simulating “what happens if” to a mental model. That is, runnable mental models are analogous to an animation, which a practitioner uses to see what happens as processes within a physical space unfold over time. It is the predictability of events that allows practitioners to build runnable mental models.

Figure 3 provides a relevant example of a runnable model, from Dutton’s 1882 study of the Grand Canyon district. Four sedimentary layers of various thickness and erodibility are shown. Superimposed on this background are four different canyon profiles, each representing the canyon at a different time, with the oldest profile as the shallowest one. By using the word “development,” Dutton (1882) is communicating a hypothetical “what happens” scenario as water continues to carve the canyon.

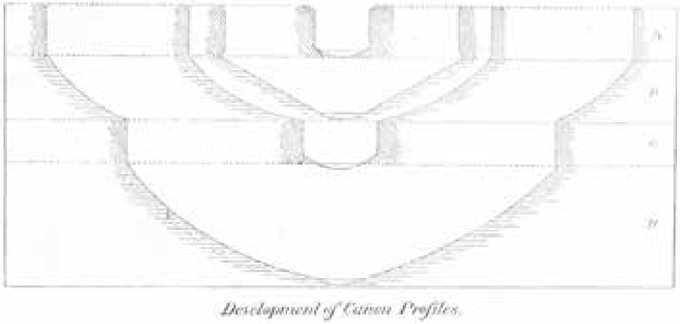

Figure 3. A runnable model of canyon development, from Dutton’s (1882, plate 40) study of the Grand Canyon. A and C are more resistant sedimentary layers; B and D are more erodible sedimentary layers.

There is currently a debate going on about the incision of the Grand Canyon, in which two runnable mental models are in conflict: the young canyon model and the ancient canyon model. The young canyon model suggests that the entire canyon was cut by the southwest-flowing Colorado River in the last six million years (e.g., Pederson, 2008). The ancient canyon model suggests that a portion of the whole canyon—specifically the western part of the canyon—was cut in part in the Late Cretaceous by the northeast-flowing California River (e.g., Flowers et al., 2008; Wernicke, 2011). In this ancient canyon model, other parts of the canyon were cut in the last six million years. We offer the contrasting models not to adjudicate which is better, but rather to employ the difference to emphasize the role of the mind in lumping and splitting based on events rather than objects. Further, we have simplified the actual debate to these two simple endmembers, and we have specifically chosen to not address the implications of the paleochannels (e.g., Young and Crow, 2014) and karst hydrology (e.g., Hill and Polyak, 2020).

The young canyon model illustrates one type of challenge in runnable mental models, which is to apply a process with a slow rate to a long period of time. When asked how a particular landscape evolved, one might consider a particular process acting over geological time—river erosion produces canyons and longer erosion produces deeper canyons. It is the size of the Grand Canyon—and therefore the amount of necessary time to carve the canyon—that is a challenge to mental modeling based on human timescale events. Here, the reasoner might employ analogy to reason from what happens with small amounts of time to project to larger epochs (Tikoff and Shipley, 2024). Mentally “running” the young canyon model is essentially a uniformitarian scaling of small annual erosion to significant depths over the last six million years. In this model, the layers are mentally filled in to provide the impetus for an explanation of what is missing. Similarly, the evolution of the canyon is filled in from a river on the surface to a river a mile below the rim.

The ancient canyon runnable mental model requires splitting. The model is based on thermochronology, a type of data that is not available to the casual observer. Thermochronology is the science of estimating the time over which rocks existed at a specific temperature using the expected diffusional loss of radioactive decay products. The temperatures, in turn, can be predicted from depth in the Earth using an assumed or determined geothermal gradient. That work reveals that rocks at the bottom of the Grand Canyon have been cooling, as they would be if near the surface and not a mile under rocks, for ~70 million years (Flowers et al., 2008; Flowers and Farley, 2012). The absent, but expected, insulation of the rocks is evidence of an earlier canyon. This new data required the creation of a new mental model (Fig. 4). The spatial variability of the thermochronometric data requires splitting the canyon-forming process into three parts (three different events): the early period when much of the western part of the canyon was cut (Late Cretaceous), a middle quiescent

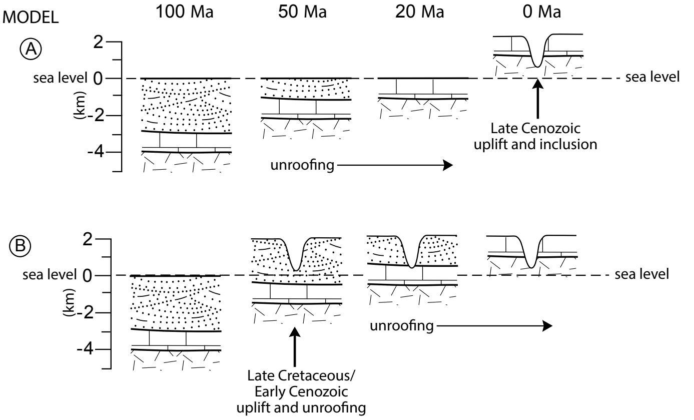

Figure 4. A schematic cartoon showing the development of (A) the young canyon and (B) the ancient canyon for the western part of the Grand Canyon. Figure modified from B. Wernicke.

period (Eocene–Oligocene), and a late period (Late Miocene–present) when other parts of the canyon were cut (*Fig. 4*).

These models, similar to many tectonic models, are useful because they are a claim to predictability. The young canyon and the ancient canyon are two different runnable mental models for the development of the Grand Canyon, each with a different set of predictions. The disagreement is about the temporal lumping of events: Did the erosion occur in a single event or was it split into a three-part sequence? The difficulty is that the young canyon model provides little predictability of the thermochronology data, which indicates a pre–6 Ma history to some parts of the Grand Canyon (e.g., Flowers et al., 2008; Karlstrom et al., 2014). The present continuity of the Grand Canyon suggests a single spatial unit, as indicated by our name for this grand entirety. This name, however, might bias the mind toward a runnable mental model based on a single event, and challenge the splitting into three events.

CONCLUDING THOUGHT

In these essays, we are making the case for lumping cognitive science and geology because it allows you to see regularities that would have been missed in the splitting. In this combined vision, the Grand Canyon embodies grandness by simultaneously revealing the power of water to erode vast amounts of stone and the mind's capacity to characterize (by lumping and splitting) across space and time to grasp its story.

AKNOWLEDGMENTS

We thank R. Flowers for conversations about the Grand Canyon that helped our presentation, R. Young for helpful information about paleochannels, and B. Wernicke for allowing us to use a figure that he created. Reviews by Mark Schmitz and an anonymous reviewer—and editorial comments by A. Egger—significantly improved this essay. NSF support for BT (2311822) and TS (2311820) is acknowledged.

REFERENCES CITED

***denotes suggested further reading**

Dutton, C.E., 1882, Tertiary History of the Grand Cañon District: U.S. Geological Survey Monograph 2, 264 p.

Ellis, W., 1938, A Source Book of Gestalt Psychology: London, Routledge & Kegan Paul, 416 p., https://doi.org/10.1037/11496-000.

Flowers, R.M., and Farley, K.A., 2012, Apatite ^{4}He/^{3}He and (U-Th)/He evidence for an ancient Grand Canyon: Science, v. 338, https://doi.org/10.1126/science.1229390.

*Flowers, R.M., Wernicke, B.P., and Farley, K.A., 2008, Unroofing, incision, and uplift history of the southwestern Colorado Plateau from apatite (U-Th)/He thermochronometry: GSA Bulletin, v. 120, p. 571–587, https://doi.org/10.1130/B26231.1.

Gibson, J.J., 1979, The Ecological Approach to Visual Perception: New York, Houghton, Mifflin and Company, 346 p.

Hill, C.A., and Polyak, V.J, 2020, A karst hydrology model for the geomorphic evolution of Grand Canyon, Arizona, USA: Earth-Science Reviews, v. 208, https://doi.org/10.1016/j.earscirev.2020.103279.

Holden, M.P., Newcombe, N.S., Resnick, I., and Shipley, T.F., 2016, Seeing like a geologist: Bayesian use of expert categories in location memory: Cognitive Science, v. 40, no. 2, p. 440–454, https://doi.org/10.1111/cogs.12229.

Karlstrom, K.E., Lee, J.P., Kelley, S.A., Crow, R.S., Crossey, L.J., Young, R.A., Lazear, G., Beard, L.S., Ricketts, J.W., Fox, M., and Shuster, D.L., 2014, Formation of the Grand Canyon 5 to 6 million years ago through integration of older palaeocanyons: Nature Geoscience, v. 7, p. 239–244, https://doi.org/10.1038/ngeo2065.

*Kellman, P.J., and Shipley, T.F., 1992, Perceiving objects across gaps in space and time: Current Directions in Psychological Science, v. 1, p. 193–199, https://doi.org/10.1111/1467-8721.ep10770407.

Pederson, J., 2008, The mystery of the pre–Grand Canyon Colorado River: Results from the Muddy Creek Formation: GSA Today, v. 18, no. 3, p. 4–10, https://doi.org/10.1130/GSAT01803A.1.

*Saffran, J.R., Aslin, R.N., and Newport, E.L., 1996, Statistical learning by 8-month-old infants: Science, v. 274, no. 5294, p. 1926–1928, https://doi.org/10.1126/science.274.5294.1926.

Shipley, T.F., and Tikoff, B., 2024, Siccar Point, Scotland, and the role of mental models: GSA Today, v. 34, no. 11, p. 36–40, https://doi.org/10.1130/GSATG103GM.1.

Shipley, T.F., and Tikoff, B., 2025, Channeled scablands, northwest US, and runnable mental models: GSA Today, v. 35, no. 1, p. 26–30, https://doi.org/10.1130/GSATG105GM.1.

Tikoff, B., and Shipley, T.F., 2024, Shark Bay, Australia, and the centrality of analogical thinking: GSA Today, v. 34, no. 10, p. 26–29, https://doi.org/10.1130/GSATG102GM.1.

Wernicke, B.P., 2011, The California River and its role in carving Grand Canyon: GSA Bulletin, v. 123, p. 1288–1316, https://doi.org/10.1130/B30274.1.

Wertheimer, M., 1923, Untersuchungen zur Lehre von der Gestalt, II [Investigations in Gestalt Theory: II. Laws of organization in perceptual forms]: Psychologische Forschung, v. 4, p. 301–350, https://doi.org/10.1007/BF00410640.

Young, R.A., and Crow, R., 2014, Paleogene Grand Canyon incompatible with Tertiary paleogeography and stratigraphy: Geosphere, v. 10, p. 664–679, https://doi.org/10.1130/GES00973.1.

*Zacks, J.M., and Swallow, K.M., 2007, Event segmentation: Current Directions in Psychological Science, v. 16, p. 80–84, https://doi.org/10.1111/j.1467-8721.2007.00480.x.

Zacks, J.M., and Tversky, B., 2001, Event structure in perception and conception: Psychological Bulletin, v. 127, p. 3–21, https://doi.org/10.1037/0033-2909.127.1.3.

NAGT

THE GEOLOGICAL SOCIETY
OF AMERICA®

This essay series is a joint effort of the National Association of Geoscience Teachers (NAGT) and the Geological Society of America (GSA). Anne Egger, Executive Director of NAGT, served as the associate editor.