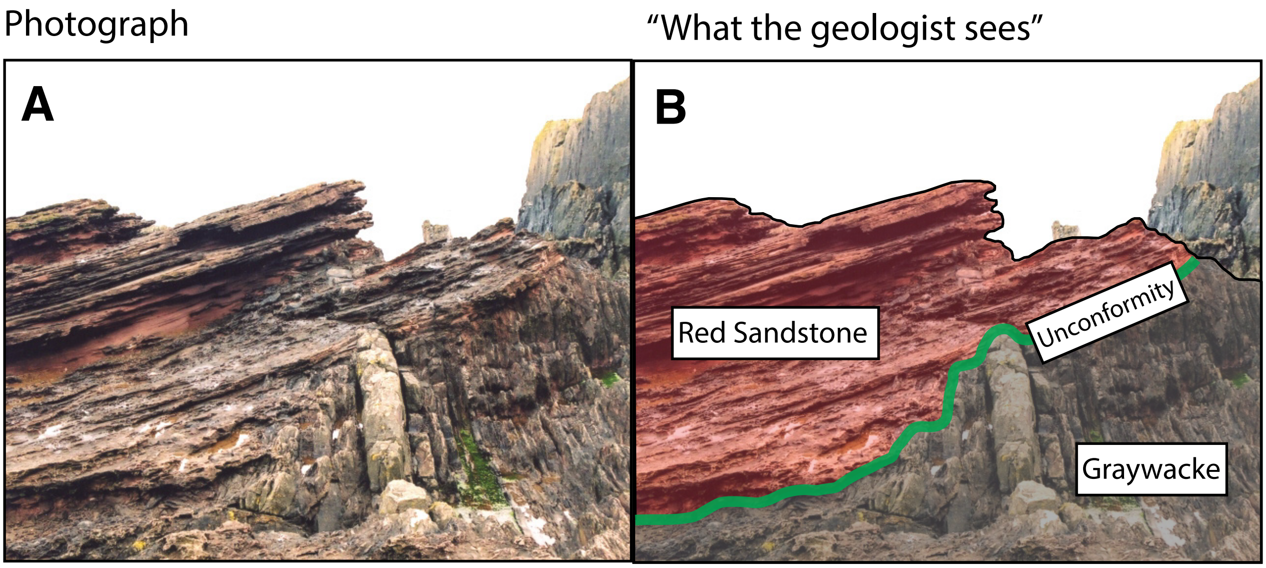

Figure 1. (A) A picture of the angular unconformity at Siccar Point, Scotland. Photo by Anne Burgess. (B) Integration of the photograph and the mental model (concept) using the approach of "what a geologist sees," adapted from Marshak (2018). This figure illustrates how professional geologists lump data ("graywacke," "red sandstone," "unconformity") to reduce cognitive load.

Siccar Point, Scotland, and the Role of Mental Models

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

"What clearer evidence could we have had of the different formation of these rocks, and of the long interval which separated their formation, had we actually seen them emerging from the bosom of the deep? We felt ourselves necessarily carried back to the time when the schistus on which we stood was yet at the bottom of the sea, and when the sandstone before us was only beginning to be deposited in the shape of sand or mud, from the waters of a superincumbent ocean. The mind seemed to grow giddy by looking so far into the abyss of time; and while we listened with earnestness and admiration to the philosopher who was now unfolding to us the order and series of these wonderful events, we became sensible how much farther reason may sometimes go than imagination can venture to follow."

—J. Playfair (1805, p. 73)

Geological logline: *The angular unconformity at Siccar Point—with its implication for significant loss of time in the stratigraphic record—is generalized into a mental model for angular unconformities.*

Cognitive science logline: *Mental models of the world incorporate knowledge about the regularities of patterns in Earth processes to identify novel cases as members of important conceptual classes.*

The angular unconformity at Siccar Point, Scotland, is iconic. Many geologists who have never been to Siccar Point can name the location when shown a picture of the angular unconformity there because they have seen the outcrop before in textbooks (Fig. 1A). Siccar Point is on the east coast of Scotland near the village of Cockburnspath, ~35 miles (56 km) east of Edinburgh. The lower, nearly vertical rocks are Silurian graywackes, a lightly metamorphosed sandstone that contains a fair amount of feldspar. The upper, shallowly dipping rocks consist of Upper Devonian red sandstones. The Silurian rocks were tilted and folded by the Caledonian orogeny, which recorded the closure of the Iapetus Ocean and construction of a mountain belt. The Devonian rocks are thought to be broadly postorogenic (colloquially called "the Old Red Sandstone") and represent an upland valley or wadi channel filled with (ephemeral) flash-flood deposits (Archer et al., 2017). The unconformity reflects 65 m.y. of time in

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which sedimentary deposition is missing from the rock record (Fig. 1B).

The unmistakable pattern of juxtaposed beddings requires an explanation: How did the different rock units get to their current position and orientation? Geologists are well aware that events leave traces, and that particular processes can lead to diagnostic patterns. What process or series of processes could have resulted in the pattern at Siccar Point? Reasoning about events that happened outside of human experience requires the mind to use analogies, drawing from the patterns of familiar events to understand the less familiar ones (see Tikoff and Shipley, 2024: *GSA Today* October issue). Sediments settling from water into horizontal beds is such an analogy, and that pattern has been codified as the "law of original horizontality."

THE UNMISTAKABLE PATTERN OF JUXTAPOSED BEDDINGS REQUIRES AN EXPLANATION: HOW DID THE DIFFERENT ROCK UNITS GET TO THEIR CURRENT POSITION AND ORIENTATION?

For sedimentary beds to be other than horizontal requires some movement to change their orientation. At Siccar Point, where events could be imagined that would change the orientation of beds, no singular event could generate beds with two different orientations. Rather, only a sequence of events that took place over time could explain this geometry: (1) The graywacke unit formed into rock; (2) the graywacke unit changed orientation; (3) there was erosion of the graywacke unit to the level of the unconformity; and (4) the red sandstone was deposited over the eroded graywacke unit. Novices and expert geologists who have engaged with this question accept that such a sequence of rock formation must have occurred over a long time.

Siccar Point is inextricably associated with James Hutton, who realized the significance of the exposure when arriving at it by boat. Hutton, aided by his field companions John Hall (chemist) and John Playfair (mathematician), understood and was first to articulate the importance of an unconformable contact. A core concept in the field of geology was born at this location: There was significant missing time represented by the unconformity surface. In an ironic twist, the term "unconformity" first appeared in a book by neptunist Robert Jameson, who opposed Hutton's plutonism. Jameson translated Abraham Werner's German phrase, which would have been literally translated as "deviating bedding." Regardless, Siccar Point expanded many minds to encompass time beyond the horizon of recorded history. With Playfair's succinct description (Playfair, 1802, 1805) and Hall's sketch of the unconformity, his companions helped Hutton convince many skeptics of an old Earth (Hutton, 1788, 1795). The argument for long time and consistent geological processes was supported by spatial logic, not by statistics or physical principles such as radioactive decay (which was not known at that time). The graywacke and red sandstone have such different orientations that they must have formed at different times. Eroded fragments of graywacke occur as angular pebbles (clasts) in the red sandstone, indicating that the graywacke was present as rock before the red sandstone became rock. We now recount these facts to students to illustrate how geological observations of the traces of past events allow confident inferences about those events. Unconformities are one of those low-level inferences that have become observations, as discussed in our first essay (Shipley and Tikoff, 2024: *GSA Today* September issue). Hutton's simple observations had the power to change minds. Why?

The question ultimately requires an answer that considers both the nature of Earth and the human mind. The only way Earth processes can form a contact with different bedding orientations is through a sequence of events in which a group of sediments was deposited, and sedimentary rocks were formed, then tilted, and then eroded; after that, another group of sediments was deposited, and sedimentary rocks were formed. This sequence of events is responsible for every angular unconformity in sedimentary rocks. The mind can mentally animate this sequence to confirm that such a sequence will result in this pattern. The pattern guides a mind to imagine events as Playfair eloquently related in the quote at the beginning of this essay. In seeing "into the abyss of time" at this outcrop, the mind has changed and can no longer believe that Earth is young (i.e., thousands of years old). Once recognized, this pattern becomes a mental model in the service of recognizing the meaning of similar patterns.

This essay highlights the important role that "mental models" play in science. Mental models are spatial abstractions of visible patterns observed in nature. The abstraction captures the key spatial properties, and the abstraction is represented in such a way that the irrelevant spatial properties are not required for recognition. Figure 1A shows a picture of Siccar Point. In contrast, Figure 2A shows a simplified sketch a geologist might make of the outcrop, and Figure 2B shows an idealized version intended to convey the abstract character of a mental model.

Although Figure 2A is arguably a more correct representation, in that it matches more of the metric spatial properties of the actual outcrop (Fig. 1A), Figure 2B is the orientation in which the processes likely occurred because it allows horizontal bedding, and it contains the unconformity (the region where there is missing time inferred from the discontinuity in bedding orientation). Thus, Figure 2B is akin to the product of mental simulation.

In the mental model of an angular unconformity, the older bedding can have any orientation. Figures 2C and 2D show different examples of angular unconformities in which the bedding in the underlying unit is variable. Despite the differences, these all fit a single mental model of an angular unconformity. Combining ("lumping") these as similar is not especially challenging, likely because the more recent sedimentary layers are in their original orientation. Figures 2E and 2F are more challenging because the younger rock sequence is no longer horizontal. Nevertheless, the expert immediately recognizes that these too are also angular unconformities. Although the configurations in Figures 2E and 2F may be less frequently observed than those in Figures 2B–2D, they do occur. Figure 3, for example, is a picture that

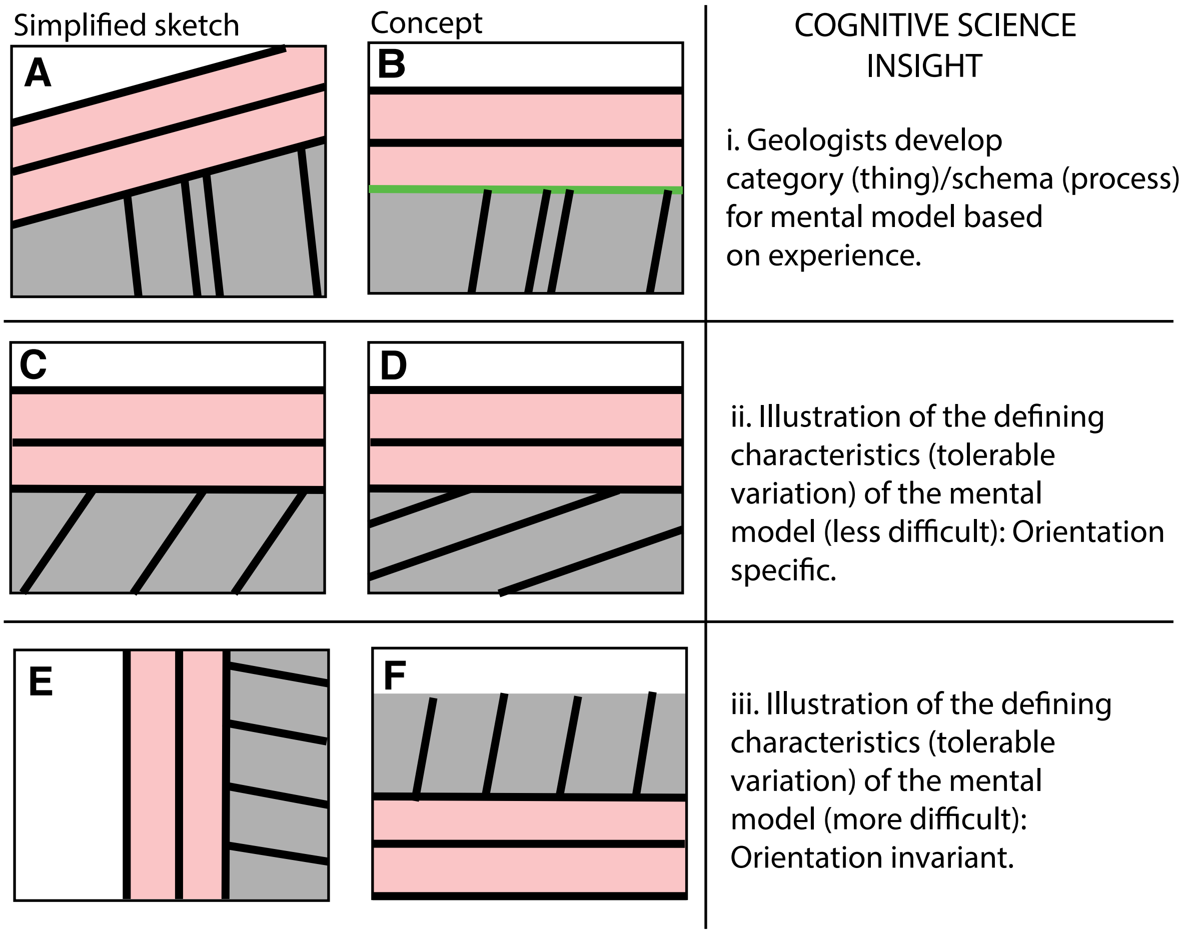

Figure 2. An attempt to illustrate the mental processing of an image from the world to arrive at an interpretation based on a mental model. We highlight three qualitatively important aspects of this process (i–iii), indicated as cognitive science insights on the right side of each of the three rows. (A) A highly simplified sketch of the outcrop. (B) The "concept" or mental model of the angular unconformity at Siccar Point, Scotland, where the green line identifies the unconformity. (C–D) Simplified sketches of different angular unconformities shown in vertical cross section, compatible with the mental model shown in B. (E) A simplified sketch of an angular unconformity in which the unconformity is vertical. (F) A simplified sketch of a different angular unconformity in which the unconformity is completely overturned.

shows overturned cross-bedding, which is a type of intraformational unconformity. Visual recognition of objects is generally orientation-dependent; it is disrupted when an object is viewed from a novel perspective. Because rocks can rotate, geoscience experts must learn to recognize important patterns, such as unconformities, in whatever orientation they appear. All of the patterns in Figure 2 fit a mental model in which some bedding ends abruptly at a contact, and the orientation of the overlying bedding matches the orientation of the contact. Thus, the mental model is flexible in some respects as to where a pattern can vary (e.g., the wide variation of the orientation of the bedding ending at a surface is permissible), whereas some aspects of a pattern are necessary conditions for a model (e.g., bedding must end at a continuous surface).

Figure 1B illustrates how the general mental model of an unconformity can be applied to this specific outcrop. When the mind begins to see the spatially separate elements as parts of a singular pattern, it is known as "unit formation." Unit formation refers to perceptually collecting separate stimuli together to experience them as a whole thing. As such, unit formation indicates statistical predictability. That is, things are treated together because doing so reflects something common to the group. In geology, parts of a formation share a common age or sequence of events that formed them, and in perception, the parts belong together in the world so that properties of each part can predict properties of other parts (as when parts of objects move together).

There is a significant body of cognitive science literature on how humans form units, beginning with the Gestalt psychologists (e.g., Wertheimer, 1923), who first recognized that a mental process grouped features, and continuing to modern accounts of object completion circuits in the brain (e.g., Weigelt et al., 2007). Shipley et al. (2013) reviewed the Gestalt principles as they apply to perception in geology. Figure 2 applies the Gestalt principles to Siccar Point. Rather than seeing a series of individual beds, experts see a package ("unit") of rocks (colored red) with a shallowly dipping orientation. Experts also see a separate package of rocks (colored gray) with a subvertical orientation. They also see the nonplanar surface between them. Note that the nonplanarity (Fig. 1) is not present in the expert's idealized mental model (Figs. 2A and 2B); it is one of the parts that is allowed to vary. Each part of the model that is fixed or variable reflects statistical regularities that arise from Earth processes. The discontinuity in bedding orientation reveals a break in time recorded in the rock. The erosional processes that caused the discontinuity do not always leave smooth surfaces, so planarity is not definitional.

Once unit formation is achieved, the model saves mental work. The owner of the model does not need to recapitulate the mental animation to confirm the meaning of the pattern. Thus, a practitioner can simply move directly from the geometrical pattern to its meaning. Evidence for this claim comes in this simple test: Look at Figure 3. Many geologists will still recognize stratigraphic up immediately, while also knowing that completely overturned stratigraphy may be relatively uncommon. In contrast, most novice geologists do not initially recognize the reoriented angular unconformities. The likely challenge for novices is that they do not treat the unconformity as a unit; before the unit formation occurs, each of the parts is processed separately. Novices first encountering Siccar Point must go beyond the properties of each part and see how they fit together as a whole. Experts may help novices to develop mental models by guiding attention to the relevant aspects of the world and being explicit about and using schematic diagrams to show which properties are definitional and which may vary from one exposure to the next.

These mental models are critical for expert geologists because they act as shortcuts that allow rapid recognition of particular phenomena. The reasoning is simple: Cognitive processing of many parts as a single package requires less cognitive work. In contrast, keeping track of separate independent things requires effort, as each additional item required to be remembered comes with a cost to the mind's ability to think about how the items might be related.

Figure 3. An upside-down stratigraphic section near Vredefort, South Africa. The cross-bedding patterns in the outcrops of the Witwatersrand quartzite, which are effectively intraformational angular unconformities, indicate that the entire section is inverted. Geologists immediately recognize the overturned stratigraphy; compare to Figure 2F. Photo by D.L. Reid (University of Cape Town).

SICCAR POINT REVEALED DEEP TIME, BUT IT ALSO REVEALS THE ROLE OF THE MIND IN ASSEMBLING EXPERIENCES INTO A WORKING MODEL THAT ENCOMPASSES GEOLOGICAL TIME.

All humans make mental models; geologists must be particularly adept at making *spatial* mental models. Basil came to realize that his field experiences had left him as a "walking library" of spatial mental models (e.g., Fig. 2B); we suspect the same is true for most field-based geologists. One's library contains unconformities, but also models of mineral habits, rock fabrics, and geological structures. Every encounter with a new outcrop can prompt a consultation of the mental library—whether conscious or not—to access relevant models tied to patterns in the data. Having a mental library of geological patterns—that come explicitly linked to a possible process or processes—is a critical resource for making geological inferences. Note that there are potential downsides to the shortcuts allowed by mental models. An important one is that with quick judgement, there is less attention to individual features as one sees what one expects to see; this situation is a visual analog of the bias engendered by a favored hypothesis (Shipley and Tikoff, 2024).

The core of Siccar Point's power to persuade is the integration of unit formation and causal processes. Although cognitive science has studied and developed accounts for how each element works in isolation, as we have discussed in this essay, the integration of these two processes in mental models is not well appreciated. This lack of attention by cognitive scientists does not reflect low frequency, as reasoning from event traces is familiar and common. For example, the sight of a crumpled bumper immediately suggests that a collision caused the deformation. One possibility is that the pattern (shape) and the process (event) are an association that is learned by rote. We find this hypothesis unsatisfactory—particularly for Siccar Point—as it does not offer an account for: (1) how Hutton, Hall, and Playfair connected pattern to process; or (2) why that connection makes a compelling argument for deep time. Cognitive science really does not offer a much better theory at this time. Yet, geologists do develop mental models to characterize patterns in terms of likely processes, in response to their minds asking, "*Why* is the world the way it is?" In this way, the geologist's scientific method complements the science of the mind by highlighting an aspect of thinking that has not been visible to cognitive science research.

Siccar Point revealed deep time, but it also reveals the role of the mind in assembling experiences into a working model that encompasses geological time. The importance of Siccar Point emerged from Hutton's deliberate search for the contact between the gray rocks he observed at St. Abb's Head to the east and the red ones he encountered in Pease Bay to the west, and then interpreting and understanding the implications of the unconformity. Humans had likely been walking past Siccar Point for a long time before one asked, “Why do those rocks look the way they do?” Once asked, a new mental model entered geologists’ libraries. A satisfactory mental model is a powerful tool, and once properly established, it functions with little effort. However, mental models adapt with the practitioner, splitting and lumping as understanding of the meanings of the patterns evolve. The challenge is to both use mental models to recognize the familiar and yet also be open to novel patterns and processes.

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