Figure 1. The Mt. Holmes intrusive center in the Dzil Bizhi 'Adani (Diné/Navajo), Untarre (Southern Paiute), or Henry Mountains (English) of central Utah. Photo by Ellen M. Nelson.

Henry Mountains, Utah: The Construction of Mental Models and the Role of Geological Exemplars

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Geology logline: *The development of the mental model for a laccolith was constructed from field evidence in the Henry Mountains.*

Cognitive science logline: *New spatial hypotheses can require forming a new category, which will be particularly easy to see in some spaces.*

They are the Dzil Bizhi 'Adani ("Nameless Mountains") in the Diné/Navajo language and Untarre in the Southern Paiute language. They were renamed the Henry Mountains in English by A.H. Thompson of the second Powell expedition of 1871–1872 (Fig. 1). Located in central Utah—an area that was and still is inhabited by Ute, Southern Paiute, and Diné people—the Henry Mountains consists of five major mountains: Mt. Ellen, Mt. Pennell, Mt. Hillers, Mt. Holmes, and Mt. Ellsworth (Fig. 2). Each of these mountains is an intrusive center of Oligocene age, with one major igneous body surrounded by a series of smaller, satellite igneous bodies. The intrusions occurred during a time of tectonic quiescence on the Colorado Plateau, such that the intrusion geometries are not affected by regional deformation. The intrusions, mostly porphyritic diorite with a fine-grained groundmass, were emplaced into the nearly flat-lying stratigraphy of the Colorado Plateau at ~2–4 km depth.

G.K. Gilbert arrived in the Henry Mountains in 1875, following the direction of his supervisor J.W. Powell to survey them "without restriction as to my order or method." In his report, Gilbert (1877) provided the evidence that he accumulated, which ultimately resulted in a new explanation for

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CITATION: Tikoff, B., and Shipley, T.F., 2024, Henry Mountains, Utah: The construction of mental models and the role of geological exemplars: GSA Today, v. 34, p. 22–25, https://doi.org/10.1130/GSATG104GM.1.

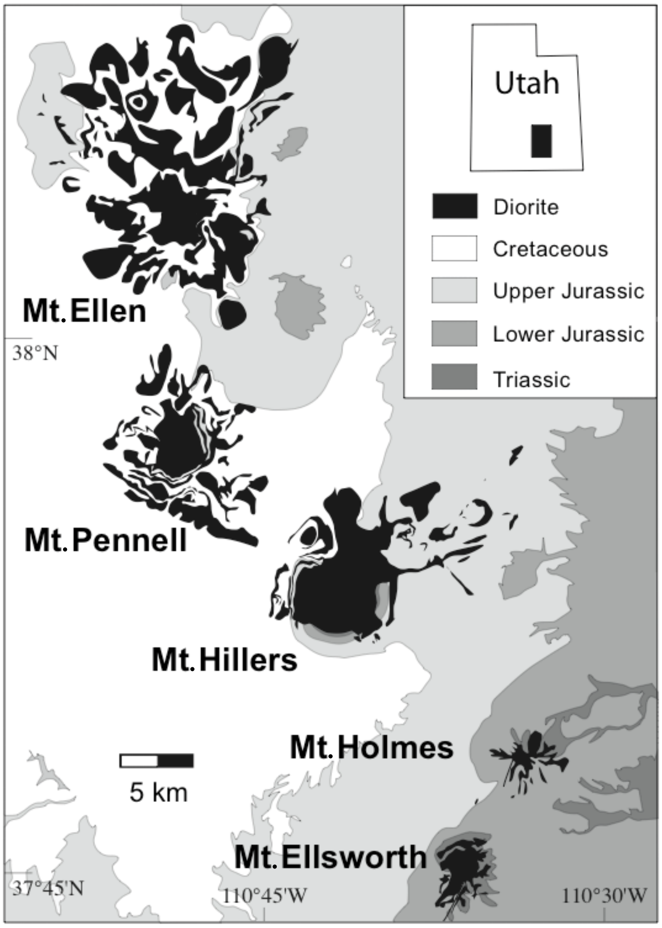

Figure 2. A geological map of the intrusive centers of the Henry Mountains, Utah. Modified from Horsman et al. (2005).

mountain formation. His field notes, which were subsequently published (Hunt, 1988a), provide insight into his thought processes as he worked through the challenges of this place. Here Gilbert made observations that, when aggregated, led him to conclude that there was a new and previously unrecognized category of intrusive igneous structure. Gilbert called the idea of a conformable igneous intrusion with a flat-bottomed and rounded top a *laccolite*; we now use the term *laccolith*. His report thus added a new member to geologists' mental library of 3-D geological structures.

It is worth being clear that psychology does not currently have a satisfactory explanation for how the mind comes up with truly new ideas. It is not for lack of trying; hundreds of articles have been written on this subject. On a personal note, Tim's mother spent most of her professional career as a psychologist trying to understand how children come up with new categories by induction. Nevertheless, by articulating what is known about the cognitive foundations of Gilbert's achievement, we can highlight what a geological exemplar such as the Henry Mountains can simultaneously reveal about the workings of the mind and of the world.

Nowhere in the Henry Mountains is a laccolith revealed in its entirety. The lithologies of the igneous and sedimentary rocks were familiar to Gilbert, although the spatial juxtaposition of the two rock types was not. A major question for Gilbert's 1875 expedition was whether the magmatic bodies of the Henry Mountains were extrusive (lava) or intrusive (Hunt, 1988a). This ambiguity arose due to: (1) the fine-grained nature of the groundmass of the igneous rock; and (2) the sedimentary-igneous contact, which had the same orientation as the bedding of the adjacent sandstone. The sedimentary–igneous relation was visible on the domed tops (upper contact) of the igneous intrusions because the physical setting on the Colorado Plateau region allowed the sandstone to erode and the slightly harder igneous rocks to remain. The bottom contact of a *major intrusive center* is not exposed, although locally conformable and subhorizontal bottom contacts of *satellite intrusions* are observed. One such bottom contact is well exposed in the aptly named "secret nap-spot gorge" of the satellite Maiden Creek sill (Horsman et al., 2005). Thus, reasoning by analogy over different spatial scales from the satellite intrusions to the main intrusion (Tikoff and Shipley, 2024: *GSA Today* October issue), one could reasonably extrapolate flat and conformable bottom contacts for the major intrusive centers.

The spatial relations among the rocks present compelling spatial logic when pieced together, although the lack of an exposed intrusion bottom contact also requires a significant mental extrapolation. How might Gilbert have put together the pieces? If Gilbert had a preexisting mental model of laccoliths, he could have used it to infer the internal form from the fragmentary observations at outcrops. However, there is no evidence that he had a preexisting mental model. Rather, his mental model of a laccolith was built from filling in surfaces between outcrops, akin to how the visual system fills in parts of objects that are occluded to "see" whole objects (Kellman and Shipley, 1992).

A single laccolith would be sufficient to add a new form to a geologist's mental library of structures. The series of laccoliths in the Henry Mountains allowed Gilbert to conclude this form was a category of forms, and that all intrusions have some set of defining characteristics as well as some aspects that vary across individual members. We will employ an analogy to make this point clear. Consider the category of "dog." The shape and color of individual dogs vary widely across the category. Variation in these and other attributes inform the observer about the spatial tolerances of the mental model of "dogness"—much like the category of unconformity (Shipley and Tikoff, 2024: *GSA Today* November issue) tolerates changes of orientation. Cognitive research on learning categories identifies two distinguishable, but not mutually exclusive, processes. A category may be formed in the mind by definitional rules (e.g., the category "siblings" is defined by a specific familial relationship, such as being part of the same litter) or by extracting a central tendency from multiple instances (e.g., a retriever is likely closer to the prototype of a dog than much larger or smaller dogs).

Many of the intrusions of the Henry Mountains are members of the "laccolith" category. Similar to the "dog" category, "laccolith" has definitional features and a central tendency. Laccoliths are defined by the geometry of an igneous intrusion into sedimentary rock, but laccoliths have different sizes and compositions. By seeing multiple examples, the mind can construct a constellation of memories in multidimensional feature space with a central tendency of this "laccolith" category. These characteristics of the mental library allow geologists to go beyond what they have seen. For instance, Torres del Paine in Patagonia, Chile, is readily classified as a laccolith by geologists empowered by mental models derived from the Henry Mountains (e.g., Leuthold et al., 2012).

The optimal order for presenting examples to teach a new category is an open question in cognitive science (Nosofsky et al., 2018). Plausible models of category formation, however, suggest that initial examples should include items that are near the center of the category. Further, initial examples should show some of the natural variation in the category. It is likely that what makes the Henry Mountains a type locale is that this collection of laccoliths—both the main intrusive centers and the satellite intrusions—satisfies both criteria. Nevertheless, the development of a new category would be challenging if the first example did not stand out clearly from other observations. For example, once a geology student has learned the basic rock category of "schist," it may be important to introduce a gneiss that completely lacks biotite. It is easiest to see something new if it clearly differs from previously observed examples and is not within the range of variability.

The recognition of the new geological form, with its variations, brought to Gilbert's mind a second idea—a new way to form mountains. Gilbert illustrates his model for intrusion and subsequent erosion of a laccolith in his 1877 report (Fig. 3). The presence of the form inside a mountain demands an explanation for how it got there. The geometry of the overlying sedimentary beds suggested they were raised as the igneous rock came in and thus were uplifted to form a mountain with an igneous core. Gilbert not only recognized this as the simplest explanation for the field observations but also used physics/hydraulics arguments to demonstrate the feasibility of this type of intrusion (Gilbert, 1877, p. 87–91). Once it is allowed that intrusive igneous rocks—without regional deformation associated with plate boundary interactions—are capable of mountain formation, the process also becomes a type of mental model.

The Henry Mountains are a geological exemplar of laccolith emplacement. Geological exemplars are places where the outcrop relations are clear and readily graspable by the mind. What are the characteristics, in addition to good exposure of the rocks, that make specific field areas so tractable to creation of new mental models? We suggest that it is likely that these locales are where confounding variables can be reduced and/or some type of spatial gradient is available that reflects a gradient in the operation of some process (e.g., erosion). In the Henry Mountains, the exemplar status results from the lack of regional deformation (lack of confounding variables), a well-known stratigraphy (lack of confounding variables), and the erosional differences arising from the N-to-S age progression of the five igneous intrusions (presence of a gradient). To clarify the last point, the northernmost Mt. Ellen intrusive center exposes an eroded igneous core, while the southernmost Mt. Ellsworth intrusive center only exposes dikes and sills fed by the underlying buried laccolith into the domed sedimentary rocks at its crest.

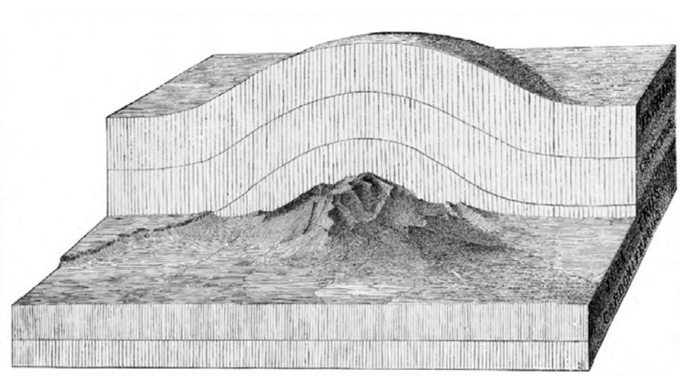

Figure 3. An interpreted laccolith without erosion (back) and with erosion (front) of the Mt. Ellsworth intrusive center, Henry Mountains, Utah. It is the frontispiece from Gilbert (1877).

It is common to see field exemplars referred to as "natural laboratories" in the geological literature. That term is likely meant to convey that these special areas reveal processes with particular acuity, as if they were extracted for analysis in a lab. However, this attempt to form a category from two distinct concepts (a natural field area and a scientific laboratory) obscures the role of the mind in geoscience. The term "natural laboratory" has three distinct problems. First and foremost, it is incoherent, as it does not describe an aspect of reality or scientific process. No field area is a laboratory, in which variables can be controlled and systems can be manipulated wholescale. The incoherence of the phrase is further revealed when considering field areas that are not "natural laboratories"; they are neither "unnatural laboratories" nor "natural non-laboratories." Second, the term inherently downplays the importance of fieldwork by lauding a specific region or outcrop as having the exalted status of "laboratory," implicitly suggesting that laboratory data would be better than field data as an object to study. Critically, the term "natural laboratory" was originally used to undermine the empirical geological data used to support continental drift by geodesists who incorrectly interpreted their theory-driven geophysical arguments to be incompatible with moving continents (see Oreskes, 1999). Finally, the term "natural laboratory" is epistemologically backward, as pointed out by Oreskes (1999): Geological concepts emerge from observations of the Earth that may be taken into the lab for study. The only arbiter of how the Earth works is the Earth itself, and fieldwork is the most direct form of obtaining that information.

The motivation to include this discussion is to make two important points about how the mind works. First, a new mental model is an accomplishment of the mind from patterns given by the Earth. In these cases, evidence comes from the coordination of object and process, which is not analogous to collecting evidence in a laboratory. Second, any well-exposed field area that clearly records a structure or process (a geological exemplar) is important for forming a mental category.

Geological exemplars are useful for teaching, introducing concepts with particular clarity even as they contribute to refining geological concepts. First, geological exemplars are often used as proving grounds for new theories that lump or split categories by thinking about geological features in a new way. The Henry Mountains were reinterpreted as geological stocks (Hunt et al., 1953), which would imply a deep vertical root rather than a flat-bottomed contact. Additional data supported Gilbert's laccolith hypothesis (Jackson and Pollard, 1988a); however, a subsequent Discussion and Reply suggest the issue has not been fully resolved (Hunt, 1988b; Jackson and Pollard, 1988b). Second, geological exemplars are revisited when new conceptual models are offered and guide scientists to look for previously ignored patterns. The Henry Mountains played this role in determining incremental emplacement of igneous intrusions into the upper crust. Prior to ~2000, most plutons were generally thought to result from the injection of a single batch of magma from the lower crust. However, the satellite intrusions of the Henry Mountains were shown to consist of a series of horizontal sheets, which amalgamated to form a pluton (Morgan et al., 2008). These sheets can be recognized by bulbous terminations along their margins, internal fabrics, and sometimes interleaved sediments between different sheets (Horsman et al., 2005). In fact, Gilbert had previously made a similar interpretation in his fieldbook: "A division in the trachyte indicates that it was injected at two times" (reported in Hunt, 1988a, p. 82).

The exercise of considering how and why the geologist's mind makes a discovery at a geological exemplar can be revealing. Note that this exercise is not exactly the same as recounting the history of the original discovery, which would necessarily focus on social answers to questions such as "why there," "why then," and "why was Gilbert so effective at seeing these relations?" Despite Gilbert's published field notes on the Henry Mountains, we will never know exactly what was going on in his mind. However, as geologists, we are always asking the same pattern-and-process question as Gilbert: "What does the Earth's pattern here tell us about the geological process (or processes) that caused them?" It might be productive for practitioners to also ask: "What does the Earth's pattern here tell us about the process of geological thinking?"

ACKNOWLEDGMENTS

E. Horsman, S. Morgan, and M. de Saint Blanquat are thanked for comments and illuminating discussions on the geology of the Henry Mountains. Reviews by D.D. Pollard and S. Semken, and editorial comments by A. Egger, significantly improved this manuscript.

REFERENCES CITED

*** denotes suggested further reading**

*Egger, A.E, and Carpi, A., 2023, Description in Scientific Research: https://www.visionlearning.com/en/library/Process-of-Science/49/Description-in-Scientific-Research/151 (accessed October 2023). Egger and Carpi (2023) use G.K. Gilbert's field notes in the Henry Mountains as an example of scientific description.

Gilbert, G.K., 1877, Report on the Geology of the Henry Mountains: Washington, D.C., U.S. Geographical and Geological Survey of the Rocky Mountain Region, 160 p., https://doi.org/10.5962/bhl.title.51652.

Horsman, E., Tikoff, B., and Morgan, S.S., 2005, Emplacement-related fabric and multiple sheets in the Maiden Creek sill, Henry Mountains, Utah, USA: Journal of Structural Geology, v. 27, p. 1426–1444, https://doi.org/10.1016/j.jsg.2005.03.003.

* Horsman, E., Broda, R.J., Gwyn, N.Z., Maurer, E.A., Thornton, E.D., and Ward, M.D., 2018, Progressive construction of laccolithic intrusive centers: Henry Mountains, Utah, U.S.A, *in* Breitkreuz, C., and Rocchi, S., eds., Physical Geology of Shallow Magmatic Systems: Dykes, Sills, and Laccoliths: Cham, Switzerland, Springer, p. 327–347, https://doi.org/10.1007/11157_2016_18.

Hunt, C.B., 1988a, Geology of the Henry Mountains, Utah, as recorded in the notebooks of G.K Gilbert, 1875–76: Geological Society of America Memoir 167, 229 p.

Hunt, C.B., 1988b, The laccolith-stock controversy: New results from the southern Henry Mountains, Utah: Discussion: GSA Bulletin, v. 100, no. 10, p. 1657–1658, https://doi.org/10.1130/0016-7606(1988)100<1657:TLSCNR>2.3.CO;2.

Hunt, C.B., Averitt, P., and Miller, R.L., 1953, Geology and geography of the Henry Mountains region, Utah: USGS Professional Paper 228, 234 p., https://doi.org/10.3133/pp228.

Jackson, M.D., and Pollard, D.D., 1988a, The laccolith-stock controversy: New results from the southern Henry Mountains, Utah: GSA Bulletin, v. 100, no. 1, p. 117–139, https://doi.org/10.1130/0016-7606(1988)100<0117:TLSCNR>2.3.CO;2.

Jackson, M.D., and Pollard, D.D., 1988b, The laccolith-stock controversy: New results from the southern Henry Mountains, Utah: Reply: Geological Society of America Bulletin, v. 100, no. 10, p. 1658–1659, https://doi.org/10.1130/0016-7606(1988)100<1657:TLSCNR>2.3.CO;2.

* 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.

Leuthold, J., Müntener, O., Baumgartner, L., Putlitz, B., Ovtcharova, M., and Schaltegger, U., 2012, Time resolved construction of a bimodal laccolith (Torres del Paine, Patagonia): Earth and Planetary Science Letters, v. 325–326, p. 85–92, https://doi.org/10.1016/j.epsl.2012.01.032.

Morgan, S.S., Stanik, A., Horsman, E., Tikoff, B., St. Blanquat, M., and Habert, G., 2008, Emplacement of multiple magma sheets and wall rock deformation: Trachyte Mesa intrusion, Henry Mountains, Utah: Journal of Structural Geology, v. 30, p. 491–512, https://doi.org/10.1016/j.jsg.2008.01.005.

Nosofsky, R.M., Sanders, C.A., and McDaniel, M.A., 2018, Tests of an exemplar-memory model of classification learning in a high-dimensional natural-science category domain: Journal of Experimental Psychology: General, v. 147, p. 328–353, https://doi.org/10.1037/xge0000369.

Oreskes, N., 1999, The Rejection of Continental Drift: Theory and Method in American Earth Science: New York, Oxford University Press, https://doi.org/10.1093/oso/9780195117325.001.0001.

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

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.

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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.