Figure 1. Shorelines from Lake Bonneville exposed on Antelope Island, Utah. The highest shoreline (Bonneville shoreline) is from the high lake level that occurred ~17,500 years ago (Oviatt, 2020).

# Lake Bonneville Shorelines, Utah, and the Role of the Mind in the Practice of Geology

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

**Geology logline:** *G.K. Gilbert developed the use of multiple working hypotheses when determining the cause of the differential elevation of shorelines at Lake Bonneville, providing a tacit recognition of the role of the mind.*

**Cognitive science logline:** *There are aspects of doing science to which we do not have conscious access, and being aware of one's mind in the practice of geology can improve outcomes and reduce bias.*

The shorelines of Lake Bonneville are a prominent feature of the eastern part of the Basin and Range Province (Fig. 1). The shorelines that record different lake levels are well preserved on mountains. A lake level can change for two primary reasons. First, the climate can change and there can be more or less water flowing into the basin than evaporating out of it. Second, the lake can erode a drainage divide and start spilling into an adjacent basin. The latter happened to Lake Bonneville when it reached its highest level and catastrophically drained into southern Idaho through Red Rock Pass. When this happened, the lake level is estimated to have dropped ~110 m in a flood lasting about a year (O'Conner, 1993).

The Lake Bonneville shorelines are also the backdrop for one of the most historically important scientific publications that both recognizes the role of the mind and provides a practical approach to support the mind in the practice of geology. It was written by geologist G.K. (Grove Karl) Gilbert, a scientist who lived over 100 years ago but is still known and revered by geological practitioners for his insights. It was in his 1886 presidential address to the Geological Society of America that G.K. Gilbert proposed his method of multiple working hypotheses, using the existence and subsequent differential uplift of the Lake Bonneville shorelines (Fig. 1) as his case study. Rather than following one hypothesis and working to advance it, Gilbert suggested identifying multiple hypotheses and collecting data that could support any of them. He articulated a new way of doing science that reduced the risk of focusing on a single hypothesis. Chamberlin (1897) popularized multiple working hypotheses and often gets the credit, but Gilbert (1886) first developed and applied the method.

* basil@geology.wisc.edu
[1] Temple University, Philadelphia, Pennsylvania 19122, USA
[2] University of Wisconsin–Madison, Madison, Wisconsin 53706, USA

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Gilbert (1886) is one of the clearest papers about the value of thinking about geological thinking ever published. We begin our essay series here because the concept of multiple working hypotheses is known to most geologists, and it highlights the value of being aware of one's thinking in the practice of geology. It is perhaps the first, and certainly the best-known, publication that raises the broader questions: "What is the geologist's mind doing as they practice geology, and how does the Earth influence that mind?" In this essay, we offer a cognitive scientific context for Gilbert's work and reflect on the potential for this approach to advance both cognitive science and geology.

IN THIS ESSAY, WE OFFER A COGNITIVE SCIENTIFIC CONTEXT FOR GILBERT'S WORK AND REFLECT ON THE POTENTIAL FOR THIS APPROACH TO ADVANCE BOTH COGNITIVE SCIENCE AND GEOLOGY.

G.K. Gilbert, like other practitioners of his time, recognized that shorelines occurred in internally drained lake basins and recorded past high-water levels.[3] The Lake Bonneville shorelines (Figs. 1 and 2) were an example of this pattern. However, he made a critical observation, not obvious to the casual viewer, that the shorelines are not perfectly horizontal. One could walk a single shoreline and it would rise 10 m over a distance of 100 km.

Note that the "observation" of a shoreline illustrates an implicit character of human, and thus scientific, reasoning. Geological observation is the balance of accumulated evidence for (and against) a claim about a property of the world: It is not, strictly speaking, a property of the world that is visible to everyone. What is the evidence for a shoreline? First, the shoreline is revealed by a break in slope, with a shallow slope above a steep slope. Second, the break in slope is more-or-less continuous. In the case of shorelines, "more-or-less" means that some portions can be subsequently eroded away and a geologist mentally ignores this type of complication. Third, the shoreline must be, for all intents and purposes, horizontal. It took Tim a long time, but he finally convinced Basil: Most of what Basil calls "observations" are really low-level interpretations—inferences—with which almost all geologists agree.

It is important to dwell on Gilbert's observation that the shorelines were not horizontal, because violations of expectations are important starting points in science. If these features are shorelines, they should all be level. That is, there is a prediction—horizontality—that is embedded in the inference that these features are shorelines. It could be that the inference is wrong, but there is no evidence that Gilbert seriously entertained this option. He focused on the alternative, that a previously unrecognized process had changed the shorelines after they formed. Gilbert figured out something important about the way the world works, and he did it by identifying an unexpected pattern in the world. There is a spatial regularity to where the shorelines are not flat, as can be seen in Gilbert's map of the elevation of the highest and most prominent shoreline (Fig. 3). A simple correlation is evident once mapped: The elevation of the top-most shoreline is highest where Lake Bonneville was deepest.

Patterns in the world commonly have multiple causes, and determining a single explanation for any observed pattern can require additional data. Keeping multiple hypotheses in mind helps motivate and guide the collection of that additional data. Each hypothesis is a high-level interpretation, which we refer to as a model, as it is an explanation for how the phenomenon could occur. Gilbert realized that if you only have one model for the data, you will both focus only on data that confirm that idea and ignore data that are incompatible with it. This phenomenon is an example of what is now called *cognitive bias* and is well-documented in the cognitive science literature (Tversky and Kahneman, 1974; Soll et al., 2015). The use of multiple and competing models tends to reduce bias and keep you open to making new observations that may cast doubt on a specific model. Gilbert recognized—and made a case for attending to—the role of the mind in the practice of geology.

Gilbert, using the Lake Bonneville shorelines as an example for his new method, came up with multiple models that could explain the data. Although

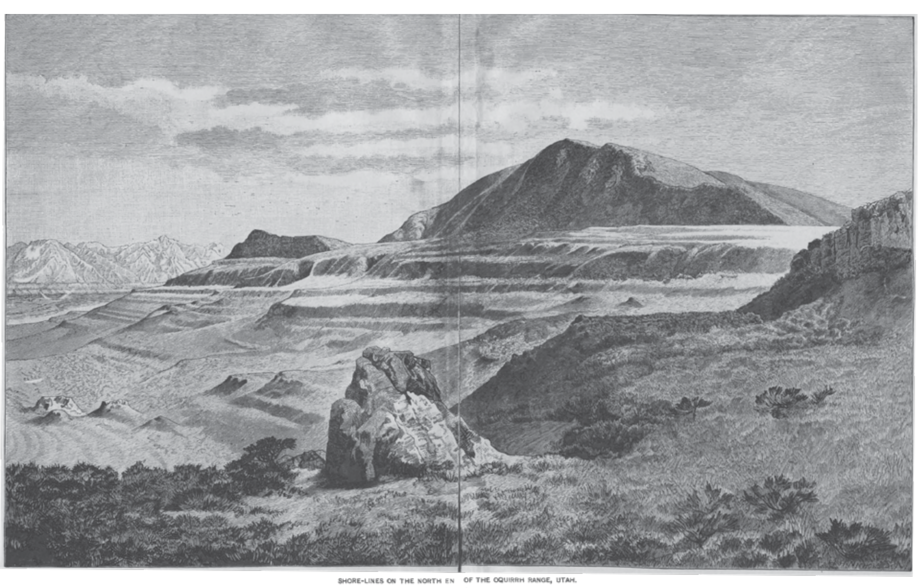


Figure 2. Field sketch of shorelines on the north end of the Oquirrh mountains, likely drawn in the 1870s. This figure is the frontispiece from Gilbert's USGS monograph (Gilbert, 1890).

[3] Shaler (1868) published a paper about shoreline modification, indicating that workers were generally aware of these geomorphic features. Further, Shaler considers the vertical movement of shorelines resulting from large-scale folding and modified geothermal gradients. Gilbert had a copy of this work in his files, which we recently obtained.

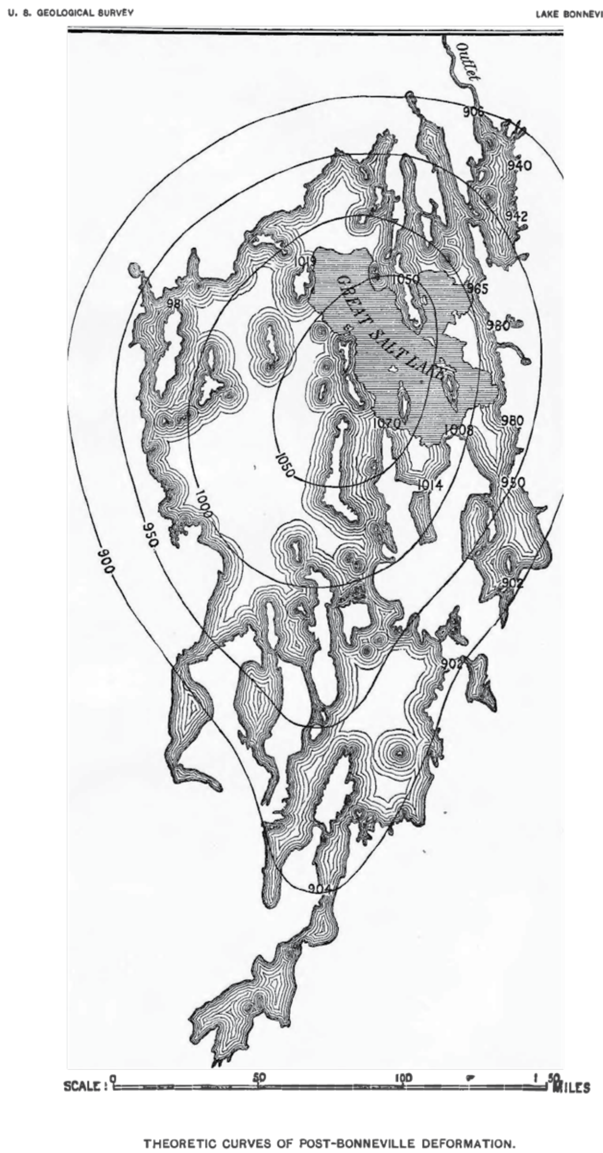


Figure 3. Map of Lake Bonneville and recent extent of the Great Salt Lake. The contour lines indicate hypothetical magnitude of post-Bonneville uplift, extrapolated from a few known points. The contours are feet above 1880s lake level. This figure is plate 50 from Gilbert's USGS monograph (Gilbert, 1890).

Gilbert did not attribute any of the models to other geologists, some models for variation in ocean shoreline elevations were proposed by Shaler (1868). He addressed, but ultimately dismissed the possibility that the shoreline uplift is a result of either gentle folding or active faulting, because neither of these explanations is consistent with the correlation between depth of the lake and amount of uplift. He then proposed three more options. First, the removal of water could cause the Earth's crust to rise in elevation proportional to the thickness of the water (a process called isostasy, although that word is not used by Gilbert). That is a huge conceptual leap, because it requires that the Earth—the prime example of stability for many people—is not stable. As Gilbert (1890) wrote, "To imagine the result it is necessary to divest the mind of the ideas of brittleness and great strength ordinarily associated with granite and other massive rocks" (p. 382). Second, the removal of water could cause changes in the gravity field and thus the geoid. Third, the removal of water could cause thermal expansion of the underlying rock. He ultimately settled on isostasy as the best of the options. So, Gilbert figured out that the Earth is capable of changing shape, "massive rocks" moving upward and downward in response to vertical loads, such as the addition or removal of water in large lakes. Equally important, however, he figured out how scientists can avoid biasing—and thereby fooling—themselves.

Gilbert was not just advocating for a new way of doing science; he was also making an observation about doing geology that allows inferences about what is going on within the mind. Gilbert identified, articulated, and proposed solutions for one of the mind's limits that are particularly important for expert practice. He did this when psychology was in its intellectual infancy and well before cognitive science had a name for the problem. The value of attending to the mind, with its known strengths and weaknesses, can be hard to see. The problem is that the mind's errors are not immediately apparent to the mind. To make a geological analogy, the non-horizontal nature of the shorelines are not immediately apparent either. The limits of human perception make it hard to see they are not horizontal, and thus hard to accept they may be tilted. Like the mind observing itself doing science, it is hard to see when it is going astray. Accepting the non-horizontality of the shorelines allowed Gilbert to recognize the important tale that Lake Bonneville was telling both about the world and the mind. This is doing science while being aware of human cognition.

In short, a scientist cannot count on noticing that they are making an error. The consequence, articulated well by J.S. Mill, is that "...while everyone well knows himself to be fallible, very few think it necessary to take precaution against their own fallibility..." (Mill, 1859, p. 32). The use of multiple working hypotheses is a safeguard against one's own fallibility. Attending to the mind is an insurance policy against risks in reasoning that could delay progress in science.

However, safeguards need to be in place to be effective. Geologists are familiar with the advice to construct multiple working hypotheses, yet may not do so every time they are in the field. Thinking through all possible explanations for observed patterns takes significant intellectual resources and is impractical for well-established inferences, such as, "that's a shoreline." Multiple hypotheses become relevant for models where there is a lack of community agreement and bias can influence practice.

Please allow us a one-paragraph digression to illustrate the crucial point that a mind cannot determine when it is making errors. When the continental drift hypothesis was first introduced (Wegener, 1915), consider whether you would have been an early adopter of this mobilist idea. Both authors agree, we think we would have been early adopters of mobilism. Even a cursory consideration of the historical facts, however, shows just how wrong our confidence is. The proportion of the scientific community that were early adopters was tiny and in all likelihood we would have been fixists. The earliest versions of a mobile Earth were widely rejected for decades, by the overwhelming majority of the geological community. Thinking that one would be an early adopter of continental drift occurs because one knows the right answer. One knows how all of the facts fit neatly together, which allows the correct answer to readily come to mind. The ease of thinking the idea—here, that the continents can move relative to each other—causes us to believe we would have also easily believed the idea when we first encountered it. But humans cannot accurately predict what we would think if we did not know something (Fischhoff, 1975).

Focusing on any single hypothesis similarly allows all the consistent facts to come readily to mind, which makes the hypothesis feel like a right answer. The bias of being inclined to believe the things that come most easily to mind is a trap. The mind will thereafter focus on a favored hypothesis to the exclusion of other potential hypotheses, and people are unlikely to recognize the uncertainty in that hypothesis. Moreover, non-conforming data will be overlooked, not collected, and/or not reported. There are effective ways to avoid this trap. One approach does not work, however: Mentally commanding yourself to not be trapped (Soll et al., 2015). One approach that does work, however, is to avoid commitment to a single hypothesis, and to design a mental workflow to allow or evaluate alternative accounts.

THE THESIS OF THIS ESSAY IS THAT THERE ARE ASPECTS OF DOING SCIENCE TO WHICH WE DO NOT HAVE CONSCIOUS ACCESS. SOME KEY MENTAL PROCESSES FOR SCIENCE REQUIRE MENTAL PROCESSES, SUCH AS RECALLING THE RELEVANT FACTS AND EVALUATING THEIR CONSISTENCY WITH A NEW OR OLD HYPOTHESES, THAT ARE COLLECTIVELY UNDERSTOOD TO REQUIRE MEMORY.

To illustrate the power of minor changes to workflow, consider this example of interpreting seismic reflection profiles: Clare Bond and colleagues (Macrae et al., 2016) documented improved performance if individuals were required to explicitly articulate the temporal ordering of events when multiple interpretations are possible. Although Bond and colleagues did not explicitly ask for multiple hypotheses, the act of articulating the logic of temporal ordering was sufficient to avoid errors that arose because the wrong answer came to mind first. Even the best-intentioned expert participants could not feel their mind making the error of thinking that what came to mind easily was a right answer. Absent knowing an error is being made, we need methods that reduce the chances of making errors.

Why should we follow Gilbert's direction, whether to employ multiple working hypotheses or other techniques, to be aware of and support the mind's practice of geology? The thesis of this essay is that there are aspects of doing science to which we do not have conscious access. Some key mental processes for science require mental processes, such as recalling the relevant facts and evaluating their consistency with a new or old hypotheses, that are collectively understood to require memory. We evaluate hypotheses and theories by how well memories cohere into a viable account of the world. These mental processes are simultaneously a discovery engine that advances science and an error engine that hinders science. By recognizing the mind's limits, we can see the value of Gilbert's guidance and ultimately the importance of knowing some fundamentals of cognitive science while practicing science.

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