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The Rocks Don't Lie, But They Can Be Misunderstood

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ABSTRACT

Although the adage "the rocks don't lie" is true—rocks are literal ground truth—their message can be misinterpreted. More generally, it is misguided to favor one form of inquiry, such as field observation, over others, including laboratory analyses, physical experiments, and mathematical or computational simulations. This was recognized more than a century ago by T.C. Chamberlin, who warned against premature adherence to a "ruling theory," and by G.K. Gilbert, who emphasized the investigative nature of geological reasoning. Geologic research involves a search for fruitful, coherent, and causal hypotheses that are consistent with all the relevant evidence and tests provided by the natural world, and field observation is perhaps the most fertile source of new geologic hypotheses. Hypotheses that are consistent with other relevant evidence survive and are strengthened; those that conflict with relevant evidence must be either revised or discarded.

INTRODUCTION

The Critical Importance of Field Observations

Geology is largely a field-based science, and field evidence has long been given primacy in interpretation of the Earth. This is sometimes expressed as "the rocks don't lie." Rocks do indeed record Earth's history and information about processes that link the lithosphere, hydrosphere, atmosphere, and biosphere. Understanding this record requires proper interpretation of field observations.

As field geologists, we have learned that the interpretation of field evidence is strongly shaped by what one has been taught as well as by prevailing theories and reigning paradigms. Moreover, one's experience with familiar materials and processes at the Earth's surface influences the interpretation of features that formed at unfamiliar rates and/or physical conditions. The rocks don't lie, but preconceptions and human experience can cause us to misinterpret what they reveal to us.

A Warning from the Distant Past

In his classic, oft-discussed paper, "The Method of Multiple Working Hypotheses," Chamberlin (1890) cautioned of the "blinding influence" of a "ruling" or "premature" theory. Because Chamberlin's advocacy of keeping a nimble mind for one's scientific work was written in the wordy, stilted, and androcentric prose of his time, we have rewritten and condensed a key portion in more modern language:

> The moment that you come up with an explanation for a phenomenon, you develop affection for your intellectual child, and with time this grows ever stronger. You proceed rapidly to acceptance of the theory, followed by unconscious selection of data that fit and unconscious neglect of data that do not. Your mind lingers with pleasure on facts that confirm the theory and feels a natural coldness toward those that do not. You search instinctively for data that fit, for the mind is led by its desires. When these biases set in, collection of data and their interpretation are dominated by affection for the favored theory until you are convinced that it has been overwhelmingly confirmed. It then rises to a position of mind control, guiding observation and interpretation—from a favored child into your master.
>
> When this last stage has been reached, unless the theory happens to be correct, all hope of progress is gone.

The Nature of Geologic Investigations

Gilbert (1886, 1896) described the methods of geological research in a way that nicely complements Chamberlin's views. Gilbert distinguished between investigators and theorists and viewed geology as investigative. He argued that geologic hypotheses rarely arise from theory, but rather through analogical reasoning inspired by the direct study of nature (Gilbert, 1896). Gilbert's emphasis on analogy and fruitfulness in the origin of geological hypotheses has been analyzed in detail by Baker (2014, 2017). Gilbert (1896, p. 12) stated an important caveat regarding field investigations: "However grand, however widely accepted, however useful its conclusion, [no hypothesis] is so sure that it cannot be called in question by a newly discovered fact. In the domain of the world's knowledge there is no infallibility."

The investigative nature of geological research has been emphasized recently by philosophers of science. Just as some crime scene evidence (e.g., fingerprints or DNA) can be highly conclusive for detective investigations, so geological questions may be most effectively resolved by what Cleland (2013) termed a "smoking gun." Cleland cited as an example the bolide impact hypothesis for the end-Cretaceous extinctions (Alvarez et al., 1980), where excess iridium and shocked quartz provide two barrels. Cleland argued that the search for a smoking gun works especially well for distinguishing among the multiple hypotheses that commonly arise in historical natural sciences such as geology.

Fieldwork is Challenging

The universe of observable features in geologic fieldwork is vast, so we must filter what we see to avoid paralysis. A soil scientist might pay little attention to granite bedrock, whereas a granite petrologist would likely do the opposite. This makes it difficult

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to see things for which one is not looking. For example, quartz xenocrysts are common in andesites and are now recognized as clear evidence of magma mixing, but this was widely ignored for decades because fractional crystallization was the paradigm under which volcanic rocks were interpreted. The emergence of Sr-isotopic studies in the 1970s showed that this was incorrect. Similarly, for decades low-angle normal faults were mapped as thrust faults, unconformities, or gravity slides, because low-angle extensional faults were regarded as mechanically impossible. Although the mechanics of low-angle normal faults are still problematic, abundant and compelling geologic evidence has led to broad acceptance of their existence (e.g., Collettini, 2011).

Therefore, as also advocated by Chamberlin, keeping alternative hypotheses—that is, alternative explanations—in mind is important in fieldwork. A particular formation may be used as a benchmark to assign adjacent strata to other formations and work out the geologic structure. If evidence arises indicating that the rocks have been overturned, the stratigraphic assignments and structure must be revised. If one's mind is closed to this possibility, then "all hope of progress is gone."

Tests of Field-Based Hypotheses: Are the Rocks Lying?

Data for testing field-based hypotheses can come from multiple sources, including laboratory analyses, remote sensing, and geophysical imaging. This paper focuses on conflicts that can arise between field-based observations and information from these other sources. In cases of disagreement, a field-oriented geologist might insist that "the rocks don't lie" and, on that basis, dismiss inconsistencies with the field-based hypothesis (Fig. 1). Nevertheless, what the rocks indicate (what they "have to say to us") may be misunderstood. Field-based interpretations that are inconsistent with results from other disciplines must be questioned, and inconsistencies should be used to drive the development of new hypotheses.

Figure 1. In granites worldwide, accumulations of K-feldspar such as this have been interpreted variously as slurries deposited on a magma chamber floor, as concentrations produced by shear sorting during magma flow, and as masses that rose buoyantly within a magma chamber. These interpretations can be ruled out on the basis of phase equilibria, mineral chemistry, volcanic petrology, and basic physics. Are the rocks lying? Photo courtesy of Bryan Law.

FAILED HYPOTHESES ABOUT THE CONSTRUCTION OF PLUTONIC SYSTEMS

We begin by summarizing how new data collected during work on the Late Cretaceous Tuolumne Intrusive Suite (TIS; Fig. 2) in Yosemite National Park forced three of the authors to abandon much of what they had been taught about plutonic systems and to develop new explanations for how they work. Bateman and Chappell (1979) had proposed a model, widely reproduced in textbooks, in which the TIS was intruded in several distinct pulses, each of which shoved aside older, but still partially molten, material. This hypothesis makes several predictions, including that (1) construction should have taken <~1 m.y.; (2) ages within a single pulse, and therefore a single map unit, should cluster even more tightly; and (3) such large magma chambers should show vertical gradients in composition. However, predictions 1 and 2 were contradicted by a spread of 10 m.y. in low-precision ages for the TIS (Kistler and Fleck, 1994, their fig. 14), far longer than predicted by the Bateman and Chappell model.

In 1994 we collected samples from the western side of the TIS for analysis using more advanced U-Pb techniques. In keeping with the nested-construction hypothesis, we predicted that the ages would reveal a duration of ~1 m.y., but our results instead matched the eastward-younging 10-m.y. range of the earlier ages (Coleman and Glazner, 1997). We had been taught that science works by falsifying hypotheses, but rather than rejecting the standard model in light of these data, we sought other explanations. This is standard practice, although it conflicts with the scientific method as commonly understood; Cleland (2001, p. 988) stated, "The famous Popperian directive to bite the bullet and reject the hypothesis in the face of a failed prediction has no logical force," owing to auxiliary conditions on the test. In our case, we concluded that our data were not precise enough to show the true small age range that had been predicted.

Meanwhile, other conflicts with the standard model arose. We set out to measure vertical variations in the Half Dome Granodiorite of the TIS over its 1800 m of local relief, expecting to find gradients in geochemistry, mineralogy, and xenolith abundance consistent with processes in a magma chamber the size of the mapped pluton. This effort failed; we found none of the predicted vertical gradients (Gray et al., 2008), nor did Putnam et al. (2015) find them in the 1-km-tall southeast face of El Capitan. Mahan et al. (2003) concluded that the McDoogle pluton south of Yosemite formed by amalgamation of vertical sheets, rather than having been intruded in one large pulse. Contacts between sheets are only noticeable where marked by screens of wall rock, and this observation planted a seed: Might there also be indistinct contacts in plutons that lacked wall-rock screens to mark them?

In 2000–2001, we used yet higher-precision analytical methods to date new samples from the western side of the TIS. These

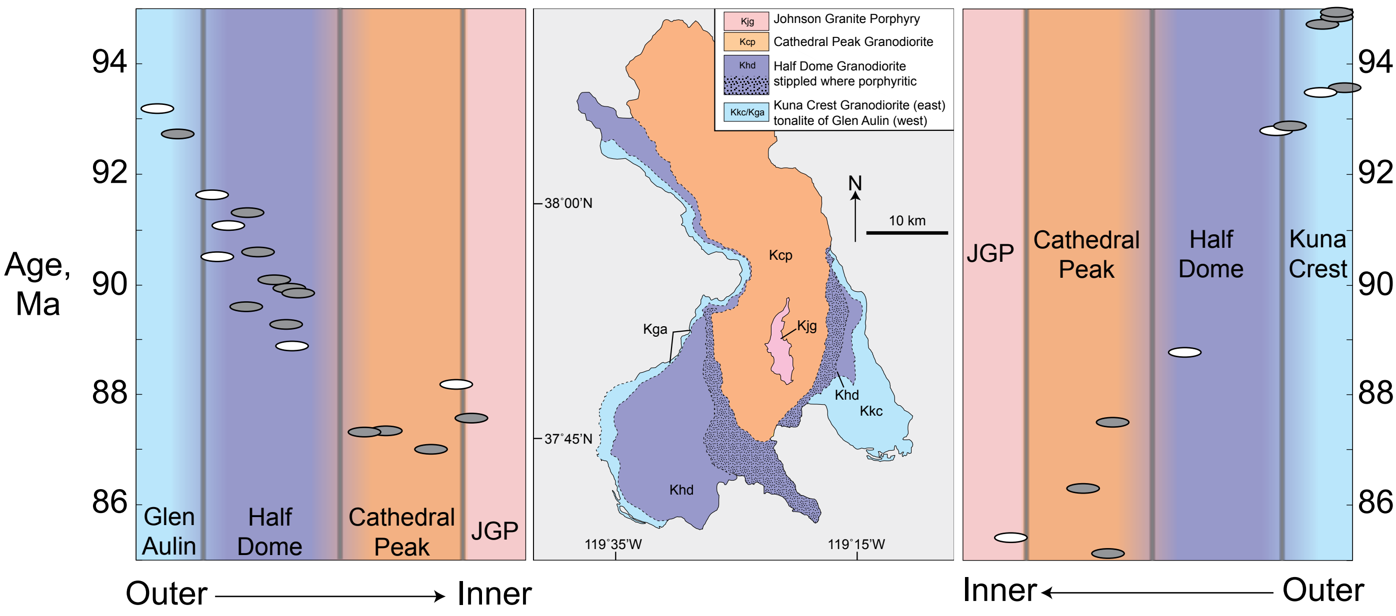

Figure 2. Summary of precise U-Pb zircon ages for the Tuolumne Intrusive Suite divided between its western (left) and eastern (right) sides. Ages are plotted at their positions relative to the inner and outer contacts of a given unit. Our ages as of 2001 (white symbols) showed eastward/inward younging of the western side of the suite; we tested and confirmed this pattern in 2001 by dating samples from the eastern side. Ages determined in other labs since then (gray symbols) have also confirmed this pattern and the 10-m.y. age span. Symbol sizes roughly indicate precision of ages and placement within each unit. Ages in gray from summary in Paterson et al. (2016). JGP—Johnson granite porphyry.

results again spanned 10 m.y., and our minds started to open to the possibility that the standard model could not account for this anomaly. We hypothesized that if the TIS had been intruded over 10 m.y., then corresponding units on the eastern side (Fig. 2) should become younger westward over the same time span. New samples collected in 2001 to test this prediction confirmed the pattern, as did later U-Pb geochronology by a number of labs (Fig. 2).

The more-precise ages revealed another failed prediction of the nested-pulse hypothesis: Most age variation occurs *within* the plutons rather than *between* them; i.e., across mapped contacts. For example, dates from the Half Dome Granodiorite span ~4 m.y., but those from near its margins differ from adjacent TIS units by <1 m.y. These results led to a new hypothesis: Plutons in the TIS were amalgamated from small increments whose boundaries are difficult to see (Coleman et al., 2004; Glazner et al., 2004).

We thus began to explore the implications of incremental assembly of plutons rather than trying to fit our data into the standard model. This was challenging because many of the processes assumed to operate in plutonic magma chambers, such as convection, crystal settling, sidewall crystallization, and stoping, cannot occur at the pluton scale if only small parts of a pluton are substantially molten at any given time.

CELEBRATED CASES WHERE GEOLOGY GOT THE BEST OF PHYSICS (APPARENTLY)

The history of geology involves well-known cases where field interpretations that were initially ruled out by physical analyses were later shown to be correct. An example is Kelvin's (1863) estimate that the Earth is <400 m.y. old, based on a thermal calculation that assumed conductive heat loss from an initially molten Earth. Compilation of an immense amount of field evidence and actualistic reasoning about process rates led geologists to insist that the Earth was much older, and that inference was ultimately vindicated by geochronology. England et al. (2007) demonstrated that the flaw in Kelvin's argument was the assumption of conductive heat transfer, and that recognition of mantle convection reconciled thermal calculations with geochronologic evidence that the Earth formed at ca. 4.5 Ga.

In another case, the continental-drift hypothesis neatly explained continuity of continental geology and paleofaunal provinces across the Atlantic Ocean and did away with the need for sunken land bridges and other speculative means of accounting for the evidence. However, physicists had correctly argued that continental drift, as originally proposed, was implausible because the mantle is far too viscous for continents to plow through it. The problem lay not in the field observations but in the mechanism used to explain them. Development of the plate-tectonics hypothesis and the recognition that continents are carried by relatively strong lithospheric plates reconciled field geology with physics (the details of the continental drift controversy are much more complex; e.g., Oreskes, 1999).

Field geology triumphed over physics in these cases not because the physics was wrong, but because incorrect physical models were used. Once a correct model was identified, the conflict evaporated.

WHEN WHAT IS CLEAR TO THE EYE IS NEVERTHELESS UNLIKELY TO BE TRUE

In geology there are many examples where seemingly incontrovertible field interpretations turn out to be controvertible after all. A few examples follow.

Resolved Controversies

In Yellowstone National Park, Iddings (1899, p. 430) examined the complex contact relations of Pleistocene basalt and rhyolite lavas (Fig. 3) and stated, "It is evident… that the rhyolite fused the basalt." Fenner (1938, p. 1458) agreed and stated that "… relations that are so plainly revealed hardly permit doubt" of Iddings's interpretation. Fenner knew that this interpretation was

Figure 3. Basalt swirls in a matrix of rhyolite from Yellowstone National Park. Iddings (1899) interpreted relationships such as this as clear evidence that the basalt was melted by the rhyolite. Although experimental petrology in the early twentieth century showed that this is thermodynamically unlikely, Fenner (1938) concurred with Iddings's field interpretation and appealed to unknown sources of energy to explain the apparently backward melting relationships. Wilcox (1944) showed that these are simply mixed magmas, an interpretation that stands to this day (Pritchard et al., 2013). Width of view 14 cm; photo courtesy of Chad Pritchard.

directly contradicted by experimental petrology (Bowen, 1928, p. 175ff.), and appealed to unknown sources of energy to explain the conflict. There was no need; Wilcox (1944) showed that the two magmas were molten at the same time and mixed, an explanation that fits the field observations, physical chemistry, and geochemistry.

Salt domes are another case where an obvious and long-accepted interpretation turned out to be largely incorrect. It appears self-evident from field relations that the relative buoyancy of salt drives it upward through overlying rocks (Nettleton, 1943), and this origin of salt domes appeared in structural geology textbooks for decades. However, seismic imaging and borehole data led to recognition that the tops of many salt domes along the Gulf of Mexico remained at a fixed depth below the sea floor and that the domal shape results from the flanks being depressed by sediment deposited in adjacent "minibasins" (Worrall and Snelson, 1989). Subsidence of the minibasins is driven by the sediment load and accommodated by lateral extrusion of underlying weak, ductile salt into domes that grow downward from a fixed roof.

Cases Where Field Observations Lead to Reasonable Yet Questionable or Invalid Interpretations

Trying to Explain the Unimaginable

Astronomy and geology require contemplation of time scales and length scales far outside those of human experience. Granitic plutons are intruded and crystallized at depths ranging from a few kilometers to tens of kilometers, over durations of 10^5 to 10^7 years, at temperatures comparable to the melting temperature of gold, from magmas at least 10,000,000 times more viscous than water. Human experience is not relevant to these conditions and can be highly misleading.

Bands in Granitic Rocks That Resemble Those Produced by Sedimentation

Banding comparable in scale to bedding in sedimentary rocks but defined by differing mineral proportions is common in plutonic rocks. Such banding is generally assumed to result from crystals settling from a large, slowly crystallizing magma body (e.g., Wager and Brown, 1968, p. 208ff.). A common interpretation of intersecting mineral layers (Fig. 4C), by analogy with cross-bedded sediment, is scour-and-fill by currents in a magma chamber (Gilbert, 1906; Irvine, 1980). Magmatic liquids in granitic rocks, however, are so viscous that current velocities of tens of kilometers per second would be needed to produce the turbulence required for erosion to form cross-bedding (Glazner, 2014).

This physical argument makes the sedimentary analogy highly unlikely; cross-cutting layers in granitic rocks likely form by other processes, such as reactions that involve diffusion coupled with a supersaturation nucleation threshold or autocatalysis (Fig. 4D; Fu et al., 1994; Ball, 2015). Crystal ripening and gradients in intensive parameters, such as temperature and chemical potential, can produce banding in igneous and metamorphic rocks (e.g., Thompson, 1959; Boudreau, 2011). Crystallizing granitic plutons are hydrous, high-temperature reaction vessels that stay hot and juicy over time scales of 10^5–10^6 years. Whether such processes operate in these vessels is not known but is testable with experiments.

K-Feldspar Megacrysts

Large K-feldspar phenocrysts (megacrysts) in calc-alkaline granodiorites (Fig. 1) provide an example of a reasonable field interpretation that is contradicted by experimental and analytical data. A common field interpretation is that megacrysts were phenocrysts that grew to large size early enough to be swept around by magmatic currents, pile up in jams, and switch magmatic hosts (e.g., Vernon and Paterson, 2008).

This interpretation is firmly ruled out on several grounds (Glazner and Johnson, 2013), only one of which we discuss here. The phenocryst interpretation requires K-feldspar to be among the first phases to crystallize, but a large and consistent body of experimental data and petrographic observation of dacite lavas shows that K-feldspar is the last major phase to begin crystallization in a dacite (= granodiorite) magma, rarely even starting to grow before the magma is half crystallized. At half crystallization, the geometric state of the magma is akin to that of loosely packed fine gravel or coarse sand, a touching framework of crystals with ~50% pore space. Most K-feldspar crystals thus grow from the last ~50% of liquid, which is dispersed in a tortuous network of millimeter-scale pores. There is no space in which large crystals of K-feldspar can grow, and therefore they likely grow and recrystallize to highly potassic compositions by a displacive process akin to growth of garnets in schist or authigenic halite in evaporites (Glazner and Johnson, 2013).

Deposition of Mudstones

An example to which one's experience with Earth-surface conditions surely ought to apply is the accumulation of mudstone. These are assumed to be a continuous record of quiescent environmental conditions in the water column directly above (e.g., Gilbert, 1895; Herbert and D'Hondt, 1990). However, Schieber et al. (2007) showed that classroom

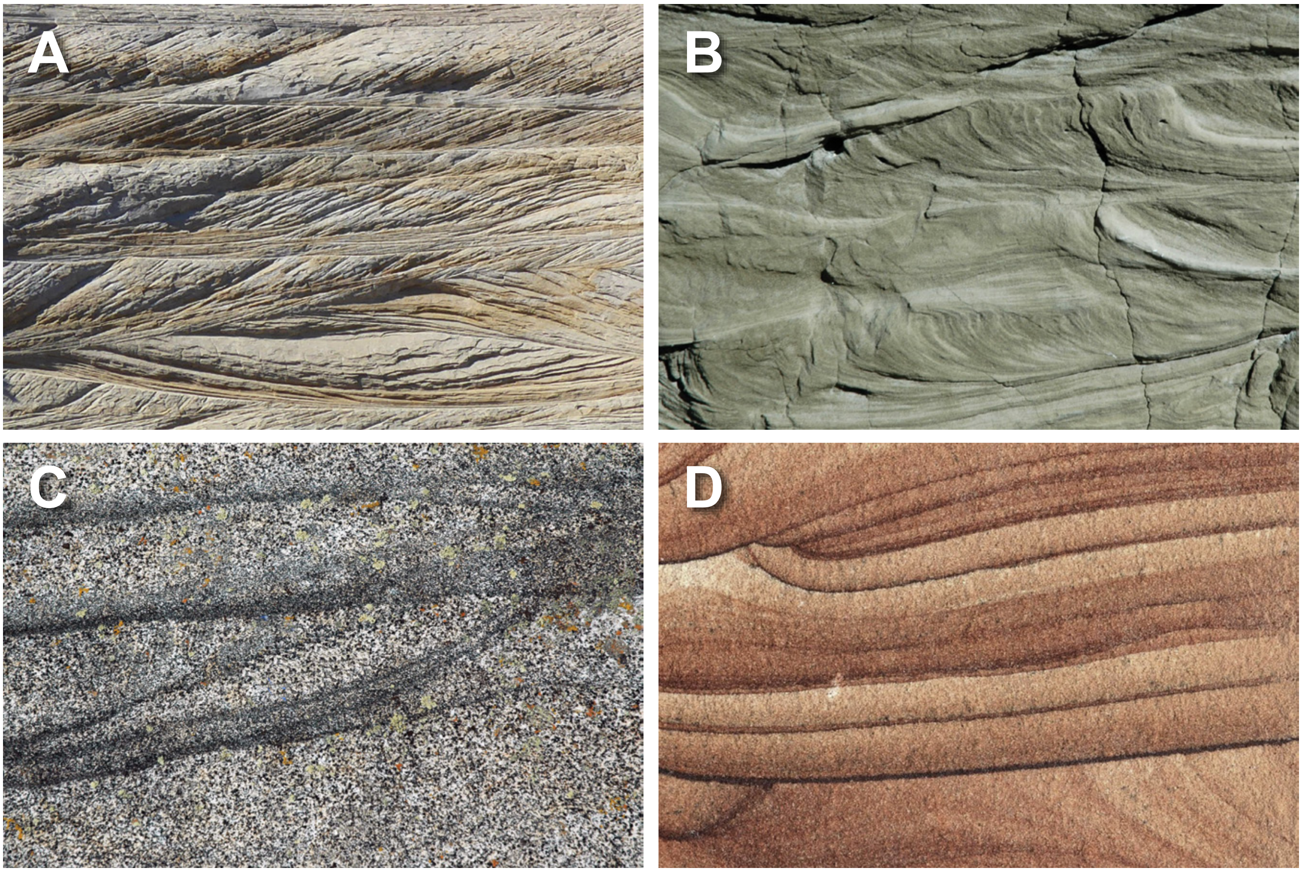

Figure 4. Geometric similarity might, but need not, mean similarity of process. (A) Cross-bedded Jurassic aeolian sandstone near Boulder, Utah, USA. Width of view ~15 m. (B) Cross-beds in fluvial Pleistocene basaltic sands near Mono Lake, California, USA. Width of view 50 cm. Bedding in both A and B formed in turbulent, high-energy environments where the Reynolds number was likely >10^4, and thus grain inertia dominated. (C) Intersecting modal layering in Cretaceous granodiorite near Mack Lake, California, USA. Width of view 60 cm. How these features form is unknown, but the extremely high viscosity of silicate liquids means that Reynolds numbers were likely 10^{-6} or less. Therefore, viscous forces were dominant, rendering impossible the sorts of grain interactions that produce crossbedding (Glazner, 2014). (D) Intersecting bands of diagenetic iron oxide in sandstone from the Triassic Chinle Formation, Utah, USA. Oxide layers do not correspond to depositional layering. Width of view 5 cm. Although these examples are geometrically similar, the erosive turbulence that truncated bedding in sedimentary rocks (A, B) cannot happen in highly viscous granitic magmas (C) and is irrelevant to the chemical processes that produce diagenetic banding in sandstones (D). The chemical processes that produced banding in the sandstone (D), however, may be relevant to banding in granodiorite (C).

settling-tube experiments may be misleading. Their experimental design allowed aggregate grains composed of micron-sized particles to grow to sand size with each circuit of the flume. This more accurately replicated natural conditions and showed that thinly bedded mud can form under currents capable of transporting these aggregates in ripples. Their work implies that muddy sediment can be eroded and transported laterally without showing obvious signs of disturbance; thus, a series of layers may contain cryptic lacunae, and any particular layer may record environmental conditions from elsewhere in the basin (e.g., Meyers and Sageman, 2004; Lazar et al., 2015).

SUMMARY

The statement "the rocks don't lie" is true, but their messages may be misinterpreted. If a field interpretation (e.g., rhyolite melting basalt, turbulence in granitic magmas) is inconsistent with results from another discipline (e.g., thermodynamics, fluid mechanics), then other explanations should be sought, regardless of the eyeball test. Just as physical and chemical reasoning applied to geologic examples must fit the geologic observations, field interpretations must satisfy fundamental physical and chemical principles. Field-based hypotheses that are consistent with other relevant information survive and are strengthened. Retaining an idea that fails valid tests simply because an alternative model has not yet been developed is unproductive. Rather, failed tests are opportunities to develop new hypotheses and to look at the rocks from different perspectives.

Consider the following quotes:

> I see the granite problem as essentially one of field geology—it is not primarily one of petrography, mineralogy, physical chemistry, or of any other ancillary discipline.

and

> The second suggestion, of deposition from a liquid magma, is too little developed for critical consideration. To constitute a useful working hypothesis it should be supplemented by the suggestion of conditions determining deposition and erosion.

The first quote is a highly restrictive statement of "the rocks don't lie" philosophy and comes from Read's (1948, p. 170) defense of granitization, a long-discredited hypothesis for the origin of granites. The second, from Gilbert (1906, p. 324), refers to his own suggestion that banded granites result from erosion and deposition in a magma chamber. Gilbert knew that ascribing those features to a familiar process was not even "a useful working hypothesis" without more definition and information. In

1906, the physical properties of magma were mostly unknown, and work on turbulence by Stokes and Reynolds was new. If Gilbert had had this information at hand, he likely would have clearly formulated, and then rejected, his preliminary, tentative, field-based hypothesis in the manner that Chamberlin (1890) envisioned.

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