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Terrestrial analogs, planetary geology, and the nature of geological reasoning

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A R T I C L E I N F O

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A B S T R A C T

Analogical reasoning is critical to planetary geology, but its role can be misconstrued by those unfamiliar with the practice of that science. The methodological importance of analogy to geology lies in the formulation of genetic hypotheses, an absolutely essential component of geological reasoning that was either ignored or denigrated by most 20th century philosophers of science, who took the theoretical/ experimental methodology of physics to be the sole model for all of scientific inquiry. Following the seminal 19th century work of Grove Karl Gilbert, an early pioneer of planetary geology, it has long been recognized that broad experience with and understanding of terrestrial geological phenomena provide geologists with their most effective resource for the invention of potentially fruitful, working hypotheses. The actions of (1) forming such hypotheses, (2) following their consequences, and (3) testing those consequences comprise integral parts of effective geological practice in regard to the understanding of planetary surfaces. Nevertheless, the logical terminology and philosophical bases for such practice will be unfamiliar to most planetary scientists, both geologists and nongeologists. The invention of geological hypotheses involves both inductive inferences of the type Gilbert termed "empiric classification" and abductive inferences of a logical form made famous by the 19th century American logician Charles Sanders Peirce. The testing and corroboration of geological hypotheses relies less on the correspondence logic of theoretical/ experimental sciences, like physics, and more on the logic of consistency, coherence, and consilience that characterizes the investigative and historical sciences of interpretation exemplified by geology.

1. Introduction

In doing field geology on Earth the geological investigator has the benefit of an interplay between (1) detailed examination of samples and rock outcrops, and (2) compilations of regional syntheses, most effectively achieved through geological mapping. In contrast, planetary geologists must contend with the directionality of space exploration, in which the surfaces of extraterrestrial bodies are first encountered globally thorough studies of remote sensing at low-resolution. Subsequent, high-resolution imagery then allows a focusing on details, but sample and outcrop studies can only come much later, and then only at one or a few discrete locations. Because of its primary position in regard to planetary geological discoveries this essay will focus on planetary surfaces and the, sometimes misunderstood, nature of geological reasoning applied to the investigation thereof.

The directionality of planetary exploration very commonly leads to a problem that has been characterized as convergence or "equifinality", in which it is thought that similar effects (landforms, structural patterns, etc.) are generated by different combinations of causative processes (Schumm, 1991). An example is the debate over the origin of the Moon's crater-like landforms first seen in telescopic views. Were they were caused by explosive volcanism or by meteor impacts? Planetary geology works at resolving such convergence issues though a combination of increased resolution (Zimbelman, 2001) and the study of terrestrial features that serve as analogs to the extraterrestrial features (Mutch, 1979). Instead of an equifinality of "craters" being formed by two different kinds of processes, terrestrial analog studies eventually indicated that there are actually different kinds of craters, each corresponding to their respective causal processes.

Thus, as long recognized by planetary geologists, "…understanding and interpretation of features on other planetary surfaces is most effectively approached through analogs from earth…" (Sharp, 1980, p. 231). "[A] planet's landforms are compared with those of the Earth, whose origin is known, or with features that have been experimentally produced" (Carr, 1984, p. 3). That the importance of analogy is so stressed by geologists (see, e.g., Mutch, 1972, p. 59–62; Mutch, 1979; Schumm, 1991; Chapman, 2007) indicates the need for a more in-depth consideration of its methodology in terms of both strengths and weaknesses.

It is unfortunate that space limitations for modern scientific papers do not generally permit a full exposition of how geologists use analogical reasoning. Instead, papers commonly make only

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brief statements as to similarity or resemblance among the phenomena that are compared. The lack of methodological treatment can lead to misunderstanding, particularly among those planetary scientists who might have little or no practical field experience with geology, and whose acquaintance with the subject might be limited to reading scientific papers or observing highly time-constrained presentations at professional meetings that emphasize research results rather than methodology.

The following example from a recent geology-oriented review paper on the fluvial history of Mars (Carr, 2012, p. 2024) is more comprehensive than most:

> Large flood channels or outflow channels are the characteristic fluvial features of the late Hesperian era…They have low sinuosity, smoothly curving walls and most contain teardrop-shaped islands around which flow has diverged and converged. On the channel floors are a range of bedforms, including longitudinal striae, cataracts, plucked zones and inner channels. *In toto*, they are remarkably similar to large terrestrial flood features, such as the Channeled Scabland of eastern Washington State in the USA…the consensus is that the channels were cut by water based on the strong resemblance to terrestrial flood features, on the availability of water as indicated by other indications of hydrological activity such as the valley networks, and on geophysical modeling of channel formation.…

Several elements in the above argument (I could probably have found thousands of other examples) illustrate points which are further elaborated below. Note that reference is made to a great many specific properties, held in common between Martian outflow channels and the catastrophic terrestrial flood channels of the Channeled Scabland (for a more complete compilation of these see Baker and Milton, 1974; Baker and Nummedal, 1978; Baker, 1973, 1978, 1982, 1985, 2009a, 2009b; Baker et al., 1992). The similarity among these properties for the two landscapes, the one rather newly discovered on Mars and the other well known from geological studies on Earth, is then used to make an inference as to the causative processed for the Martian channels.

2. Role of analogies in planetary geology

All science relies upon the use of analogy (Hess, 1966), where "analogy" implies similarity among like features of two otherwise different things. Models and computer simulations are more logically exact analogies, in which attributes presumed to be fundamental to the two things being compared (attributes such a basic physics or mathematical structure) are incorporated into a simplified system that can then be compared (via testing) via their correspondence to the "real world." Geologists commonly use logically less exact forms of analogy, but geological analogies take advantage of natural regularities that allow direct comparisons between "real world" entities, such that a newly discovered phenomenon can be compared to phenomena already known. In this way insights gained from the comparison contribute to further investigation into the cause of the unknown phenomenon. What the geologist gives up in logical exactness through the use of analogy is, in a sense, compensated for by a more direct connection to the natural phenomenon of interest, unfiltered by the presumptions necessary to define a simplifying "system" that is necessary for mathematical formulation. Moreover, geological analogies serve not much to provide definitive explanations as to provide a source for hypotheses that move geological research into productive lines of inquiry.

How analogy functions in geological reasoning was described more than a century ago by Grove Karl Gilbert. Like his contemporary commentator on geological methodology, T.C. Chamberlin (see, e.g., Chamberlin, 1890, 1904), Gilbert held that the central concern for a geological investigator of natural phenomena, as distinguished from the concerns of a theorist (Gilbert, 1886, p. 286), lay in the formulation of hypotheses. Although he recognized that hypothesis generation was partly a subjective matter, a quality that led many 20th century philosophers to dismiss it from methodological concern and instead to emphasize the methodologies of theorists, particularly in physicists, Gilbert (1886, p. 287, 1896, p. 2), nevertheless, held hypothesis generation to be the central methodological issue for geology. Moreover, he proposed that geological hypotheses are always invented through analogy, or, as he stated it (Gilbert, 1896, p. 12), "…that tentative explanations are always founded on accepted explanations of similar phenomena."

Gilbert (1896, p. 12–13) further noted that hypothesis generation by analogy carried with it the following requirement, "…fertility of [hypothesis] invention implies a wide and varied knowledge of the causes of things, and the understanding of Nature in her varied aspects is an essential part of the intellectual equipment of the investigator." The latter involves the ability to recognize how facts can grouped, "…in accordance with their conspicuous common characters" (Gilbert, 1886, p. 285), a methodology that he labeled "empiric classification" and which he considered to be equivalent to establishing superficial relationships among phenomena by inductive inference. This is an important point to which I will later return: analogical reasoning in geology involves two components, one that is inductive and leads to a kind of classification that derives from an immense amount of experience with the types of phenomena under investigation, and a second component that makes the leap to hypothesis generation, a leap that Gilbert (1896, p. 1) was willing to term, "a 'scientific guess'…unless the title 'guess' carries with it something of disrespect…"

In his most explicit statement on geological hypothesis generation via analogy, Gilbert (1886, p. 287) presents the inference as a logical proportion with the object of inferring causes (which he terms "antecedents" to phenomena), as follows:

> Given a phenomenon, A, whose antecedent we seek. First we ransack the memory for some different phenomenon, B, which has one or more features in common with A, and whose antecedent we know. Then we pass by analogy from the antecedent of B, to the hypothetical antecedent of A, solving the analogic proportion—as B is to A, so is the antecedent of B to the antecedent of A.

In applying Gilbert's logical proportion to a planetary problem an investigator might initially identify some class of phenomena, A (say, for example, an complex assemblage of fluvial-like landforms on Titan), for which the investigator is seeking understanding for the workings of formative processes that generated those features. The investigator would then seek another phenomenon B (a similar complex of landforms or landscape elsewhere), which (1) has key features in common with A and (2) has formative generating processes (causes) that the investigator truly knows. Unlike the newly discovered geological phenomena on Titan or other planetary surfaces, geological phenomena on Earth are much more likely to have both their key features and their causes truly known, and thus they become the best candidates to serve as phenomenon B in Gilbert's logical proportion. Further following Gilbert's methodology, then, if A and B are indeed similar, then the known causes of B (in this case, the terrestrial fluvial landscapes analogous to those on Titan) will allow the investigator to infer, i.e., to formulate a fruitful working hypothesis for, the possible or likely causes of A (the fluvial-like landform complex on Titan). Thus, the sharing of key features between terrestrial analogs and