Geological reasoning: Geology as an interpretive and historical science

Robert Frodeman *Department of Geological Sciences* and *Department of Philosophy, University of Colorado, Boulder, Colorado 80301*

ABSTRACT

The standard account of the reasoning process within geology views it as lacking a distinctive methodology of its own. Rather, geology is described as a derivative science, relying on the logical techniques exemplified by physics. I argue that this account is inadequate and skews our understanding of both geology and the scientific process in general. Far from simply taking up and applying the logical techniques of physics, geological reasoning has developed its own distinctive set of logical procedures.

I begin with a review of contemporary philosophy of science as it relates to geology. I then discuss the two distinctive features of geological reasoning, which are its nature as (1) an interpretive and (2) a historical science. I conclude that geological reasoning offers us the best model of the type of reasoning necessary for confronting the type of problems we are likely to face in the 21st century.

INTRODUCTION

Contemporary philosophy has not recognized geology as a fertile ground for reflection; today, one finds no "philosophy of geology" as one does a philosophy of physics and of biology. With the slight exception of the plate tectonics revolution, the two main schools of contemporary philosophy, Analytic and Continental, have ignored geology. They have assumed (few thought to argue the point) that an examination of geology was unnecessary for understanding the nature of science.[1]

Nothing better exemplifies philosophy's neglect of geology than the striking lack of attention given to the concept of geologic time. The discovery of "deep" or geologic time equals in importance the much more widely acknowledged Copernican Revolution in our conception of space.[2] But despite the prominence of the concept of time within contemporary (especially Continental) philosophy, philosophers have ignored the decisive role played by Hutton and Werner in reshaping our sense of time.[3]

This neglect may be explained by the generally held assumption that geology is a derivative science.[4] Geological reasoning has been thought to consist of a few rules of thumb (e.g., uniformity, superposition) guiding the use of mathematics and the application of the laws of chemistry and physics to geologic phenomena. Geology was also seen as having a host of problems that undercut its claims to knowledge: incompleteness of data, because of the gaps in and the poor resolution of the stratigraphic record; the lack of experimental control that is possible in the laboratory-based sciences; and the great spans of time required for geologic processes to take place, making direct observation difficult or impossible.

These factors have made geology seem to be a less-than-ideal candidate for philosophic consideration. In fact, the philosophy of science has traditionally viewed physics (namely, classical mechanics) as the paradigmatic science. Physics was the first science to establish itself on a firm footing, exemplifying the true nature of science as certain, precise, and predictive knowledge of the world. Since the 17th century, all other sciences (and philosophy) have been judged in terms of how well they meet these standards.[5]

Physics also fulfilled the demand that scientific knowledge be analytically derived. This is the belief, originating with Descartes, that objects and processes are understood by breaking them down into their simplest parts.[6] A "synthetic" science such as geology was thought to resolve itself into its constituents of physics and chemistry. Important here too was the belief that science constituted a unified subject, distinguished by one universally applicable methodology. By describing this single logical procedure one would have a general account that with a few modifications would be sufficient for all the sciences.

Most of the thinking on the nature of geological reasoning has come from within the geologic community itself. While limited in amount, and too often neglected, there exists an important body of work beginning with essays dating from the classic era of geology (e.g., Gilbert 1886; Chamberlin, 1890), when the connection between natural science and philosophy was much more explicit in the minds of scientists. Recent work in this area ranges from reflections on the methodology underlying a particular field of geology (e.g., Anderton, 1985) to more synoptic accounts of geological reasoning (Albritton, 1963; Schumm, 1991; Ager, 1993). In their own class are the writings of Stephen Jay Gould, whose work often bridges the gap between geology and the humanities and who may be the only geologist widely known outside the field.[7] Finally, there are two texts that explicitly focus on the task of giving a full-fledged philosophy of geology: Kitts (1977) and Von Engelhardt and Zimmerman (1988).

This work has made real and lasting contributions to our understanding of geology and science in general. But most of this work is characterized by two qualities. First, it largely accepts the description of geology as a derivative science. Second, for historical and cultural reasons that I will discuss below, philosophically inclined geologists have usually turned to only one of the two major traditions of contemporary philosophy—Analytic Philosophy—for help in describing their science.

I believe that the received view of geology as outlined above is mistaken. My interest as a philosopher is in challenging the assumption that geology is merely applied and imprecise physics, vainly attempting to achieve the latter's degree of resolution and predictability. Rather, I believe that the challenges and difficulties inherent to geological reasoning have prompted geologists to develop

[1]For footnotes 1–26, refer to the Endnotes between the text and References Cited near the end of this paper.

GSA Bulletin; August 1995; v. 107; no. 8; p. 960–968.

a variety of reasoning techniques that are quite similar to some of those described and used within Continental Philosophy.

My claim, then, is that geological reasoning consists of a combination of logical procedures. Some of these it shares with the experimental sciences, while others are more typical of the humanities in general and Continental Philosophy in particular. This combination of techniques is not utterly unique to geology; in fact, I would argue that such a combination is to one degree or another present in most types of thinking, scientific or otherwise. But I claim that this combination is especially characteristic of geological reasoning. If this view is correct, then the "physics envy" that geology sometimes seems to suffer from (i.e., the sense of inferiority concerning the status of geology as compared with other, "harder" sciences) is misplaced.

The rest of this essay explains and develops these claims. I begin with a brief review of the philosophy of science in the 20th century. This section provides the background necessary for understanding the standard claims concerning the nature of geological reasoning as well as the position I will be staking out. In the next two sections I turn to a description of the two most distinctive features of geological reasoning: its nature as a hermeneutic (i.e., interpretive) and a historical science. I conclude that geological reasoning does indeed embody a distinctive methodology within the sciences, and one which offers a better overall model than does physics for understanding the nature of reasoning within the sciences and within everyday life.[8]

This essay is a synthetic work, bringing together ideas from a number of different authors and traditions. Its overall goal is political, in the sense that I hope it encourages conversation between intellectual communities who have much to say to one another, but who too often are estranged. For much of what follows I make no claim to originality. Rather, my claim is that the question of how geologists (and scientists in general) actually reason is of real importance and that it has not been given the attention it deserves. The dangers of an unrealistic understanding of the nature and limits of science are exemplified by the putative "failure" of the U.S. National Acid Precipitation Project, which was arguably a failure of expectations rather than of science (Herrick and Jamieson, in press).

THE PHILOSOPHY OF SCIENCE IN THE 20TH CENTURY

One prominent geologist has described the relationship between geology and philosophy as follows: ". . . earth scientists do not find philosophical discussions of their field very interesting. In fact, many scientists treat the philosophy of science with 'exasperated contempt.'" (Schumm, 1991, p. 5). It is nonetheless true that self-understanding in the sciences, including geology, is derived in part from what philosophers have told science about itself. This description—science's own understanding of the nature of science—is now significantly different from the account of science that has recently been developed within both Analytic and Continental philosophy of science. Many scientists, busy with their own work, are only vaguely aware that the philosophy of science has been in turmoil since the mid-1970s. Although these changes are far from complete, the beginnings of a new consensus are discernible.[9]

To appreciate the nature of this new consensus, and what it means for our understanding of the science of geology, we must first review the status quo to which it is a response. During the 20th century, Western philosophy has consisted of two main schools of thought, Analytic and Continental. The fundamental difference between these two approaches has turned on their attitude toward the nature and scope of scientific knowledge. At their most basic, the original claims of Analytic Philosophy (ca. 1940) can be reduced to two: (1) all knowledge available to humans is exclusively derived through the method employed by science, and (2) the scientific method itself consists of an identifiable procedure of inductive and deductive logic sharply distinguished from other types of thought (i.e., other philosophic or literary techniques such as traditional metaphysics, phenomenology, or literary criticism).

Early Analytic philosophers such as Russell (1914), Carnap (1937), and Reichenbach (1928, 1958) developed a powerful characterization of the scientific method. Their conclusions may be summarized by the following three claims. First, the scientific method is **objective**. This means that the discovery of scientific truth can and must be separate from any personal, ethical/political, or metaphysical commitments. This is the basis of the celebrated fact/value distinction, which holds that the facts discovered by the scientist are quite distinct from whatever values he or she might hold. Personal or cultural values must not enter into the scientific reasoning process. A closely related point was the insistence that one must distinguish between the "logic of discovery" and the "logic of explanation." Identifying the particular social or psychological processes responsible for the scientist's insights was the job of the social scientist. The philosopher of science was only interested in the logical procedures that justified a scientific claim.

Second, the scientific method is **empirical**. Science is built upon a rigorous distinction between observations (which again were understood, at least ideally, as being factual and unequivocal) and theory. Facts themselves were not theory-dependent; observation was thought to be a matter of "taking a good look." The distinction between statements that describe and statements that evaluate was viewed as unproblematic.

Third, the scientific method constitutes an epistemological monism. Science was thought to consist of an single, identifiable set of logical procedures applicable to all fields of study. This reduction of all knowledge to one kind of knowledge proceeded in two steps, summarized by the terms "scientism" and "reductionism." Scientism is the belief that the scientific method provides us with the only reliable way to know. Reductionism is the further claim that it is possible to reduce all sciences to one science, physics.

It is important to note that the original research program of Analytic Philosophy, known as Logical Positivism, was challenged from within Analytic Philosophy by the early 1950s. Authors such as Quine (1953), Goodman (1951), and Popper (1953) raised fundamental questions concerning many of the points mentioned above. But for our purposes the crucial point is this: these debates stayed "in-house" in the sense that the basic orientation of Analytic Philosophy remained intact until at least the mid-1970s. Thus, while the exact status of scientific knowledge became more problematic, the general assumption that science (i.e., physics) was the model for knowing was not seriously questioned. Similarly, the degree of objectivity of scientific knowledge may have been unclear, but science was still thought of as essentially value-free in comparison with ethical or political issues. Finally, while the positivist belief in the strict reducibility of all knowledge to physics was abandoned, the belief in the existence of one uniform method for all the sciences was still generally held to.[10]

Thus—and this bears emphasis—while at the "cutting-edge" of Analytic Philosophy, these assumptions were to some degree being questioned, and the received wisdom—within the philosophic community and for others such as those within the scientific community—retained a fundamentally positivistic orientation. Our basic story concerning the nature of science came to be questioned only with the Kuhnian revolution.[11]

The claims of Continental Philosophy—the other main school of contemporary philosophy—concerning science can also be summarized in two points: (1) whereas science offers us a powerful tool for the discovery of truth, science is not the only, or even necessarily the best way that humans come to know reality, and (2) the existence of "the" scientific method (understood as above) is a myth. Science has neither the priority in the discovery of truth, nor the unity and cohesiveness of one identifiable method, nor the distance from ethical, epistemological, and metaphysical commitments that Analytic Philosophy claims it has. Thus, Continental Philosophy's basic orientation (since Hegel, ca. 1806) comes from its attempt to define the scope and limits of scientific knowledge as well as to identify what other ways we have for discovering truth. The 200 year history of Continental Philosophy can be seen as a series of attempts to invent or define other ways of knowing (e.g., dialectics, phenomenology, hermeneutics, existentialism).

Initially, Analytic Philosophy and Continental Philosophy engaged in a common debate on the nature of knowledge, but by the mid-20th century an informal division of labor had taken place. Analytic Philosophy focused on the intricacies of the philosophy of science. It understood philosophy as being ancillary to science, codifying and making explicit the logic of science that scientists already practiced, as well as deflating the claims of other pseudo-scientific and non-scientific modes of knowing. For its part, Continental Philosophy mostly ceded the analysis of science to Analytic Philosophy. Its main interest in science was not in scientific methodology per se, but in identifying what science left out in its "one dimensional" (Marcuse, 1964) approach to knowledge and experience. Continental Philosophy focused its attention on those types of experience not amenable to the scientific method: art, culture, subjectivity, and the force of the irrational in our lives. Continental Philosophy insisted that these areas were not truly understandable through the scientific method.

Thus, as a first approximation, it is accurate to say that Analytic Philosophy became that part of philosophy concerned with the natural world, while Continental Philosophy concerned itself with those questions relating to our cultural and personal life. One result of this division was that Continental Philosophy (with its pluralist attitude toward the question of how we know) did not use its conceptual tools to describe the nature of reasoning in the various sciences, particularly the natural sciences. Another was that what most scientists came to know as philosophy was the tradition and assumptions of Analytic Philosophy, particularly in the guise of Logical Posivitism.

This division of philosophy has begun to change only during the past few years. The single most important cause of its breakdown has been the influence of Thomas Kuhn (1970).[12] Trained as a physicist before turning to the history and philosophy of science, Kuhn shook the foundations of Analytic philosophy of science. Kuhn undermined each of the assumptions described above, arguing persuasively that the history of science is not simply the story of unequivocal progress. Rather, conceptual revolutions in science are often the result of abandoning one set of questions or assumptions for another.

Kuhn argued that there is often no common measure for comparing different accounts of a given set of phenomena. Each account may be irreducible to any other, the differences in description being the result of the different types of questions asked, the different types of criteria used, and the different goals of the research. This claim entailed that knowledge, rather than being value free, cannot be separated from human interests. What is called scientific truth now may depend as much on our needs and desires as on any unequivocal or objective set of criteria.[13]

For instance, epistemological and pragmatic values can be in competition. If our criteria for understanding is predictive control, we may decide to tolerate theoretical inconsistencies. If, on the other hand, our paramount goal is rational consistency, we may set aside the question of prediction or pragmatic control. More overtly political decisions can also affect what seems to be an "objective" process: if the *energy crisis* is defined as a problem of supply ("we need more oil"), we will find a different set of facts and a different range of possible solutions than if it is defined as a problem of demand ("we need to conserve"). Kuhn thus made it possible to imagine a plurality of scientific approaches to a given problem, each with its own particular strength or virtue.

The irony is that while Kuhn undercut the main body of assumptions of Analytic Philosophy, raising issues from a perspective more typical of Continental Philosophy, he has been placed traditionally (if not always comfortably) within the framework of Analytic Philosophy. Conversely, Continental Philosophy itself (with a few exceptions) still has not examined scientific knowledge with the tools at its disposal.[14] My project here is to use the approach and concepts of the Continental tradition to describe what is distinctive about the theory and practice of geology.

GEOLOGY AS A HERMENEUTIC SCIENCE

The two distinctive characteristics of reasoning in the earth sciences that I will discuss in the following sections are geology's nature as a **hermeneutic** (interpretive) and as a **historical** science.

The term *hermeneutics* means theory of interpretation; hermeneutics is the art or science of interpreting texts. A text (by which is meant, typically, a literary work) is a system of signs, the meaning of which is not apparent but must be deciphered. This deciphering takes place through assigning differing types or degrees of significance to the various elements making up the text. The status of this deciphered meaning has been the source of some dispute; in the 19th century it was claimed that, when properly applied to a text, hermeneutic technique resulted in knowledge as objective as that of the natural sciences. In the 20th century, however, hermeneutics has claimed that the deciphering of meaning always involves the subtle interplay of what is "objectively" there in the text with what the reader brings to the text in terms of presuppositions and expectations. In effect, hermeneutics rejects the claim that facts can ever be completely independent of theory.[15]

Hermeneutics originated in the early 19th century as a means of reconciling contradictory statements in the Bible through a systematic interpretation of its various claims. In the early 20th century hermeneutics was applied to historical (including legal) documents to help discover the original meaning of the author. Hermeneutics was (and still is) used when a theologian argues which parts of the Bible to read literally and which metaphorically, and what weight to give to each part. Similarly, the literary scholar proceeds hermeneutically when she claims that a narrator's comments are to be taken seriously rather than ironically, as does the psychologist when he interprets a slip of the tongue to be significant or not.

In the 20th century, however, hermeneutics has moved from being a rather straightforward methodology of the Geistwissenshaften (i.e., the humanities; literally, the "spiritual sciences") to a more general account of knowing. Hermeneutic philosophers such as Heidegger (1927, 1962) have argued that all human understanding (including the natural sciences, although this was not his main concern) is fundamentally interpretive. Not only books, but the entire world was a "text" to be read; in no field does one find completely objective data or information "purely given." How we **perceive** the object is always shaped (though not completely determined; objects assert their own independence) by how we **conceive** and **act on** the object with the sets of tools, concepts, expectations, and values that we bring to the object.

When we apply this point to geology, this becomes the claim: geologic understanding is best understood as a hermeneutic process. The geologist assigns different values to various aspects of the outcrop, judging which characteristics or patterns in the rock are significant and which are not. Examining an outcrop is not simply a matter of "taking a good look." Rather, the geologist picks up on the clues of past events and processes in a way analogous to how the physician interprets the signs of illness or the detective builds a circumstantial case against a defendant.

Most of us are familiar with the hermeneutical aspect of understanding, the shift in our awareness of an object when we approach it with a fresh set of concepts or expectations. This happens regularly to students when they are first introduced to a subject. While in college I enrolled in an introductory course in art history. Lacking previous instruction in art, but armed with my prejudices, I approached the course with a sceptical attitude. Each class began with lights dimmed, as the professor showed a slide of a famous work of art. She then gave us a few minutes to consider it on our own. Typically—especially at the beginning of the semester—I saw nothing of any significance in the slide, and I could not understand why it was considered a great work of art. Yet it became a truism that after a few minutes of lecture, during which the professor introduced a set of concepts for "reading" the artwork, the piece would undergo the most striking change. Aided by these concepts, I now saw the piece as if for the first time. Like art history, with which it shares a strongly visual component, geology is an especially hermeneutic science: the outcrop typically means nothing to the uninitiated until the geologist introduces concepts for "seeing" the rock.[16]

This shift from the belief that data are objectively given to the scientific observer, to the view that all human knowledge is fundamentally hermeneutic—that our perceptions are always to some degree structured by our conceptions—has portentious implications for our understanding of both the nature of scientific knowledge and the relationship between science and society at large. In sum, it makes the question of human interests—personal, ethical/political, and metaphysical—intrinsic rather than external to the work of science. The theoretic assumptions that the scientist brings to his or her work—what counts as significant, what work is worth doing—structure to one degree or another all that is examined, seen, and reported.

Contemporary hermeneutics claims that this mix of percept and concept is fundamental to all human understanding. All the world is a text; all understanding is, in the words of Merleau-Ponty (1960; contained in Johnson, 1993), a combination of "eye and mind." The exact degree of "objectivity" (to use a word that no longer serves us well) in our accounts of the world is open to argument; but the belief in the scientist as the purely objective observer is no longer viable. But this does not entail (except on the most radical reading) that all of our accounts of the world, scienctific or otherwise, are entirely subjective. The truths of science, as with most things, fall somewhere in the middle.

Philosophic hermeneutics does not purport to offer a strict methodology analogous to how Analytic Philosophy understood the scientific method to operate. The role of hermeneutics is not to develop a set of rules for proper interpretation, but to clarify the general conditions under which understanding takes place. There are, however, three basic concepts of hermeneutics which are worth outlining, for they play a fundamental role in any hermeneutic process, including geological reasoning. These are the hermeneutic circle, the forestructures of understanding, and the historical nature of knowledge.[17]

The founding concept of hermeneutics is known as the hermeneutic circle. Heidegger (1927, 1962) argued that understanding is fundamentally circular; when we strive to comprehend something, the meaning of its parts is understood from its relationship to the whole, while our conception of the whole is constructed from an understanding of its parts. So, for instance, the meaning of this sentence is conceived in terms of the entire paper, and vice versa. More to the point, our understanding of an outcrop is based on our understanding of the individual beds, which are in turn made sense of in terms of their relationship to the entire outcrop. This back-and-forth process of reasoning operates on all levels; wholes at one level of analysis become parts at another. Thus, our understanding of a region is based on our interpretation of the individual outcrops in that region, and vice versa; and our interpretation of an individual bed within an outcrop is based on our understanding of the sediments and structures that make up that bed, and vice versa. On a still more complex level, our overall comprehension of the Cenomanian–Turonian boundary event is determined through an intricate weighing of the various types of evidence (e.g., lithology, macro- and micropaleontology, and geochemistry). This overall interpretation is then used to evaluate the status of the individual pieces of evidence.

Such circular reasoning is usually viewed as a vice, a logical fallacy to be avoided at all cost. But Heidegger argued that this type of circularity is not only unavoidable, it is actually, if properly handled, the means by which understanding progresses. Understanding begins when we develop a first conception of the overall meaning of the object. Without this initial conception we would have no criterion for making sense of the object. This provisional interpretation is called into question when we are "pulled up short" by details in the object (or text) that do not jibe with our overall conception. This forces us to revise our interpretation of the whole as well as our interpretation of the other particulars. Comprehension deepens in this circular fashion, as we revise our conception of the whole by the new meaning suggested by the parts, and our understanding of the parts by our new understanding of the whole.

One consequence of the hermeneutic circle is that it puts to rest the claim that it is possible to approach an object in a neutral manner, open to all possibilities. Rather, we always come to our object of study with a set of prejudgments: an idea of what the problem is, what type of information we are looking for, and what will count as an answer. What keeps these prejudgments from slipping into dogmatism and prejudice—that is, what makes science as distinguished from ideology still possible—is the fact that they are not "blind." We remain open to correction, allowing the text or object to instruct us and suggest new meanings and approaches.

This brings us to a second point revelant to geological reasoning. Heidegger identified three types of prejudgments or "fore-structures" that we bring to every situation. First are our preconceptions, the ideas and theories that we rely on when thinking about an object. Concepts are not neutral tools; rather, they allow us to get hold of an object in a particular way, opening up certain possibilities and encouraging certain ways of understanding while closing off others. Thus, for instance, to approach the Western Cordillera with concepts like *ophiolite complexes* and *accretionary terranes* will affect what one sees in the field. These preconceptions include our initial definition of the object to be investigated as well as the criteria used to identify which facts are significant and which are not.

Second is our foresight, our idea of the presumed goal of our inquiry and our sense of what will count as an answer. Heidegger argues that without some vague (and, one hopes, open-minded) sense of what type of answer we are looking for, we would not recognize it when we find it. Again, this implies that the values of the scientist—what he or she hopes to find or achieve—are intrinsic rather than extrinsic to the scientific enterprize.

Third, we always approach the object of study with a set of practices we have in advance, what Heidegger called our "fore-having." These are the culturally acquired set of implements, skills, and institutions that one brings to the object of study. In field geology, implements include the geologist's hammer, 0.10% HCl, a measuring tape, a hand lens, a Jacob's staff, pencil and paper, and a Brunton compass. At the lab there is another set of tools: display trays, rock saws, computers, acids, a light microscope, and a scanning electron microscope.

As with our preconceptions, the nature of these tools shape the type of information collected; without a light microscope one could not study the structure of nannoplankton; without a mass spectrometer isotopic geochemistry would be impossible. With a different set of tools other data would be gathered that would give us a different (possibly a quite different) sense of the object. This concept of "fore-having" also includes the various skills that the geologist learns in the field or the laboratory: map-making, measuring strike and dip, preparing samples, cleaning and preserving specimens, and even how to properly wield a hammer to split a rock without destroying fossils. Included here as well are the mathematical and statistical techniques used in research.

Just as crucial, however, and often discounted, are the social and political structures of science: professors, various graduate students, research groups, professional associations, and other types of groups. Science is a social as well as a mental activity, dependent on the existence of a community of scholars. The work of science proceeds through having colleagues to bounce ideas off of, professional societies and journals to define "hot" topics and favored lines of research, and graduate students for help with running labs and collecting samples.[18]

The third basic concept of hermeneutics, applicable to geology and indeed to all the sciences, is the historical nature of human understanding. Here the claim (distinct from the argument of the next section) is that the particular prejudgments we start with have a lasting effect. It is often claimed that, no matter what assumptions or goals we begin with, the scientific method will eventually bring us to the same final understanding of objective reality. Hermeneutics argues otherwise: our original goals and assumptions result in certain facts being discovered rather than others, which in turn lead to new avenues of research and sets of facts. Any scientist can name areas of potential importance that do not get pursued because of the lack of time and resources or the lack of sufficient commitment on the part of the scientific community. As these decisions get multiplied over the decades the body of scientific knowledge comes to have a strongly historical component.

Heidegger's claims as they relate to science and especially to geology can be summarized in two theses. First, he rejects the view that data are purely given and that theories are totally objective constructions. Rather, science is seen as involving various types of values that are not only unavoidable but also necessary and productive to the discovery of truth. Second, science is not only something that one **thinks**; it is also something one **does**. Science is a social and historical activity structured to a significant degree by the scientist's skills and equipment, as well as by the institutional structures of the scientific field and the culture at large.

GEOLOGY AS A HISTORICAL SCIENCE

Hull (1976) identified four historical sciences: cosmology, geology, paleontology, and human history. A historical science is defined by the role that historical explanation plays in its work. While explanation within the historical sciences uses many of the tools common to all sciences (i.e., the deductive-nomological model of explanation, defined below), there remains a fundamental and distinctive difference in historical explanation. This difference as it relates to geology can be characterized in terms of three points: the limited role or relevance of laboratory experiments, resulting in geology's dependence on other types of reasoning; the problem of natural kinds (i.e., the question of defining the object of study within historical geology); and geology's nature as a narrative science.

Insofar as their work is based on laboratory experimentation, the experimental sciences (e.g., physics and chemistry) are essentially non-historical: the particularities of place and time play no significant role in the reasoning process. Work takes place in the lab, an ideal space where conditions can be controlled. Truth claims in these disciplines presuppose that other researchers can recreate the identical conditions of the initial experiment within their own laboratory. Thus, for a truth claim to count as scientific, a scientist in Oslo must be able to reproduce results identical to those of the original experimenter in Seattle. In this sense, time and history have no place in the experimental sciences.[19]

Of course, in another sense time and history are an inescapable part of every science; a chemical reaction takes time to complete, and every chemical reaction is historical in that it has some feature, no matter how insignificant, that distinguishes it from every other reaction. But our **interest** in chemical reactions typically is not in chronicling the specific historical conditions that affect a given reaction, but rather in abstracting a general or ideal truth about a given class of chemical reactions. Even the chemicals used are idealized, in that the supplies used by the chemist have been assayed for purity. A particular chemical reaction thus becomes merely an instance of a general law or principle.

In the historical sciences, in contrast, the specific causal circumstances surrounding the individual entity (what led up to it, and what its consequences were) are the main concern of the researcher.[20] In geology, the goal is not primarily to identify general laws, but rather to chronicle the particular events that occurred at a given location (at the outcrop, for the region, or for the entire planet). This means that hypotheses are not testable in the way they are in the experimental sciences. Although the geologist may be able to duplicate the laboratory conditions of another's experiment (e.g., studying the nature of deformation through experiments with play-doh), the relationship of these experiments to the particularities of Earth's history (e.g., the Idaho-Wyoming overthrust belt) remains uncertain.

The crucial point here is that the historical sciences are distinguished by a different set of criteria for **what counts as an explanation**. To borrow and adapt an example from Hull (1976), when we ask why someone has died, we are not satisfied with the appeal to the law of nature that all organisms die, true as that is; we are asking for an account of the particular circumstances surrounding that person's demise. Similarly, in geology we are largely interested in historical "individuals" (this outcrop, the Western Interior Seaway, the lifespan of a species) and their specific life history. It is possible to identify general laws in geology that have explanatory power—e.g., Walther's law—but the weight of our interest lies elsewhere. The central role played by the question of what counts as an explanation again highlights—and this is one of the main points of this essay—the impossibility of separating knowledge from human interests.[21]

Faced with the difficulties of modeling the geologic past because of problems of temporal and spatial scale and the singularity and complexity of geologic events, the geologist turns to other types of explanation, such as reasoning by analogy, the method of hypothesis, and eliminative induction. A thorough analysis of the strengths and weaknesses of these and other argumentative techniques is the subject of another paper.[22] Here I limit myself to a discussion of the role of arguments from analogy in geological reasoning.

Arguments from analogy play a crucial role in the historical sciences; the assumption of analogy between past and present is what makes it possible to treat these subjects as sciences at all, that is, as amenable to rational explanation. Just as claims within human history must assume that we can analogize from what we know of human motivations today to make sense of past actions, reasoning in historical geology is built upon the assumption that "the present is the key to the past"—that present-day geologic processes operate in a manner similar to those of the past.

Within geology the assumption of analogy between past and present has been given explicit recognition in the principle of uniformitarianism. Recent discussions of uniformity (Rudwick, 1976a; Berggren and Van Couvering, 1984; Gould, 1987) have described the confused way this principle has sometimes been used. Following Rudwick, Gould argues that geologists have at times conflated four different types of uniformity. The first two, the methodological claims of uniformity of law and process, are nothing more than geology's version of science's twin assumptions that nature is governed by lawlike behavior, and that we should not invent new or unknown causes until we have exhausted the ones we have. The second two, uniformity of rate (gradualism) and of state (i.e., that the Earth is in steady state, with no periods of significantly warmer climate, higher sea level, or more volcanic activity) make substantive claims about the Earth's history that have been largely rejected by the geological community.

The overall effect of Gould's account is deflationary; uniformitarianism becomes a rather common-sense principle embodying no peculiarly geological claims. By separating methodological from substantive uniformitarianism Gould empties the principle of any specifically geological meaning. He therefore arrives at a position identical to Nelson Goodman (1967), who concludes ". . . the Principle of Uniformity dissolves into a principle of simplicity that is not peculiar to geology but pervades all science." The nature of geological reasoning is again not different in principle from any other science.

But this reduction of uniformitarianism to the principle of simplicity leaves too much unexplained. The problem is that the present is too small a window into the past to provide the geologist with a full set of analogs. This is true in two senses. First, by rejecting the claims of uniformity of state, the geologic community is acknowledging that some of the depositional environments of the past (e.g., epeiric seas, Bretz floods) do not exist today; but, one can scarcely draw a strict analogy from a nonexistent contemporary environment. Second, there are inescapable disanalogies between our human experience of time and the expanses of geologic time. Thus, uniformity can never tell us how to adjust modern conditions to rocks that have been altered by diagenesis or other time-dependent factors. By traveling to the Caroina coast, we can see a burrower and the trail it leaves behind, but no process that we can observe today will tell us how this burrow will look after 100 million yr. Of course, we can attempt to model these differences in the lab or on a computer, but this ultimately only recapitulates our problem, for we cannot be certain of the parameters we set, nor can we run our model for geologic amounts of space or time.[23]

Physicists may, if they like, retest the gravitational constant at the beginning of each day; and historians of human culture have modern examples of revolution or mass hysteria to examine for comparison with records of the past. But geology (as well as the other historical sciences of paleontology and cosmology) is historical in a deeper sense; given the complexity of geologic events, our lack of experience of all geologic environments and of geologic spans of time, and our interest in the singularity of each event, geologists cannot simply project the present onto the past. Of course, the geologist is not entirely disarmed; the extrapolation from current rates of erosion to arguments concerning the time it takes a mountain range to be leveled provide us with some sense of things. This result via analogy is then compared with the results of other lines of reasoning, such as the method of hypothesis, where one "reasons back" from the existence of a feature to a hypothesized explanation consistent with the evidence at hand. But it is this sense of the overall coherence of a theory, rather than a simple correspondence between present and the past, that defines geologic reasoning.

There is a second aspect of the historical sciences that merits mention. Historical entities present a unique challenge as an object of study (cf. White, 1963; Hull, 1976, 1981). The issue is deceptively simple: How does one define the object of study? In other sciences, the objects of study appear as "natural kinds." The nucleus of an atom consists of neutrons and protons, the distinction between which seems written into the very structure of the atom. But historical entities do not spring into being fully formed, nor do they remain unchanged to the time of their destruction. The researcher in the historical sciences is faced with identifying the set of characteristics that define an individual entity, and with deciding how much change can occur before we have a new entity rather than simply a modification of the old. Thus, in considering the Colorado Plateau as a historical entity, we are faced with defining its nature and extent and at what point in the geologic past it became an identifiable and discrete "individual." Similarly, the paleontologist must decide when a fossil in an evolving lineage constitutes a new species.

White (1963) and Hull (1976) argue that it is the concept of a central subject that allows the construction of a historical explanation. A central subject is the organizational identity that ties together disparate facts and incidents. In human history a wide variety of entities can function as the principle of organization: individuals or social groups, corporate entities (companies, nations), even ideas (the idea of progress). In geology there is a similar range of historical individuals: the Laramide orogeny, the Cretaceous Western Interior seaway, the Bridge Creek Limestone, and the species *Mytiloides mytiloides* are examples of central subjects.

Central subjects provide the coherence necessary for an intelligible narrative to be constructed out of a seemingly disconnected set of objects or events. But since these subjects are not natural kinds, they can be defined in different ways. This means that geologists may come to define different objects of study and thus develop different interpretations of what at first appeared to be an unproblematic subject of investigation. A simple example of this is the different interpretations that can result from dividing a stratigraphic section into different units according to different criteria, for example, by physical characteristics (shale, standstone, etc.) or in terms of genetically associated relationships (transgressive-regressive sequences, etc.).

Finally, the historical sciences are distinguished by the decisive role of narrative logic in their explanations. Narrative logic is a type of understanding where details are made sense of in terms of the overall structure of a story. Unlike the experimental sciences, where predictions are made by combining general laws with a description of initial conditions (the deductive-nomological model), the historical sciences are not primarily in the business of making predictions. Historical narratives do not explain an event by subsuming it under a generalization, but rather by integrating it into an organized whole. Thus an outcrop does not "make sense" until it contributes to and is a component of an overall story.[24]

Narrative is often dismissed as a vague and literary form of knowledge lacking in the logical rigor and evidential support appropriate to the "hard" sciences.[25] But this begs the question of whether narrative has a logic or rigor of its own and whether scientific explanation itself is dependent on narrative logic. Continental philosophers have argued that these two types of knowing are integrally related to and complement one another. In *Time and Narrative*, Paul Ricoeur (1985; see also Ricoeur, 1987) claims that narrative is our most basic way of making sense of experience. Scientific explanation is based on narrative in the sense that, through telling a story, we create a context that defines and gives meaning to our research and data. Thus, the examination of the Greenland Ice Sheet Project ice core is explained and justified by our concern with global climate change, and the study of black shales is funded because of the larger "story" it fits within (e.g., its relevance to hydrocarbon exploration). In historical geology, scientific reasoning is placed within the context of a narrative of a locality or region of Earth (or the entire Earth). It is characteristic of their discipline that geologists tell a story that gives a larger context and meaning to their research—a skill that all scientists may be called upon to master in an era when science faces a struggle for funding.

CONCLUSION AND DISCUSSION

In this account of geological reasoning I have argued that while geology depends in part on the classic deductive-nomological method of the experimental sciences, geology is also distinguished by a discrete set of logical procedures. Viewing geology from the perspective of physics skews our understanding of geological reasoning. Geology only partially lives up to the classic model of scientific reasoning. But rather than viewing geology as somehow a lesser or derivative science, I have argued that geological reasoning provides an outstanding model of another type of scientific reasoning based in the techniques of hermeneutics and those of the historical sciences. Geology is a preeminent example of a synthetic science, combining a variety of logical techniques in the solution of its problems. The geologist exemplifies Levi-Strauss's (1966) *bricoleur*, the thinker whose intellectual toolbox contains a variety of tools that he or she selects as appropriate to the job at hand.

There are two important consequences of these claims. First, scientific reasoning in general and geological reasoning in particular are complex operations. It stands to reason that a greater degree of self-consciousness about the nature of the reasoning process can help the scientist in his or her work. Second, the goal of this essay is not only to identify the different logical procedures operating within the sciences, but also to point the way to a more relevant and vibrant notion of reasoning within the sciences and our culture in general.

Scientific reasoning is too often caricatured as a cookbook method that provides us with infallible answers. This misrepresentation damages both science and culture when the inevitable disappointment sets in. The scientific reasoning process typified by geology offers an account of reasoning more applicable to the uncertainties and complexities of our lives. We are seldom in possession of all the data we would like for making a decision, and it is not always clear that the data we possess are unbiased or objective. We are forced to fill in the gaps in our knowledge with interpretation and reasonable assumptions that we hope will be subsequently confirmed. Thus, the methods of a hermeneutic and historical science better mirror the complexities we face as historical beings.

It is likely that this type of reasoning will become more crucial in the next century. Many of the issues we face (global warming, and various types of risk and resource assessment) are by their nature both scientific and ethical, with the scientific aspect of the problem deeply influenced by interpretation and uncertainty. Yucca Mountain may symbolize the type of problems we will face, as we ask how to scientifically evaluate the viability of this proposed site for the permanent disposal of nuclear waste, while including in our decision-making the rights of future generations to a safe environment.[26] In an uncertain world, where we are constantly asked to compare incommeasurables (present needs versus obligations to the future; quantitative and qualitative factors) geology provides another, and I believe better, model for reasoning than has our traditional model of the sciences.

ACKNOWLEDGMENTS

Thanks to Erle G. Kauffman, whose support has been vital; to Chris Buczinsky and Dugald Owen, who have discussed these issues with me on many occasions; and to Stephen Jay Gould, Victor R. Baker, and an anonymous reviewer, whose comments saved this paper from numerous errors and omissions.

ENDNOTES

1. Philosophic consideration of the revolution in plate tectonics can be found in Giere (1988). Typical conclusions by philosophers concerning the status of geology are those of Nelson Goodman (1967, p. 99) ("In conclusion, then, the Principle of Uniformity dissolves into the principle of simplicity that is not peculiar to geology but pervades all science and even daily life.") and Richard A. Watson (1969, p. 488) ("Geology is a science just like other sciences, for example physics or chemistry."). Although not concerned with the question of the status of geology as a science, John Sallis's *Stone* (1994) is a recent exception to the general neglect of geology within philosophy.

2. For accounts of the Copernican Revolution in our conception of space, cf. Koyre (1957) and Kuhn (1957). The phrase "deep time" for geologic spans of time was coined by John McPhee (cf. McPhee, 1981).

3. Time has been the central issue within Continental Philosophy since Hegel, ca. 1806. One measure of this is the importance of Heidegger's *Being and Time* (1927, 1962), the most influential work in Continental Philosophy in the 20th century. But despite the prominence of historicist approaches to epistemology within contemporary Continental Philosophy, to my knowledge no attention has been given to the concept of geologic time. Awareness of the cultural or philosophic implications of the revolution in geologic time is more typical of the history of ideas than of philosophy (cf. Gillispie, 1959; Toulmin and Goodfield, 1965; Goldman, 1982).

4. In addition to the authors cited in Endnote 1, cf. Schumm (1991) ("It is generally agreed that geology is a derivative science.") and Bucher (1941).

5. My account here is a gloss upon a story that is obviously quite complex. One might well reply that today, when the philosophy of science considers physics the paradigm science, it is physics *qua* relativity theory and quantum mechanics rather than classical mechanics that are being reflected on. My claim rests upon the distinction between the state of knowledge within a given field, and the representation of that field outside the realm of specialists. Possibly the most remarkable thing about the new physics is how little impact it has had on our culture's epistemological views, whether within the intellectual community or with the public at large. Physics *qua* classical mechanics still provides us with our basic model for understanding the nature of knowledge. Consider, for instance, how introductory physics is taught in U.S. colleges to this day. At my own institution (University of Colorado), introductory physics begins with several weeks on classical mechanics. Quantum mechanics is not taught until the third semester of physics, long after the vast majority of students have stopped taking physics classes. Thus, while physicists struggle to integrate quantum physics into an overall picture of reality, the received wisdom has continued to be that classical mechanics still provides the model for understanding the nature of science, and indeed of knowledge in general.

6. For the classic statement of this claim, cf. Descartes's *Rules for the direction of the mind* (1964; written in 1627, first published in 1701).

7. Gould (1987, 1989) is especially relevant to the points I will be making. Cf. Gould (1989, p. 277–291) for an argument that parallels much of what follows.

8. In the interests of full disclosure, it should be noted that my own limited training in geology (I am presently completing a Masters in geology) is in biostratigraphy. Someone with another type of training (e.g., geochemistry) might well put more emphasis on the causal aspect of geological reasoning. Nevertheless, I believe it is possible to set these differences to one side in recognition of the fact that what is crucial about geological reasoning is (1) its historical and interpretive components, and (2) how these components tie into the undeniably causal element of geology.

9. What follows summarizes a complex and controversial history. The complexity in part derives from the fact that we are simultaneously considering discussions within the community of philosophers of science, as well as the impact of these discussions on those within the scientific community. For other accounts see Hacking (1983), Rajchman and West (1985), Rorty (1979), Giere (1988), Rouse (1987), and Kitchner (1993). It should be emphasized that the new view of science that I argue for in terms of Continental Philosophy, could also, with some modifications, be made in terms of recent Analytic philosophy of science. Much (though far from all) of the latter (e.g., see Kitcher, 1993) is keenly aware of the hermeneutic nature of science. Thus, my account of Analytic philosophy of science becomes inadequate and even to some extent unfair when we consider its work during the past decade. But these new developments have not made much of an impression upon the scientific community's understanding of the nature of the scientific method. I make these points through Continental Philosophy first because of my own greater familiarity with this tradition. But more importantly, I believe that Continental Philosophy has greater conceptual resources for describing the nature of geology and of the sciences in general.

10. Feyerabend was an important early exception to the belief in the unity of the scientific method. Cf. Feyerabend (1965).

11. This positivist orientation remains important within Analytic philosophy of science to this day. Recent work in the fields of cognitive science, artifical intelligence, and evolutionary epistemology still share these general assumptions. Cf. Giere (1988), Kornblith (1985), Churchland (1986), and Thagard (1992).

12. While Kuhn's work was the single most important impetus for the changes that I will discuss, he is to a certain degree a symbolic figure representative of a larger movement within the philosophy of science. Other important authors include Toulmin and Goodfield (1965), Hanson (1959), and Feyerabend (1965, 1977).

13. This is a "strong" interpretation of Kuhn's work (1962). Kuhn has vacillated on the degree to which the results of science are shaped by social values. In his later essays (cf. Kuhn, 1977) he has retreated from some the claims made in *The structure of scientific revolutions*. This has not stopped others from following the earlier, more radical Kuhn. Rouse (1987) speaks of there being two Kuhns, one more radical and the other more conventional in his attitude toward this question.

14. Exceptions to the general neglect of the philosophy of science by Continental Philosophy include the work of Heelan (1983), Kockelmans and Kisiel (1970), and Rouse (1987).

15. For an introductory text in hermeneutics, see Bleicher (1980). Gadamer (1975) offers a more sophisticated historical account.

16. On the visual nature of the science of geology, see Martin J. S. Rudwick (1976b).

17. The argument that follows depends on an entire tradition of hermeneutic philosophy, the most important source being Heidegger (1927, 1962).

18. To adequately consider this topic would require another paper. Since Latour and Woolgar's *Laboratory life: The social construction of scientific fact* (1981), there has been a great deal of work on the social and political influences on scientific research. Important sources in this area include Pickering (1992), Traweek (1988), and Knorr Cetina (1981).

19. Cf. Collins and Pinch (1993) for an account of the extraordinary difficulties in duplicating experiments often faced by researchers in the experimental sciences.

20. I do not mean to deny the fact that there is another aspect of geological research that emphasizes laws and processes (i.e., physical geology). But my focus is on what is distinctive about geology when compared with other sciences, that is, the perspective and interests of historical geology.

21. The classic statement of this point is made in Habermas's *Knowledge and human interests* (1971).

22. The first chapter of Rachel Laudan's *From mineralogy to geology* (1987) discusses 19th century accounts of the various logical procedures used by scientists (procedures, I would argue, that are still constantly employed today). Stanley Schum (1991) offers a succinct discussion of the distinctive aspects of geological reasoning in *To interpret the Earth: Ten ways to be wrong*. Schumm groups his ten ways into three categories: problems of scale and place, of cause and process, and of system response.

23. Derek V. Ager (1993, p. 81) makes a similar point in *The nature of the stratigraphical record* when he asks, "Is the present a long enough key to penetrate the deep lock of the past?"

24. Gould (1989, p. 280–291) also argues for the narrative nature of geology and the historical sciences in general.

25. There is a wide and varied literature on the question of narrative and the historical sciences. Cf. Carr (1986) for an excellent summary and a set of references.

26. For further discussion of this point, see Frodeman and Turner (1995).

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Manuscript Received by the Society July 18, 1994
Revised Manuscript Received December 21, 1994
Manuscript Accepted December 28, 1994

Printed in U.S.A.