The Role of Historical Science in Methodological Actualism

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This article examines the role of historical science in clarifying the causal structure of complex natural processes. I reject the pervasive view that historical science does not uncover natural regularities. To show why, I consider an important methodological distinction in geology between uniformitarianism and actualism; methodological actualism, the preferred method of geologists, often relies on historical reconstructions to test the stability of currently observed processes. I provide several case studies that illustrate this, including one that highlights how historical narratives can improve predictive models.

1. Introduction. Much of the small but burgeoning literature on historical science focuses on evidential reasoning patterns scientists use when reconstructing the past from traces and whether such methods are reliable. These accounts explore the unique epistemic challenges faced by historical scientists—degraded evidence, the inability to conduct new experiments or make direct observations—and how scientists succeed (or fail) to overcome such challenges. Addressing these challenges often involves delineating the boundaries of historical and experimental sciences and examining the methods used to justify different types of scientific claims.

Although there is disagreement about how (and to what extent) historical science diverges from other kinds of science, there is some consensus that the discovery of laws or stable regularities falls outside its scope. The assumed view is we extract knowledge of general causal relations from observing

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processes in the present and then use this knowledge to justify inferences about the past. This connects to an important debate in modern geology about the principle of uniformity or the idea that "the present is the key to the past."

I argue that this commonly accepted picture of the relationship between regularities and historical science is mistaken. Historical investigations often play an important and ineliminable role in advancing our knowledge of causal structure and stable regularities. When confronted with complex geological processes that occur over large regions of space and time, historical science acts as an experimental context to test the stability of currently observed regularities. As a result, historical investigations enhance our understanding of the complex causal webs that produce natural processes and help predict how such processes might evolve or shift in the future.

I begin with a discussion of the literature on historical science, arguing there is a general tendency to distinguish between investigations into the past and the search for regularities. I then turn to a long-standing discussion about uniformitarianism and actualism in geology and show that theoretical interpretations of actualism appear to suggest a similar division of labor between the discovery of regularities and inferences about the past. However, in practice, methodological actualism often requires using knowledge of the past to determine the stability of currently observed regularities. I illustrate this with several case studies, including one that highlights how explaining the past can shape predictions about the future.

2. The Irregularity of Historical Science

2.1. Cleland's Prototypical Historical Science. One account that draws a sharp line between reconstructing the past and gaining causal insight comes from Carol Cleland. On her view, differing temporal locations of scientists with respect to their objects of inquiry gives rise to different methods of science. Historical scientists—who are looking to explain traces found in the present by an appeal to events in the past—are in a different epistemic position than experimental scientists who seek out regularities that generate reliable predictions about the future. Cleland claims this difference arises from what Lewis named the "asymmetry of overdetermination" (1979).

According to the asymmetry of overdetermination (see fig. 1), events are epistemically underdetermined by their causes but epistemically overdetermined by their effects.[1] A complete causal description of an event requires

1. Cleland actually thinks the underdetermination of events by causes is both epistemic and metaphysical, whereas the overdetermination of causes by events is purely epistemic. I do not discuss this distinction here because it is irrelevant to the discussion at hand.

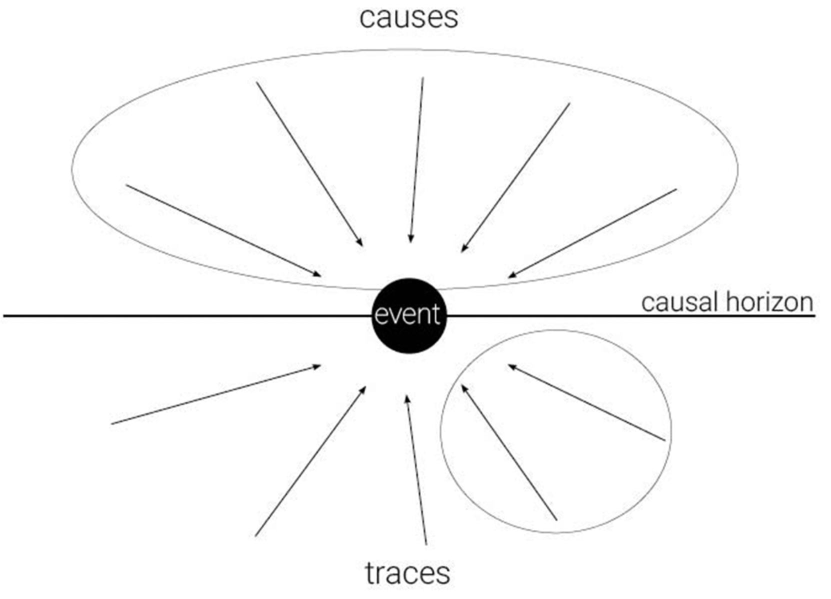

Figure 1. Asymmetry of overdetermination. While scientists need knowledge of all causal contributors in order to predict an event, they need only know some of the traces to infer the event happened.

knowledge of every causal factor that contributes to the event. For example, while throwing a baseball at a window may cause the window to break, there is no guarantee that the window will break (it will depend on the nature of the throw, the material that constitutes the window, if there is anything in the ball's path to divert it, etc.). Even if the ball does cause the window to break, the mere knowledge that it was thrown is not sufficient for knowledge that the window broke. Hence, events are underdetermined by their causes. In contrast, one need not observe every trace of an event in order to infer the event happened. Observing the broken window with the baseball on the floor surrounded by several shards of glass is convincing evidence that the baseball went through the window, even if we fail to locate every shard of glass. That the baseball broke the window is overdetermined by the numerous traces the event leaves.

The asymmetry of overdetermination, in conjunction with our epistemic position, provides the framework for scientific inquiry. Historical sciences exploit well-known regularities retroactively, using them to uncover explanations rather than make predictions. Determining such regularities lies beyond what I call the "causal horizon" and falls into the domain of experimental science, which aims to extract and codify the natural regularities used to make predictions about future events.[2] On Cleland's view, this is primarily done by performing a large number of controlled experiments to determine the stability of observed patterns. Experimental science delivers generalized information about causal structure, and historical science uses this information to reconstruct the past using inferences to the best explanation of currently observed traces.

Because predictions, on Cleland's view, are grounded in knowledge of laws and stable regularities, the discovery of which lies beyond the scope of historical science, historical science plays no role in improving our ability to predict events. An example Cleland uses to illustrate this phenomena is seismology: we are great at figuring out why earthquakes happened but unable to predict when they will happen (2011, 567).

To summarize, Cleland thinks historical sciences are unique because they investigate events retroactively, from effects to cause, and are therefore able to exploit the asymmetry of overdetermination in a way that predictive science cannot. However, these historical investigations rely on preexisting knowledge of causal relationships and stable regularities, which is the domain of experimental science.

2.2. Windelband and the Idiographic/Nomothetic Divide. Another way to draw a line between historical science and experimental science is the idiographic/nomothetic distinction coined by Wilhelm Windelband. In attempting to flesh out a new taxonomy for scientific disciplines, Windelband states: "In their quest for knowledge of reality, the empirical sciences either seek the general in the form of the law of nature or the particular in the form of the historically defined structure. . . . If I may be permitted to introduce some new technical terms, scientific thought is *nomothetic* in the former case and *idiographic* in the latter case" (1894/1980, 175). While Cleland emphasizes the differing temporal perspectives of scientific investigators, Windelband focuses on the narrative character of historical science. Nomothetic scientists are interested in general or law-like claims, while idiographic scientists reconstruct the way these laws play out in a particular series of events. He refers to the output of nomothetic science as "knowledge of laws," while idiographic science produces "knowledge of events" (180).

Windelband agrees idiographic science plays some role in understanding the causal structure of our world, but that role is limited to determining the concrete conditions in which laws are instantiated; historical science is critical for identifying the token causes of particular events, but knowledge of

2. Cleland divides historical science and experimental science by a time asymmetry. Interestingly, this time asymmetry also implies an asymmetry regarding the type of causal information that can be uncovered by historical science. Hence, I call this temporal division the "causal horizon."

general causal relationships is produced by nomothetic science. This general knowledge of regularities can then be combined with our knowledge of the past in order to produce a detailed causal explanation.

Although Windelband does not deny that knowledge of particular events is important, it is knowledge of laws that allows us to understand the structure of our world in a way that reveals how various interventions might affect it. "Knowledge of general laws always has the practical value of making possible both predictions of future states and a purposeful human intervention in the course of events" (Windelband 1894/1980, 180). Idiographic sciences, in contrast, give us historical context but do not enhance our ability to understand how various human interventions affect and shape future events. Like Cleland, Windelband denies that investigations into the past uncover general causal knowledge.

2.3. Challenges to the Distinction. There has been a fair amount of pushback to drawing rigorous distinctions between historical science and the search for stable regularities. However, even those who deny such a distinction exists say little about the role historical science plays in sharpening our understanding of the general causal structure of geological processes.

For example, Jeffares (2008) argues, contrary to Cleland, that historical scientists engage not only in experiments but also in the development and testing of regularities in order to secure their claims. His primary example is the research of Schick and Toth (1994), who were interested in confirming that the marks on particular bones were made by tools rather than animals. To do this, they conducted experiments on bones to see the differences between the marks left by hominid tools and the marks left by canines. According to Jeffares, this shows that historical scientists do not only investigate the past but also learn something about general processes and causal structure (namely, how the traces left from tools are different from the traces left by canines). He goes on to say that "the historical sciences are as interested in understanding the general causal structure of the world as much as any other science" and "the tools required to make claims about the past are the same as the tools required to make predictions about the future" (Jeffares 2008, 475).

Although Jeffares points toward a connection between historical science and the search for regularities, his general view is that theories play an important role in historical science. Of course, historical scientists may sometimes try to generate such theories—as Schick and Toth did—in order to make sense of historical traces. However, as Cleland is quick to point out, this is easily viewed as historical scientists practicing experimental science and applying it to historical claims, not historical science itself coming to bear on our understanding of stable regularities (2011, 566). Cleland reiterates the idea at work in Windelband: historical scientists occasionally investigate the regularities at work in a particular historical context, but this research involves controlled experiments on present processes and is not itself historical.

Derek Turner also resists drawing a clear line between historical and experimental science. He argues that scientific investigations into historical patterns, like the Lilliput effect, cannot be neatly categorized as either idiographic or nomothetic science (Turner 2014).[3] The Lilliput effect is the tendency of "animals living immediately after mass extinction events [to] have smaller body sizes than the animals living before" (498). Several different accounts have been offered for why this is the case. Turner claims that the investigation into which hypothesis explains the pattern goes beyond the bounds of idiographic science but falls short of pinpointing a stable regularity. After all, it might turn out that there is no stable regularity here and the change in body size is caused by different factors in different cases. Turner does not offer an account of how science does or ought to proceed in these contexts but suggests that there is important philosophical work to be done here.[4]

In summary, current accounts of historical science tend to at best mystify and at worst deny the relationship between reconstructions of the past and the discovery of stable regularities or laws of nature. This is a mistake; historical science plays a very important role in understanding the causal structure of complex natural processes and often leads to refining our predictions of future events. Before I explain precisely how this works, however, we must turn from the philosophical discussion of historical science to a long-standing theoretical debate in geology.

3. Uniformitarianism in Geology. The foundation of modern geology is the principle of uniformity, which states, in simple terms, *the present is the key to the past*. By studying current geological processes, we gain insight into the past and find natural explanations for why things are the way they are. While the origins of this idea are debated, most agree it was popularized by Charles Lyell, a geologist who, like James Hutton, made a rigorous attempt to explain the formation of earth's surface by appealing to processes observed in the present. He described his project as *Principles of Geology:*

3. Turner has long been a critic of the distinction (2007, 7–8). Turner even argues that narratives can be predictive if we assume things will continue on as they did in the past. However, this involves the problematic assumption that things always "continue on as they did" (115–16), also called substantive uniformitarianism, which I discuss at length in the next section.

4. It is worth noting that Currie (2018) has also pushed back on a strong divide between historical science and experimental science, largely because it results in a limited view of what counts as trace evidence and a failure to see the important role of dependencies between past events. However, he seems to follow Cleland and others in thinking that historical science exploits causal knowledge rather than contributes to it.

Being an Inquiry How Far the Former Changes of the Earth's Surface Are Referable to Causes Now in Operation (Lyell 1837). The term uniformitarian was coined by William Whewell, a reviewer of Lyell, who contrasted Lyell's view with *catastrophism*. "Have the changes which lead us from one geological state to another been, on a long average, uniform in their intensity, or have they consisted of epochs of paroxysmal and catastrophic action interposed between periods of relative tranquility? These two opinions will probably for some time divide the geological world into two sects, which may perhaps well be designated as the Uniformitarians and the Catastrophists" (Whewell 1832, 126).

In Lyell's time, many proponents of catastrophism assigned supernatural origins to the catastrophic events that formed the earth.[5] Contrary to this mystical approach, Lyell insisted that geological phenomena are produced by the persistent work of uniform processes. Where a catastrophist might claim that the Grand Canyon resulted from violent storms during the biblical flood, uniformitarians insist it was formed by consistent erosion from the Colorado River. Uniformitarianism is sometimes referred to as *actualism*, because it suggests that the only true causes are those actually (or currently) observable (Hooykaas 1963, 10).

Uniformitarianism offers a defense of geology as scientific: although geologists often study the past, the uniform nature of physical processes provides a framework in which scientists can infer from current states to previous states. We observe radioactive decay of ^{14}C. This knowledge about how ^{14}C decays allows us to infer the age of particular samples given the amount of ^{14}C they contain. This inference is justified because we assume the process we currently observe is uniform; it operated in the same way in the past as it does now.

Lyell succeeded in developing a modern geology that pursues empirical explanations rather than religious ones, but the thesis of uniformitarianism itself has undergone serious criticism from geologists for entirely natural reasons. One major disagreement has been terminological: precisely what do we mean by uniformitarianism? This is crucial because taken in its strongest form, which assumes that previous causes were the same not only in kind but also in energy, uniformitarianism is provably false (Hooykaas 1963, 1).

5. Although the historical catastrophism/uniformitarianism debate is often framed in terms of religious vs. secular approaches to geology (e.g., Gould 1965a), this is an oversimplification. For example, Cuvier argued for catastrophism on the grounds that some geologic changes appear to have been drastic and revolutionary, and "a slow cause cannot explain a fast effect" (Hooykaas 1963, 3). Additionally, most contemporary geologists would agree that the right approach involves a mix of uniformitarianism and catastrophism, given the geologic significance of events like volcanic eruptions or asteroid impacts.

George Gaylord Simpson discusses this issue in reference to William Farrand's strong formulation of uniformitarianism.

> Farrand expresses a common, probably the usual modern understanding of uniformitarianism as follows: "The geologists's concept that processes that acted on the earth in the past are the *same processes* that are operating today, on the *same scale* and at approximately the *same rates*." . . . But this principle also seems to be flatly contradicted by geological history. Some processes (those of vulcanism or glaciation for example) have evidently acted in the past on scales and at rates that cannot by any stretch be called "the same" or even "approximately the same" as those of today. Some past processes (such as those of Alpine nappe formation) are apparently not acting today, at least not in the form in which they did act. There are innumerable exceptions that disprove the rule. (Albritton 1963, 232)

Although many currently observable geological processes were at work in the past, evidence suggests these processes do not occur in a uniform or law-like manner throughout time. Consider, for example, the formation of glaciers. As snow accumulates over time, the lower layers of snow become increasingly compressed, forcing out the air and transforming the size and shape of the grains of snow. How long this process takes depends on a variety of factors, including the amount of snowfall and the temperature at the snowfall site. Moreover, during greenhouse periods, global temperatures are too warm for the advancing of glaciers, so the process of glaciation does not really occur at all. In this sense, glacier formation—although it is a natural process and one that we think explains a variety of geological data—fails the conditions of strong uniformitarianism.

One response to this issue, by Stephen J. Gould, is that the original doctrine of uniformitarianism encodes two different theses: substantive uniformitarianism and methodological uniformitarianism. He associates the strong version of uniformitarianism with substantive uniformitarianism, which he decries as obviously false, but also points to a weaker, more tenable version of the view that he calls methodological uniformitarianism. "The present is a key either because we can extrapolate observed rates or conditions to past times (leading to substantive uniformitarianism) or because we establish our natural laws by observing present processes and then extrapolate the laws (leading to methodological uniformitarianism). Both postulate uniformity but, according to whether this be a uniformity of rates of the material processes themselves or of the abstracted laws by which they operate, two distinct concepts arise" (Gould 1965a, 226).

According to Gould, we can eradicate the problematic aspects of uniformitarianism by restricting its scope to natural laws; this is the methodological assumption he takes to be at the heart of modern geology. He points out that this methodological assumption, in conjunction with simplicity—the assumption "that we will postulate no unnecessary theoretical processes as long as observable ones can successfully explain past changes"—justifies explanations of the past by only "presently-observable causes" (Gould 1965a, 227).

Gould argues that methodological uniformitarianism is by no means novel to geology—it is essentially the principle of induction. But given that the use of induction is an essential part of science, why point to uniformitarianism as a "special feature" of geology? "Thus we see that methodological uniformitarianism amounts to an affirmation of induction and simplicity. But since these principles belong to the modern definition of empirical science in general, uniformitarianism is subsumed under the general statement: 'geology is a science'" (Gould 1965a, 227). If Gould is correct, then the principle of uniformity—what was thought to be the mark of distinction of the geological sciences—is either false (substantive uniformitarianism) or true but trivial (methodological uniformitarianism).

I think Gould's analysis of uniformitarianism is a bit too quick, and there is important space between substantive and methodological uniformitarianism. In a reply to his original paper, Gould defines the terms as follows:

a. A testable proposition asserting constancy of rates of change or material conditions through time—substantive uniformitarianism.
b. An undemonstrable, though entirely necessary, procedural assumption asserting spatial and temporal invariance of laws describing the operation of nature's processes—methodological uniformitarianism.

(Gould 1965b, 919)

Notice that the assumptions differ in two ways. One is a substantive assumption, and the other is methodological. But that is not the only difference. In the first case, what is taken to be constant is rates of change or material conditions through time—in other words, we assume the constancy of natural processes. In the latter case, our methodology assumes the constancy of the "laws describing the operation" of these processes. But this suggests four different possibilities (see table 1).

Gould only discusses substantive uniformitarianism and methodological actualism (although he calls the latter methodological uniformitarianism, for

TABLE 1. Varieties of Uniformitarianism

	Constancy of Material Processes	Constancy of Laws
Substantive	Substantive uniformitarianism	Substantive actualism
Methodological	Methodological uniformitarianism	Methodological actualism

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the sake of clarity I call it methodological actualism), but his definitions leave room for substantive actualism and methodological uniformitarianism. I take the primary question of this article to be methodological, so I set aside the substantive forms of uniformitarianism and actualism and instead focus on the following methodological approaches:

> **Methodological Uniformitarianism**. An undemonstrable, although entirely necessary, procedural assumption asserting constancy of rates of change or material conditions through time.

> **Methodological Actualism**. An undemonstrable, although entirely necessary, procedural assumption asserting spatial and temporal invariance of laws describing the operation of nature's processes.

The difference between methodological uniformitarianism and actualism, then, is whether scientific practice assumes the invariance of observed rates of change or laws describing the operation of nature's processes.[6] But one might worry, especially in the case of complex geological processes that occur very slowly, how we extrapolate the laws describing the operation of nature's processes from empirically observed regularities that include material rates of change. Gould seems to think the answer is simple: do not include rates of change in the formulation of the "law." This approach is reflected in the example he offers of a law of nature: "a distinctive type of modern polished bedrock surface is always produced by glacial action" (Gould 1965b, 920).

On Gould's view, geological laws are extrapolated from observation by simple induction: whenever we find a particular type of polished rock in nature, we find glacial action nearby. This permits us to infer from the existence of such rocks in places where no glaciers are present that there were glaciers there at some point in the past. But how can we be certain that this law does not secretly encode uniformitarian assumptions? Perhaps glacial action is the only process we have seen produce polished rocks on an observable timescale, but there are other natural forms of erosion that produce a similar effect when allowed to operate for thousands of years.

To further clarify the problem, consider the following analogy. Suppose that scientists run a number of experiments tracking the rate at which freely falling objects accelerate toward earth. After analyzing the data from numerous experiments, they come to the following empirical generalization:

6. Substantive actualism, however, is simply the claim that natural laws are spatially and temporally invariant. However, if we take laws of nature to be, by definition, invariant, this claim is true but trivial. What is not trivial, as I will show, is the methodological application of this truth in geology.

(**A**) The acceleration due to gravity is 9.8 m/s^2.

We might think such a generalization is justified by induction: we consistently observe freely falling objects accelerating at this rate, so we infer they always fall at this rate. However, suppose a scientist measures the rate of a freely falling object at the North Pole. She will observe that the ball falls a bit more quickly than 9.8 m/s^2. Similarly, the further away she moves from the surface of the planet, the smaller the acceleration due to gravity will be.

According to Gould's method, the way we avoid mistakenly including assumptions about the uniformity of rates of change in natural processes is to just "drop out" the part of the generalization that refers to the rate of change. In the case of acceleration due to gravity, this suggests we can extract a law of nature from the aforementioned empirical generalization if we just ignore the specific rate at which objects fall. Therefore, from our observations we can infer the following law of nature:

(**B**) Because of gravity, objects accelerate toward earth.

This new "law" is more general than our first empirical generalization: it will be true at the poles and high altitudes where the acceleration due to gravity is not 9.8 m/s^2. However, B still fails to meet a traditional definition of a law of nature—a universal, exceptionless truth that is invariant throughout space and time. After all, if we are deep in space, objects no longer accelerate toward earth. If we find ourselves on the surface of the moon, objects will accelerate toward the moon rather than earth.[7]

Even if we remove the specific rate of change from our empirical generalization, we do not immediately arrive at a law of nature. However, perhaps we do not need generalizations as strong as laws to perform the explanatory or predictive work of regularities in science. Several philosophers have argued that regularities in science fall on a continuum—while laws are perfectly stable regularities, less stable regularities are also useful and important elements of scientific theories.[8] In particular, Mitchell (1997) argues that in

7. The fluctuations in gravitational acceleration can be explained by Newton's universal law of gravitation, $F = G(m_1 m_2/r^2)$, which states that the gravitational force between two objects (F) is equal to the gravitational constant (G) times the product of their masses (m_1 and m_2) over the square of the distance between their centers of gravity (r). It is worth noting that this generalization does contain information about rates of change; it just does so in a way that is generally applicable.

8. For examples of stability accounts, see Mitchell (1997), Lange et al. (2000), and Woodward (2000). Others, such as Nancy Cartwright, suggest it is better to handle exceptions by attaching particular conditions to laws, creating ceteris paribus laws (Cartwright and McMullin 1984). A full analysis of these various approaches falls outside the scope of this article, but for more information, see Reutlinger et al. (2019).

biological sciences, the "laws" described always encode various contingencies but are still useful elements of biological explanations and prediction. Nevertheless, to properly apply these less than ideal regularities, we must know something about the conditions under which they break down. As Mitchell points out, "To know when to rely on a generalization that does not apply to all space and time we need to know when it will apply, and this can be decided only from knowing under what specific conditions it has applied before and the caveats its mode and manner of representation warrant for explanatory and predictive applications" (2000, 259).

To avoid the misuse of stable regularities, we need to know the contexts in which they apply. In some cases, like the case of gravitational acceleration, boundaries on the domain of observed regularities are fixed by theory. Newton's universal law of gravitation states that the closer two masses are, the greater the intensity of the gravitational force between them. To practice methodological actualism rather than methodological uniformitarianism in the case of gravitational acceleration, then, means to assume the invariance of Newton's universal law rather than A. But what are scientists to do in cases in which the laws that govern the observed processes are unknown? How might they determine the conditions of application for observed regularities?

One common way to discover said conditions is by what Cleland calls a controlled experiment—change one or more of the conditions under which the regularity was observed and then test it again. But complex geological processes often happen over such a large region of space or occur so slowly it is impossible to "reconstruct" them in a laboratory or control for an individual factor. For example, suppose a scientist wants to know how the melting of glaciers that cover earth's surface will affect oceanic circulation. A host of pragmatic difficulties make it impossible to generate a physical experiment to test models of current oceanic circulation under such stress. One alternative to physical experiments commonly used in geoscience is a simulated experiment run on a computer model of the earth. However, these numerical models rely on our best empirical generalizations of oceanic circulation, so they encode precisely the uniformitarian assumptions under investigation. How, then, might a scientist test whether oceanic circulation radically changes when the glacier cover is decreased by half?

The answer to such questions often lies, rather surprisingly, in historical science. Historical reconstructions can serve as an analog to controlled experiments in the development of geological understanding.[9] Historical reconstructions reveal how currently observed processes behaved under radically different conditions. While it is true that scientists do not control the

9. The German geologist Karl von Hoff held a similiar view. For a discussion of this, see Hooykaas (1963, 6–7).

differences in conditions, as is possible in (idealized) laboratory experiments, examining the behavior of these processes in historical contexts helps determine their stability and reveals how they alter under different geological conditions. As a result, historical reconstructions directly contribute to scientific knowledge of regularities and causal relationships. Contra Cleland, Windelband, and Gould, the process of extrapolating causal structure is by no means distinct from investigations into the past.

4. Applied Methodological Actualism. In this section, I show how historical science determines the limits of observed regularities and offers insight into the complex causal structure of earth's climate. First I discuss how scientists extract temperature records from ice cores and argue that historical science reveals the uniformitarian assumptions often hidden in extrapolations from observable data. I reiterate this point with a case from dendroclimatology, in which historical science revealed the sensitivity of fir growth to various environmental factors. Finally, I discuss how attempts to explain historical anomalies in the temperature record led to the discovery that oceanic circulation is sensitive to mode switches.

4.1. Defrosting the Temperature Record. A good deal of reliable evidence for global climate change comes from investigations into the cryosphere, particularly from the study of glaciers. Glaciology is a historical science insofar as it reconstructs glacier formation, although glaciologists also investigate current issues such as contemporary glacier dynamics. The discipline draws on a wide range of other scientific specializations such as geophysics, geochemistry, climatology, and oceanography.

One reason glaciology serves as a reliable gateway to the past is that glaciers are made of ice, and cold temperatures severely impede the ordinary degradation of scientific evidence. Glaciers contain frozen samples of rock and soil, as well as occasional fossils. However, some of the most significant information we have gleaned from studying glaciers comes from the stable oxygen isotopes that partially constitute them.

Ice is made of water, and water is a compound of hydrogen and oxygen. Oxygen atoms come in a variety of weights, or isotopes, depending on the number of neutrons they contain. Paleoclimatologists are especially interested in stable isotopes because, unlike radioisotopes that decay and emit radiation, they remain unchanged indefinitely. Moreover, the ratio of heavy to light isotopes in a given sample of ice encodes a great deal of information about weather and climate. In a glacier, the different isotopic ratios constituting different layers of ice can unlock critical information about the climate in which these ice sheets were formed.

Although there are a variety of stable isotopes studied in paleoclimatology, for this discussion I will focus on the analysis of oxygen isotopes, specifically ^{16}O (the light isotope) and ^{18}O (the heavy isotope).[10] While ^{16}O is by far the most common isotope (over 10,000 times more common than ^{18}O), samples of water contain instances of both isotopes. For any given sample of water, there is a specific ratio of $^{18}O/^{16}O$ known as the heavy to light ratio, or

$$\delta^{18}O. \tag{1}$$

Lighter isotopes are more likely to evaporate into the air, and heavier isotopes are more likely to fall during precipitation because of gravitational effects. Weather cycles and precipitation affect the ratios of heavy to light isotopes in different bodies of water, a process known as fractionation.

Because glaciers are composed of water that once evaporated and became snowfall, they tend to have fewer heavy isotopes than standard ocean water. But what accounts for the difference in $\delta^{18}O$ from one snowfall to another depends largely on changes in temperature. Water evaporates and then condenses as it rises and reaches cooler temperatures. Eventually, some of this condensed water is released as precipitation. When the air in the atmosphere of earth is cooler, precipitation begins occurring at lower latitudes, and most of the heavy isotopes are released before reaching the arctic glaciers. This accounts for especially high levels of light isotopes in sheets of ice and also gives information as to how temperatures varied over long periods of time.

Determining how to extract a temperature record from a $\delta^{18}O$ record is no small task, for a variety of reasons.[11] To start with, there is no model that rigorously captures the relationship between changes in $\delta^{18}O$, precipitation patterns, and temperature. In other words, while scientists are quite sure that temperature drives fractionation, it is difficult to identify the specific contribution made by temperature from a plurality of causes (like the source location of the evaporated water, temperature changes at the source location, weather anomalies, etc.). A first approach to this problem is to use modern-day calibration techniques to determine a correlation pattern between changes in $\delta^{18}O$ and the temperature at the site of snowfall. For example, scientists might first focus on the past 100 years of snowfall in a particular glacier for which we have recorded temperatures, calibrate the relationship between temperature and isotope ratios, and use that model to interpret isotope ratios that occurred during earlier periods for which we have no temperature record.

At first glance, this application of modern calibration techniques seems to fit Gould's description of methodological actualism and reinforce the distinction between the search for laws and the reconstruction of historical

10. While there is a third stable isotope of oxygen, ^{17}O, it is not commonly used in stable isotope analysis because it is not very abundant, so I will not discuss it here.

11. I am indebted to Richard Alley for his reconstruction of this history, which I follow closely in this section (Alley 2010).

narratives. Scientists observe present processes, extract from them a general, law-like relationship between temperature and $\delta^{18}O$, and apply this relation to data about the past in order to reconstruct the temperature record. But this seemingly law-like relationship encodes uniformitarian assumptions: the rate of change that occurs in fractionation is assumed to be constant. This opens the use of modern calibrations to actualist criticism. As I stated previously, multiple factors (including anomalies) can affect the ratios of isotopes in the ice sheets. How can we rule out these other contributing factors when projecting the calibration over tens of thousands of years? How do we restrict our assumptions to merely natural laws?

Fortunately, $\delta^{18}O$ is not the only paleothermometer used by glaciologists. Borehole temperatures have also proved useful in constructing a past temperature record. These measurements come from drilling deep into rock beneath the glaciers and measuring the temperature of the air at different depths. The laws of heat diffusion help construct a strong signal of the general pattern of temperature changes in the past on the basis of the temperatures at different depths. Borehole measurements are more actualistic, given that they rely primarily on well-established laws of physics. However, while the borehole signal clearly captures increases and decreases in temperature, it does not provide a clear timescale according to which these changes happened (Alley 2010, 1097).[12]

An ingenious breakthrough was made by Paterson and Clarke (1978). Rather than calibrate paleothermometers to modern conditions and apply the results to data about the past, the Paterson-Clarke technique calibrates two historical measurements to each other. That is, it couples together $\delta^{18}O$ and borehole-depth measurements to determine the relationship between isotopic records and temperature and in doing so tailors the correlation to the particular history of the glacier at hand.

Essentially, the technique employs retrodictive curve-fitting. Scientists obtain measurements of the borehole temperatures relative to depth and the isotopic record relative to age. The borehole temperature/depth measurements are used to form a curve. Next, scientists "hypothesize" that there is a linear relationship between the isotopic ice record and the curve created by the borehole temperature measurements. A linear equation can be constructed using the isotopic record. This equation is then used to "predict" the borehole temperature profile. Chances are it will not fit perfectly the first time around,

12. A helpful analogy for thinking about borehole temperature-depth profiles, which was suggested to me by Richard Alley, is the use of temperature measurements to determine whether a turkey is fully cooked. That is, we know that the heat will move from the outside of the turkey to the inside, and our knowledge of how this diffusion works gives us a sense of how long the turkey has been in the oven by measuring its temperature at different locations (pers. comm., May 17, 2018).

but through a variety of optimization procedures a fit is eventually found. That the equation fits the curve serves as confirmation that the temperature record created by inverting the $\delta^{18}O$ ice record is accurate.

From a philosophical perspective, the Paterson-Clarke technique is especially interesting. While the technique posits a law-like relationship between $\delta^{18}O$ and temperature, calibrating the relationship to a borehole temperature/depth profile fits the relationship to the history of an individual glacier. Therefore, any particular success of the Paterson-Clarke technique does not provide a fully generalizable model of the relationship between $\delta^{18}O$ and temperature. However, applications of the technique were successful enough to reveal huge errors in the attempts to use modern calibrations to construct a historical record. This reconstruction revealed that the calibration extracted by observations of present processes was too uniformitarian.[13]

Reflecting on the Paterson-Clarke technique reveals the complex evolution of geological understanding. Although scientists began with "induction as usual"—they observed the present correlation between temperature and fractionation, extrapolated a generalized version of this relationship, and assumed it was invariant over time—this methodology proved too uniformitarian. The correlation they extrapolated was not a law of nature but a regularity that assumed the invariance of rates of change. However, by reconstructing actualistic historical narratives of how temperature and fractionation patterns correlate in particular glaciers, scientists were able to recognize the instability of this currently observed regularity and begin to recognize conditions under which it ceases to apply. Just as a controlled experiment allows us to see that the acceleration due to gravity changes at the North Pole, the Paterson-Clarke technique shows that the observed relationship between $\delta^{18}O$ and temperature is not invariant over time.

4.2. Recovering the Fir Signal. Another example of the important role historical science plays in determining the stability of present geological

13. This last point is clearly shown by the results obtained in various applications of the technique. The first application, made by Paterson and Clarke at the Devon glaciers in Canada, was unsuccessful because of interference in the borehole temperature profile that occurred from melting and refreezing. This led Paterson and Clarke to recommend the technique be applied in a place with negligible melting (Alley 2010, 1097). When the technique was later applied in Greenland, a place where melting is certainly negligible, very clean results were obtained (Cuffey et al. 1992, 1994, 1995; Johnsen et al. 1995). In fact, the results were so effective, they revealed large errors in previous attempts to interpret the isotopic ratios according to modern calibrations (Alley 2010, 1097). Despite success in Greenland, scientists have not yet been able to cleanly apply these techniques to high altitude, low latitude glaciers in the tropics because of worries about melting.

processes comes from the field of dendroclimatology—the use of tree rings to reconstruct information about past climates. Trees form rings annually, reflecting their growth over a year. Because the growth of the tree (and therefore the size of the rings) is correlated with conditions such as precipitation, tree ring analysis can be used to reconstruct information about climate conditions in the deep past. Of course, a variety of factors can influence tree growth, so it can be tricky to isolate the primary causes of variation of growth in a particular tree (or set of trees). We can construct calibrations that correlate tree ring growth with observed precipitation, for example, but it is often historical reconstructions that help us determine how stable these correlations are and what additional factors may affect tree growth.

For example, Wilson, Luckman, and Esper (2005) created a dendroclimatic reconstruction of the precipitation in the Lower Bavarian Forest spanning 500 years. In this region there are a number of historic buildings that were constructed with local wood. Researchers overlapped ring data from this historical wood with living trees to form an extended ring-width record. The samples involved in the study came from Norway spruce (*Picea abies* (L.) Karst) and silver fir (*Abies alba* Mill.). There was concern as to whether the fir data would be useful, because several studies of fir in present conditions suggest its climate signal is weak and not strongly related to precipitation (Wilson and Elling 2004, 19–20).

However, the study revealed something surprising: from 1480 to 1899, the fir and spruce strongly correlate with each other and report the same precipitation pattern, suggesting the precipitation signal in the fir is as strong as the signal in the spruce. The signal of the fir begins to decline when measured against calibrations that emphasize data after 1930. Wilson and Elling (2004) argue this weakening of the fir signal is because of an increase of SO_2 emissions in the from local refineries and power plants during the 1960s. The spruce signal also weakens during this time, but not as strongly as the fir signal, suggesting that the fir growth is more sensitive to the effects of emissions than spruce is.

Once again, the instability of an observed regularity was revealed by historical science. Observations of present day fir growth suggest that it is not strongly correlated with precipitation; scientists supposed this was a general truth. However, a reconstruction of the historical relationship between fir growth and precipitation revealed the relationship is not invariant—by examining the growth/precipitation relationship under radically different historical conditions we gain insight about the conditions under which observed regularities apply. The fir case also suggests that a particular condition—the presence or absence of SO_2 emissions—plays an important role in the correlation between fir growth and precipitation. Here again historical science plays the role of an experiment, providing important information about the limits of observed regularities.

This picture stands in stark contrast to Gould's gloss on methodological actualism—that geologists simply extrapolate abstract laws and rely on their stability. Scientists certainly extrapolate calibrations on the basis of observed data. But scientists also recognize that these extrapolations, while a necessary part of the scientific process, are usually not laws. Rather ironically, then, the assumption that only the laws of nature are stable often means, in practice, assuming that generalizations we extrapolate from the data are not stable and working to determine the conditions under which they break down.

These cases also reveal that, contrary to the picture painted by Cleland and Windelband, investigations into the past often extend and revise our knowledge about the stability of observed regularities, helping to disentangle the complex set of factors that affect natural processes. Because historical science gives us insight concerning the stability (and instability) of natural processes over large timescales, it also sheds light on how current processes may alter in the future. In the next section, I discuss the introduction and verification of Walter C. Broecker's hypothesis that there are alternating modes of operation in the Atlantic meridional overturning circulation (AMOC). This case shows that historical scientists do not always exploit known causal relationships to explain the past but sometimes discover novel causal relationships that suggest surprising possible effects in the future.

5. Broecker's Hypothesis. The historical temperature record from Greenland glaciers reveals abrupt changes in temperature have occurred multiple times (see fig. 2). Two key examples are the 8.2 kya event and the abrupt cooling into and warming out of the Younger Dryas, which happened between roughly 16.8 and 14.7 kya BP (Alley 2007, 243).[14] These events seem to interrupt slower, more general warming and cooling trends.

To explain these jumps in temperature, Broecker hypothesized that the deep oceanic currents that circulate heat throughout the North Atlantic may have more than one stable mode of operation. Unlike surface currents, which are primarily driven by winds, deep water currents are impelled by density gradients. Because cold water is denser than warm water and saltwater is more dense than freshwater, colder, saltier patches of water from the north tend to flow southward, while warmer patches of water travel from low latitudes to higher latitudes. This results in thermohaline circulation (also called AMOC) and greatly affects the European region, resulting in milder winters for those closer to the ocean.

Because these deep currents are driven by density gradients, an influx of freshwater from the melting of glaciers will shift the density distribution and

14. There is also the Little Ice Age, which is more recent but was milder than these earlier events.

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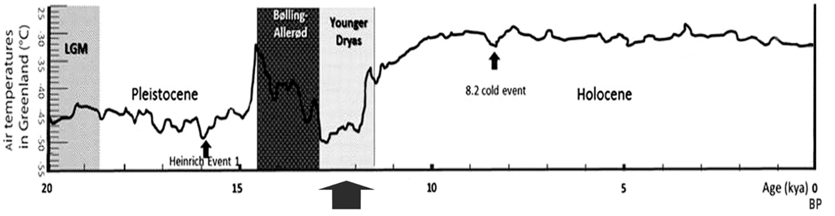

Figure 2. Evolution of temperature in the postglacial period according to Greenland ice cores (Younger Dryas). (Source: Platt et al. 2017.) Color version available as an online enhancement.

presumably change the pattern of circulation in AMOC. Before Broecker's hypothesis, scientists assumed this sort of change would occur smoothly and slowly; AMOC was suspected to slow at a rate calibrated to the rate of freshwater release from glacier melt. However, Broecker suggested the abrupt jumps in the historical temperature record may have been caused by sudden shutdowns or pattern changes in thermohaline circulation. If we think of thermohaline circulation operating like a train on a track, Broecker claimed there may be alternate tracks onto which AMOC can switch or that the entire train may come to a sudden halt rather than a smooth slow down. Were this to happen, it would result in an immediate and major climate event, as all of the heat transferred to the north from the south (and the cooling effects on the south from the north) would instantaneously change their path or cease completely.

Before Broecker's hypothesis, researchers proceeded under the assumption that AMOC always behaves as it currently behaves; while models allowed for continuous slow downs due to the releasing of freshwater from glaciers, they did not predict (or anticipate) sudden mode switches. As a result, there was no indication that a sudden change in AMOC may cause a sudden increase (or decrease) in temperature. Therefore, Broecker's hypothesis did not exploit a known causal relationship to explain historical traces but inferred the existence of an unrecognized causal relationship from anomalous historical data.

The implications of Broecker's suggestion are not merely historical. If AMOC has more than one mode of operation, this plays a huge factor in predicting future changes in climate. As Broecker, Peteet, and Rind put it,

> Until now, our thinking about past and future climate changes has been dominated by the assumption that the response to any gradual forcing will be smooth. But if, as proposed by Oeschger, the system has more than one quasi-stable mode of operation, then the situation is more complex. Present general circulation models will at best allow us to study only the changes

> that will take place if the system remains in its current operational mode. Thus, if the changes that characterized glacial time and those that will characterize the coming CO_2 superinterglacial time involve mode switches, investigations of the transient climate response have to allow for this possibility. (1985, 25)

Broecker's hypothesis resulted in a number of tests, most of which appear to confirm it. One retrodiction that immediately followed from Broecker's hypothesis was the existence of a bipolar seesaw. If AMOC were to shut down, there would be abrupt warming in the south corresponding to abrupt cooling in the north. Temperature records from the Greenland ice core were compared with temperature records in Antarctica, and the seesaw was confirmed: spikes in cold temperatures in the north were accompanied by similarly abrupt increases in warmth in the south. Additional evidence for AMOC shutdown was found in various experiments run on climate models, and tracers that are used to track oceanic circulation also confirm past shutdowns or mode switches of AMOC. All of this evidence suggests shutdown and or alternate modes of thermohaline circulation around the same time that abrupt changes in climate occurred.

As a result of these and other verifications, most of the scientific community agrees with Broecker that AMOC has more than one quasi-stable mode of operation.[15] But while Broecker's hypothesis emerged as a plausible explanation of an anomaly in the historical record, the hypothesis itself is not merely historical: it provides important insight into the causal structure of oceanic circulation and reveals that prior models of AMOC were too uniformitarian. Given the confirmation of Broecker's hypothesis, oceanic traces from previous jumps in climate provide information about how oceanic circulation radically alters under different conditions, much in the way controlled experiments reveal deviations in regularities. Moreover, the discovery that previous AMOC shutdown led to abrupt climate change provides evidence that similarly abrupt changes may occur in the future.

6. Conclusion. In theory, methodological actualism sounds like induction as usual. Geology proceeds, as all sciences do, by assuming that natural laws are invariant over time and space. However, because the natural processes studied by geologists are complex and sensitive to global changes in climate, it is difficult to extrapolate natural laws that describe them merely from observations of the present. Geologists are aware of this dilemma and often use historical reconstructions to test the stability of currently observed processes

15. Much of this discussion follows Alley (2007). For a dissenting opinion, see Wunsch (2006).

over large time periods. In this sense, historical reconstructions act as analogs to controlled experiments by determining the boundaries of observed regularities and illuminating the conditions under which they apply. From this we learn that the discovery of causal structure does not, as many have suggested, fall outside the purview of historical science. We also learn that, rather surprisingly, methodological actualism often involves outright assuming that extrapolated calibrations are not time and space invariant, because they simply are not laws.

This brings us to the quote by James Hutton often cited as the framework for modern geology: "In examining things present, we have data from which to reason with regard to what has been; and, from what has actually been, we have data for concluding with regard to that which is to happen thereafter" (1788, 288). Although Hutton was writing with uniformitarianism in mind, we can certainly read him with a healthy pinch of methodological actualism: the present gives us data and frameworks for thinking about how to approach the past, even though processes in the past may have deviated from processes in the present. As we discover the ways in which currently observed processes deviated in historical contexts, we gain important insight about potential alterations in the future.

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