MEASUREMENT, DECOMPOSITION AND LEVEL-SWITCHING IN HISTORICAL SCIENCE: GEOCHRONOLOGY AND THE ONTOLOGY OF SCIENTIFIC METHODS

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Abstract

Philosophers of the historical sciences have focused to a significant extent on the problem of epistemic access facing these sciences: how do historical scientists overcome the relative scarcity of data about the past, compared to the present? Solving this problem usually requires solving another one, which I call the 'problem of ontic access:' how do historical scientists get access to entities and processes with properties that are potentially informative about the past? The case of geochronology illustrates one solution to this problem: historical scientists can get access to entities and processes with properties that are potentially informative about the past by exploiting the metaphysical structure of their domain. Geochronology experienced a spectacular explosion of its research boundaries in the 20th century. I explain this productivity by analyzing the ontology implicit in geochronological techniques. The productivity of isotope geochronology was based on (a) mereological decomposition in order to (b) exploit differences of properties obtaining between the parts and the whole, and (c) an exceptional complementarity between mass spectrometry and the lower-level properties, allowing application to a wide range of geological contexts. The technologically mediated ability of the scientists to exploit the metaphysical structure of their domain was crucial to their success.

1 Introduction

The establishment of an absolute timescale for geological events is one of the great achievements of 20th century science. In the 19th century, the fossil record had allowed rocks of equivalent period of origin to be correlated, and a complete sequence of rock formations could be established for the entire sequence of geological periods in the last 500 million years of Earth's history. [1] This method provided a relative timescale, allowing rocks to be ordered in time relative to each other. It did not, however, allow their absolute age to be determined.[2] In order to determine absolute age, some sort of time-keeper was needed. The decay of radiogenic isotopes turned out to be the key.

This paper is about the problem of time-measurement in historical geology and the role of technology in solving it. There has been increasing interest in the role of technological progress in the literature on the historical sciences. To my knowledge, Marco Tamborini (2019) has pushed this trend the farthest, arguing that the historical sciences are "technosciences," in that the phenomena they study are technologically produced. In a number of publications, Adrian Currie has cited historical scientists' opportunistic use of diverse technologies as part of a methodological approach he calls 'methodological omnivory' (Currie 2018). More recently, he has argued that technology plays an important role in extracting new information from legacy data (Currie 2021).

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[1] See Rudwick (2014) and Bowler (1992, 211ff) for overviews of these developments.

[2] "Absolute" geological age is actually relative, usually determined with respect to the present, as in so many years before the present (BP). I follow Lucas (2005) in calling "absolute" a timescale that is independent of the data being studied. Calendrical systems, for example AD/BC or BP, are absolute timescales. In contrast, a relative timescale is one that presupposes the data being studied. Relative sequences of fossils, mineral deposits, artefacts, and periodizations, are examples of relative chronologies. The data-dependence of the geological periodizations is reflected in the fact that the main divisions of stratigraphy are defined by the dominant forms of life contained in it. Thus the eras are the Azoic, meaning "lifeless;" the Archaeozoic, referring to "primeval life;" the Proterozoic, meaning "very early life;" Paleozoic (ancient life), Mesozoic (middle life), and Cainozoic (modern life).

My overarching thesis is that an important step in the solution to the problem of time-measurement was the solution of another problem, what I call the ‘problem of ontic access.’ Technology is essential for solving this problem because the latter requires manipulating entities and processes with properties that are potentially informative about the past. I begin by characterizing the problem of ontic access in section 2. In section 3, I consider radiometric dating in the historical-epistemic context in which it emerged. Section 3.1 shows how the general problem of measuring time interferes with a problem besetting the historical sciences, what Derek Turner has termed the ‘asymmetry of manipulability.’ In section 3.2, I argue that these two problems were solved, albeit tentatively at first, by radiometric methods. I argue that the quest for a geologic time-keeper lead to a shift in the implicit ontology of geochronological methods that was crucial for the eventual success of geochronology. Mereological decomposition (section 3.3.) allowed geochronologists to exploit the decay law, and was itself made possible by the available technology. In section 3.4, I show how this choice of methods made possible an expansion of the aims of geochronology, and geology more broadly, beyond the spatiotemporal boundaries of traditional geology.

Throughout this case study, my emphasis is on the *productivity* of the decompositionist approach. Nevertheless, the account has epistemological implications that are discussed in section 4. There, I argue that the adoption of radiometry can be understood as an instance of ontological ‘level-switching,’ a strategy that attempts to mitigate information destruction at a given compositional level by seeking less vulnerable processes at another compositional level. Though philosophers have largely focused on evidential reasoning practices in the historical sciences, I conclude that the ontological features of historical-scientific methods may also provide useful insights into how those sciences make progress.

2 The Problem of Ontic Access

In general, the role of technological progress in the historical sciences has been construed as one of enabling historical scientists to mitigate or even overcome the obstacles created by information-destroying processes. Such processes are one of the main causes of what Forber & Griffith (2011) call the "problem of epistemic access" facing historical reconstruction:

> historical reconstruction often lacks important epistemic recourses available to other lines of inquiry. When reconstructing history we lack the ability to intervene experimentally to test hypothesized causal relationships among events in the past. Moreover, our inability to reproduce or observe repetitions of most historical events ensures that historical reconstruction, unlike tasks involving the identification and testing of regularities, is limited by restricted sources of data … the task of historical reconstruction faces a further epistemic difficulty: the traces of a past event are subject to disturbance by heterogeneous causal processes over long spans of time, biasing or destroying information extractable from residual traces of the past event. Due to these difficulties, historical reconstruction typically proceeds without sources of replicable data that are insulated from information biasing or destruction. (2)

In short, the problem of epistemic access is that because the historical scientists cannot use the same methods to acquire knowledge of the past that other scientists use to acquire knowledge of the present—experiments, renewed observations, preservation of samples from destructive processes—they face a relative scarcity of data. They thus face what Turner (2007) calls an 'epistemic asymmetry' relative to scientists of the present.

To give an example of information destruction that is relevant to this paper, rocks containing radioactive isotopes can be dated using the law of radioactive decay. Over long stretches of time, however, some of the radioactive isotopes, or its product isotopes, can either leak out of the rock or be added to it. Either modification will bias the measured age, making the rock appear either younger or older than it is. Leakage and accretion sometimes make radiometric dating less informative about the past than it otherwise might be.

Nevertheless, this problem is, in a sense, a good one to have, for it presupposes that we have discovered, understand, and are able to manipulate, a process that is at least potentially informative about the past. Measurement and observation are necessarily measurement and observation of properties of entities and processes. In the example above, these properties would include the relative abundances of the radioactive and product isotopes in the rock, and the decay constant characteristic of the radioactive isotope. The measurement of these properties presupposes that we have discovered and understand (to some extent) the isotopes and their properties, and are able to manipulate them—directly or indirectly—so as to be able to measure those properties. Measurement in general requires that we have discovered and understand (to some extent) the measured entities, processes and their properties, and are able to manipulate them. That knowledge and ability are a necessary step towards a useful measurement. I call satisfying this requirement the 'problem of ontic access.' The epistemic problem for the historical sciences—overcoming the relative scarcity of data—has an ontic side, discovering, understanding and manipulating entities and processes with properties that are potentially informative about the past.

The problem of ontic access is related to a common claim in the philosophy of historical science: that understanding the historical record—the traces left behind by past events—requires understanding the processes by which that record is formed.[6] Certainly, the problem of ontic access does require understanding the relevant processes. But it requires the ability to act on those processes as well. It has both cognitive and material aspects. On the cognitive side, it requires that we have discovered and understand the measured entities, processes and their properties. On the material side, it requires that we be able to manipulate them. The cognitive and material aspects depend on each other, for discovery and understanding permit manipulation, and vice-versa. The discovery of new research opportunities will be one of the main themes of this paper.

The problem of ontic access raises the question, how *do* historical scientists get access to entities and processes with such properties? An important part of the answer is *technology*, because scientists need technology in order to act on—manipulate—their domain and get access to entities and processes with the desired properties.[7] Though this statement might sound like a truism to some, this role of technology is an underappreciated driver of scientific change. In this paper, I argue that the problem of time-measurement in historical geology

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[6] The basic reason for this requirement is that some kind of theory is required in order to infer securely from the record to the past. See in particular Kosso (2001), Jeffares (2008), and Currie (2016). I thank an anonymous reviewer at *Studies in History and Philosophy of Science* for pointing this out to me.

[7] That the problems of epistemic and ontic access are distinct may be seen from the scientific practice of reanalyzing 'legacy data'—historical documents recording observations and measurements—in order to produce new data (Currie 2021). The production of new data from legacy data does not require a renewed interaction with a specimen.

revolved crucially around the mereological nature of the entities and processes used to measure time. In brief, I argue that *the extraordinary productivity of 20th century isotope geochronology was based on the physical transformation of samples into their constituent parts, in order to exploit regularities, obtaining among the parts, by means of an exceptional complementarity between the instrument and those regularities.* This solution to the problem of time-measurement had such a wide range of application that it revealed many new research opportunities that geologists could pursue, thus making possible the expansion of research boundaries.[8]

Technology played a crucial role in this process, in two regards. First, it allowed geochronologists, and geologists more generally, to access entities and processes with radically different properties than had theretofore been accessible to them. The most well-known property is radioactive decay, but stable isotope effects were also very important. Moreover, the key instrument involved, the mass spectrometer, exploits properties of charged particles. Second, it allowed those regularities to be applied to samples reflecting the extremely wide range of conditions under which those regularities hold. To characterize this role more generally, albeit in slogan form, one might say that the instrumentation *permitted the exploration of the possibilities implied by the regularities*. The emergence and exercise of this function is manifested in the trajectory of 20th century geochronology. Early 20th century geochronology started as a quest for a reliable method of measuring geologic time. In achieving this aim, the goals of the field were altered—in the form of enrichment rather than

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[8] My approach here bears some resemblance to what Currie & Walsh (2018) identify as ontic-driven explanations of scientific method and change, in which “the adoption of a method or approach (and its subsequent success or otherwise) is explained in reference to the kind of system in which the scientist is interested” (119).

replacement, be it said—because isotopes turned out to have properties that provided research opportunities that wouldn't have been available with the other entities and processes that were considered as candidate time-keepers. The pursuit of these opportunities made an important contribution to the integration of diverse fields into what came to be called the "Earth and planetary sciences."

'Technology' is a vague term, however, and so henceforth I will prefer to use 'scientific methods' or 'techniques.' By 'scientific method,' I intend a four-fold combination of background knowledge (including the theory of the instrument, as well as auxiliary assumptions), instruments, operational procedures, and data analysis techniques, used together, more or less coherently, to achieve an epistemic aim. This characterization goes significantly beyond the more common understanding of technology as instrumentation because, at least in the scientific context, it is not possible to understand the use of instruments in isolation from the other elements. A method thus understood is akin to a 'system of practice' in Hasok Chang's (2012) sense. My analysis is also informed by Peter Galison's (1997) notion of 'instrumental traditions' that have constraints and potential of their own, not necessarily dictated by the concerns of theorists or even experimentalists.

3 Measuring Time Without Clocks

3.1 Time measurement

In order to understand the options available to geologists in the early 20th century, it is helpful to consider the nature of clocks in general.[9] The basic principle of a clock is to exploit a process that can serve as a proxy for the passage of time.[10] To measure the amount of time that has passed, two things must be known: the end-points and the rate of the process. The progress of the process is measured by a counter. For example, with mechanical watches, the proxy is an oscillating balance wheel, and the counter is the escapement mechanism that ticks off the cycles and moves the hands, at an appropriate rate, to indicate the time. With digital watches, the number of cycles of the signal emitted by a crystal oscillator is a proxy for the time elapsed during signal emission, and the counter is an electronic circuit that shows the time in a numerical display. With water-clocks, the proxy is the flow of a column of water, which can be measured by means of a scale marking the height of the water (Landes 2000, 8). The juxtaposition of watches and the water-clock reflects the fact that, historically, two general kinds of processes have been used:

a. Continuous flow processes, such as the movement of the sun with solar clocks, the flow of water with water clocks, or the flow of sand in an hour-glass.

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[9] For a general discussion of oscillating clocks from a physics perspective, see Jones (2000). For a more philosophical general treatment, see Dowden (n.d.). For a discussion of the historical development of clocks, including continuous flow clocks, see Landes (1987) and (2000).

[10] In the philosophy of measurement, Tal (2016, 300) defines a clock as including "both artificial and natural systems for measuring time." Following Jones (2000), Tal allows that the oscillator may be a "naturally occurring process such as the Earth's rotation around its axis." According to the physicists Halliday, Resnick and Walker (1994, 5) "[a]ny phenomenon that repeats itself is a possible time standard."

b. Oscillatory processes, such as the swings of a pendulum, the oscillations of a foliot, quartz resonances, or atomic transitions.

The reason for employing these kinds of processes is that they exhibit a *principle of constancy over time*: either the flow rate, or the rhythm of oscillation, is assumed constant.[11] This assumption greatly facilitates time measurement.[12]

Now, with artificial clocks the proxy process is either observable or manipulable by humans. With some clocks, it is directly observable through the senses, as with water clocks or pendulum swings. With others, it is not observable but remains indirectly manipulable, as with atomic clocks. Unfortunately for historical scientists, neither option is available to them, because they must measure time spans stretching back well beyond the existence of humans. For them, whatever proxy process they use will necessarily be both unobservable and unmanipulable because they could not be around to directly observe or manipulate it. This problem is a manifestation of what Turner (2007) calls the 'asymmetry of manipulability.' Unlike sciences like chemistry or physics, which can (arguably) at least manipulate entities they can't observe, the historical sciences do not have the option of manipulating the past.

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[11] In metrology, this principle is called the 'stability' of the clock: "The frequency of a clock is said to be stable if it ticks at a uniform rate, that is, if its cycles mark equal time intervals". Perfect uniformity is, of course, an idealization (Tal 2014, 300-301).

[12] In principle, constancy may not be necessary, so long as the rate law be known. The celebrated geochronologist Arthur Holmes seems to have entertained some such possibility (1947, 117-118). Presumably, knowledge of the end-points of the process and integration would allow the passage of time to be computed. In practice, however, knowledge of the rate law for a variable proxy can be hard to come by. This difficulty is greatly exacerbated, in the historical sciences, by the problem of the 'asymmetry of manipulability' to be discussed below. In this connection, it is worth noting that the search for a process that is constant over geologic time can be, and was, related to uniformitarianism. Indeed, both Holmes (1947) and the American geologist Joseph Barrell (1917) criticized proponents of geological time-keepers for assuming an overly strict uniformitarianism. As shown above, however, the constancy desideratum is not intrinsically geological but is derived from the requirements of time-keeping.

The significance of asymmetry for time measurement is that historical scientists must find a process that exhibits constancy, is theoretically tractable, and that leaves detectable traces behind. In the next section, I discuss how early 20th century geologists, interested in measuring time, found a promising candidate, and what made it promising.

3.2 Classical versus radiometric geochronology

In the case of geochronology, several macroscopic phenomena were investigated as candidates for time-keeper:[13]

- Counting of tree-rings
- Counting of sediment deposits in lakes, known as "varves"
- Correlation of glacial and interglacial periods with astronomical cycles
- Analysis of evolutionary lineages, specifically the rates of evolution of morphological features
- Stratigraphical clocks, based either on rhythmic alternations in sediments or the cumulative effect of geologic processes such as deposition and denudation
- The accumulation of salt in the oceans since their formation
- The alleged cooling of the Earth since its alleged early molten state
- The slowing of the Earth's rotation through tidal dissipation of energy

None of these methods proved both general and reliable for dating geological objects. An important problem was that the proxy processes lacked sufficient intrinsic constancy to serve as reliable clocks, being strongly influenced by contextual factors. In his monograph of 1917,

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[13] For an overview, see Zeuner (1958, Chapter X) and Dalrymple (1991). The last three were, of course, estimates of total time used to infer the age of the Earth.

“Rhythms and the Measurements of Geologic Time,” the American geologist Joseph Barrell critically examined all attempts to measure time via stratigraphical clocks (excluding varves), oceanic salt accumulation, and the cooling theory. His verdict was that none of them was based on a process constant over the entire Earth or throughout geologic time. [14] So, for example, the rate of accumulation of strata is a function of the rates of deposition, denudation, and diastrophism. The rate of each of those processes varies with time and space, as do the ways in which they interfere with each other. Indeed, this interference indicates a further problem, that some of these processes are reversible. For example, sedimentary deposits are removed by erosion, and dissolved sodium is removed by solid precipitation. The interference of these counteracting processes complicates the determination of a rate. To take another example, the rates of morphological change of organisms are dependent on their environment (Sterelny 2007, Zeuner 1958, Chapter XII). And the rate of transfer of heat from the Earth’s interior, the basis of Lord Kelvin’s cooling method, varies with the conductivity of the rocks within the Earth (Shipley 2001). These last two examples illustrate a further limitation on scope, that some of the methods were limited to specific problems like the age of the Earth, or specific contexts that could support the existence of the given proxy.[15]

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[14] See Zeuner (1958), Holmes (1947), and Barrell (1917) for critiques of these methods.

[15] Certain oscillatory processes, namely varve deposition and correlation of glaciation with astronomical cycles, appear to have been more reliable. But they were time-limited, with e.g. varve counting only going back 15,000 years or correlations between glaciations and astronomical cycles 1,000,000 years. This time-limitation excluded dating of older samples, notably those from Precambrian times. Though varves much older than 15,000 years could be found, they could not be dated with respect to the present. Moreover, even they were not immune to worries about the potential variability and reversibility of deposition (Zeuner 1958, ch. II; Holmes 1937, ch. III).

By mid-20th century, however, a method had been settled on, based on the non-geological proxy of radioactive decay.[16] After its discovery in the late 19th century, it was quickly recognized that the phenomenon of radioactivity could be used for measuring time. Ernest Rutherford (1906) was the first to propose that the proportion of radioactive atoms that disintegrate in a given time interval is an unvarying constant and therefore a potential clock. A particularly important kind of radioactive decay, in the early 20th century, was that of uranium into lead. Several scientists tried to exploit this process to develop an absolute geological timescale and establish estimates of the age of the Earth. In order to measure the age of a sample, the quantities of both the residual ‘parent’ atom (e.g. uranium) and the decay product or ‘daughter’ atom (e.g. lead) had to be measured. Until the 1930s, this was done using bulk chemical techniques, involving chemical analysis of the sample followed by gravimetric or volumetric measurements. With the discovery that uranium and other elements had multiple radioactive isotopes, however, it was recognized that accurate age determination would require separation of the isotopes. Separation could not be accomplished with chemical techniques, however, and so age determination came to rely on a kind of instrument known as the mass spectrometer. The latter separates isotopes by means of electric and magnetic fields (the precise combination of fields depends on the specific design).

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[16] For historical accounts of the gradual acceptance of the new method, see the chapters by Wyse Jackson, Yochelson & Lewis, and Dalrymple collected in Lewis & Knell (2001).

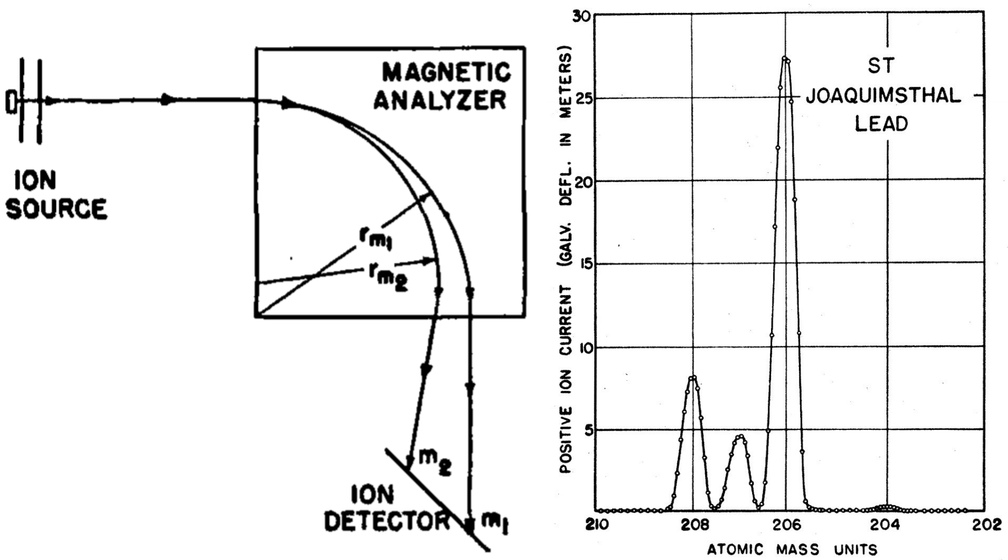

Figure 1. The diagram at the left represents a mass spectrometer. The atoms in the sample are ionized in the ion source, and then separated by mass in the mass analyzer, before hitting the detector, which records the current obtained for each atomic mass. From Inghram (1948, 222). The output is a mass spectrum, of which one is shown at right for a radioactive uranium ore. Each peak represents the intensity of current measured for each mass. Those at 206 and 207 were generated by radiogenic isotopes of lead, the one at 204 by stable ones, and the one at 208 by both. From Nier (1939, 155).

The radioactive decay of uranium into lead was the most used process until the 1950s, when other isotope systems became available. The fundamental law of radioactive dating is

$$\text{1.}\quad D = D_0 + N(e^{\lambda t} - 1)$$

where D_0 represents the number of daughter isotopes at time $t = 0$ and D represents the number of daughter isotopes at t, and N represents the number of parent isotopes present at time t. λ is the disintegration constant of the parent isotope (e.g. uranium-235). It represents both the fractional decay rate as well as the probability that the given nucleus will disintegrate in the interval of time dt.

(1) is derived from the Curie-Rutherford-Soddy (CRS) law below, according to which the number of nuclei that disintegrate per unit time is a constant fraction of the number of nuclei present:

$$2. \qquad \frac{dN}{dt} = -\lambda N.$$

λ is expressed in units of the reciprocal of time, typically yr^{-1}. The law has been shown to be valid for nuclei with very short (10^{-3} s) or very long (10^{9} y, or 10^{20} s) lifespans. It holds regardless of the conditions in the medium. The law of decay remains unchanged regardless of phase, temperature, pressure, presence of electromagnetic field, or chemical environment. For a given type of nucleus, λ remains the same over time. This constancy is due to a fact about radioactive decay: because the energy required for the process is so large relative to that of other natural processes, the probability of decay is unaffected by the environment, except in nucleosynthetic contexts like stars or supernovae.[17] The energy released is also great, making the process irreversible under geologically relevant conditions, in contrast to the deposition- or salt-based methods mentioned above.

Equation (2) can be rearranged and integrated:

$$3. \quad \int_{N_0}^{N} \frac{dN}{N} = \int_0^t -\lambda dt$$

Integrating, one obtains:

$$4. \quad \ln \frac{N}{N_0} = \lambda t$$

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[17] For relatively accessible overviews of the pioneering attempts by Gamow, Fermi and others to derive decay constants from quantum mechanics, see Glasstone (1950, VII) and Friedlander & Kennedy (1949, VI).

(4) can be further manipulated to yield (1). (1) can then be rearranged to give the formula for the apparent age:

$$5.\quad t = \frac{1}{\lambda}\ln\left\{\left[\frac{D-D_0}{N}\right]+1\right\}$$

The apparent age is a concept of time as an isotope ratio converted into time units. As alluded to in the introduction, interpreting it as a geologic age is not straightforward. The apparent age is chemical and isotopic. It is of physical significance only if certain conditions are met. Two of these are the assumption that the sample has remained a closed system since solidification, and that it was homogeneous when it solidified. These conditions will be discussed further in section 3. When they are met, the age can be interpreted as the time since solidification of the sample. In turn, for the solidification event to have geological significance, it must be attributed to a mineral or rock-forming geological process, like magmatism, metamorphism, or sedimentation. A further step is to then contextualize that process within a geological event of interest, like the formation of the Earth, the movement of mid-ocean ridges, mountain range formation, etc. Significant calibration is required, including against nonradiometric methods (Bokulich 2020, Wylie 2020). The first geologic timescales making use of U-Pb dates, for example, were calibrated against stratigraphic data (Holmes 1947, 1959-60).

In a sense, however, the need for interpretation is a good problem to have. The law's omission of geological information indicates a source of geochronology's great productivity, for it is an expression of the conditions under which it can be applied. The constancy of λ is expressed mathematically in the integration of (3). Thus the form of the time formula (5) expresses the fact that the probability of decay is constant regardless of environmental conditions, with the exception of nucleosynthesis and electron capture (see section 3). It follows that an apparent age can be calculated regardless of those conditions, and hence that its range of application is extremely broad.

Of course, this law could not be applied without the measurement of isotope ratios, and hence the separation of isotopes. Indeed, the apparent age results from the combined use of background knowledge, including the law and other theory; from instruments, not just mass spectrometers but also chemical equipment; from the procedures used to operate those instruments; and from data analysis techniques such as the determination of peak intensities and, of course, the actual computation.[18] Moreover, the use of the mass spectrometer is not associated with any specific kind of geologic context, and so can take samples from widely different sources.

In summary, the method, as practiced in the mid-20th century, involved four basic steps:

i. A mineral was analyzed chemically to determine the total amounts of lead and uranium
ii. The lead was then ionized and electromagnetically separated into its isotopes in a mass spectrometer.
iii. The relative proportions of the lead isotopes were determined from the mass spectrum.
iv. These proportions, together with the amounts of lead and uranium from (i), were then used to calculate the apparent age or date of the mineral, *t*, from a rearranged version of equation (1).

This method proved extremely successful and allowed an absolute dating system of unprecedented range to be established. Unlike biostratigraphical methods, the long half-lives of some of the isotopes allowed ages to be determined for the Precambrian, for which fossils are

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[18] I.e., it results from the application of a ‘method,’ as characterized in the introduction.

scarce. The discovery of extinct radioisotopes would later extend geologists' reach to well before the formation of the Earth (section 2.3). Indeed, the fact that decay is an on-going process for non-extinct radioisotopes allowed ages, in the sense of the time elapsed since formation to the present, to be established at all. This continuity with the present avoided gaps due to interruptions of the process, a problem affecting some of the classical methods.[15] Finally, the constant fractional decay rate meant that a given decay process could be used for any age-range over which its half-life permitted measurement, without worrying that the rate might be time-dependent.

3.3 Decompositionism to the rescue

The mereological features of the method played a crucial role in its success. It is an example of what I will call a "decompositionist method." Decompositionist methods decompose their objects into constituent parts in order to support inferences about them, for example their chemical composition. It is a sub-type of what Chang (2012) has called the 'compositionist' type of system of practice. Chemical analysis, chromatography, dissection, and mass spectrometry can all be considered decompositionist methods.[19] These methods presuppose an ontology: they assume that the world is structured by compositional levels of organization.[20] Here, it is important to emphasize the activities involved in the application of

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[19] Compositionism is itself a sub-type of the more general class of analytical methods, which characterize objects or processes in terms of elements, of which they are compounds. Compositionism is a sub-type of analytical method because the latter need not involve physical decomposition of a substance. For example, many chemical analytical techniques identify the chemical composition of a substance without destroying it, e.g. NMR, IR, etc.

[20] I here make use of Chang's (2009, 2008) view that the intelligibility of epistemic activities requires the assumption of ontological principles, like the principle of single value enabling the measurement of physical properties like temperature and length. To be clear, I do not claim that geochronologists' beliefs about the fundamental structure of the world changed, only that the methods that ended up being successful in this episode presuppose compositionism for their intelligibility.

the methods (Chang 2012). The method described above involves a *transformation* of the object of inquiry: from a rock or mineral to elementally pure chemical compounds, and from an isotopic mixture into pure isotopes.[21] The importance of the spectrometer lies in the fact that the isotopic separation can only be accomplished under conditions that exploit the mass difference between isotopes, since chemical, mechanical and thermal separation is impossible. For the most part, geochronologists use mass spectrometry to create those conditions.

The compositionist ontology is evident in these transformations of the object of inquiry: from rock into compounds representing its constitutive elements, and then from elements into their constitutive isotopes. Following Wimsatt (1994, 222)), I will characterize these levels as "hierarchical divisions of stuff … organized by part-whole relations, in which wholes at one level function as parts at the next (and at all higher) levels." Because of the compositional hierarchy they presuppose, analytical methods, if successful,[22] give access to entities that belong to a different ontological level than the original object. Such access is afforded by modern chemical analytical methods, which identify substances in terms of their molecular structures, and molecular structures in terms of their atomic parts.

Whether a method involves a shift of level has ontic consequences, in the sense of determining the properties of the target systems that scientists will have to deal with. The shift creates the possibility that the constituents may have radically different properties than the

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[21] The chemical analysis in step (i) above did not yield pure elements but rather new compounds through chemical reactions. It allowed each element of interest in the mineral to be separated from the other elements, in the form of a new compound that was pure with regard to the element of interest. It thereby "represented" the latter and was amenable to mass-spectrometric analysis. For example, the lead spectrum shown in Figure 1 was obtained from samples of lead iodide.

[22] Success is not guaranteed, in part because the presupposition of a compositional hierarchy can fail. Wimsatt argues that this is especially likely at higher levels due to their increasing complexity, diffuseness and overlap with other levels. (Wimsatt 1994, 257ff).

object they constitute, as for example a molecule has radically different properties than the macroscopic substance it is a constituent of. As a result of this difference, the adoption of an analytical technique can radically change the horizon of properties that scientists can study and exploit. This change of properties should be no surprise, for a change of levels typically involves a change of the size or size ranges of the entities, as well as a change of the regularities of their behavior (Wimsatt 1994, 238ff and 233ff). The greater the difference in levels, the greater the difference in size and regularities one should expect.

Radiometry involved a double decomposition featuring two ontological shifts, from compound to element (in the form of a representative compound), and from element to atom in the second. Since the isotopic nature of the atoms was essential for the accuracy of the technique, one might even say that the second involved a shift from element to *nucleus*. The nuclear aspect is crucial for understanding the ultimate impact of the technique, for it is the shift to nuclear energy scales that ultimately explains the invariability of the decay rate (section 3). This change of properties illustrates the feature of compositional levels noted above, that the greater the difference in levels, the greater the difference in size and regularities one should expect. In this case, size mattered.

3.4 The flourishing of isotope studies[23]

The constancy of the decay rate was of momentous consequence for the future of geochronology, and geology more broadly, for it made possible a broad array of applications beyond the original goal of establishing an absolute timescale for geological time-periods. The

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[23] Besides the authors cited in-text, the following overview relies on K. A. Nier (2016), Rudwick (2014), Johnson et al. (2013), and Allègre (1992).

overall impact of isotope methods was to shatter the spatial, temporal and “parametric” limits of traditional geology. Spatial, by allowing new modes of access to the Earth’s interior and the rest of the solar system. Temporal, by reaching beyond the fossil record to all of terrestrial and solar system history. Parametric, by allowing the history of parameters like temperature or polar ice cap volume to be inferred.

A seminal development in the spatiotemporal expansion of geology was the ability to date both common rocks and meteorites in the 1950s. Improvements in the U-Pb method made possible more accurate and detailed studies of elemental and isotopic abundances in meteorites, which allowed Claire Patterson and colleagues to show that the Earth, meteorites, and planetary system had all been formed together about 4.56 billion years ago. The combined study of meteorites and terrestrial samples permitted improved estimation of the cosmic abundances of the elements and isotopes, which in turn provided the basis for theories of the processes by which the elements are created in stars. Knowledge of these abundances allowed variations in specific cosmological contexts to be recognized and hence inferences to be made about the evolution of the solar system. For example, the discovery of minute variations in oxygen isotope ratios in meteorites, and of extinct radioactive isotopes for certain elements, supported the theory that the solar system arose from a heterogenous nebula to which different stellar sources had contributed.

Thus the results of the quest for an absolute timescale could be parlayed into broader cosmological studies of events far beyond the spatiotemporal limits of traditional geology, including of: the age, history, and chemical composition of meteorites and planetary objects in general; the history of the moon; the composition and history of planetary atmospheres; the history of individual planets and of the solar system as a whole; the age, origin and history of the chemical elements; and the history of isotope systems going back to the early solar system. Isotopic data also allowed stronger connections to be forged between the Earth's astronomical cycles and its glacial fluctuations, in particular by confirming Milutin Milankovitch's theory of how the solar radiation received by the Earth covaries with parameters of its orbit over time. This expansion created closer links among lines of research in geochemistry, planetary astronomy, geo-, astro- and nuclear physics, and geology.

The discovery of stable isotope fractionation was important for the "parametric" expansion of geology. Stable isotope fractionation refers to chemical processes, rather than nuclear ones, that produce variations of the isotopic compositions of light elements. Though they are not produced by decay, these variations are another consequence of the ontological shifts discussed above, for they result from kinetic and equilibrium isotope effects caused by the quantum mechanical properties of atoms. Fractionation in the course of geological processes would produce durable variations in isotope ratios that could be measured by mass spectrometry. Doing so would allow other parameters of Earth and solar system history to be determined, besides dates. A momentous example of this versatility was the demonstration, in the early 1950s, that oxygen isotope ratios in some fossils varied in relation to the ambient temperature when the organisms were alive. This discovery marked the beginning of paleoclimate studies. Other important parameters include past volumes of polar ice caps and initial radiogenic parent/daughter isotope ratios, which provide information on the structural origins of rocks (e.g., mantle v. crust).

This last point brings me to another aspect of expansion. Besides being extended "outwardly" to the solar system, both the radiogenic and stable isotope approaches could be extended "inwardly," to the study of past and present processes in the Earth's crust, oceans and interior. Research was conducted on the time for the core and mantle to become substantially differentiated from each other; the chemical differentiation of the mantle into lower and upper layers; the source of hot-spot plumes in the lower mantle; the cycling of material between the mantle and the continents; and the age and process of formation of the continents. This research also shed light on the origin and development of the atmosphere and oceans through mantle degassing. The geological time scale was refined and timelines established for events in the evolution of life. These advances strengthened connections between geology, geophysics, geochemistry and biology.

This growth was not solely due to the implicit ontology of the technique. Cold War funding, other scientific developments (e.g. on the theoretical plane), and the painstaking development of instruments were also vital.[24] The sheer variety of isotope systems that exist in nature was also essential, since no one system can be used for all these studies.[25] Nevertheless, most of these studies made use of some variation of the basic method, combining mass spectrometry with an isotope system, with the variation typically involving significant tailoring of the instrument to specific system characteristics.

Of course, none of this growth would have been possible had the method been found to be irremediably unreliable, for example if the discrepancy between the apparent and geological

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[24] See de Laeter (1998), **BBB** (forthcoming), and references therein for studies of these other factors.

[25] The geologist James M. Mattinson estimated about 40 decay systems had become available by 2013 (Mattinson 2013, 312).

ages could not be corrected in most cases. Nevertheless, the robustness of radioactive decay (and stable isotope effects) across an extremely wide variety of environmental contexts made these applications possible. The processes themselves, and the instrumentally mediated access to them, are essential for explaining the development of this field.

4 Level-switching as an approach to epistemic scarcity

My emphasis on compositional levels informs the problem of epistemic access to the deep past that philosophers have focused on. In this section, I will argue that mereological level-switching is a distinctive approach to the problem, and examine reasons for the success and limits of that strategy.

A number of solutions have been proposed, by philosophers, to account for how historical scientists overcome epistemic scarcity. These include:

a. *Smoking guns*: The scientists search for telltale traces of past events to discriminate between alternative hypotheses. Such traces allow them to overcome the fact that they can't do experiments to test their hypotheses. They are aided by the fact that only a subset of the traces left by an event are needed to infer that it occurred, what Cleland calls the "asymmetry of overdetermination" (Cleland 2002).

b. *Consilience of lines of evidence*: Rather than depend on a smoking gun, the scientists support hypotheses through the consilience of multiple independent lines of evidence. The effects of information destruction are mitigated by the mutual support of the different lines (Forber and Griffith 2011).

c. *Coherence testing*: Coherence between a narrative explanation and theoretical and empirical constraints (Currie and Sterelny 2017), or between measurements (Bokulich 2020), supports inferences about the past.

d. *Methodological omnivory*: The scientists maximize the epistemic potential of fragmentary remains by combining multiple and disparate methods tailored to their local context of inquiry. There is no general "historical method" (Currie 2018, 2021).

e. *Presenting data in novel ways*: The scientists remedy the imperfections and incompleteness of traces of the past by using technology to produce presentations of deep historical phenomena. These presentations then become the objects of investigation (Tamborini 2019).

f. *Revisiting old data*: The scientists devise new ways of extracting information from legacy data (Currie 2021, Wylie 2017).

g. *Experimentation*: The scientists experiment after all, in order to discover regularities. The latter are then exploited to draw inferences about the past (Jeffares 2008) or the future (Page 2021).

Most of these solutions focus on the scientists' evidential reasoning. In contrast, the analysis of the preceding sections has shown that ontology, specifically, the *compositional level of organization* targeted by the field's methods is an important methodological consideration in these sciences as well. Forber & Griffith (2011, 2) briefly allude to this consideration when, in the context of a discussion of evolutionary biology, they point out that information-destroying processes at the molecular level might not be as severe as at the morphological level. The case of geochronology illustrates one reason why levels might be relevant: historical processes unfold within a context, and a process at a given level of organization will display a certain degree of context-dependence. The unfolding of the process will be affected by its context to a greater or lesser degree.

According to Wimsatt (1994, Section II.6), the behavior of entities at higher levels of organization tends to be more context-dependent than that of entities at lower levels. The idea is that increasing complexity adds properties. Higher-level entities tend to have more properties than lower-level entities. Entities interact causally with each other through their properties. Therefore, there will tend to be more ways of interacting with higher-level than lower-level entities. It follows from this tendency that a higher-level entity will have more ways of interacting with its context than lower-level entities. For example, an entity can interact with part of its context through subset *A* of its properties, and it can interact with another part through subset *B*.

Wimsatt argues that because of this difference, it is better to think of higher-level regularities in terms of mechanisms than laws, for "the latter, but not the former suggests a search for exceptionless generalities and explanatory completeness, whereas the former fit naturally into a scheme which is satisfied by providing a characteristic ceteris paribus articulation of causal factors" (1994, 258).

The difference also suggests a heuristic for developing methods: if a process at a given level is too context-dependent to be reliable, then look for a lower-level process that can accomplish the same goal. To give the heuristic a name, I will call it 'level switching' to avoid the philosophically loaded term 'reduction.' Since, other things being equal (and this is an important caveat to which I will return shortly), lower-level processes tend to be less context-dependent, it is reasonable to look for a more reliable process at the lower level. In terms of the dichotomy between mechanisms and laws, one might say that this strategy attempts to recover the law-like regularity, missing at the higher level, by moving to the lower. As far as the historical sciences are concerned, the hope is that information-destroying processes encountered at the higher level will be avoided at the lower, as Forber & Griffith's morphological/molecular distinction suggests.[26]

For some readers, level-switching may seem similar to methods of idealization and de-idealization in historical science identified by Currie (2018, chapter 10). According to Currie, historical scientists sometimes proceed by seeking support for hypotheses initially formulated at a relatively high level of idealization. Once these more general hypotheses have been tested, the scientists remove some of the idealization, generating more fine-grained hypotheses, and seek further evidence for the latter. An example he gives is the "Snowball Earth" hypothesis, according to which a worldwide freeze might account for signs of glaciation in the tropics during the Neoproterozoic period. Glaciation of the tropics, however, might take different forms, for example snow or slush, and might have been caused by increases in different greenhouse gases, for example carbon dioxide or methane. Different tests are required to distinguish between these different, more fine-grained hypotheses.

Level-switching as I intend it here, however, has to do not with how hypotheses are formulated and tested but rather with the activities involved in the application of compositionist methods. As discussed in section 3.2, isotope methods involved the

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[26] This strategy bears some similarity to reductive strategies for explaining complex systems (e.g. Bechtel and Richardson 1993, Wimsatt 2007, Strevens 2005). My concern here, however, is not with explanation but rather with the activities involved in gathering information to make inferences about the past.

transformation of the object of inquiry in such a way as to provide ontic access to entities at different compositional levels of organization than the original object. Whereas the methods described by Currie prescribe steps in evidential reasoning—formulate and test a more general hypothesis, then formulate and test more specific ones—the methods described herein prescribe steps in the physical transformation of wholes into their constituent parts. In other words, the former are solutions to the problem of epistemic access, the latter to the problem of ontic access (though of course the two problems are interdependent, as noted in the introduction).

This strategy is, in effect, the one adopted by 20th-century geochronologists. The law-like regularity that was gained was radioactive decay, as expressed in equation (1). To see how decay illustrates level-switching, consider the example of a crystal containing radioactive isotopes. It can be analyzed in terms of four levels of organization:

i. *The nucleus:* The nucleus can be considered in abstraction from its atomic context, i.e. without taking the electrons into account. Due to the high energies involved in nuclear processes, the latter are not affected by its environment except in extremely high-energy contexts like stellar interiors or the Earth's core. Decay is otherwise a spontaneous process in which the interaction with the environment is essentially one-way.

ii. *The isotope:* The individual isotope is an atom, and so consists of a nucleus and orbiting electrons. There are now electromagnetic interactions between the nucleus and the electrons. The latter allow the isotope to interact with its environment through chemical bonding, in addition to radioactive decay.

iii. *The ensemble of isotopes:* The individual atom is now part of a group of isotopes distributed in a medium. The members of the ensemble continue to undergo chemical bonding and decay, of course. In addition, their ensemble-ness has properties of its own, such as the parent/daughter ratio and the spatial distribution of isotopes across the system. These properties are determined by the movements of the ensemble's constituents within, into and out of the system.

iv. *The crystal:* The ensemble is a component of a macroscopic, three-dimensional object, the crystal, which, in addition to undergoing these nuclear, chemical, and diffusive processes can also be extracted from its natural environment, mechanically manipulated, inspected, mounted into an instrument, chemically treated and so forth.

This example displays an accumulation of properties on going up the levels. The fourth level, the crystal, is capable of interacting with its environment through radiation,[27] chemical bonding, migration of elements and isotopes, and mechanical processes. In contrast, the original level, the nucleus, was mainly capable of interacting through nuclear processes like radiation, fission and fusion.

The example also indicates at what levels the context will tend to assert itself. Conditions that affect the ensemble properties of isotopes (iii) affect isotope ratios, and so potentially confound inferences based on them. Indeed, reliability of isotopic age determination turned out to be dependent on two crucial conditions:[28]

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[27] This is the case, for example, with the formation of pleochroic halos in rocks through radiation.

[28] See White (2015, Section 2.2) for a detailed discussion of these conditions.

i. The system of interest (e.g., a rock) as a whole and each analyzed part of it was closed between $t = 0$ and time t (see equation 1). That is, there has been no transfer of the parent or daughter isotope into or out of the system.
ii. The system was at isotopic equilibrium at $t = 0$, i.e. the distribution of isotopes was homogeneous.

The extent of migration of elements into or out of the sample ((i)) depends heavily on contextual factors, like the presence of contaminants in the environment. Condition (ii) depends on the diffusion rate of the elements before the sample solidified. This rate in turn depends on the element and the properties of the material through which it diffuses. The latter properties will be influenced by contextual factors. For example, as a molten crystal cools, the rate of argon loss will be different for the crystal rim than the crystal interior, due to a higher concentration gradient at the surface of the sample (White 2015, Section 2.3.2). If we are using the popular ^{40}Ar/^{39}Ar dating system, the result is that we will measure a different age for the rim than the interior. Thus the surface/environment interface is a possible source of error in such cases. More generally, homogeneity depends on the diffusion of elements between subsystems of the sample, and between the subsystems and the sample's environment. Geochronologists spent much of the mid- and late-20th century working out ways to correct for these sources of error.

In short, though the move to a lower level afforded access to a time-keeping mechanism that was largely insensitive to contextual factors, that insensitivity can give out at the ensemble level because of element migration and inhomogeneities of distribution. Though some may see this giving-out as problematic for the level-switching concept, I count it as a virtue of the latter that it can account for both the benefits and the limitations of the strategy. It is also worth noting that violations of (i) and (ii) affect the end-points of the process (section 2), the amounts of parent and daughter nuclei, but not the fractional decay rate λ.[29] In contrast, the present rate of sediment accumulation, to take one classical example, is extremely dependent on contextual factors at a given location, as is the variation of that rate over time (Holmes 1947, 117-119).

Instrumentation plays an important role in level-switching, for it allows scientists to access the right levels. Not all level-changes will grant access to sufficiently different properties to solve the problem. Most of the classical methods listed in section 2.2 involved some sort of part-whole relationship, for example tree rings are parts of trees, varves are parts of lakes, and strata are parts of rock formations. But the difference between levels has to be great enough to yield a sufficiently different set of properties. Nuclear processes are governed by the strong force. Geologic processes, on the other hand, are governed by the gravitational and electromagnetic forces, which are very much weaker. So processes governed by them involve

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[29] This understanding of the impact of context on this process was expressed by a key player in this episode, Arthur Holmes, in 1937:

> The quantum theory provides a reason for this insensibility of the radioactive elements to external influences. It is not difficult to remove electrons from the outer part of an atom, but radioactivity is a property of the nucleus, and the latter cannot be affected except by the application of radiation as energetic as its own. In the case of uranium the radiation emitted corresponds, as shown by Sir James Jeans, to the unimaginable temperature of 5,800,000,000o C. Evidently the conditions encountered by rocks in the earth's crust are unlikely to affect atomic nuclei. (Holmes 1937, 127)

This stability was tested in many ways (Barrell 1917, 873-874; Holmes 1937, 126-137; Dickin 2018, 11). The only potentially interfering process, on Earth, that was discovered is that of electron capture, which produces a new nucleus and which shows a slight dependence on pressure. Capture only significantly affects the decay rate, however, at depths where the decay systems are so chemically open as to be useless for dating anyway, as one might expect given the two conditions above (Dickin 2018, 11).

much smaller energies. It follows that geologic proxies will be subject to energy flows from environing geologic processes in ways that nuclear processes will not.

5 Conclusion: Ontic access enables epistemic access

This analysis raises broader questions. First, are there other cases where a level-switching strategy has been tried? I have already mentioned Forber & Griffith's (2011) example of evolutionary biology. There may be interesting similarities and differences between the case of geological clocks and that of biological clocks (Valde 2019). With respect to paleontology, Derek Turner has discussed how information about the colors of the dinosaurs, lost in the macroscopic fossil record, could be recovered by scanning electron microscopic and X-ray analyses of the microscopic constituents of fossils (Turner 2016). There is a further question of whether level-switching must always go to ontologically lower, rather than higher, levels.

Philosophical studies of the methods of the historical sciences have largely focused on evidential reasoning practices. This study suggests that the ontological features of the methods may also provide useful insights into how those sciences make progress. I have argued that the extraordinary productivity of isotope geochronology was based on (a) mereological decomposition in order to (b) exploit differences of properties obtaining between the parts and the whole, and (c) an exceptional complementarity between the instrument and the lower-level properties, allowing application to a wide range of geological contexts. The difference of properties opened up radically new methodological possibilities, in comparison to classical geology, that could only be exploited with the aid of technology. The technologically mediated ability of scientists to manipulate their domain was decisive in turning geochronology into a successful science.

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7 References

Allègre, C. (1992). *From Stone to Star.* Trans. D. K. Van Dam. Cambridge, MA: Harvard University Press.

—. (2008). *Isotope Geology.* Cambridge, MA: Cambridge University Press.

Barrell, J. (1917). "Rhythms and the Measurements of Geologic Time." *Bulletin of the Geological Society of America* 28: 745-904.

Bechtel, W. and R. C. Richardson. (1993). *Discovering Complexity.* Princeton: Princeton University Press.

Bokulich, A. (2020). "Calibration, Coherence, and Consilience in Radiometric Measures of Geologic Time." *Philosophy of Science* 87: 425-456.

BBB. Forthcoming. [pub. info to be filled in.]

Bowler, P. J. (1992). *The Earth Encompassed.* New York: W. W. Norton & Company.

Chang. H. 2012. *Is Water* H_2O*?* Dordrecht: Springer.

—. 2009. "Ontological Principles and the Intelligibility of Epistemic Activities." In H. W. de Regt, S. Leonelli, and K. Eigner, *Scientific Understanding: Philosophical Perspectives.* Pittsburgh: University of Pittsburgh Press.

—. 2008. “Contingent Transcendental Arguments for Metaphysical Principles.” In M. Massimi, *Kant and Philosophy of Science Today*. Cambridge: Cambridge University Press.

—. 2004. *Inventing Temperature.* Oxford: Oxford University Press.

Cleland, C. E. 2002. “Methodological and Epistemic Differences between Historical Science and Experimental Science.” *Philosophy of Science* 69: 474-496.

Currie, A. M. 2016. “Hot-Blooded Gluttons: Dependency, Coherence, and Method in the Historical Sciences.” *British Journal for the Philosophy of Science,* 68: 929-952.

—.2018. *Rock, Bone, and Ruin: An Optimist’s Guide to the Historical Sciences.* Cambridge, MA: MIT Press.

—. 2021. “Stepping Forwards by Looking Back: Underdetermination, Epistemic Scarcity and Legacy Data.” *Perspectives on Science,* 29 (1): 104-132.

Currie, A. and K. Walsh. 2018. “Newton on Islandworld: Ontic-Driven Explanations of Scientific Method. *Perspectives on Science,* 26(1): 119-156.

Dalrymple, G. B. (2001). “The age of the Earth in the Twentieth Century: A Problem (Mostly) Solved.” In C. L. E. Lewis and S. J. Knell, *The Age of the Earth: from 4004 BC to AD 2002.* London: The Geological Society.

—. 1991. *The Age of the Earth.* Palo Alto: Stanford University Press.

De Laeter, J. R. (1998). “Mass Spectrometry and Geochronology.” *Mass Spectrometry Reviews,* 17: 97-125.

Dickin, A. P. (2018). *Radiogenic Isotope Geology.* Third edition. Cambridge, UK: Cambridge University of Press.

Dowden, B. (n.d.) Frequently Asked Questions about Time. *The Internet Encyclopedia of Philosophy,* ISSN 2161-0002, https://iep.utm.edu/, October 23, 2022.

Forber, P. and E. Griffith. (2011). "Historical Reconstruction: Gaining Epistemic Access to the Deep Past." *Philosophy and Theory in Biology,* 3: 1-19.

Friedlander, G. and J. W. Kennedy. (1949). *Introduction to Radiochemistry.* New York: John Wiley & Sons.

Galison, P. *Image and Logic.* Cambridge, MA: MIT Press.

Glasstone, S. (1950). *Sourcebook on Atomic Energy.* New York: D. Van Nostrand Co.

Halliday, D., Resnick, R., and J. Walker. (1994). *Fundamentals of Physics, Fifth Edition.* New York: John Wiley & Sons, Inc.

Holmes, A. (1937). *The Age of the Earth.* Second edition. London: Thomas Nelson & Sons Ltd.

—. (1947). "The Construction of a Geological Time-Scale." *Transactions of the Geological Society of Glasgow* xxi: 117-152.

—. (1959-1960). "A Revised Geological Time-Scale." *Transactions of the Geological Society of Glasgow* 17: 183-216.

Inghram, M. G. (1948). "Modern Mass Spectroscopy." In L. Marton, *Advances in Electronics, Volume 1.* New York: Academic Press, Inc.

Jeffares, B. (2008). "Testing Times: Regularities in the Historical Sciences." *Studies in History and Philosophy of Science* C 39 (4): 469-75.

Johnson, C. M., McLennan, S. M., McSween, H. Y., and R. E. Summons. "Smaller, Better, More: Five Decades of Advances in Geochemistry." In Marion E. Bickford, *The Web of Geological Sciences: Advances, Impacts, and Interactions.* Boulder: The Geological Society of America.

Jones, T. (2000). *Splitting the Second.* Bristol: IOP Publishing Ltd.

Kosso, P. (2001). *Knowing the Past: Philosophical Issues of History and Archaeology.* Amherst, NY: Humanity Books.

Landes, D. S. (2000). *Revolution in Time.* Cambridge, MA : Harvard University Press.

—. (1987). "Techniques et Révolutions Scientifiques: L'Exemple de la Mesure du Temps." *History and Technology* 4: 531-541.

Lucas, G. (2005). *The Archaeology of Time.* London: Routledge.

Mattinson, J. 2013. "The Geochronological Revolution." In Marion E. Bickford, *The Web of Geological Sciences: Advances, Impacts, and Interactions.* Boulder: The Geological Society of America.

Nier, A. O. C. (1939). "The Isotopic Constitution of Radiogenic Leads and the Measurement of Geological Time. II." *Physical Review* 55: 153-163.

Nier, K. A. (2016). "The Development of Mass Spectrometry in the Earth and Planetary Sciences." In M. L. Gross and R. M. Caprioli, *The Encyclopedia of Mass Spectrometry, Volume 9: Historical Perspectives Part A: The Development of Mass Spectrometry.* Amsterdam: Elsevier.

Novick, R. & Haueis, P. (2023). "Patchworks and Operations." *European Journal for Philosophy of Science* 13: 1-21.

Page, M. D. (2021). "The Role of Historical Science in Methodological Actualism." *Philosophy of Science* 88: 461-482. In N. Oreskes and J. Krige (eds.),

Rudwick, M. J. (2014). *Earth's Deep History.* Chicago: University of Chicago Press.

Rutherford, E. (1906). *Radioactive Transformations.* London: Archibald Constable & Co., Ltd.

Shipley, B. C. (2001). "'Had Lord Kelvin a Right?': John Perry, Natural Selection and the Age of the Earth. In C. L. E. Lewis and S. J. Knell, *The Age of the Earth: from 4004 BC to AD 2002.* London: The Geological Society.

Sterelny, K. (2007). "Macroevolution, Minimalism, and the Radiation of the Animals." In D. L. Hull and M. Ruse, *The Cambridge Companion to the Philosophy of Biology.* Cambridge, UK: Cambridge University Press.

Strevens, M. (2005). "How are the Sciences of Complex Systems Possible?" *Philosophy of Science,* 72: 531-556.

Tal, E. (2016). "Making Time: A Study in the Epistemology of Measurement." *British Journal for the Philosophy of Science*, 67: 297-335.

Tamborini, M. 2020. "Technoscientific Approaches to Deep Time." *Studies in History and Philosophy of Science Part A*, 79: 57-67.

Turner, D. (2007). *Making Prehistory.* Cambridge, MA: Cambridge University Press.

—. (2016). "A second look at the colors of the dinosaurs." *Studies in History and Philosophy of Science Part A*, 55: 60-68.

Valde, K. G. (2019). *Philosophical Perspectives on Time in Biology.* Dissertation. Cambridge, MA: Boston University.

White, W. M. (2015). *Isotope Geochemistry.* Chichester: John Wiley & Sons, Ltd.

Wimsatt, W. (1994). "The Ontology of Complex Systems: Levels of Organizations, Perspectives, and Causal Thickets." *Canadian Journal of Philosophy Supplementary Volume,* 20: 207-274. Reprinted in Wimsatt, (2007). *Re-Engineering Philosophy for Limited Beings.* Cambridge, MA: Harvard University Press.

Wylie, A. (2017). "How Archaeological Evidence Bites Back: Strategies for Putting Old Data to Work in New Ways. *Science, Technology, & Human Values*, 42: 203-225.

—. (2020). "Radiocarbon Dating in Archaeology: Triangulation and Traceability." In S. Leonelli and N. Tempini, *Data Journeys in the Sciences.* Cham: Springer.

Wyse Jackson, P. N. (2001). "John Joly (1857-1933) and His Determinations of the Age of the Earth." In C. L. E. Lewis and S. J. Knell, *The Age of the Earth: From 4004 BC to AD 2002.* London: The Geological Society.

Yochelson, E. L. & Lewis, C. L. E. (2001). "The Age of the Earth in the United States (1891-1931): From the Geological Point of View." In C. L. E. Lewis and S. J. Knell, *The Age of the Earth: from 4004 BC to AD 2002.* London: The Geological Society.

Zeuner, F. E. (1958). *Dating the Past.* 4th edition. London: Methuen & Co. Ltd.