WHAT MAKES THE HISTORICAL SCIENCES TICK? GEOCHRONOLOGY AND THE ONTOLOGY OF SCIENTIFIC METHODS

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Abstract

There has been increasing philosophical interest in the role of technological progress in the historical sciences. Geochronology is the field of geology devoted to the measurement of geologic time. It experienced an explosion of its research boundaries in the 20th century. I explain this productivity by analyzing the ontology implicit in geochronological techniques. The immediate object of inquiry of geochronological measurement is the 'apparent age' of a sample. This concept is not intrinsic to the geological domain, but to the measurement method, and its adoption allowed the measurement of geologic time to be detached from specific geologic processes. The application of the concept presupposes a mereological decomposition of geologic samples into their constituents. I argue that mereological relations introduce a further dimension in our understanding of the methodology of the historical sciences. In conclusion, I argue that the geochronological case illustrates a more general dynamic caused by modern science's dependence on technology.

1 Introduction

The establishment of an absolute timescale for geological events is one of the great achievements of 20th century science. In the early 19th century, a stratigraphical column had been established, allowing every stratum of rock to be assigned to a unique period of deposition in the Earth's history. These strata are accumulated (and later often eroded, dislocated, folded and broken up) in the course of time, in ancient seas, lakes, rivers, deserts or glaciated areas. The study of these strata is called stratigraphy. The basic principle underlying it is the law of superposition, according to which one layer covering another must be younger than the covered layer, unless displacements occurred after deposition. This law, however, did not permit strata in one location to be correlated with those in another, because the same kind of rock had been laid down at different periods in the Earth's history in different locations. It had been discovered that certain fossils were characteristic of particular epochs and could be found in all rocks formed at that time, whatever their mineral composition. The fossils allowed rocks of equivalent period of origin to be correlated, and a complete sequence of rock formations could be established. This corresponded to a complete sequence of the geological periods in the last 500 million years of Earth's history. [1]

This sequence 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. This paper is about the problem of time-measurement in historical geology and the role of technology in solving it.

[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).

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, 2015). Recently, he has argued that technology plays an important role in extracting new information from legacy data (Currie 2021).

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. In Currie's vocabulary, technology allows them to overcome the situation of 'epistemic scarcity' those scientists find themselves in. Technology is generally viewed as a means to this pre-given end in this literature.

In contrast, my focus here is on certain productive functions of technology. These functions are "productive" in the sense that they shape both the concepts used and the kinds of questions asked, and answered, in the field. In the case at hand, these functions arise from the need to apply the concept of time to the deep past. This application is a species of what Chang (2004, ch. 3) calls the 'metrological extension' of a concept, which occurs "when we make the concept measurable in a new domain."

Making the concept of time measurable in the deep past involved the primary function I have in mind, that of *precisifying the concept of time employed*. Historical sciences are, of course, intimately concerned with time and must presuppose some concept of it to engage in historical reconstructions. Histories of geochronology typically credit modern geochronology with making geological age quantitative. Less celebrated, but crucial for understanding the historical dynamics of the field, is the distinction between the 'apparent age' (also called the 'date') of a sample, and its 'geologic age' (or just 'age'). This distinction arises from the application of the law of radioactive decay to the geologic domain, and is intimately connected to the technology used to apply it. The apparent age is a mathematical result derived from the decay law that has to be geologically interpreted to give a geological age. This need for interpretation complicates chronological inferences, and so may be considered an epistemic cost. On the other hand, the law's abstraction from geologic context reflects the wide range of conditions under which it holds. The ability to exploit this range has yielded many epistemic benefits. This ability is technologically mediated. The law could not be applied were it not for the existence of specific instrumentation, of which the workhorse is mass spectrometry.

This instrumentation enables a second function of technology to come into play. It allows the law to be applied to samples reflecting the extremely wide range of conditions under which the law holds. To characterize this function more generally, albeit in slogan form, one might say that the instrumentation *permits the exploration of the possibilities implied by the law*. 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—albeit in the form of enrichment rather than replacement—because the time-keeper that was found, radioactive decay, turned out to have properties that provided research opportunities that wouldn't have been available with the other candidates that were considered. 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."

Rather than use the vague term 'technology,' I will frame the technological question in terms of 'scientific methods.' 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 sense (2012). Nevertheless, my analysis is 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.

In this paper I will consider radiometric dating in the historical-epistemic context in which it emerged. Section 2 begins with a general discussion of how clocks work, focusing on the nature of the proxy processes that are used to measure time. I then relate these notions to the geochronological case, showing how the general problem of measuring time interferes with a problem besetting the historical sciences, what Derek Turner has termed the 'asymmetry of manipulability.' I argue that these two problems were solved, albeit tentatively at first, by radiometric methods. I then 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. In section 3, I use Wimsatt's (1994) theory of compositional hierarchies to argue that this success can be understood as resulting from an ontological shift to lower levels of organization. Indeed, I will argue that the quest for a geologic time-keeper lead to a shift in the ontology of geochronology that was crucial for its eventual success. Mereological decomposition allowed geochronologists to exploit the decay law, and was itself made possible by the available technology. Throughout this account, what I want to emphasize is the *productivity* of the decompositionist approach in this case.

I apply this argument to the problem of epistemic scarcity in geochronology. I argue that the adoption of radiometry can be explained as largely an attempt to mitigate the context-dependence of more classic geological methods. Though mitigation was only partial,[3] it was sufficient to allow a plethora of applications to be developed, thus turning a situation of epistemic scarcity into one of abundance. In conclusion, I argue that the geochronological case illustrates a more general dynamic caused by modern science's dependence on technology.

2 Measuring Time Without Clocks

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.[4] The basic principle of a clock is to exploit a repetitive process that can serve as a proxy for the passage of time.[5] The number of repetitions is kept track of by a counter. For example, with mechanical watches, the proxy is an oscillating

[3] As shown in detail by Bokulich (2020) and Wylie (2020).

[4] 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).

[5] 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."

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 counted 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.
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.[6] In theory, it does not seem necessary that the rate of the process be constant in order to measure time, 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 general, 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

[6] 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).

manipulability' to be discussed in the next paragraph. In practice, then, time measurement is greatly facilitated by the assumption of constancy.

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.

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 other clocks, it is not observable but remains indirectly manipulable, as with atomic clocks. Unfortunately for historical scientists, neither option is unavailable 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.[7]

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

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[7] Currie (2019) disputes that this asymmetry can ground a distinction between experimental and historical science. He does, however, acknowledge an epistemic privilege for sciences that can repeat experiments. And this seems to me the essential point here: makers of artificial clocks can engage in repeated experimentation and tinkering to perfect the proxy process and counter, whereas geochronologists cannot. Moreover, his view supports my claim above that the problem of finding a good proxy was rooted in the requirements of time-keeping rather than in the doctrine of uniformitarianism.

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.

2.1 Classical versus radiometric geochronology

In the case of geochronology, several macroscopic phenomena were investigated as candidates for time-keeper:[8]

- 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, "Rhythms and the Measurements of Geologic Time," the American geologist Joseph Barrell critically examined all attempts to measure time via stratigraphical clocks (excluding varves),

[8] 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.

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.[9] 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. This 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).

True, 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 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).

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

By mid-20th century, however, a method had been settled on, based on the non-geological proxy of radioactive decay.[10] 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 an instrument known as the mass spectrometer.

[10] 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).

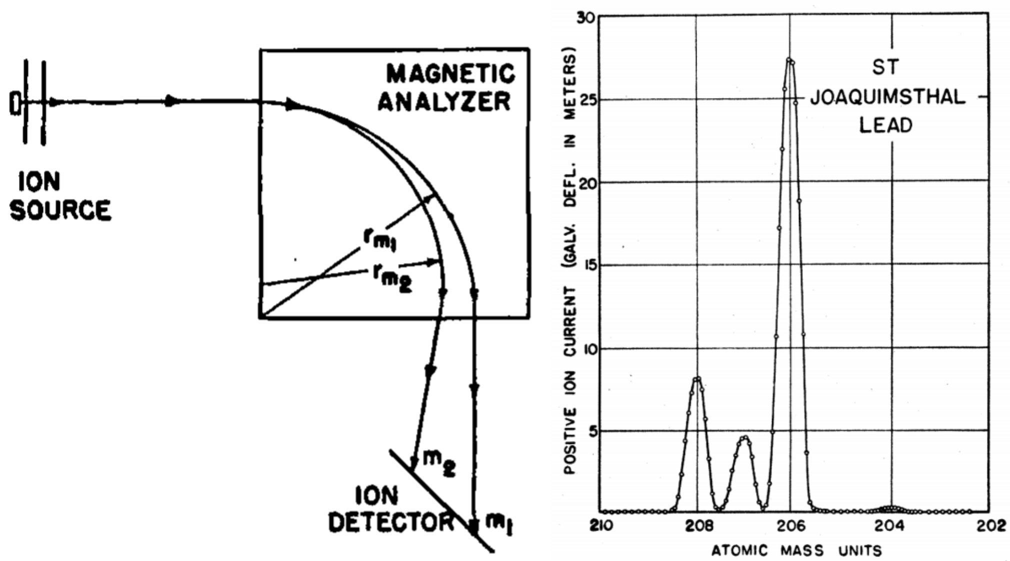

Figure 1. The diagram at the left represents a mass spectrometer. The atoms in the sample are ionized in the ion source, and then separated by mass in the mass analyzer, before hitting the detector, which records the current obtained for each atomic mass. From Inghram (1948, 222). The output is a mass 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

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

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). 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).

The apparent age has physical meaning, referring to the time elapsed since the rock or mineral containing the radioactive elements finally solidified or crystallized.

2.2 Precisifying the concept of time employed

To see why I claimed, in the introduction, that the method precisifies the concept of time deployed, let us take a closer look at how (1) is arrived at.[11] (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 the probability that any given nucleus will disintegrate in the interval of time dt. It 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 released is so large relative to that of other natural processes, the

[11] The following discussion relies on Allègre 2008.

rate of decay is unaffected by the environment, except in nucleosynthetic contexts like stars or supernovae. For the same reason, the process cannot be reversed, 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:

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

(4) can then be expressed as

$$5.\quad \frac{N}{N_0} = e^{-\lambda t}$$

Further manipulation then yields (1). (1) can then be rearranged to give the formula for the apparent age:

$$6.\quad t = \frac{1}{\lambda} \ln \left\{ \left[\frac{D - D_0}{N} \right] + 1 \right\}$$

The apparent age is a concept of time as an isotope ratio converted into time units. As noted, interpreting it as a geologic age is not straightforward. The apparent age is chemical and isotopic. It is of physical and geologic 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. In addition, the apparent age has to be associated with a significant geological event in the history of the rock or mineral. Significant calibration is required, including against nonradiometric methods (Bokulich 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 is a source of 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 (6) expresses the fact that the rate 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. Here, it is important to emphasize the activities involved in the application (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. The chemical analysis in (i) 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. 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. 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. 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.

The adoption of this method resulted in what I've been calling the 'precisification' of the concept of time. This process resembles the definition of concepts by genus and difference. I use the term 'precisification,' however, to allow for cases where a discontinuity, or other conceptual tension, is introduced by a new species. In such cases the process resembles precising definitions, which reduce ambiguity or vagueness.[12]

That said, my purpose in drawing these analogies is not to make a claim about how scientific terms are defined, but rather to characterize the process by which they came about in the case at hand. The general concept of an 'age' is, of course, taken from everyday usage where its meaning involves the passage of time since the origin or formation of a thing. The concept of a 'geological age' is a precisification of the general concept brought about by the application of the latter to geology. It can be further precisified by the kind of data used to determine it, e.g. as a relative or absolute age (see footnote 1). Radiometry introduces a further distinction, between the geologic age and the apparent age. The driving force behind each step could vary. The notion of a 'geologic age' in general would seem to be dictated by the domain

[12] This discussion of precisification is loosely inspired by Gaston Bachelard's notion of 'phenomenotechnics.' According to Bachelard, scientific change occurs through the 'deformation' of concepts as they are applied in experiment. For overviews, see Gaukroger (1976) and Rheinberger (2005).

of interest. And one could always distinguish between a temporal ordering and a quantification. But the distinction between geologic and apparent age is one made both possible and necessary, for the practitioners, by the adoption of a specific method of measurement. Possible, because the apparent age is a concept that depends on the nature of the method. Necessary, because the practitioners could not successfully apply the method to the geological domain without introducing the distinction.

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 scarce. The discovery of extinct radionuclides 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 radionuclides allowed ages, in the sense of the time elapsed since formation to the present, to be established at all. This avoided gaps with the present due to interruptions of the process, a problem affecting some of the classical methods. Finally, the constant 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.

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. 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.[13] These methods come with an ontological commitment: they presuppose a world structured by compositional levels of organization. This commitment is evident in the transformation of the object of inquiry: The rock is first transformed into compounds representing its constitutive elements. These elements are then separated 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,[14] give access to entities that belong to a different ontological level than the original object.[15] This is the case with 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

[13] 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.

[14] 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. Because of these features, it may “get more difficult to localize an entity or phenomenon by level unambiguously and for all contexts.” He cites ecosystems and the biosphere as examples (Wimsatt 1994, 257ff).

[15] For a sampling of the state of the art in the philosophical literature on levels of organization, see Brooks, DiFrisco, and Wimsatt (2021). Though the concept of levels has been challenged (e.g. Potochnik 2021), I find it convenient to discuss this case in terms of them, insofar as it helps think about the role of part-whole relationships and scale in geochronological methods. But I do not think the analysis presented here depends on the acceptance of levels as a broader doctrine.

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.

2.3 The flourishing of isotope studies[16]

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

[16] 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.

Of course, all this growth was not solely due to ontological shifts. Cold War funding, other scientific developments (e.g. on the theoretical plane), and the painstaking development of instruments were also vital.[17] The sheer variety of isotope systems that exist in nature was also essential, since no one system can be used for all these studies.[18] 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.

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[17] See Shindell (2014) and Doel & Oreskes (2002) for studies of the impact of Cold War funding, de Laeter (1998) and **BBB** (under review) for studies of the technological developments, and Doel (1997) for a theory-focused account.

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

3 Level-switching as an approach to epistemic scarcity

My emphasis on developmental possibilities informs the problem of epistemic access to the deep past that philosophers have focused on. The history of geochronology, and offshoots like stable isotope mass spectrometry, produced a plethora of methods for studying the past. Rather than epistemic scarcity, geochemists are faced with epistemic abundance. How did they achieve this situation? In this section, I will argue that mereological level-switching was part of the answer, 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. This allows 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 2001, 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).

The analysis of the preceding sections has shown that 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.[19] The case of geochronology illustrates one reason for this: 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.

[19] Finkelman (2019) claims that information in the life sciences is hierarchical in general, and argues that this fact plays an important role in paleontologists' inferences.

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.[20] 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.[21]

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.

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[20] That said, I do not claim that level-switching must always go downwards. As Adrian Currie has pointed out to me, switching up a level can unify an apparently unique phenomenon with a set of other phenomena (Buskell and Currie 2021).

[21] 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 a certain kind of inference.

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,[22] 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:[23]

[22] This is the case, for example, with the formation of the pleochroic halos discussed above.
[23] 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 element 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.

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 5,800,000,000° 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).

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 2.1 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 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.

4 Conclusion: Expanding the Parametric Space of Geochronology

In conclusion, I return to the role of technology in the historical sciences. Though it is often said that the historical sciences study the deep past, the concept of time deployed in those sciences is rarely problematized. In this paper, I have examined the role of technology in geochronology and argued that it plays an important role in (i) making time into a concept measurable in the deep past, that it does so by (ii) enabling the application of the law of radioactive decay to the geologic domain, and (iii) that it permits the exploration of the possibilities implied by the law.

To put the matter in a broader perspective, one way of thinking about the relation between technology and time is in terms of a 'parametric space' (Rescher 1978). Physical processes can be characterized in terms of certain parameters, of course, and these parameters can take on certain values within a spectrum. Familiar examples are space, time, temperature, pressure, velocity, frequency, mass, density. Together, these parameter-ranges comprise a 'parametric space' within which physical phenomena can be positioned. Technology plays an indispensable role in exploring this space. In the case of geochronology, technology played this role in two ways. First, by providing a tool for measuring time in a particular way. Second, by permitting the exploration of the resulting, expanded, parametric space.

For Rescher, the exploration of parameter space by means of technology is a general function of the latter in the natural sciences, which depend on discovering new kinds of data to test and develop theories. So, though the details of how this function is realized in a given science are contextual, the function itself transcends the particular science. In the case of the historical sciences, the kinds of data involved are traces of past events. Trace-based reasoning depends on (i) identifying traces and (ii) having regularities to support inference from the traces to past events (Currie 2019). Technology allows scientists to find traces and to apply regularities linking those traces to the past. With a given technology, scientists will eventually exhaust the information obtainable from the traces accessible with that technology (note that this is not the same problem as information destruction). New technology will be needed to discover new traces. The history of 20th-century geochronology is an excellent illustration of this dynamic as it, to a considerable extent, consisted in a co-evolution of technology and trace discovery, as geochronologists exploited the potential of mass spectrometry to access the many kinds of isotope systems in nature, thereby deepening their reach into the past.

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