GEOBIOLOGY

Sophia Roosth – *New York University*

Suggested Citation: Sophia Roosth, "Geobiology," *Encyclopedia of the History of Science* (September 2025)
doi: 10.34758/zzgv-av25

Geobiology is a scientific field that combines the tools, methods, and theories of the earth and life sciences to study the co-evolution of Earth and its biosphere.[1] Geobiologists and allied scholars in fields such as micropaleontology, biogeochemistry, geochronology, and astrobiology travel the world in search of Precambrian fossils – that is, the lithified or silicified remains of organisms that are more than 541 million years old. Sometimes, they search for these organisms' chemical biosignatures. Such biosignatures include isotopic compositions indicative of organic processes, as well as traces of organic molecules, minerals, or biologically formed sediments that can indicate, but not necessarily fully prove, the presence of ancient life. An even more indirect biosignature useful to astrobiologists is planetary atmospheres (past or present) that either could possibly sustain or be the result of metabolic processes. Such chemical traces are especially important to Precambrian geobiologists, as ancient life is unlikely to fossilize bodies, molds, casts, or traces of an organism. Geobiologists hope that a preponderance of multiple such indices in a single locale (whether an outcrop or an entire planet) will further scientific understandings of the origins of life on Earth as well as suggest ways researchers might seek evidence of life elsewhere – on Mars and icy moons, for example. The theoretical engine of geobiology is the faith that Earth and life are mutually informing forces, that life cannot be meaningfully sutured from its inorganic milieu (or, more

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[1] While there is a rich literature on the history of geology, little has been said on the history of geobiology. Martin Rudwick is the most prolific historian of geology, whose work has charted the pre-Darwinian earth sciences from the eighteenth century to the Victorian era, narrating both the origins of the concept of "deep time" as applied to Earth history as well as the relationship of the earth sciences to Christianity. Rudwick, *The Great Devonian Controversy*; Rudwick, *Bursting the Limits of Time*; Rudwick, *Worlds Before Adam*; Rudwick, *Earth's Deep History*. The history of the Cambrian-Silurian controversy in the early Victorian period is carefully recounted by Secord, *Controversy in Victorian Geology*. Adelene Buckland details the surprising relationship between the Victorian novel and geology: Buckland, *Novel Science*. Naomi Oreskes offers an account of why the theory of plate tectonics ("continental drift") remained controversial, particularly among American geologists, for much of the twentieth century: Oreskes, *The Rejection of Continental Drift*; Oreskes, *Plate Tectonics*. For a history of twentieth-century Phanerozoic paleobiology, and how it was shaped by computer sciences, genetics, and "big data," see Sepkoski, *Rereading the Fossil Record*; Sepkoski and Ruse, *The Paleobiological Revolution*.

accurately, that all of life and nonlife on Earth constitute one another ***as a milieu***).[2] Further, it posits that the planet has changed in concert with the evolution of early life and that microbial metabolism is one of, if not the, central driver of Earth's atmosphere. Although geobiology did not cohere into a directed research agenda until the late 1950s and 1960s, one early precursor for geobiological reasoning comes with Vladimir Vernadsky's coinage of the term "biosphere."

Geobiological research today is diverse, incorporating traditional fieldwork such as stratigraphy, sedimentology, and paleontology, laboratory methods such as isotope geochemistry and molecular sequencing, and computer modeling. Nonetheless, it is united by a concern for how the biosphere and the geosphere have formed one another over billions of years. While evolutionary biologists and ecologists study how organisms evolve by adapting to environmental niches, life scientists are less concerned with the flipside of natural selection – that, as organisms evolve, they necessarily sculpt the physical structure and chemistry of the planet on which they live. For example, geobiologists have shown that the evolution of photosynthetic cyanobacteria, coincident with reduced volcanic activity, triggered the oxygenation of the Earth's atmosphere and radically changed ocean chemistry, which in turn affected what kinds of both minerals and organisms could subsequently evolve in these new environments.

Because answering a question as complex and multifaceted as the coevolution of life and Earth requires multiple methods, tools, and principles that have been developed in diverse fields ranging from evolutionary biology to geochemistry to microbial ecology to stratigraphy, micropaleontology, and much else, it is a somewhat unwieldy field with porous and changeable boundaries. While it bears many of the familiar markers of a scientific discipline – dedicated journals, conferences, and awards – even its own practitioners can and do disagree about what does or does not "count" as geobiology. As such, it represents a limit case for historians of science interested in historicizing research programs that are situated at the interface of or in between other, more firmly settled, scientific disciplines, or ones that are less intuitively defined than, say astronomy or chemistry. Such debates shed light on how scientific disciplines or subdisciplines engage in ongoing boundary-work as fields grow, splinter, adapt, or integrate. Finally, much has been written in recent years by historians seeking to understand the historical precursors and conditions for the Anthropocene as both a putative geological period and as an analytic device. Importantly, because geobiologists have long insisted that life has shaped and continues to shape the planet, geobiology might provide a corrective to recent scholarship that has spent time ruminating on the geological as a concept without also paying close attention to geologists themselves and what their work looks like.

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[2] I here use the term *milieu* rather than the more common "ecosystem" or "environment" to point to how organisms and their contexts are mutually influential. For a conceptual history of this use of milieu, see Canguilhem, *A Vital Rationalist*; Canguilhem, "The Living and Its Milieu."

Vladimir Vernadsky was a Soviet geochemist and self-described "cosmic realist" whose use of "biosphere" was inspired by discussions with Edouard LeRoy, Henri Bergson, and Pierre Teilhard de Chardin while traveling in France and teaching at the Sorbonne from 1922 to 1925.[3] LeRoy and Bergson were then philosophers of biology at the Collège de France; Teilhard was a Jesuit mystic, philosopher, and professor of geology who in his 1922 book *Cosmogenesis* conceived of the "noösphere," which is a concept positing that the planet itself, taken as a whole, exhibits consciousness.[4] Following Teilhard's thinking, in 1926 Vernadsky coined "biosphere" (Биосфера, *biosphera*) to describe how life acts as a geological force that irreversibly shapes Earth.

Vernadsky credits an earlier use of "biosphere" to Austrian geologist Eduard Suess, whom he had met in Vienna in 1911.[5] In *Das Antilz der Erde*, Suess defines the biosphere as an idea that "assigns to life a place above the lithosphere, concerned only with life on this planet and all the conditions in regard to temperature, chemical composition, and so forth, necessary for its existence, and leaves on one side all speculative hypotheses as to possible presence of living beings on other heavenly bodies. Determined by these conditions, the biosphere is a phenomenon limited not only in space, but also in time."[6] Suess's biosphere, unlike Vernadsky's, was a category by which to describe the niche that nurtures life as we know it, not a theory by which to elucidate how biological and geological energies are impressed upon one another.[7]

Astonishingly, long before microfossils had been identified in Precambrian rocks, Vernadsky postulated their existence. Central to his argument about the biosphere were a series of premises: a denial of abiogenesis, a Lyellian commitment to uniformitarianism, and, following the work of James Hutton, a faith in Earth as a kind of super-organism. From these principles, he deduced that biological processes have always exerted a powerful physical and chemical force on the planet and, further, that one cannot fruitfully study geological history without taking living phenomena into account. Accordingly, he wrote in 1926: "The oldest Archean beds furnish indirect indications of the existence of life; ancient Proterozoic rocks, and perhaps even Archean rocks, have preserved actual fossil remains of organisms....

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[3] Guillaume, "Vernadsky's Philosophical Legacy"; Piqueras, "Meeting the Biospheres."

[4] Teilhard de Chardin, "Geobiologie et Geobiologia." Teilhard de Chardin, *Man's Place in Nature*. Vernadsky et al., *The Biosphere*.

[5] Piqueras, "Meeting the Biospheres."

[6] Suess, *The Face of The Earth* Vol. 4, 637.

[7] Suess, *Die Enstehung der Alpen* [*The Origin of the Alps*]; Hutchinson, "The Biosphere"; Piqueras, "Meeting the Biospheres"; Vernadsky et al., *The Biosphere*.

Archean rocks correspond to the oldest-known accessible parts of the crust, and contain evidence that life existed in remotest antiquity at least 1.5 billion years ago."[8]

Vernadsky's work was pilloried by Soviet Marxist scientists soon after publication for being overly vitalistic, and Vernadsky remained outspoken in his defense of scientific autonomy in subsequent decades. While *Biosphere* was translated into French three years later in 1929, it was unavailable to English readers for decades. Vernadsky would not be recognized, either within or beyond the USSR, until midcentury, when growing concerns about climate change made his work newly relevant.[9] His son, George Vernadsky, completed a dissertation at the University of St. Petersburg in 1917, and then relocated annually while fleeing the Soviet Secret Police, eventually emigrating to Prague before receiving an invitation in 1927 to teach as a research associate in Russian History at Yale University.[10] While at Yale, he introduced his colleague, eminent ecologist G. Evelyn Hutchinson, to his father's work. Hutchinson required that all his students read Vernadsky's work in French as early as 1935, and had two of his papers translated into English in 1944 and 1945. The second paper appeared in print just days after Vernadsky's death.[11] Hutchinson's championing of Vernadsky's work made Vernadsky relevant to midcentury American ecology, as attested to by the fact that he was cited in Eugene Odum's foundational *Fundamentals of Ecology* (1953).[12] However, U.S. earth scientists during the Cold War, focused as they were on physical geology, geophysics, and natural resource discovery, and siloed from the life sciences, would not learn of Vernadsky's ideas until the 1990s.

Among the many precipitating factors for the emergence of contemporary geobiology was Stanley Tyler and Elso Barghoorn's discovery of Precambrian fossils in the "Gunflint Iron Formation" stretching from Minnesota to Southern Ontario. The co-evolution of Earth and life transpires on the order of hundreds of millions of years, and megascopic fossils are too shallow in planetary time to allow scientists to illuminate this history. While the possibility of Archean fossils has long been contemplated by geologists – indeed, the problem of a missing Precambrian fossil record vexed Darwin in the *Origin* – proof positive of vestiges of Precambrian life was only established in the 1950s. Stanley Tyler, a mineralogist at the University of Wisconsin, studied iron ore, a substance whose supply was indispensable to the midcentury American steel industry. In 1950, Tyler found in a test pit dump of a Michigan

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[8] Vernadsky et al., *The Biosphere*, 56.

[9] Ghilarov, "Vernadsky's Biosphere Concept"; Oldfield and Shaw, "V.I. Vernadskii."

[10] He would later serve as a full Professor of Russian History at Yale (1946-1956). Ferguson, "George Vernadsky, 1887 – 1973."

[11] Trubetskova, "From Biosphere to Noosphere"; Vernadsky, "Problems of Biogeochemistry"; Vernadsky, "The Biosphere and the Noösphere."

[12] Ghilarov, "Vernadsky's Biosphere Concept"; Oldfield and Shaw, "V.I. Vernadskii."

steel corporation a sample of black rock he believed might be coal, but found himself baffled by the rock's age. The oldest known coal at the time was Carboniferous (dating to about 359 million years ago), and geologists at the time understood that coal was the residuum of seedless swamp forests that decayed into peat and then carbonized following tidal events. But this coal was found in rocks Tyler knew to be immensely older, much older than any land plant: the test pit was located, he noted, in the Upper Huronian Michigamme Formation, meaning that if the rock had originated in situ, it was approximately 1.9 billion years old.[13] The appearance of coal that predated plants seemed like a contradiction in terms. If coal is dead life, what life was ancient enough to make this coal?

While visiting Cambridge, Massachusetts for the meeting of the Geological Society of America, he shared his samples with Robert Shrock, chair of MIT's Department of Geology and Geophysics, who directed him to Elso Barghoorn, a new biology professor at Harvard University who had studied fungi that degraded soldiers' binoculars in the Pacific Ocean Theater during World War II. Barghoorn confirmed that the samples were, in fact, Precambrian coal, and he and Tyler began to collaborate. Tyler and Barghoorn determined that 1.9 billion-year old algae had silicified in the coal; these were the oldest known such fossils to date.[14] Until then, paleontology had only dealt with relatively recent and big fossils – dinosaurs, ferns, trilobites – but the discovery of microfossils extended paleontology into the Precambrian and even Archean eons.[15]

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[13] Stanley Tyler to Elso Barghoorn, February 15, 1951, Papers of Elso Barghoorn, HUG(FP) 113.10 Box 25, folder 6, Harvard University Archives.

[14] A series of technological developments enabled Barghoorn and Tyler to verify their findings. Radiometric dating was pioneered by multiple physicists in the first years of the twentieth century but first applied to geology in 1910 by British physicist and geologist Arthur Holmes and his mentor, Frederick Soddy. The principle of radiometric dating is this: different chemical elements naturally occur in multiple isotopes, meaning that the number of neutrons in the nucleus of the element varies (each different number of neutrons is called a "nuclide"). These isotopes are unstable, and different isotopic elements have different standard half-lives over which they decay. By measuring nuclide decay in a sample, a scientist essentially has a "molecular clock" by which to date a sample. This method provided a new and absolute measure for dating both rocks and the age of the planet itself, which supplemented stratigraphic (or "relative") dating methods. Holmes, *The Age of the Earth*; Lewis, *The Dating Game*. By the end of World War II, the increasing prevalence of mass spectrometry, as well as an influx of atomic physicists into the earth sciences, made radiometric dating a common technique in geology, with profound implications for theories of ancient Earth and life. Simply put, mass spectrometry is an analytical method that sorts the components of a sample by their mass in order to identify its elemental, isotopic, and molecular constituents. Shindell, "End of the World." Most importantly, radiometric dating established that the Cambrian age (which in 1930 was renamed the "Phanerozoic") was insignificant compared to the vast expanse of Precambrian time. While stratigraphy and the fossil record had allowed geologists to broadly date Cambrian history, it was now possible also to differentiate between different periods in the Proterozoic (that is, the geological eon immediately predating the Cambrian), even absent any fossils.

[15] Today, the oldest known putative fossilized microbialites are over 3.7 billion years old, though whether the structures in those rocks were formed by biological activity is currently contested. For recent histories of nineteenth-century vertebrate paleontology, see Rieppel, "Bringing Dinosaurs Back to Life"; Rieppel, "Prospecting for Dinosaurs."

In the summer of 1953, Tyler discovered another formation while trout fishing in Lake Superior on a day off from prospecting iron-ore beds in southern Ontario. The outcrop he spied from his boat was thick with stromatolites interspersed with black chert. Stromatolites are somewhat like ancient fossilized coral reefs, if microbes rather than coral had built those reefs. Then known as *Cryptozoon* ("hidden animal"), stromatolites had been debated for half a century as to whether they were "real" biogenic fossils or "pseudofossils" (something that looks lifelike but has been proven inorganic).[16] Yet under the microscope, Tyler found within the chert structurally well preserved microscopic lifelike forms embedded in silica, "providing," in his words, "a glimpse through the Precambrian metamorphic veil."[17] After receiving dozens of slides from Tyler, Barghoorn was overwhelmed: he described the slides as "sensational" and reflected, "To study the morphology of extinct life at the pre-Cambrian level of development is something I had never thought I would be privileged to do."[18] The two decided to publish a report on their discovery to avoid being scooped by the Ontario Department of Mines. In 1954, they made a brief announcement in the pages of *Science* of their discovery of Precambrian cyanobacteria.[19] Tyler and Barghoorn set about preparing a longer, comprehensive manuscript on the Gunflint findings, collating more than 800 microscopic slides. Their work was slowed by multiple factors, but after a publishing race with his colleague Preston Cloud, Barghoorn published under duress a comprehensive account of the Gunflint in *Science* in February 1965.[20]

A few months later, Preston Cloud published his own paper, which verified Tyler and Barghoorn's discovery, putting to rest the worry that "they [Precambrian fossils] could have been produced by nonvital processes." He declared that these microfossils "are the most ancient recorded structures which closely resemble specific living organisms."[21] For the first time, the geological community universally endorsed the existence of Precambrian fossils. This was a sea change: scientists learned that much older life was thickly salted beneath our feet, most of it invisible to the unaided eye. Dinosaurs were old news and ancient microbes

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[16] Roosth, "The Shape of Life."

[17] Schopf, *Cradle of Life*, 38.

[18] Elso Barghoorn to Stanley Tyler, November 25 and December 14, 1953, Papers of Elso Barghoorn, HUG(FP) 113.10 Box 25, folder 6, Harvard University Archives.

[19] Tyler and Barghoorn, "Structurally Preserved Plants." Geobiologists Lynn Margulis and Andrew Knoll would later describe these black cherts as central to the foundations of modern geobiology: they were the "microbial Rosetta stones in the search for ancient life," teeming with "up to 1.5 million microfossils per cubic centimeter." Margulis and Knoll, "Elso Sterrenberg Barghoorn, Jr.," 97.

[20] Barghoorn and Tyler, "Microorganisms from the Gunflint Chert." Preston Cloud named himself Professor of Biogeology, though most researchers at the time (and now) describe themselves as geobiologists.

[21] Cloud, "Gunflint (Precambrian) Microflora," 27–28.

became mascots for a new discipline that would eventually coalesce under the name "geobiology."

A Precambrian land rush ensued. The first laboratory dedicated exclusively to geobiology (the Baas Becking Geobiology Laboratory) was established in Canberra, Australia in 1965, this named after the late microbial ecologist Lourens Baas Becking, who wrote a short scientific monograph titled *Geobiology* in 1934, in which he articulated the fundamental geobiological principle: "the organism is part of the Earth and its lot is interwoven with that of the Earth."[22] During this time, a handful of laboratories in the United States and abroad were working in part on Precambrian fossils. In the U.S., these were populated largely by the students of Elso Barghoorn and Preston Cloud, including Stanley Awramik, William Schopf, and Andrew Knoll (though many of these students would teach in geology departments and variably identify as paleontologists, paleobotanists, paleobiologists, or "biogeologists").[23] Papers on Precambrian fossils and paleoenvironments published during these years appeared in a range of journals devoted to paleobiology, paleontology, Precambrian research, and geochemistry.[24]

Tyler, Barghoorn, and Cloud's publications demonstrated, among other things, that Precambrian microfossils are most likely to be preserved in fine-grained shales and cherts. Aided by radiometric dating and advances in electron microscopy, a new generation of scientists had a good sense of both where and how to look for such organisms in the Earth's oldest sedimentary rocks, and a surge of Precambrian microfossil discoveries began in 1965. For example, William Schopf, Barghoorn's graduate student, identified 800-million-year-old microfossils in the Australian Bitter Springs Formation.[25] In the 1970s, Barghoorn and another graduate student, Andrew Knoll, discovered 3.4 billion year-old fossilized bacteria in Australia.[26]

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[22] Becking's definition of geobiology was largely presentist, as he focused on the contemporary relationship of extant microorganisms to their environments, rather than the geological record of life on Earth. He is best remembered for the (often misquoted) aphorism, "everything is everywhere: but the environment selects." Canfield, *Baas Becking's Geobiology*, 2.

[23] While I here focus on early U.S. geobiology, other laboratories investigating Precambrian biology were concurrently being established in Canada, Australia, and Western Europe.

[24] If journals, conferences, and textbooks are the mark of a mature discipline, then the field did not come into its own until the early twenty-first century: the journal *Geobiology* was established in 2003; the Gordon Research Conference on Geobiology was inaugurated in 2011; and undergraduate textbooks were only published in the last ten years.

[25] Schopf, "Microflora of the Bitter Springs Formation."

[26] Knoll, Barghoorn, and Golubić, "Paleopleurocapsa Wopfnerii Gen. et Sp. Nov."; Knoll and Barghoorn, "A Gunflint-Type Microbiota."

Among Barghoorn and Knoll's closest colleagues was evolutionary biologist Lynn Margulis. In the 1980s and 1990s, Lynn Margulis lobbied for an unabridged version of Vernadsky's *The Biosphere* to be translated into English. At the time, Margulis, a professor at Boston University (and later the University of Massachusetts, Amherst) and a close friend of Elso Barghoorn, was already distinguished amongst scientists for her theory of symbiogenesis, in which she took aim at neo-Darwinians by positing that prokaryotic cells incorporated one another as organelles to conceive eukaryotic cells: life did not succeed by competition, but by "networking."[27] She was lambasted and stigmatized for symbiogenesis until the preponderance of evidence balanced in her favor three decades later. She also popularized (alongside James Lovelock) the "Gaia hypothesis," which holds that Earth is "a complex entity involving the earth's atmosphere, biosphere, oceans, and soil. The totality constitutes a feedback or cybernetic system which seeks an optimal physical and chemical environment for the biota."[28] Margulis's understanding of Gaia was heavily informed by the first two decades of geobiological research, and in forwarding her theory, she cites, among others, Barghoorn, Stanley Tyler, Preston Cloud, Stanley Awramik, and William Schopf's work on topics including Precambrian stromatolites, microfossils, and paleoenvironments.[29] Gaia, like Vernadsky's biosphere, was a figure with which to think across the earth and life sciences in order to grapple with how life and Earth have contoured and determined one another's physical, chemical, and morphological features across planetary time.

Margulis learned of Vernadsky from philosopher of science Jacques Grinevald, who summarized portions of Vernadsky's work, based on the French translations, at the first Gaia meeting in 1987.[30] To Margulis, Vernadsky was a prophet of geobiology – and of Gaia – half a century ahead of his time. She wrote:

> Vernadsky teaches us that life, including human life, using visible light energy from our star the Sun, has transformed our planet over the eons. He illuminates the difference between an inanimate, mineralogical view of Earth's history, and an endlessly dynamic picture of Earth as the domain and product of life, to a degree not yet well understood. No prospect of life's cessation looms on any horizon. What Charles Darwin did for all life through time, Vernadsky did for all life through space.[31]

By joining Vernadsky's thinking on the biosphere to contemporary geobiological research, Margulis forwarded a research agenda that aptly describes the theoretical framework and

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[27] Margulis, *Origin of Eukaryotic Cells*.

[28] Margulis and Lovelock, "Biological Modulation of the Earth's Atmosphere," 473.

[29] Margulis and Lovelock, "Biological Modulation of the Earth's Atmosphere."

[30] Grinevald, "Conference on Gaia."

[31] Margulis et al., "Foreword to the English Language Edition," in *The Biosphere*, 18.

precepts of geobiology. She writes, "the surface temperature, chemistry of the reactive gaseous components, the oxidation-reduction state and the acidity-alkalinity of the Earth's atmosphere and surface sediments are actively… maintained by the metabolism, behavior, growth, and reproduction of organisms… on its surface."[32] Stated otherwise, our Earthly ecosystems, geobiologists now understand, were *made by microbes*. Only by integrating methods and principles from multiple fields in both the earth and life sciences could scientists begin to explain the intricate and extensive interaction between the geosphere and the biosphere across geological timescales.

The many Precambrian microfossils being unearthed during this time, did not, however, go unchallenged. At the time, most fossils were identified morphologically – by how they looked. And more often than not, these fossilized ancient microbes were spheres or filaments, which could readily be mimicked by bubbles, crystals, and other inorganic artifacts. To characterize this problem, in 1972 geologist Hans Hoffman coined "dubiofossils" to describe controversial fossils. "Fossils," Hoffman wrote, were generally accepted (for the time being) as biological; "pseudofossils" resembled life but were inorganic; "dubiofossils" (also known as *Problematica* or *Miscellanea*) were equivocal.[33]

Indeed, one ongoing puzzle for geobiologists is the problem of how to sort life from non-life when looking at ancient fossils. The dubiousness of dubiofossils points to a concern in historical ontology: as Ian Hacking has demonstrated, there is no such thing as a "natural kind" apart from social interpretation.[34] Nonetheless, he shows that the names of things (here, Hacking uses the minerals jade and nephrite as examples) produce meaningful historical ambiguities about the qualities, value, and effects that a named kind has.[35] The *dubio*- of dubiofossil is important precisely because it sutures social meaning (an entity about which geologists are uncertain) to a supposedly natural kind (the fossil).

These debates came to a head in the so-called "Apex Chert" controversy, which lasted for more than three decades. The controversy involved multiple factors, including arguments over which scientists' discoveries should be given priority, as well as critiques of various laboratories' sampling methods and analysis. But the heart of the debate was literally about the shape of life. Stanley Awramik, a leading geobiologist, in 1977 collected samples in which he reported finding microscopic organic filaments and spheroids in the Warrawoona Group near North Pole, Western Australia, claiming that these were the oldest known signs of life

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[32] Margulis, *Symbiosis in Cell Evolution*.

[33] Hofmann, "Precambrian Remains in Canada," 27.

[34] Hacking, *The Social Construction of What?*.

[35] Hacking, "The Contingencies of Ambiguity."

on Earth.[36] Schopf then reported that he had independently gathered microfossils at a nearby locale, and between 1986 and 1993 published his evidence that these microfossils definitively proved that microbial life teemed as early as 3.465 billion years ago.[37] Geomicrobiologist Roger Buick, who had studied the North Pole area extensively, remained skeptical. Asking "at what level of morphological complexity can an object be considered an undoubted microbial relic?" Buick concluded, "no universally acknowledged microfossils have ever been found in Archean rocks."[38]

As the debate stretched into the first years of the twenty-first century, many geobiologists diagnosed the so-called "Apex chert" fossils (so named for the deposit in the Warrawoona Group in which they were found) as "dubiofossils" at best. Some researchers insisted that Schopf's Apex chert "fossils" were, in fact, growths of arsenic and antimony that had coalesced on the surface of an ancient submarine hot spring.[39] As Henry Gee wrote in the pages of *Nature*, "it is hard to tell the difference between a bacterium – especially a fossil bacterium – and a bubble."[40] Richard Kerr posed a similar question in *Science*: are these the "earliest signs of life [or] just oddly shaped crud?"[41] Martin Brasier diagnosed the problem as one of deduction: for many geobiologists studying early life, "if it looks like a cyanobacterium… then the most parsimonious explanation is that it is a cyanobacterium."[42]

The Apex Chert controversy clarified for geobiologists the limits of identifying early life on Earth, and reveals how big ontological questions about life and its origins often get worked out on a fossil-by-fossil basis. Geobiologists have formalized criteria for gauging the likelihood that a fossil had been imprinted by either early life on Earth or life on other planets, even as they sometimes disagree on which criteria should take precedence when biogenicity is equivocal. In recent years, geobiologists have distanced themselves from morphology as

[36] Awramik, "The Pre-Phanerozoic Fossil Record"; Awramik, Schopf, and Walter, "Filamentous Fossil Bacteria." In 1979, members of the Precambrian Paleobiology Research Group (PPRG), a 47-member scientific working group that met regularly at Schopf's laboratory at UCLA, had embarked on fieldwork at a nearby locale. In 1980, they published in *Nature* their discovery there of Archean microfossils – then the oldest known fossils by over 500 million years.

[37] More boldly, he also claimed that his fossils had been photosynthetic organisms, a full billion years before the next-oldest evidence of photosynthesizing microbes. Schopf disputed Awramik's fossils, arguing that they were of doubtful provenance and citing problems of site-specificity and replicability. Schopf, "Microfossils of the Early Archean Apex Chert"; Schopf and Packer, "Early Archean (3.3-Billion to 3.5-Billion-Year-Old) Microfossils."

[38] Buick, "Microfossil Recognition in Archean Rocks," quotations on 445 and 442.

[39] Brasier et al., "Earth's Oldest (~3.5 Ga) Fossils"; Brasier, Green, and McLoughlin, "Characterization and Critical Testing."

[40] Gee, "Biogeochemistry."

[41] Kerr, "Earliest Signs of Life."

[42] Brasier et al., "Earth's Oldest (~3.5 Ga) Fossils," 258.

a sound indicator of ancient life. That is, morphological similitude – or comparison of ancient to extant life – is *not enough*: "lifelike" dubiofossils were more often than not inorganic patterns. Citing anti-positivist philosopher of science Karl Popper, who argued that scientific theories cannot definitively be proven, but must be falsifiable, Brasier offered the most conservative criterion for identifying fossilized life: "very ancient/alien microfossil-like structures (or stromatolites or geochemical and isotopic signals older than c. 3.0 Ga) should not be accepted as being of biological origin until possibilities of their non-biological origin have been tested and can be falsified."[43] Less conservative geobiologists noted that such a standard would not only disprove all fossils from the Archean eon, but, if applied to more recent fossils, would place them into question as well – indeed, *no* fossil can be definitively proven as having once lived. Scientific research hinges on falsifiability, to which Brasier's criterion, given his reference to Popper, ironically does not adhere. As a rejoinder, Andrew Knoll countered Brasier's "null hypothesis" with the more tractable "Knoll hypothesis": "A good biomarker is something that is simply difficult (not not impossible) to make through inorganic processes."[44] Papers disproving the Apex chert continue to be published, most recently in 2016, when David Wacey diagnosed the Apex chert as "not microfossils, merely blobs of carbon, fortuitously arranged."[45]

The geobiological conundrum of whether something is fossilized life or non-life remains lively to this day. In September 2016, *Nature* reported that 3.7-billion-year-old putative stromatolites had been discovered in Greenland.[46] Stromatolites, fossilized microbial mats, are some of the easiest identifiable evidence of life on early Earth. Nonetheless, many scientists remained incredulous: while geobiologist Abigail Allwood wrote that these fossils exhibit characteristics that "are fairly credibly hallmarks of microbial activity,"[47] Roger Buick rhetorically rolled his eyes, remarking, "I've got fourteen queries and problems that need addressing before I'll believe it."[48] Similarly, in spring 2017, geobiologist Dominic Papineau and colleagues reported that fossilized microorganisms were identified in 3.77-4.28 billion year-old iron-rich rock in Quebec: hematite tubes and filaments whose form is similar to microorganisms that today live in hydrothermal vents (deep-sea fissures from which superheated water spews, which host a diverse array of Archean microbiota).[49] No one is sure

[43] Brasier et al., "Earth's Oldest (~3.5 Ga) Fossils," 259. Popper, *The Logic of Scientific Discovery*.

[44] As quoted in Kirschvink and Weiss, "Mars, Panspermia, and the Origin of Life."

[45] Wacey et al., "3.46 Ga Apex Chert 'Microfossils,'" 296.

[46] Nutman et al., "Rapid Emergence of Life."

[47] Allwood, "Geology."

[48] Witze, "Claims of Earth's Oldest Fossils Tantalize Researchers."

[49] Dodd et al., "Evidence for Early Life."

whether either of these findings are ancient petrified organisms or not. The closer putative fossils are to the origins of both life and the Earth, any clear line demarcating fossilized life from non-life blurs and smudges into obscurity.

Today, geobiology remains highly interdisciplinary, though it now boasts many of the hallmarks of a mature scientific field – a professional society, international conferences, dedicated peer-reviewed journals, departments where students can earn doctorates in geobiology, and funding streams from both federal agencies and private foundations. Still, it is unsurprising that geobiology has to date received so little historical attention, given that it is itself a young field of research that, because of its inherent interdisciplinarity, remains hard to sharply delineate. The earth sciences more broadly have been relatively neglected by historians of science, compared to the physical and life sciences, and those historians who have addressed the twentieth-century earth sciences have often focused their attentions on topics such as plate tectonics and oceanography. That is beginning to change, and new scholarship on earth sciences in the service of militarism and empire, as well as scholarship on geology in the Global South, is an especially welcome corrective. Yet while historians of science including Martin Rudwick and James Secord have chronicled how naturalists and earth scientists in the late eighteenth and nineteenth centuries began collecting and interpreting evidence of geological "deep time," much less has been said about geological temporalizing by scientists in the mid to late twentieth century, even as the much shallower horizon of the Anthropocene has captured historians' sustained attention.

What do the remains of life *look* like? Geobiologists now know that the stony ghosts of ancestral life look a lot like all sorts of other things. Or, to turn the question on its head, lots of old things look a lot like what geobiologists expect old life to look like, whether in its form, complexity, or simplicity. Often, little visibly distinguishes the vital from the non-vital when looking for ancient life written in stone. Geobiologists now turn away from fossil *texts* to focus on biological, geological, and mineralogical *contexts*, looking for multiple biological signatures in a single locale, such as the surrounding paleoenvironment in which the rock lithified, signs of degradation during fossilization, as well as analytic biochemistry and chemical biomarkers. Such criteria, they hope, will more fruitfully differentiate, to borrow the language of geologist John Eiler, "the oldest fossil" from "just another rock."[50] As geobiologists join forces with geochemists, geochronologists, stratigraphers, and paleomagnetists, they utilize a diverse and stringent array of non-morphological criteria in concert to render ancient life recognizable, even interpretable. As such, the social accomplishment by which this diverse set of scientists agrees upon interpreting a rock as a Proterozoic or Archean fossil when they

[50] Eiler, "The Oldest Fossil."

see it is itself something of a feedback loop that presses back the horizons of life's origins, the environmental conditions in which it arose, and what, exactly, life ***was***.[51]

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[51] Some portions of this entry were previously published in 2018, first in *Aeon* and syndicated in *American Scientist*. Roosth, "The Shape of Life."

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