PROVOCATION

Notes on Mineral Evolution

Life, Sentience, and the Anthropocene

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Abstract Mineral evolution (ME) is a geologic paradigm postulating that Earth's minerals formed sequentially and have interacted with life forms for billions of years. The evolution of Earth and its minerals is therefore entangled with the evolution of life. This "Provocation" ponders the implications of ME for the environmental humanities in general and for Anthropocene narratives in particular. ME relies on non-Darwinian evolutionary principles. In common with other branches of Earth system science, it also destabilizes prevailing ontological categories. Life becomes more material, matter more alive. This essay suggests that the development of sentience in the Phanerozoic eon exerted an emergent, autonomous influence on the interaction of minerals and life. Conscious human agency and its effects on planetary transformation are therefore the culmination of a very long process. However, the *control* that our conscious agency can exercise upon planetary transformation is very limited even over human time scales, let alone geologic ones.

Keywords mineral evolution, sentience, agency, Anthropocene

> How many aeons did nature expend in fashioning a precious jewel? And how many aeons did the jewel lie gleaming in the earth until fate brought it forth?
> —Natsume Soseki, *Sanshiro*

This essay registers some implications for the environmental humanities of a new geologic paradigm, especially with regard to evolutionary theory and the relationship of life to matter. What significance should be attached to the claim that life and minerals coevolved? What is the relationship of change on Earth to cosmic change? These questions lead me to speculate about the significance of sentience and agency for the evolution of Earth. Human intentions have brought our species to a point in its history where its activities are producing significant geophysical effects, some of which

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will manifest geologically. We are not the first: the intentional agency of other species has shaped Earth. But at the temporal scale of mineral formation, can intentional agency produce intended effects? How do these questions bear on the idea of the Anthropocene?

Mineral Evolution

Despite its economic importance, geology is not a glamour science. Yet geology has made fundamental contributions to scientific knowledge. Geologists established the immense age of Earth, and Alfred Wegener's discovery of continental drift turned out to be essential for understanding the deep-time circulation of carbon at and near Earth's surface.[1] The term *Anthropocene*, which in recent years has come to stand for the impact of our species on planetary geophysics, was invented by a biologist and popularized by an atmospheric chemist,[2] but it is a geologic term, and it falls to geologists to decide whether to formally accept it as such.[3] Geology, then, is an essential tool for interpreting what Earth is and what we upon it are.[4]

Mineral evolution (ME) may be another far-reaching contribution from this Cinderella science. Just as Darwinian evolutionary theory responded to the question, "Why do the myriad living species differ from and resemble one another as they do?" so ME aspires to answer the question, "Why do the Earth's five thousand or so mineral species differ from and resemble one another as they do?" The mineralogist-cum-astrobiologist Robert M. Hazen, the chief exponent of ME, possesses a sophisticated appreciation of the philosophy and sociology of science and a verbal flair that colors even his research papers.[5] He has spun its origin yarn, one of those semimyths that haunt scientific chronicles. "At a Christmas Party in 2006, Harold Morowitz asked me a simple question. 'Were there any clay minerals in the Archean?'"[6] The Archean eon is when the first archaeological evidence of cellular life appeared, more than 2.5 billion years ago. The question, Hazen implies, fell upon him like the proverbial apple upon Newton. Two years later, he and seven other geologists published the paper that launched ME.[7]

A mineral is a substance that has a specifiable chemical formula and an ordered (nearly always crystalline) structure. Minerals make up most of Earth. They go down

1. Berner, *Phanerozoic Carbon Cycle*; N. Clark, *Inhuman Nature*, 12.

2. Crutzen and Stoermer, "'Anthropocene,'" 17.

3. Subcommission on Quaternary Stratigraphy, "Working Group on the 'Anthropocene,'" quaternary .stratigraphy.org/workinggroups/anthropocene/ (accessed May 1, 2016).

4. Yusoff, "Geologic Life."

5. Carnegie Institution for Science, Robert M. Hazen Geophysical Laboratory, hazen.carnegiescience .edu/ (accessed November 4, 2015).

6. Carnegie Institution for Science, Robert M. Hazen Geophysical Laboratory, "Mineral Evolution," hazen.carnegiescience.edu/research/mineral-evolution (accessed November 4, 2015). On Morowitz, see George Mason University Neuroscience Program, "Harold J. Morowitz," neuroscience.gmu.edu/people/morowitz (accessed November 4, 2015).

7. Hazen et al., "Mineral Evolution."

beneath us, getting hotter and denser, until they merge with the planet's molten metal core. Rocks are composed of a single mineral or several fused together, and soil is a loose mixture of mineral fragments with living and dead things. Over the eons of geologic time, minerals shift, churn, dissolve, and re-create themselves on and near Earth's surface, leaving behind physical and chemical traces of their former states and positions. Reading these traces, geologists have pieced together a rough and gappy chronicle of the planet's estimated 4.54 billion years.

ME explains where minerals occur on this timeline by linking the conditions of their formation to astrophysics and biology. The details are technical, but the basic claims are straightforward.

First, minerals result from "a sequence of deterministic, irreversible processes"[8] acting over eons upon interstellar dust that leads from relative simplicity to increasing diversity and complexity.

Some terrestrial minerals are fairly simple and very common, but many others are very complex and extremely rare. The elements that constitute them were once remnant nanoparticles of a supernova, the only phenomenon capable of synthesizing most of their ninety or so elements.[9] Earth formed from their gravitational accretion and collision, chiefly from a dozen or so substances: nitrogen, oxygen, pure carbon in the forms of graphite and diamond, silicon, metals, water, carbohydrates, and silicates. These form the "ur-minerals" of which comets, asteroids, and meteors are made.

As Earth and the Earth-like planets formed, gravity and heat drew most of the iron and nickel toward the center and began the concentration of scarcer elements in the crust. Hazen and his colleagues estimate that by the beginning of the Archean eon, four billion years ago, when Earth's crust had more or less stabilized, physical processes had created something like fifteen hundred minerals. The other terrestrial planets underwent a similar concentration and share the same mineral ensemble today. On Earth, however, minerals did not cease to evolve. More minerals formed as protocontinents of granites and carbonates floated on the underlying basalt and interacted with the abundant surface water and, later, with early life.

Second, many of Earth's minerals are consequences of the activity of living organisms.

The biological origin of some minerals has long been recognized but not generally acknowledged as a sign of a symbiotic relationship almost as old as Earth. ME contends that life and minerals have been complementary phenomena since life began. The idea was suggested nearly a century ago by Vladimir Vernadsky and again by James Lovelock in the 1970s,[10] but Hazen's formulation is more comprehensive and detailed, and it is informed by contemporary research. Hazen depicts minerals as providing cover for the

8. Ibid., 1712.

9. Ryan and Norton, *Stellar Evolution and Nucleosynthesis*.

10. N. Clark, *Inhuman Nature*, 14.

genesis of life "when Earth was blanketed by a thick noxious atmosphere tinged orange with hydrocarbon smog," "bathed in lethal radiation," and disrupted "by a steady stream of violent volcanic eruptions, asteroid bombardments and comet impacts." Early life obtained matter and energy from minerals, and then life in turn began to generate new minerals. "Life arose from minerals; then minerals arose from life."[11] One such biogenic mineral has been named hazenite.[12]

In the Proterozoic eon of unicellular life (2.5–0.542 billion years ago), new minerals came into being as a consequence of photosynthesizing cyanobacteria, which extracted energy and matter from sunlight and the early atmosphere's abundant carbon dioxide. The free oxygen released in the process bonded with metals to create vast ore bodies, while the associated drawdown of carbon dioxide appears to have led to intervals of dramatic planetary cooling. There is evidence that the planet was covered or almost covered in ice, perhaps often. Finally, during the last half a billion years of our Phanerozoic eon, eukaryotic and multicelled organisms enabled the formation of new minerals by oxygenating the atmosphere to something like its current level of 21 percent and breaking down rocks into soil.[13] With a touch of hyperbole—for it seems more likely that Earth has usually looked bluish—Hazen fancies the long-term mineral phases of the planet as a sequence of colors, from basalt black to oxidized red, the white of "snowball Earth," and the green of photosynthesizing plants.[14] Each of these phases engendered environments conducive to the formation of distinctive mineral ensembles.

ME is to mineralogy as biological evolution is to biology, reframing its subject as a multidisciplinary grand narrative. It also invites comparison with the periodic table proposed by Dmitri Mendeleev in 1869.[15] As the periodic table did, ME implies formerly overlooked patterns in established data and suggests new lines of corroborative research.[16] Some programs have already borne fruit in investigations of mercury,[17] beryllium,[18] zircon,[19] and carbon[20] minerals. As for clay, it took Hazen and his collaborators seven years to respond to Morowitz's question. In a detailed case for the fifty-six known clay types being products of successive changes in Earth's geology—such as the development of oceans, a crust rich in magnesium and iron, plate tectonics, the Great Oxygenation Event, and the rise of the terrestrial biosphere—they concluded that there *were* clay minerals in the Archean, but not many. Life, first as bacteria and later also as

11. Hazen, "Mineral Fodder."
12. Yang, Sun, and Downs, "Hazenite, KNaMg2(PO4)2•14H2O."
13. Hazen, "Mineral Fodder."
14. Hazen, "Evolution of Minerals."
15. Eric Scerri, *Periodic Table*.
16. Ibid.
17. Hazen et al., "Mercury (Hg) Mineral Evolution."
18. Grew and Hazen, "Beryllium Mineral Evolution."
19. Bradley, "Mineral Evolution and Earth History."
20. Hazen et al., "Carbon Mineral Evolution."

plants, vastly augmented the production of the talc and smectite minerals without which most terrestrial clays would not exist.[21]

ME is based on well-established scientific principles and empirical findings that command a high degree of professional consensus. On the other hand, paleogeology is highly speculative. The tentative character even of the seemingly most secure hypotheses on which it relies is illustrated by recent challenges to the standard model of planetary formation.[22] Scarcely anything is known about mineral formation at the high temperatures and pressures that exist below the earth's surface.[23] No one knows where the oceans came from or why they have endured for billions of years without either vaporizing or freezing. New data might show many details of ME to be astray, so caution is appropriate. However, the fundamental paradigm seems unlikely to face serious challenge.

In the following notes I open four lines of thought suggested by ME that are relevant to the environmental humanities and ecological thought generally. First, I contrast ME with Darwinian evolution and discuss its framing within the hypothesis of cosmic evolution. Next, I consider how the long-term relationship of life and minerals, and the merging of living with nonliving matter implied by ME, bears on human self-understanding and relationships with Earth. Third, I introduce sentience as an evolutionary factor in Earth's history, complementing the evolution of minerals and life. As life conforms to the laws of matter but adds some of its own, so sentience presumably conforms to the laws of both matter and life while adding still more. Human sentience plays a prominent role in the mineralogy of the Anthropocene, and this reflection leads me to conclude with a discussion of agency and the relevance of intentions to Earth history.

Evolution

ME is of course an evolutionary theory—it explains why phenomena change in the way that they do—but it is not a Darwinian theory. It is in fact a more powerful type of evolutionary theory, since it claims to be able to do two things for minerals that Darwinian selection cannot do for living things: provide a causal account of their *origin* and make some probable predictions about their *sequencing*.

Natural selection cannot account for the origin of life, because a reproductive mechanism has to exist before natural selection can begin its work. The most thoroughgoing attempt to apply Darwinism to the entire development of planetary life begins with "replicating molecules."[24] How elements organized themselves into these improbable chemicals cannot be answered in Darwinian terms.[25] Nor does natural selection

21. Hazen et al., "Clay Mineral Evolution"; Yeager, "Microbes Drove Earth's Mineral Evolution."
22. Tsiganis, "Planetary Science"; Batygin, Laughlin, and Morbidelli, "Born of Chaos."
23. Hand, "How Buried Water Makes Diamonds and Oil."
24. Maynard-Smith and Szathmary, *Major Transitions in Evolution*, 6.
25. Pross, *What Is Life?*, 109; Hoffman, *Life's Ratchet*.

have a specific direction—in that sense it is scalar. It is time-asymmetric—you cannot run it backward—but the only sequencing involved is the perpetual tendency of replicators to become more efficient at replicating under the continually changing circumstances in which they replicate. Changes may be explicable in retrospect, but they are not predictable. However, it is very widely assumed—and was by Darwin himself sometimes—that natural selection entails a tendency for replicators to become increasingly complex. That is apparently what happened on Earth: from unknown but presumably simpler origins emerged prokaryotic cells, which are extraordinarily complicated pieces of molecular machinery. Later, different combinations of prokaryotic cells joined together to form eukaryotic cells, and then three kinds of eukaryotes—fungi, plants, and animals—each formed colonies of multicelled organisms. The evolutionary history of these kingdoms, particularly the animal and vegetable kingdoms about which most is known, displays similar complexifying tendencies: the successive developments of seeds and flowers, limbs, nervous systems, exoskeletons and skeletons, wings, feathers and fur, viviparity, neotony, and so forth. All this suggests that life's evolution incorporates a complexifying tendency. Stephen Gould argued that the appearance of complexification is nothing more than an artefact of the widening variation of life forms over time, combined with the limit of simplification imposed on living organisms by the necessities of biological functioning (presumably represented by viruses). Random variation therefore dictates a tendency for the most complex organisms of later times to be more complex than the most complex organisms of earlier times, but evolution by natural selection does not dictate an increase in the complexity either of individual organisms or of life as a whole.[26]

If ME has a principle of change analogous to Darwinian selection, it is the second law of thermodynamics, the law that decrees that dynamic systems tend toward the lowest possible energy level. This law explains not only the evolution of minerals but their origins in the gathering together of elements in space from the particle dust of a supernova. It explains the successive formation of different minerals as a consequence of the laws of physics and chemistry acting in plausible terrestrial (and extraterrestrial) environments. Just as the second law dictates that in the interior of very large stars the synthesis of neutrons and protons into elements must occur in a fixed sequence (hydrogen, helium, lithium . . . carbon . . . iron . . . uranium), so, in the very different environment of the solar system and Earth, the same law dictates that the synthesis of minerals also occurs in a fixed sequence (diamond . . . carbides . . . silicates . . . oxides . . . sulphides . . . carbonates . . . granites . . . metallic oxides . . . biogenic limestone . . .).[27]

ME not only accounts for the origin of minerals, it also claims that their subsequent evolution can be predicted, not in detail but in general terms. It is a vector,

26. Gould and Lewontin, "Spandrels of San Marco"; Gould, *Life's Grandeur*.
27. Hazen et al., "Mineral Evolution," 1694–95.

tending toward a specific "direction," a sequential ordering shaped by physiochemistry and cosmology. Hazen's early formulations were markedly deterministic, implying that minerals formed in a fixed order; but subsequent research showed that many rare minerals—including hazenite—formed in circumstances that cannot be predicted from general geophysical principles. Hazen suggests the term *mineral ecology* to register this contingency.[28] "Contingent" minerals formed after life, with its unpredictable patterns of development, was already an important factor in the Earth system. Mineral ecology therefore represents a convergence of evolutionary developments: on one hand, the vectors of nonliving matter, driven by physical and chemical laws; on the other, the accelerated, dispersed genealogies of living matter, driven by the contingencies of reproduction and survival.

Hazen is among the growing number of philosophical scientists persuaded by astrophysicist Eric J. Chaisson's case for cosmic evolution.[29] Chaisson attempts to reconcile the second law of thermodynamics with the fact that many complex systems, from galaxies to life forms, evolve into even more complex systems. The implication is that in the origin and development of life Darwinian selection is not the only factor at work, a position reminiscent of the structuralism of D'Arcy Wentworth Thompson.[30] One of Hazen's recent statements draws mineral and biological evolution together under a universal paradigm of evolutionary change:

> Complex systems display diversification in type, patterning, and behaviour over time through varied selective mechanisms. Such systems are observed in numerous natural and cultural contexts, including nucleosynthesis, minerals, prebiotic organic synthesis, languages, material culture, and cellular life. These systems possess such qualitatively similar characteristics as diversification into new environments (radiation), episodic periods of innovation (punctuation), and loss of types (extinction). Comparisons among these varied systems thus point to general principles of complexification.[31]

Cosmic evolution seems more scientifically plausible today than it would have a century ago, largely because developments in mathematics have enhanced understanding of complex systems. Leading pioneers of this approach included Stuart Kauffman, Ilya Prigogine, and John Holland.[32] The new mathematics shows how relatively simple elements may, under the right circumstances, form complex systems that harness iterative feedback to assemble and repair themselves, adapt to changing circumstances,

28. Carnegie Institution for Science, Robert M. Hazen Geophysical Laboratory, "Mineral Ecology," hazen.carnegiescience.edu/research/mineral-ecology (accessed November 4, 2015).

29. Chaisson, *Cosmic Evolution*.

30. D. W. Thompson, *On Growth and Form*.

31. Hazen and Eldredge, "Themes and Variations."

32. Kauffman, *Origins of Order*; Prigogine and Stengers, *End of Certainty*; Holland, *Adaptation in Natural and Artificial Systems*.

and manifest emergent properties.[33] Such systems include planets, living cells, galaxies, stars, molecules, computers, cities, species—in fact any slice of reality that contains a large number of interactive elements through which energy flows and creates a potential for stable disequilibrium. It often helps if the energy flow fluctuates, and complex systems typically develop internal cycling mechanisms, like Earth's carbon cycle, vertebrate blood circulation, or the variation of sunspot activity. Conforming with the principle of cosmic evolution, such systems adapt and evolve.[34]

Minerals and Us

What are minerals to us, and what are we to minerals? Both are matter, but no mineral is alive, and no living thing is a mineral. Admittedly, the definition of *living* is equivocal, and so is the definition of *mineral*: whether it ought to include noncrystalline substances like opal, obsidian, and native metals or substances derived from life forms like amber, pearl, and petroleum are matters for debate, about which many mineralogists hold strong opinions.[35] Nevertheless, there is no question that minerals—even minerals that may contain recycled biogenic matter, like travertine, pyrite, and opal (if the latter is deemed a mineral)—are composed of different molecules from living organisms arranged differently. Silicon and aluminium, the most abundant mineral elements, are almost entirely absent from living organisms, while carbon and oxygen are ubiquitous in living organisms but relatively scarce in minerals. Yet "life arose from minerals; then minerals arose from life."[36] At this point, it is helpful to revisit the old question of the relationship of life to matter.

Biology has treated living things as entirely material since Hermann von Helmholtz's experiments in the mid-nineteenth century.[37] It accepted the materialist hypothesis because it works. When life was attributed to the action of a vital substance with different properties from inanimate matter, it remained a mystery. When scientists proceeded on the basis that life conformed to the same laws as matter, new and enticing vistas of understanding and utility opened up. The claim is a purely negative one, setting a limit to the range of permissible theories: it means that life does not violate the laws of physics and chemistry. The distinction between life and nonlife therefore appears not as a clear division but as a tangled chemical continuum. "The life–non-life boundary is not thin and it is not rigid."[38] New technologies—artificial intelligence, genetic engineering, enhanced prosthetics—provide many illustrations of this truth.

33. Mitchell, *Complexity*.
34. Prigogine and Stengers, *End of Certainty*, 73.
35. Nickel, "Definition of a Mineral."
36. Hazen, "Mineral Fodder."
37. Hoffman, *Life's Ratchet*, 36–41.
38. Morton, *Ecology without Nature*, 270.

For human life in general and the fields of thought that still call themselves "the humanities," identifying life as matter, especially *sentient* life, is not the straightforward heuristic it is for science. The ongoing ethical and political disputes about those new technologies underline the extent to which they conflict with taken-for-granted and deeply held orderings of knowledge. Whereas earlier renditions of environmentalism tended to share those orderings, the "new materialism" associated with scholars such as Bruno Latour, Donna Haraway, Jane Bennett, and Karen Barad welcomes the merging of life and matter.[39] Matter is "lively," "vibrant,"[40] "beastly."[41] "Stone discloses queer vivacity, and a perilous tender of mineral amity," writes Jeffrey Jerome Cohen.[42] Such words and phrases point to something precious, attractive, disquieting, or terrifying about matter—a step, sometimes quite explicit, toward a renewal of pantheism or animism.[43]

For ME, the convergence of life and matter is not a question of inert matter pervading life or liveliness pervading matter. The central issue is predictability. If the relevant variables of a physical state are known—the flow of electricity through a resistance, the forces acting on a bridge—then the laws of physics make it possible to calculate the state's attributes under various conditions—how much heat the resistance will generate, what loads the bridge can safely bear. The laws of physics do not make it possible to calculate in *exact* detail how a material state will behave. It would be necessary to know everything about it, and not only is such knowledge physically impossible to acquire, it is ruled out by quantum theory. "Perfect prediction à la Laplace is impossible, not only in practice but also in principle."[44] However, it is possible to make extremely accurate predictions about most material states because their behavior is constrained by the laws of probability. Rocks, for example, never use the matter and energy from the soil and air around them to twine up gates and drainpipes, not because it is strictly impossible for their atoms to so arrange themselves but because the possibility of their doing so is infinitesimal. Living vines, however, twine up drainpipes as a matter of course. Life does not violate the laws of physics but stretches the laws of probability to their limits. That is why predictive explanation requires another level of theorizing: biology and genetics explain the twining of the vine as a consequence of chemical reactions ensuing from an inherited instruction set, the vine's genome. The boundary between life and matter, albeit wide and flexible, thus remains significant: nonliving matter is not controlled by instruction sets.[45]

39. Latour, *Reassembling the Social*; Haraway, *Simians, Cyborgs, and Women*; Bennett, *Vibrant Matter*; Barad, "Matter Feels"; Dolphijn and van der Tuin, *New Materialism*; Tiainen, Kontturi, and Hongisto, "Movement, Aesthetics, Ontology."

40. Bennett, *Vibrant Matter*.

41. Chakrabarty, "Climate and Capital," 6.

42. Cohen, *Stone: An Ecology of the Inhuman*, 6.

43. Rose, "Val Plumwood's Philosophical Animism"; Van Dooren and Rose, "Lively Ethnography."

44. Mitchell, *Complexity*, 33.

45. Marletto, "Life without Design."

Sentience and Agency

In the solar system's infancy, minerals evolved in accordance with astrophysical principles. Thus Earth was formed. Then life developed from Earth, and minerals and life began to affect one another. For a long time, however, Earth has harbored a third phenomenon, for which the best available word may be *sentience*.[46] Notoriously, the activity of sentient humans is currently affecting Earth. Clive Hamilton writes, "Will . . . can no longer be separated from Earth's history."[47] Hamilton is referring to human will, but many living organisms relate to their environments in terms mediated by sensory apprehension and calculation. For at least half a billion years, minerals, life, and sentience have interacted—or, to use Barad's more precise term, "intra-acted."[48]

Just as with living and nonliving, a continuum lies between sentient and nonsentient. Plants, unicellular protists, and even prokaryotes demonstrate remarkably nuanced reactions to their environments.[49] Whenever it began, it is certain that sentience was present on Earth by the early Phanerozoic eon, in the frenzy of the "Cambrian explosion," when multicelled animals evolved with specialized sense organs and with neurons, ganglia, and brains to transmit and decode the information they gathered.[50] It seems likely that animals were able to develop these because their parasitism on other living cells made more surplus energy available to them than to synthesizing plants or fungi.[51]

Sentience opened up new pathways of evolutionary development. One such pathway was increasingly elaborate ways of eating and avoiding being eaten, as hunters and hunted engaged in a classical Darwinian struggle.[52] Another was the elaboration of sexual selection among the eukaryotic organisms that reproduced sexually.[53] However, the most significant *mineralogical* consequence of sentience could well have been the coevolution of sentient pollinating insects and flowering plants. The supplanting of conifers by angiosperms a hundred million years ago was facilitated by pollinating insects, stimulated by the response of angiosperms to the insects' sensation-mediated selection of blossoms. All this would likely have accelerated mineral weathering, inducing the global cooling that culminated in the Pleistocene Ice Ages.[54]

46. Sentience and cognition bear distinct metaphysical and methodological connotations. I use the "inward" one to underline its special character. It goes without saying that this discussion is in need of an enormous amount of refinement.

47. C. Hamilton, "Human Destiny in the Anthropocene," 33.

48. Barad, *Meeting the Universe Halfway*, ix.

49. Marder, "Plant Intentionality"; J. Hamilton, "Bad Flowers"; Saigusa et al., "Amoebae Anticipate Periodic Events"; Boisseau, Vogel, and Dussutour, "Habituation in Non-neural Organisms"; Hird, *Origins of Sociable Life*.

50. Fox, "What Sparked the Cambrian Explosion?"

51. Conceivably, the convergent evolution of similar senses in different animal phyla signifies cosmic evolution at work.

52. Fox, "What Sparked the Cambrian Explosion?"

53. Grosz, *Becoming Undone*; Grosz, *In the Nick of Time*.

54. Volk, "Rise of Angiosperms as a Factor in Long-Term Climatic Cooling."

The origin and nature of sentience is mysterious. If life is an emergent property of matter, it seems to follow that sentience must be an emergent property of life: it is after all dependent on and correlated with life, as life is dependent on and correlated with matter. But sentience is associated with the possession of "states of experience,"[55] the states that some philosophers call qualia. Whether or not all sentient beings experience states of experience is debatable, but at least one does, for we ourselves have them and know that having them makes us sentient. The problem with qualia is that they are not simply phenomena that are extremely improbable, like metabolism and reproduction. Qualia are *something else*. Neurology can demonstrate close correlations between states of experience and brain states, but correlating the experience of yellow with a neural state—or with light of a certain range of wavelengths—does not tell us anything about the experience of yellow: "yellow" belongs to a different order of being.[56] That is why sentience has been called "*the* hard problem" and why many philosophers cling to dualism or take the panpsychist option, the idea that matter is itself fundamentally sentient.[57]

The possession of "states of experience" is not the only peculiar attribute of sentient beings. Sentient beings also have intentions. Indeed, it is only by discerning intentions that we attribute states of experience to organisms other than ourselves. The insect scurries from a disturbance; a bird courts its mate; a predator seizes its prey. We conclude that they are sentient: they apprehend a world, orient to specific phenomena in that world, have desires and moods, and act in accordance with them.[58] If life projects itself into the future by harnessing energy for metabolism and reproduction, *sentient* life, to the extent that it is sentient, *wills* itself into the future by formulating intentions and acting to achieve them.

To be possessed of will is to have "agency."[59] The word circulates widely, in many different contexts. An agent is that which is responsible: if you want to start or stop something, find its agent. The sort of responsibility involved is open: it can be administrative (as in shipping), negotiating (as in theatrical), disguised (as in secret), ethical (as in "free"),[60] chemical (as in bleaching), or physical (as in destructive). There are further subdivisions: chemical agents, for example, might be solvents, catalysts, or reactants.[61]

55. Chalmers, "Facing Up to the Problem of Consciousness," 201.

56. Notable attempts to resolve the dilemma include Armstrong, *Materialist Theory of Mind*; Dennett, *Consciousness Explained*; and E. Thompson, *Mind in Life*.

57. Chalmers, "Facing Up to the Problem of Consciousness," 201. See also Strawson, "Realistic Monism"; Chalmers, "Panpsychism and Panprotopsychism."

58. The investigation of animal consciousness is a major theme of the environmental humanities. See, for a small sample, Beisel, Ginn, and Barua, "Living with Awkward Creatures"; Lestel, Bussolini, and Chrulew, "Phenomenology of Animal Life"; Van Dooren, *Flight Ways*; and Whitehouse, "Listening to Birds in the Anthropocene."

59. Several issues concerning agency in this and following sections are discussed in Barandiaran, Di Paolo, and Rohde, "Defining Agency."

60. Strawson, "Free Agents."

61. There is more to say. Agents are necessary or sufficient conditions, but not all necessary or sufficient conditions are considered agents. But this question need not be investigated here.

These are all very different kinds of agency. Being a physical or chemical agent is not only easy but mandatory, while being a sentient agent—let alone an ethical or political one—is super difficult. The former only has to do what the second law of thermodynamics requires of it: the rock falls, crushing the shrubs beneath it; the acid sheds hydrogen and forms a salt. A sentient agent, such as you—a complex material system endowed with will—needs to "perceive a situation" (whatever that means), "formulate an intention" (whatever *that* means, but it must incorporate some way of realistically modeling and choosing possible future states), and, finally, act in such a way as to fulfill the intention. I see the apple and feel my hunger; I predict that the apple will satisfy my hunger; I reach for the apple, bring it to my mouth, bite into it, chew, and swallow. At every step of this stupendously complex "reconfiguring [of] material-discursive apparatuses of bodily production,"[62] I am tacking against the wind of entropy: I have to prevent the second law from telling me what to do, "I" being a self-organized collective of billions of self-creating and self-maintaining molecular nanomachines whose existence, even if I know they exist, I cannot even keep in mind let alone be responsible for. And all I have done is bitten into an apple. Like all of life's processes, but to a fantastically unlikely degree, an intentional action of the simplest kind involves leveraging present losses against speculative future gain. It is like chemical capitalism, ratcheting itself into a semipermanent state of disequilibrium,[63] casting hooks into the future in order to drag itself there.

The agency of sentient beings—both our own and that of others—dominates our everyday consciousness and seems very powerful to us because it fills our conscious experience. Its limitations are easily downplayed or overlooked. We like to believe that we are or should be the drivers of our own lives, but even in this closest-to-home project we vastly inflate the significance of our individual consciousness. In reality, the biological and social machinery we are connected to is doing almost all the work.

First, a sentient organism controls only a minute proportion of its total activities. Our lives would be unsustainably exhausting if we had to concentrate on keeping our hearts beating or creating antibodies to ward off every threat. Second, the agency of an intentional action is not at all the same as the intention of that action. In philosophy, this distinction features as the *de re / de dicto* distinction.[64] I wanted to eat the apple; I did not want to be ejected from Eden. Insects facilitated the evolution of flowering plants by being attracted to spread pollen; they did not intend to trigger the Pleistocene. As Karl Marx observed of humans, they make their own history, but they do not make it as they please.[65]

Finally, even sentient agency that is successful can continue to be successful for only a relatively short period of time. Intentions are temporary—typically confined to

62. Barad, "Matter Feels."

63. Hoffman, *Life's Ratchet*.

64. Dummett, *Frege*; Sajama and Vihjanen, "Representation and Reality."

65. Marx, "Eighteenth Brumaire of Louis Bonaparte," 594.

intervals of microseconds to hours, though some animals with long memories can harbor intentions for decades, and human animals even aspire to produce intended effects on the world long after their deaths. But the contingency of material existence places an inherent limit on the efficacy of intentional agency. Each passing moment exponentially diminishes the likelihood that the goals of an action will be approximated. The gap between intention and result widens inexorably until their relationship ceases to be recognizable. "Every act soon eluded the grasp of its propagator, to be swept away in a clamorous tide of unforeseen consequence."[66]

The hand that signs the paper fells a city, but only if others can read the paper, are willing to obey its instructions, and are able to carry them out.[67] Then, centuries later, those who learn of the destruction of that doomed city will struggle to recall its name and the name of its destroyer and will decline to ascribe any great significance to its passing.

Within the temporality of human history, this factor is prominent enough. Within the temporality of geophysical and geologic exchange, the scope of will to effect events in accordance with intentions is null. Awareness of this fact is one aspect of the existential upheaval that shadows the Anthropocene, the latest aspect in a series that runs from Copernicus through Darwin and Freud.[68] Dipesh Chakrabarty observes that the histories of Earth, the human species, and the last few centuries that historians typically study "are normally assumed to be working at such different and distinct paces that they are treated as processes separate from one another for all practical purposes."[69] "The wall between human and natural history has been breached. We may not experience ourselves as a geological agent, but we appear to have become one."[70]

None of this should be taken to imply that we do not have agency or "free will." Within limited zones of time and space, we can exercise exquisite control of specific physical activities. More generally, we can and usually do care for ourselves and our loved ones, perhaps over several generations; perform tasks assigned to us; formulate new goals that suit us better than old ones. Sometimes we can rebel successfully against oppressive regimes and persuade people of the wisdom of new ways of living. We can reach mysteriously beyond the here and now, as we do when we speak words, use a tool, or write a computer program. But all these successes are limited by the state of our understanding when we realize them, depend on processes over which we have no influence, and are subject to the ceaseless flux of existence, which on the scale of geologic time destines them to ephemerality.

66. McCarthy, *Crossing*, 174.

67. "Dylan Thomas Reads the Hand that Signed the Paper." BBC One, Dylan Thomas, 1938, www.bbc.co.uk/programmes/p01zkw98 (accessed 31 January 2016).

68. Morton, *Ecology without Nature*, 265.

69. Chakrabarty, "Anthropocene and the Convergence of Histories," 44.

70. Chakrabarty, "Climate of History," 221.

Anthropocene Minerality and Agency

Awareness of the impact of agency upon Earth and its minerals is acute in our present situation, characterized, as Hazen remarks, "by wildly accelerated feedbacks between life and rocks, with a special emphasis on a single organism: Homo sapiens."[71] In the evolution of humans, emergent systems begat still more emergent systems, piggybacking one upon another: Technologies and languages enabled humans to project their will much farther into the future than other animals.[72] When, a million or so years ago, animals somewhat like us began to make tools, control fire, and speak in sentences, they set upon a course that culminated in the Great Acceleration.[73]

It is a perverse sort of vanity to accuse ourselves of being the most geologically disruptive of all organisms. As Haraway reminds us, "from the start the greatest planetary terraformers (and reformers) of all have been and still are bacteria and their kin."[74] The Great Oxygenation Event produced a far more profound and enduring alteration of Earth than anything of which *Homo sapiens* is likely to be capable. All the same, it is notable for a primate to populate every continent and manipulate widely different ecosystems to its advantage, and it is unprecedented for a mammal to cultivate plants and tend animals for food and power, dig up clays and ores to make pottery and metals, and so forth. To mine and burn carbon buried millions of years ago, with swift repercussions for the global climate, seems to many important enough to warrant a name, and the one currently in vogue is *Anthropocene*.

The Anthropocene concept is anchored in mineralogy, conjuring entities of a few million years hence that are recognizable as geologists. Hypothetically, they would notice a distinct mineralogical stratum and recognize it as a geochronological epoch marking the presence of our species. Anthropocene strata will be recognizable because their minerals will contain evidence of human activity. In particular, fossil fuel burning will produce more carbonate with specific isotopic signatures. Ocean acidification; changes in the nitrogen and phosphorus cycle; the repositioning of sand, hydrocarbons, and metals; mass extinctions; and a sudden rise in temperatures may also leave traces that have a chance of being detected, especially if the archaeologists of the distant future are better funded than present-day ones.[75]

Many geologists of the present are uncomfortable with the idea. An epoch is a stratigraphically distinct period of several million years. The Holocene epoch we are still officially in—the name means "entirely recent"—only began fourteen thousand years ago. (The preceding epoch, the Pleistocene, was a relatively brief two and a half million years.) No one believes that the present condition of humanity will last

71. Hazen, "Mineral Fodder."

72. Hazen includes both in his list of evolutionary "complexifications." Hazen and Eldredge, "Themes and Variations," 43.

73. Steffen, Crutzen, and McNeill, "Anthropocene."

74. Haraway, "Anthropocene, Capitalocene, Plantationocene, Chthulucene," 159.

75. Zalasiewicz, Kryza, and Williams, "Mineral Signature of the Anthropocene."

anything like fourteen thousand years, let alone two and a half million. For better or worse, everything will be vastly different in a century or two if not sooner. So if we are on the verge of a new geologic epoch, we are not there yet but in what geologists call a boundary, a period evidenced geologically by a line separating two distinct strata.[76] Indeed, the entire Holocene could well be a boundary, since fourteen thousand years is a minute interval in geologic perspective. But the fundamental point remains: whatever it is called, human activity appears to be ushering in a geologic epoch distinct from the Pleistocene.

The Anthropocene was the unintended—and almost entirely unimagined—consequence of intentional actions. Many debates about it appear to take for granted that because human actions created it, human actions can prevent or at least ameliorate it—for example by limiting carbon dioxide emissions, executing geoengineering projects, or overthrowing capitalism. "Thus now," writes Timothy Clark,

> innumerable popular science books on the crisis, how "'we" got here and the cultural transformations "we" must urgently undergo to avert further disaster are all implicitly investing in the Enlightenment faith that a deficit of understanding is at the root of the issue, and that once people know and understand the insidious dangers of the Anthropocene, the appropriate individual, social and political measures will follow.[77]

However, the general limitations on sentient agency discussed above apply with no less force to ME and the Anthropocene. Time's arrow means that it is never possible to restore the past, even within limited and isolated times and spaces. The vast expanse of mineralogical temporalities, in which species come and go, continents wander and collide, and minerals come into being, utterly defeat the capacities of human agency. Even if—impossibly—we knew precisely what actions would be most likely to prevent or ameliorate the consequences of human actions in time frames relevant to mineral formation, there is no way of aligning human intentions so as to execute them.

Again, while it is true that humans taught themselves how to get hold of fossil fuels and burn them for energy, and only an animal capable of will could have done that, humans are entangled with many other entities in the Earth system. "'Our' geological force is not ours alone and owes a *debt* (of force) to the mobilisation of other geological materials: fossil fuels. . . . Prioritising ourselves as a species within the generation of meaning and material effects, while minimising the force of fossil fuels in organising forms of life, fails to properly acknowledge the active power of fossils that subtend this equation."[78] The burning of fossil fuels is almost always told as a narrative of living organisms disrupting Earth, but it can also be told as a narrative of long dead and buried

76. Drury, "Sign of the Times; the Anthropocene."
77. T. Clark, *Ecocriticism on the Edge*, 160.
78. Yusoff, "Geologic Life," 785.

horsetail ferns and club mosses reappearing to harry the living: *Revenge of the Carboniferous Zombies*.[79]

Yet another consideration weakens the scope of human agency at the scale of Earth history. The point is frequently made that the Anthropocene is not a product of "humans" conceived as a species or as an aggregate of persons.[80] Relatively small numbers of people, located in strategic intellectual, industrial, and government positions, make the relevant decisions. Nor are its effects distributed evenly. So it is not the human *species*, but specific human *groups*—capitalists, rich nations, fossil fuel lobbies—that are responsible for the environmental crisis. It is not really the Anthropocene but the Capitalocene, the Plantationocene, or so on.[81] But if species cannot be intentional agents, why should social groups or categories be any different? The agency even of organized groups poses many problems, let alone disorganized ones.[82]

"The Earth," Hazen endeavors to assures us, "will continue to evolve as a dynamic living world whether or not our species survives. But saving ourselves will require a deeper understanding of the strange, twisty relationship between rocks and life, a relationship that sustains the only home we have ever known."[83] Presumably he has in mind something like the "species thinking" advocated by Chakrabarty and others.[84] But what could the "we"—"our species"—possibly be here? What would it be like for "us" to be "saved"? Kathryn Yusoff stages a "conversation" between two learned fossils about "the human." The pre-Anthropocene fossil questions the unity of the human, the Anthropocene fossil its significance.[85]

Conclusion

Framing the formation of the Earth's minerals within a schematic cosmological narrative, ME proposes that life and minerals have been deeply entangled since life began and suggests that their coevolution is a strand of the evolution of the cosmos. Minerals created the conditions under which life emerged, and then life interacted with the evolution of minerals.

Sentience and its accompaniment intentional agency then emerged from life and coevolved with both life and minerals. However, while the intentional behavior of sentient organisms, including humans, can have long-term effects on Earth history and on mineral formation, organisms cannot affect Earth history *intentionally*. Intentions enter Earth history as causes, but intentions are too transient to enter Earth history *as* intentions.

79. Ibid.; Williams, "Haraway Contra Deleuze and Guattari," 43.
80. Malm and Hornborg, "Geology of Mankind?"
81. Haraway, "Anthropocene, Capitalocene, Plantationocene, Chthulucene."
82. See, e.g., O'Madagain, "Group Agents: Persons, Mobs, or Zombies?"
83. Hazen, "Mineral Fodder."
84. Chakrabarty, "Climate of History," 212.
85. Yusoff, "Geologic Life," 782–87.

These conclusions may seem dispiriting, but they are not so. If the unimaginably long temporality of ME is a discomforting reminder of human insignificance, that is no bad thing. We are a limited species, limited in duration and power. We do not simply live *on* Earth, doing things to it. We *are* Earth, though a remarkably peculiar part of it. Ultimately, our agency can be nothing other than the agency of Earth itself.

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References

Armstrong, D. M. *A Materialist Theory of Mind*. London: Routledge, 1993.

Barad, Karen. "Matter Feels, Converses, Suffers, Desires, Yearns, and Remembers: Interview with Karen Barad." In *New Materialism: Interviews and Cartographies*, by Rick Dolphijn and Iris van der Tuin. Ann Arbor, MI: Open Humanities, 2012. doi:10.3998/ohp.11515701.0001.001.

———. *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning*. Durham, NC: Duke University Press, 2007.

Barandiaran, Xabier, Ezequiel Di Paolo, and Marieke Rohde. "Defining Agency: Individuality, Normativity, Asymmetry and Spatio-temporality in Action." *Journal of Adaptive Behavior* 1 (2009): 1–13. barandiaran.net/textos/defining_agency.

Batygin, K., G. Laughlin, and A. Morbidelli. "Born of Chaos." *Scientific American*, May 2016, 20–29.

Beisel, Uli, Franklin Ginn, and Maan Barua, eds. "Living with Awkward Creatures: Vulnerability, Togetherness, Killing." *Environmental Humanities* 4 (2014): 113–205.

Bennett, Jane. *Vibrant Matter: A Political Ecology of Things*. Durham, NC: Duke University Press, 2010.

Berner, Robert A. *The Phanerozoic Carbon Cycle: CO2 and O2*. Oxford: Oxford University Press, 2004.

Boisseau, Romain P., David Vogel, and Audrey Dussutour. "Habituation in Non-neural Organisms: Evidence from Slime Moulds." *Proceedings of the Royal Society B* 283, no. 1829 (2016). doi:10.1098/rspb.2016.0446.

Bradley, Dwight C. "Mineral Evolution and Earth History." *American Mineralogist* 100 (2015): 4–5.

Chaisson, Eric J. *Cosmic Evolution: The Rise of Complexity in Nature*. Cambridge, MA: Harvard University Press, 2001.

Chakrabarty, Dipesh. "The Anthropocene and the Convergence of Histories." In *The Anthropocene and the Global Environmental Crisis: Rethinking Modernity in a New Epoch*, edited by Clive Hamilton, Christopher Bonneuil, and Francois Gemenne, 44–56. London: Routledge, 2015.

———. "Climate and Capital: On Conjoined Histories." *Critical Inquiry* 41, no. 1 (2014): 1–23.

———. "The Climate of History: Four Theses." *Critical Inquiry* 35, no. 2 (2009): 197–222.

Chalmers, David. "Facing Up to the Problem of Consciousness." *Journal of Consciousness Studies* 2, no. 1 (1995): 200–219.

———. "Panpsychism and Panprotopsychism." Unpublished manuscript, consc.net/papers/panpsychism.pdf (accessed November 4, 2015).

Clark, Nigel. *Inhuman Nature: Sociable Life on Dynamic Planet*. Los Angeles: Sage, 2010.

Clark, Timothy. *Ecocriticism on the Edge: The Anthropocene as a Threshold Concept*. London: Bloomsbury, 2015.

Cohen, Jeffrey Jerome. *Stone: An Ecology of the Inhuman*. Minneapolis: University of Minnesota Press, 2015.

Crutzen, Paul J., and Eugene F. Stoermer, "The 'Anthropocene.'" *IGBP Newsletter* 41 (2000): 17–18.

Dennett, Daniel. *Consciousness Explained*. New York: Little, Brown, 1991

Dolphijn, Rick, and Iris van der Tuin. *New Materialism: Interviews and Cartographies*. Ann Arbor, MI: Open Humanities, 2012. doi:dx.doi.org/10.3998/ohp.11515701.0001.001.

Drury, Steve. "A Sign of the Times; the Anthropocene." *Earth-Pages: Research News from the Earth Sciences* (blog), May 30, 2011. earth-pages.co.uk/2011/05/30/a-sign-of-the-times-the-anthropocene/.

Dummett, Michael. *Frege: Philosophy of Language*. Cambridge, MA: Harvard University Press, 1981.

Fox, Douglas. "What Sparked the Cambrian Explosion?" *Nature* 530 (2016): 268–70. doi:10.1038/530268a.

Gould, Stephen Jay. *Life's Grandeur: The Spread of Excellence from Plato to Darwin*. London: Cape, 1996.

Gould, Stephen Jay, and R. C. Lewontin. "The Spandrels of San Marco and the Panglossian Paradigm: A Critique of the Adaptationist Programme." *Proceedings of the Royal Society B* 205, no. 1161 (1979): 581–98. doi:10.1098/rspb.1979.0086.

Grew, Edward S., and Robert M. Hazen. "Beryllium Mineral Evolution." *American Mineralogist* 99 (2014): 999–1021.

Grosz, Elizabeth. *Becoming Undone: Darwinian Reflections on Life, Politics, and Art*. Durham, NC: Duke University Press, 2011.

———. *The Nick of Time: Politics, Evolution, and the Untimely*. Durham, NC: Duke University Press, 2004.

Hamilton, Clive. "Human Destiny in the Anthropocene." In *The Anthropocene and the Global Environmental Crisis: Rethinking Modernity in a New Epoch*, edited by Clive Hamilton, Christopher Bonneuil, and Francois Gemenne, 32–43. London: Routledge, 2015.

Hamilton, Jennifer. "Bad Flowers: The Implications of a Phytocentric Deconstruction of the Western Philosophical Tradition for the Environmental Humanities." *Environmental Humanities* 7 (2015): 191–202.

Hand, Eric. "How Buried Water Makes Diamonds and Oil." *Science* 350 (2015): 613–14.

Haraway, Donna. "Anthropocene, Capitalocene, Plantationocene, Chthulucene: Making Kin." *Environmental Humanities* 6 (2015): 159–65.

———. *Simians, Cyborgs, and Women: The Reinvention of Nature*. New York: Routledge, 1991.

Hazen, Robert M. "The Evolution of Minerals." *Scientific American* 3 (2010): 58–65.

———. "Mineral Fodder." *Aeon Magazine*, June 24, 2014. aeon.co/essays/how-life-made-the-earth-into-a-cosmic-marvel.

Hazen, Robert M., Robert T. Downs, Linda Kah, and Dimitri Sverjensky. "Carbon Mineral Evolution." *Reviews in Mineralogy and Geochemistry* 75 (2013): 79–107.

Hazen, Robert M., Dimitri A. Sverjensky, David Azzolini, David L. Bish, Stephen C. Elmore, Linda Hinnov, and Ralph E. Milliken. "Clay Mineral Evolution." *American Mineralogist* 98 (2013): 2007–29.

Hazen, Robert M., Joshua Golden, Robert T. Downs, Grete Hystad, Edward S. Grew, David Azzolini, and Dimitri A. Sverjensky. "Mercury (Hg) Mineral Evolution: A Mineralogical Record of Supercontinent Assembly, Changing Ocean Geochemistry, and the Emerging Terrestrial Biosphere." *American Mineralogist* 97 (2012): 1013–42.

Hazen, Robert M., Dominic Papineau, Wouter Bleeker, Robert T. Downs, John M. Ferry, Timothy J. McCoy, Dimitri A. Sverjensky, and Hexiong Yang. "Mineral Evolution." *American Mineralogist* 93 (2008): 1693–1720.

Hazen, Robert M., and Niles Eldredge. "Themes and Variations in Complex Systems." *Elements* 6 (2010): 43–46. doi:10.2113/gselements.6.1.43.

Hird, Myra J. *The Origins of Sociable Life: Evolution after Science Studies*. Basingstoke: Palgrave Macmillan, 2009.

Hoffman, Peter M. *Life's Ratchet: How Molecular Machines Extract Order from Chaos*. New York: Basic, 2012.

Holland, John H. *Adaptation in Natural and Artificial Systems: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence*. Cambridge, MA: MIT Press, 1992.

Kauffman, Stuart A. *The Origins of Order*. Oxford: Oxford University Press, 1993.

Latour, Bruno. *Reassembling the Social: An Introduction to Actor-Network-Theory*. Oxford: Oxford University Press, 2005.

Lestel, Dominique, France Jeffrey Bussolini, and Matthew Chrulew. “The Phenomenology of Animal Life.” *Environmental Humanities* 5 (2014): 125–48.

Malm, Andreas, and Alf Hornborg. “The Geology of Mankind? A Critique of the Anthropocene Narrative.” *Anthropocene Review* 1, no. 1 (2014): 62–69.

Marder, M. “Plant Intentionality and the Phenomenological Framework of Plant Intelligence.” *Plant Signaling and Behavior* 7, no. 11 (2012): 1365–72.

Marletto, Chiara. “Life without Design.” *Aeon Magazine*, July 16, 2015. aeon.co/essays/how-constructor-theory-solves-the-riddle-of-life.

Marx, Karl. “The Eighteenth Brumaire of Louis Bonaparte.” In *The Marx-Engels Reader*, edited by Robert C. Tucker, 594–617. New York: Norton, 1978.

Maynard-Smith, John, and Eors Szathmary. *The Major Transitions in Evolution*. Oxford: Oxford University Press, 1997.

McCarthy, Cormac. *The Crossing*. New York: Vintage, 1995.

Mitchell, Melanie. *Complexity: A Guided Tour*. Oxford: Oxford University Press, 2009.

Morton, Timothy. *Ecology without Nature: Rethinking Environmental Aesthetics*. Cambridge, MA: Harvard University Press.

Nickel, Ernest H. “The Definition of a Mineral.” *Canadian Mineralogist* 33 (1995): 689–90.

O’Madagain, Cathal. “Group Agents: Persons, Mobs, or Zombies?” *International Journal of Philosophical Studies* 20, no. 2 (2012): 271–87.

Prigogine, Ilya, with Isabelle Stengers. *The End of Certainty: Time, Chaos, and the New Laws of Nature*. New York: Free Press, 1997.

Pross, Addy. *What Is Life? How Chemistry Becomes Biology*. Oxford: Oxford University Press, 2012.

Rose, Deborah Bird. “Val Plumwood’s Philosophical Animism: Attentive Interactions in the Sentient World.” *Environmental Humanities* 3 (2013): 93–109.

Ryan, Sean G., and Andrew J. Norton. *Stellar Evolution and Nucleosynthesis*. Cambridge: University of Cambridge Press, 2010.

Saigusa, Tetsu, et al. “Amoebae Anticipate Periodic Events.” *Hokkaido University Physical Review Letters* 100 (2008). eprints.lib.hokudai.ac.jp/dspace/bitstream/2115/33004/1/PhysRevLett_100_018101.pdf.

Sajama, Seppo, and Simo Vihjanen. “Representation and Reality.” In *Consciousness, Cognitive Schema, and Relativism: Multidisciplinary Explorations in Cognitive Science*, edited by Matti Kamppinen, 98–217. Dordrecht: Springer, 1993.

Scerri, Eric. *The Periodic Table: Its Story and Significance*. Oxford: Oxford University Press, 2007.

Steffen, W., P. J. Crutzen, and J. R. McNeill. “The Anthropocene: Are Humans Now Overwhelming the Great Forces of Nature?” *AMBIO* 36, no. 8 (2007): 614–21.

Strawson, Galen. “Free Agents.” In *Real Materialism and Other Essays*, 359–86. Oxford: Oxford University Press, 2008.

———. “Realistic Monism: Why Physicalism Entails Panpsychism.” In *Real Materialism and Other Essays*, 53–74. Oxford: Oxford University Press, 2008.

Thompson, D’Arcy Wentworth. *On Growth and Form*. Cambridge: Cambridge University Press, 1942.

Thompson, Evan. *Mind in Life: Biology, Phenomenology, and the Sciences of Mind*. Cambridge, MA: Harvard University Press, 2007

Tiainen, Milla, Katve-Kaisa Kontturi, and Ilona Hongisto. “Movement, Aesthetics, Ontology.” *Cultural Studies Review* 21, no. 2 (2015): 4–13. doi:dx.doi.org/10.5130/csr.v21i2.4737.

Tsiganis, Kleomenis. “Planetary Science: How the Planets Didn’t Form.” *Nature* 528 (2015): 202–4.

Van Dooren, Thom. *Flight Ways: Life and Loss at the Edge of Extinction*. New York: Columbia University Press, 2014.

Van Dooren, Thom, and Deborah Bird Rose. “Lively Ethnography: Storying Animist Worlds.” *Environmental Humanities* 8, no. 1 (2016): 77–94.

Vernadsky, V. I. “The Biosphere and the Noosphere.” *American Scientist* 33 (1945): 1–12.

Volk, Tylor. “Rise of Angiosperms as a Factor in Long-Term Climatic Cooling.” *Geology* 17 (1989): 107–10.

Whitehouse, Andrew. “Listening to Birds in the Anthropocene: The Anxious Semiotics of Sound in a Human-Dominated World.” *Environmental Humanities* 6 (2015): 53–71.
Williams, Linda. “Haraway Contra Deleuze and Guattari: The Question of the Animals.” *Communication, Politics, and Culture* 42, no. 1 (2009): 42–54.
Yang, Hexiong, Henry J. Sun, and Robert T. Downs. “Hazenite, KNaMg2(PO4)2•14H2O, a New Biologically Related Phosphate Mineral, from Mono Lake, California, U.S.A.” *American Mineralogist* 96 (2011): 675–81.
Yeager, Ashley. “Microbes Drove Earth’s Mineral Evolution.” *Nature,* November 14, 2008. doi:10.1038/news.2008.1226
Yusoff, Kathryn. “Geologic Life: Prehistory, Climate, Futures in the Anthropocene.” *Environment and Planning: Society and Space D* 31, no. 5 (2013): 779–95.
Zalasiewicz, Jan, Ryszard Kryza, and Mark Williams. “The Mineral Signature of the Anthropocene in Its Deep Time Context.” *Geological Society, London, Special Publications* 395 (2014): 109–17.